ALUMINIUM AND THE SEA

ALCAN AEROSPACE, TRANSPORTATION AND INDUSTRY

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ALCAN

THE GROWTH IN THE USE of aluminium in shipbuilding, especially in the construction of high-speed ships, prompted the Pechiney Group in 2001 to create PECHINEY MARINE, an entity endowed with significant resources and capable of handling all aspects of the "maritime markets" in aluminium.

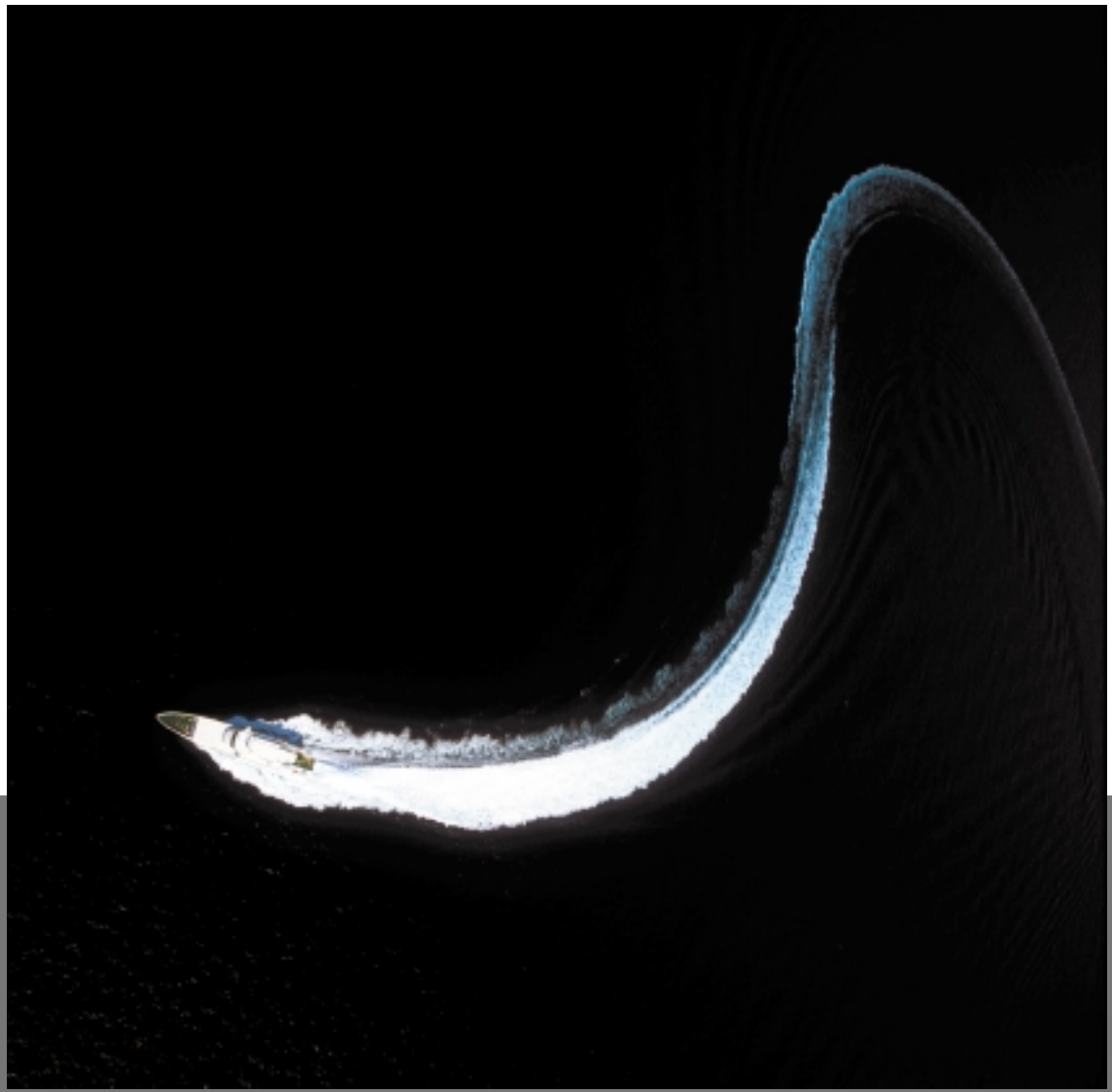
Pechiney's first brochure entitled "Aluminium and the Sea" was published in 1992 and received an excellent world-wide response in maritime circles, including naval architects, shipyards and shipowners. The brochure answered the needs of users wishing to use aluminium in marine applications and wanting to know more about it.

Given the scale of the growth in aluminium usage in larger vessels - 100 metres and more in length - this second brochure explores certain major aspects of shipbuilding in aluminium such as arc welding and fatigue strength in more depth.

Experience acquired in shipbuilding over many decades, especially with high-speed ships, illustrates the benefits which aluminium can offer to naval architects, yards and shipowners and more generally to users of aluminium for marine applications.

After the Pechiney integration into the Alcan Group in 2004, ALCAN MARINE succeds PECHINEY MARINE.

THE PRINCESS



MARINE

1. ALCAN MARINE: AN ENTITY DEDICATED TO THE MARITIME MARKET

The evolution that we have seen in the maritime uses of aluminium in high-speed ships, in shipbuilding (yachts, service vessels, superstructures) and in offshore applications calls for a fuller consideration and investigation of the technical aspects of the use of aluminium in markets that have a high engineering content.

In order to better respond to the needs and concerns of users of aluminium semi-finished products, Alcan Marine brings together engineering skills that are found throughout the Alcan Group:

- in production, with our production plants making aluminium sheets, plates and shapes,
- in research and development, with specialists in the calculation of structures and fatigue and metallurgists developing new alloys as well as optimising the properties of existing alloys,
- in the global commercial network of the Alcan Group.

Alcan Marine has three main objectives:

- to develop the marine applications of aluminium,
- to promote innovation in aluminium shipbuilding,
- to offer its clients the benefit of Alcan Group's many years of experience and expertise in the marine applications of aluminium.

2. PRESENTATION OF THE BROCHURE *ALUMINIUM AND THE SEA*

This brochure is published as part of our desire to provide aluminium users with a sound information base on the applications of aluminium.

It addresses all the players in the industry - naval architects, designers and research consultancies, shipyards, ship owners and operators - who use aluminium in marine applications: ships, offshore equipment and coastal installations.

THE LYNX



A number of important aspects have been developed, among them arc welding, now the most widespread method of fabrication in shipbuilding, and fatigue strength. The increase in the size of aluminium vessels is a recent phenomenon and brings with it its own particular problems.

It goes without saying that the sole aim of this brochure is to inform the reader about the properties of aluminium alloys intended for marine uses and about methods of application.

It cannot be a substitute for specialist literature that deals with the technologies used in aluminium shipbuilding. Nor can it take precedence over the regulations of classification societies, standards and codes of engineering practice with which designers are bound to comply, including the selection of aluminium alloys.

This brochure is the work of Christian VARGEL, a former Chief Engineer in the Pechiney Group and author of the book *Corrosion de l'Aluminium*, 528 pages, published by DUNOD in February 1999 and published in English by ELSEVIER in October 2004 under the title *Corrosion of Aluminium*,

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Notes:

For the sake of simplicity, the term "ALUMINIUM" as used in this brochure means aluminium alloys and not the unalloyed metal.

All the figures given in this brochure are in the units of the International System (IS).

This publication is not a contract document and shall in no way incur the liability of Alcan on account of the information contained herein.

This information is given purely as a guide and it is for the reader to verify its accuracy and to consult the Alcan Group and other experts before use.


PECHINEY



THE VESUVIO JET

Chapter 1
ALUMINIUM, THE MARINE METAL

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1. ALUMINIUM,

IT IS AN OLD STORY that goes back over a century, and one which incidentally accompanied the birth of the aluminium industry.

The industrialisation of aluminium production by dry electrolysis began in 1886 with the utilisation of the patent of Paul Louis Héroult in France and Charles Martin Hall in the United States.

Less than a decade later, from 1891 to 1897, a number of attempts were made both in Europe and the United States to build ships from aluminium. Although short-lived, these experiments proved highly illuminating and informative, and the performance of these vessels revealed the full potential of aluminium for marine applications.

In the Nineteen Thirties, aluminium's adventure in ship construction was re-launched on new concepts based on the use of special alloys and methods of assembly that have continued to advance to the present day.



The Aluminum World.

A JOURNAL FOR MANUFACTURERS OF ALUMINUM AND ITS ALLOYS, DEALERS IN ALUMINUM GOODS, AND FOR THE METAL INDUSTRY IN GENERAL, WITH SPECIAL REFERENCE TO THE REDUCTION OF ORES BY ELECTRICITY.

VOL. II. NEW YORK, DECEMBER, 1895. No. 3.

ALUMINUM: ITS ALLOYS AND THEIR USE IN SHIP CONSTRUCTION.

BY JAMES C. McGUIRE, ESQ., ASSOCIATE.*

Owing to the limited knowledge of the uses and manner in which aluminum is used and worked, the author of this paper thinks it advisable to describe some of the metal's principal characteristics, before dealing directly with the final uses to which it is put, or for what purpose it is and can be used in ship construction.

The metal aluminum, as manufactured to-day on a commercial basis, is made entirely by the electrolytic process.

The ordinary aluminum of commerce runs about 99 or 99.5 per cent. pure, the impurities being iron and silicon in about the following proportions:

Aluminum ..... 99.25 per cent.
Silicon ..... .50 per cent.
Iron ..... .25 per cent.

Aluminum can be and has been made as high as 99.90

The Aluminum World, *December 1895* [2]. Figure 1

1. HISTORICAL REVIEW

Although much more expensive than steel, some 30 times more in 1895 [1] (1), aluminium quickly aroused the interest of maritime circles (figure 1). Its light weight was initially the principal reason for the use of aluminium in shipbuilding.

(1) *By the year 2000 aluminium was around 4 to 5 times more expensive than steel, or between 2 and 2.5 times allowing for a 50% reduction in weight.*

1.1 Early beginnings, 1890 to 1900

The very first boat known to be made of aluminium, a "steam launch" 5.50 metres in length, with a beam of 1.28 metres and a draft of 0.61 metres, was built in 1891 by the Swiss shipyard Escher Wyss in Zurich [3]. Its hull alone weighed 440 kg. This boat was powered by a steam engine that ran on oil (figure 2).

THE AMPORELLE



THE MARINE METAL

Alfred Nobel, the inventor of dynamite and creator of the famous prize, placed an order with the same shipyard for a boat, "Le Mignon". This vessel was 13 metres long, had a 1.80 metre beam and a draft of 0.61 metres, and was kept moored in front of Nobel's villa at San Remo in Italy. It too was powered by an oil-fired steam engine. During trials on Lake Zurich, "Le Mignon" attained a speed of 13 km/h (8 knots).

In France, a wealthy aristocrat and keen regatta yachtsman, Comte Jacques de Chabannes de la Palice, appointed a naval architect to design the first aluminium sailing boat in history, "Le Vendenesse". This vessel was built at Saint Denis near Paris, and was launched on the 6 December 1893.

"Le Vendenesse" was 17.40 metres long overall, with 180 m^2 of canvas and a displacement of 15 tonnes. The 2 mm thick aluminium skin, riveted to steel frames, saved 40% on the weight of the hull.

Inspired by experience with the Vendenesse, the holders of the America Cup had the skin of their boat "Defender" made from aluminium. With its weight thus reduced, it won the America Cup unopposed in September 1895 (figure 3).

Navies too took an interest in aluminium. Thus it was that in 1894 the French navy placed an order for a torpedo-boat, "Le Foudre", with the British shipyard Yarrow & Co. This vessel had a length of 19 metres, a beam of



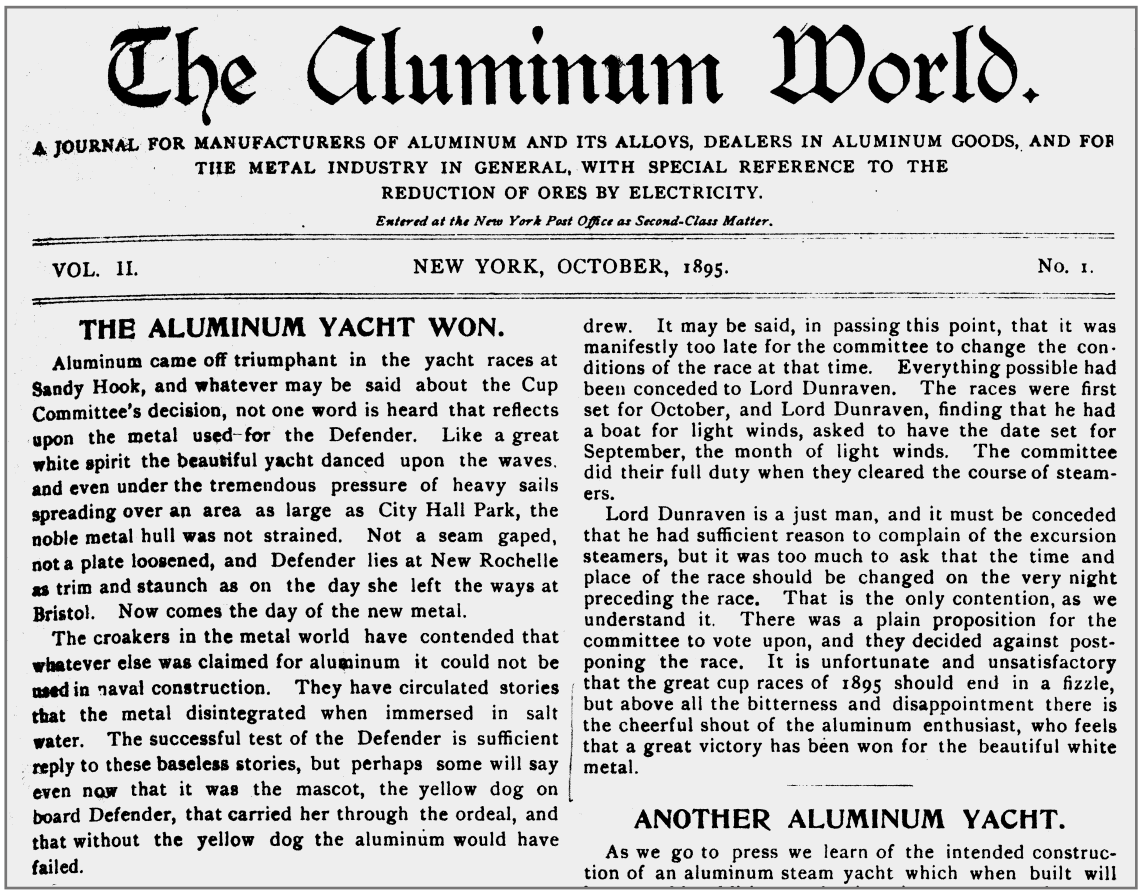
Aluminium launch (1891). Figure 2

2.80 metres and a draft of 1.45 metres with a displacement of 14 tonnes. The bare hull weighed just 2500 kg. The skin and frames were made from aluminium sheet 1 to 5 mm thick [4].

In 1895 the same yard also constructed a 58 metre (190 feet) long torpedo-boat, the "Sokol", for the Russian navy. Powered by a 4000 HP engine, it attained the speed record for the time of 32 knots [5].

THE HSV ALISO





The Aluminum World.

A JOURNAL FOR MANUFACTURERS OF ALUMINUM AND ITS ALLOYS, DEALERS IN ALUMINUM GOODS, AND FOR THE METAL INDUSTRY IN GENERAL, WITH SPECIAL REFERENCE TO THE REDUCTION OF ORES BY ELECTRICITY.

Entered at the New York Post Office as Second-Class Matter.

VOL. II. NEW YORK, OCTOBER, 1895. No. 1.

THE ALUMINUM YACHT WON.

Aluminum came off triumphant in the yacht races at Sandy Hook, and whatever may be said about the Cup Committee's decision, not one word is heard that reflects upon the metal used for the Defender. Like a great white spirit the beautiful yacht danced upon the waves, and even under the tremendous pressure of heavy sails spreading over an area as large as City Hall Park, the noble metal hull was not strained. Not a seam gaped, not a plate loosened, and Defender lies at New Rochelle as trim and staunch as on the day she left the ways at Bristol. Now comes the day of the new metal.

The croakers in the metal world have contended that whatever else was claimed for aluminum it could not be used in naval construction. They have circulated stories that the metal disintegrated when immersed in salt water. The successful test of the Defender is sufficient reply to these baseless stories, but perhaps some will say even now that it was the mascot, the yellow dog on board Defender, that carried her through the ordeal, and that without the yellow dog the aluminum would have failed.

drew. It may be said, in passing this point, that it was manifestly too late for the committee to change the conditions of the race at that time. Everything possible had been conceded to Lord Dunraven. The races were first set for October, and Lord Dunraven, finding that he had a boat for light winds, asked to have the date set for September, the month of light winds. The committee did their full duty when they cleared the course of steamers.

Lord Dunraven is a just man, and it must be conceded that he had sufficient reason to complain of the excursion steamers, but it was too much to ask that the time and place of the race should be changed on the very night preceding the race. That is the only contention, as we understand it. There was a plain proposition for the committee to vote upon, and they decided against postponing the race. It is unfortunate and unsatisfactory that the great cup races of 1895 should end in a fizzle, but above all the bitterness and disappointment there is the cheerful shout of the aluminum enthusiast, who feels that a great victory has been won for the beautiful white metal.

ANOTHER ALUMINUM YACHT.

As we go to press we learn of the intended construction of an aluminum steam yacht which when built will

The Aluminium World, *October 1895* [7].

Figure 3

The superstructures of a number of ships of the US Navy were made of aluminium but were rapidly replaced by … steel [6].

The use of aluminium in naval construction was not pursued beyond 1900 owing to the fact that the service life of these vessels was generally very short. The aluminium showed signs of severe corrosion in contact with seawater just a few weeks or at most several months after they were launched [8].

There were a number of reasons for this failure:

- the metal itself. In order to harden aluminium to obtain acceptable mechanical properties, up to 6% copper was added to it in Europe [9] and up to 4% of nickel in the USA [10]. It is well known that these elements are not at all favourable to corrosion resistance, a situation aggravated by an ignorance of the metallurgy of age hardening alloys at that time (2),
- heterogeneous methods of assembly. Parts made of aluminium were riveted to frames made of steel (using steel rivets and even rivets in cuprous alloy!!!) These were ideal conditions for producing galvanic corrosion whose effect on the aluminium was both rapid (within just a few weeks) and severe on a material already sensitised by the presence of copper or nickel,
- contemporary surface finishes were unsuitable for aluminium, not to say catastrophic for corrosion resistance due to the use of red lead oxide, as was the case on a number of ships such as the torpedo-boat "Le Foudre".

The service life of aluminium vessels operating in fresh water environments at the time was much longer on the other hand. In 1893, five aluminium launches with a length of 12 metres and a beam of 3 metres were constructed in France at the initiative of the Ministry for the Colonies. They were made in sections that could be taken apart and carried on men's backs, and were intended for use in the exploration of two major African rivers, the Congo and the Niger; they had a service life of several years, beyond 1900 [11].

(2) *The age hardening of aluminium alloys containing copper - "the duralumins" - was discovered by Wilm in 1908.*

1.2 Weight reduction, safety and decoration of ships 1920 - 1950

The experience of the final decade of the 19th century had demonstrated that aluminium could be used to significantly lighten a boat and hence to increase its speed. The triumph of "Defender" in the America Cup of 1895 was proof of this.

In the first half of the 20th century, from 1920 onwards, aluminium regained an increasingly important place in both civil and military shipping. There were three main reasons for this:

- the availability of aluminium-magnesium wrought alloys of the 5000 series. These are ideally suited for marine applications in general and for shipbuilding in particular (cf. Chapters 2 and 3),
- the need to reduce the weight of warships to meet the requirements of the Washington Conference of 1922,
- the safety (and comfort) of passengers travelling on liners.

In the Nineteen Twenties, the first and probably most widespread applications were parts moulded from an alloy with 13% silicon, known at the time as "alpax", used in the equipment of warships, such as the casings of engines, pumps and fans, electrical enclosures, doors [12], etc.

Out of considerations of safety (superior strength in the event of fire) and weight, officers' cabins were increasingly equipped with furniture made from aluminium, usually painted duralumin [13, 14].

Aluminium also found increasing use in the interior equipment of merchant vessels and liners:

- both for safety reasons, superseding timber furniture that would burn and give off smoke and fumes in a fire,
- and to enhance decoration (3) on prestigious liners. The furniture in the cabins of the Normandie for example were made from "duralumin" [15], while the public areas on many liners (salons, dining rooms etc.) were adorned with motifs in aluminium that were often commissioned from famous designers [16].

Through its association with luxury, prestige, comfort and safety, aluminium found widespread use on the last transatlantic liners to be launched. 1600 tonnes of alu-

GRILLES AROUND THE LIFT SHAFT OF THE LINER *MAURETANIA*

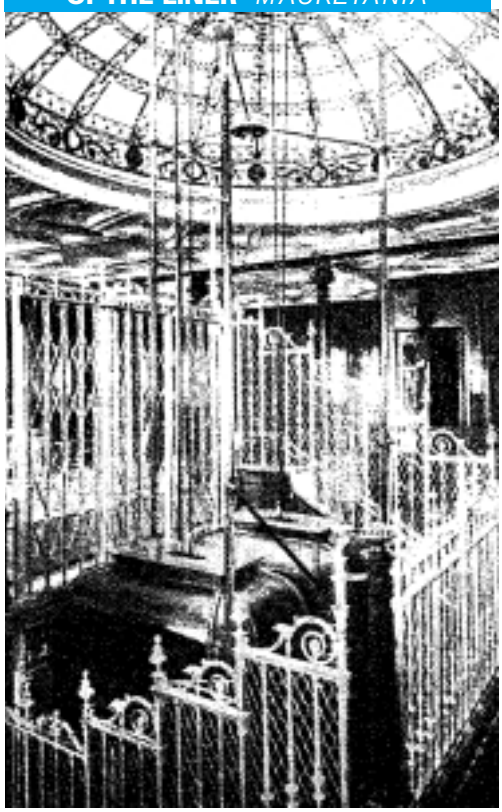


Figure 4

(3) *Including the many outstanding artistic creations in the Art Deco style.*

RIVETED CONSTRUCTION OF THE *DIANA II*



Figure 5

minium alloys were used on the France, launched in 1962, in superstructures, funnels, lifeboats etc. [17].

The first boats to be made entirely of aluminium were launched at the beginning of the Nineteen Thirties. These were the first marine applications of an alloy with 3% of magnesium (4) whose industrial production had just been perfected:

- in Great Britain, the first all-aluminium racing yacht, the "Diana II", was built and launched at Southampton in August 1931. It was 19 metres long with a displacement of 10.5 tons. It was fabricated by riveting according to the customary practices of the day (figure 5). Requisitioned by the British Admiralty from 1939 to 1945, the "Diana II" ended its career in the Nineteen Fifties still in very good condition [18].
- in Canada, three years later in May 1934, came the patrol boat "Interceptor" with a length of 21.50 metres.

(4) *Equivalent to the 5754.*

2. THE DEVELOPMENT OF ALUMINIUM-MAGNESIUM ALLOYS OF THE 5000 FAMILY

Detailed studies of aluminium-magnesium alloys of the 5000 family (or series) began in 1900 [19]. The development of industrial wrought alloys as we know them today was carried out in the period 1930 -1960.

A number of eminent European and American metallurgists and corrosion experts contributed to this achievement. They include E. H. Dix of Alcoa [20, 21], P. Brenner of VAW [22, 23] and A. Guilhaudis of Pechiney [24, 25].

These studies succeeded in limiting the amount of magnesium in wrought alloys to 5% and identifying the ranges of sensitisation temperature (5) as a function of the magnesium content. The H116 temper was the result of this work.

Corrosion tests in seawater and sea spray were used to verify the high corrosion resistance of wrought alloys in aluminium-magnesium (5000 series) and aluminium-magnesium-silicon (6000 series) in marine environments [26, 27], even when unprotected (neither painted nor anodised) [28].

Numerous tests were carried out on welded assemblies and hybrid assemblies (with other usual metals) to investigate the influence of methods of assembly, to measure the extent of galvanic corrosion phenomena and to research ways of avoiding them.

In the USA in 1936, a section of boat fitted with a transmission shaft, a propellor and other items of equipment was subjected to an immersion test (6) [29, 30]. The purpose of this test was to study the behaviour of aluminium in shipbuilding on a representative mockup.

Marine applications, especially on board mercantile vessels and warships, were convincing enough for it to be accepted from 1930 on that aluminium displayed excellent corrosion resistance in maritime environments [31].

Once the benefits of aluminium in shipbuilding had been recognised, official bodies responsible for shipping control, associations of naval architects and aluminium manufacturers established codes of practice [32] and guidance for usage [33, 34].

The experience that has been accumulated since 1930 coupled with developments in the working of "marine" aluminium alloys and advances in assembly techniques using arc welding which finally replaced traditional riveting in 1955, is such that since the Nineteen Sixties aluminium has been a real option in the construction of ships and coastal installations.

In addition, given the advantages which it offers to marine applications - light weight, corrosion resistance etc. (7) - aluminium has become one of the materials of choice in the development of many marine applications.

(5) *Preferential precipitation at the grain boundaries of the intermetallic βAl_3Mg_2.*

(6) *The "Alumette", with a length of 4.30 m, a beam of 3.30 m and a draft of 1.65 metres, was tested in January 1936 by immersion in seawater at Newport.*

(7) *Cf. Chapter 2, Aluminium's Advantages.*

3. MARINE APPLICATIONS OF ALUMINIUM

Since 1960, aluminium has become firmly established in many different sectors throughout the world [35]:

- high speed passenger ships
- boating and yachting,
- work boats and surveillance vessels,
- fishing boats,
- offshore,
- coastal installations including marinas,
- the superstructures of ships of all kinds, etc.

3.1 High speed ships

From 1960 onwards, a large number of conventional passenger transport vessels were constructed in aluminium. These were generally monohulls with lengths that initially did not exceed 25 – 30 metres.

The first high speed ships – catamarans – were launched in Scandinavia in the early Nineteen Seventies. These passenger ships were 20 to 25 metres long and with seating capacities ranging from 100 to 200 depending on how then were fitted out.

This type of boat must be as light as possible, and is the reason why most of the high speed ships (HSS) launched over the past 30 years are made of aluminium (Table 11).

They have become a rapid mode of transport and are used on scheduled ferry services carrying not only passengers but vehicles as well (cars, coaches, trucks etc.).

The size and capacity of high speed ships has continued to increase since 1980 and today, catamarans and monohulls can exceed 100 metres in length.

ANNUAL LAUNCH OF HIGH SPEED SHIPS (*)

Type of ship	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	Total
Catamarans	17	29	38	25	26	32	28	46	44	39	46	52	36	39	33	33	46	**609**
Wave Piercers		1	3	5	4	1	3	3	2	4	5	3	6		3	3	1	**47**
Hydrofoils/Hovercrafts	6	8	6	12	12	18	8	4	5	10	1	1	6		1	1	5	**104**
Monohulls	14	12	16	7	13	8	7	12	10	13	22	11	15	17	5	5	9	**196**
Surface effect ships	5		7	5	7		3	1	4	2				1			1	**36**
SWATH				2	1												1	**4**
Total	**42**	**50**	**70**	**56**	**63**	**59**	**49**	**66**	**65**	**68**	**74**	**67**	**63**	**57**	**42**	**42**	**63**	**996**

(*) Statistics from Fast Ferry International. Table 1

CAPACITY OF HSS - NUMBER OF SEATS (*)

Number of seats	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	Total
50-99	7	13	18	5	5	6	7	5	1	4	2	6	5		1	6	11	102
100-149	10	4	6	4	4	12	1	4	8	7	4	5	2	8	7	7	7	100
150-199	1	1	5	8	5	8	4	6	10	3	7	16	10	6	5	5	16	116
200-249	6	7	8	15	10	7	2	8	7	6	9	3	8	4	2	1	5	108
250-299	5	10	10	8	16	10	5	9	9	6	1	5	2	2		4	6	108
300-349	5	1	12	10	13	7	11	18	10	12	14	11	8	2	6	2	1	143
350-399	1	4	4	12	3	7	11	8	9	6	5	2	5	5	3	6	3	94
400-449		7	5	4	4		2	3	4	7	5			3	4	5	9	62
450 et +	2		2	1	1		1		1	7	3	4	7	9		1	1	40

(*) Statistics from Fast Ferry International. Table 2

Among the aluminium vessels over 100 metres long launched in the Nineteen Nineties, we can list:

- the 4 Stena HSS 1500 catamarans first used on the Irish Sea in 1996 [36]. These boats, 126.6 metres long and with a 40 metre beam, were built in Finland by Finnyards and weigh 1500 tonnes unladen. They can seat 1500 passengers and carry 375 cars, 120 coaches and 50 trucks at a maximum speed of 40 knots,

- the catamarans 122.5 metres long and 25.8 wide [37] built by the Canadian CFI yard for BC Ferries in 1999. These boats weigh 1281 tonnes. They can seat 1018 passengers and carry 250 cars, 242 trucks (or 242 coaches) at a maximum speed of 34 knots.

- the 11 TMV 115 Aquastrada built by the Italian yard of Rodriquez, length 115.25 metres [38, 39], capacity 900 passengers, 200 cars, speed 36 knots,

- the Fincantieri MDV, 100 metres in length [40], with a capacity of 782 passengers and 175 cars, and a speed of 40 knots,

- The Bazàn Alhambra which is 125 metres long [41, 42] , with a capacity of 1200 passengers and 244 cars and a speed of 40 knots

- the two Corsaire 11000, Aliso and Asco, built by Alstom Leroux Naval [43] and launched in 1996 and 1997, with a length of 102 metres, can carry 500 passengers, 148 cars and 112 coaches at a speed of 37 knots.

3.2 Boating and yachting

Aluminium occupies a privileged place in this sector, offering as it does the chance to build one of a kind boats that are made to measure and customised to suit the preferences of the buyer who will often also choose his own naval architect and shipyard and personally monitor the construction process.

The number of yachts that are over 24 metres long is expanding rapidly, both in terms of the number of units and the size of the vessels. 48 of the 282 yachts launched in 1999 for example were over 46 metres long, while of the 482 yachts launched in 2003, 98 exceeded 46 metres (8). Over half of all yachts have aluminium hulls.

The masts and superstructure of yachts are made from aluminium alloys which can be anodised to meet the very exacting aesthetic criteria for this equipment.

3.3 Work boats

Although it is in competition with steel and above all with FRP (fibre-reinforced plastic), aluminium nevertheless occupies a very important place – accounting for at least half of the units in service – in all types of work boat used for fishing, marine cultures, coastal surveillance, customs and police, or serving offshore oil installations.

As well as its light weight and the ease with which one of a kind boats can be made (no moulds), aluminium offers safety (fire resistance, no release of smoke or fumes in a fire) and a long service life (with no alteration to the properties of the material).

Boats made from aluminium meet the needs of offshore operators with their capacity, speed and safety. It is common to find aluminium boats over 40 metres long that are capable of carrying between 50 and 100 persons and 200 tonnes and more of freight [44, 45].

3.4 Ship superstructures

Fitting aluminium superstructures on civil or military ships is an idea that goes back to the Nineteen Thirties. Reducing the weight of the "upper works" of a vessel has the direct effect of lightening the rest of the vessel and improving its stability (9).

Today, aluminium superstructures are a very common feature of high speed ships over 120 metres long and cruise ships etc., but it is not unusual to find trawlers of 20 to 30 metres with wheelhouses made from aluminium.

When monohull high speed ships have a hull made of steel, their superstructures are always aluminium - this is true of the Fincantieri Pegasus, 95 metres long [46], the Fincantieri Jupiter with a length of 145.6 metres [47], the Liamone (134 metres long) and the Aeolos Express (119 metres long) built by Alstom Leroux Naval [48].

Connecting structures made of steel to superstructures made of aluminium was greatly simplified by the introduction of aluminium–steel "transition joints" in the early Nineteen Seventies (10).

(8) *Source: Order Book of ShowBoats International.*

(9) *By affecting the "r - a".*

(10) *Cf Chapter 7.*

3.5 Offshore

The uses of aluminium in the oil industry were limited so long as the petroleum industry remained ignorant about the fire resistant properties of aluminium.

Numerous experiments in the Nineteen Fifties with drill stems and various items of equipment including heat exchangers etc. highlighted the full potential of aluminium in this area, with its lightness of weight, good resistance to environments charged with sulphur dioxide SO_2, marine environments etc. [49, 50, 51].

The first known applications in the offshore industries came in the Venezuelan oilfield in Lake Maracaibo in 1957 [52]. In this aquatic environment rendered highly aggressive by the presence of brackish water (generally more aggressive than natural seawater), the aluminium structures of the oil platforms displayed very good resistance to corrosion [53].

Since then, aluminium has made inroads into offshore applications, first in the construction of landing pads for helicopters ("Helidecks") and then as living quarters [54, 55, 56].

Given the trend of offshore oil exploration to ever greater depths, aluminium is set to become widely used in platforms in order to reduce their weight, increase their payload, improve their stability and facilitate their mobility and installation (requiring less powerful lifting equipment).

The excellent corrosion resistance of aluminium alloys in marine environments greatly reduces maintenance costs (no painting for example). Finally, the residual value of these installations is enhanced as a result.

A number of underwater research vessels and very many marker buoys are made from aluminium, and there is one American oceanographic research submarine that has been constructed in aluminium alloy [57].

3.6 Coastal installations

The growth in private leisure boating and yachting was soon followed by the construction of numerous marinas to provide berthing for these craft. In France and throughout Europe, all of these installations have been made from aluminium alloy since 1970. There are, for example, over 300 kilometres of jetties on France's Atlantic and Mediterranean coasts, providing berths ("rings") for over 500,000 craft. The oldest aluminium marinas in France were built more than 30 years ago.

This type of application illustrates the potential of aluminium in marine environments, with the initial extra cost of aluminium compared with other materials (steel or concrete) being very largely offset by the lack of maintenance that is needed.

Aluminium is used very widely in the manufacture of signs for roads and towns, and in street furniture for coastal towns and cities. Its pleasing appearance and freedom from maintenance (due to its outstanding corrosion resistance) accounts for the choice of urban planners.

4. INNOVATION

The growth in the marine uses of aluminium, including shipbuilding since 1950, has been due primarily to aluminium's properties: its lightness and resistance to corrosion in maritime environments.

Since the early Nineteen Seventies, aluminium has been key to the development of high speed ships because innovations in terms of alloys and semis have met the expectations of naval architects and shipbuilders, allowing them to create vessels that are larger and offering higher all-round nautical performance.

This claim is borne out by the fact that most of the major projects in the development of rapid passenger and cargo transport, with new concepts of naval architecture, are based on the use of aluminium [58, 59, 60]. Cases in point include the Japanese TSL very long ship project (11) and the BGV project (12) of the naval architect Gilles Vaton.

The metallurgy of aluminium is being enriched with new alloys that perform better in terms of mechanical properties [61].

Methods of assembly by arc welding, laser or friction are evolving towards an optimisation of energy input with a view to reducing strain and enhancing the quality of welded joints which in turn determines the fatigue strength of welded structures in the zones subject to greatest stress.

(11) *TSL = Techno Super Liner of MES (Mitsui Engineering & Shipbuilding).*

(12) *B.G.V. meaning Bateau de Grande Vitesse (High Speed Boat) and also Bureau Gilles Vaton.*

Developments in structural bonding with adhesives specially adapted to the marine environment make it possible to achieve hybrid assemblies and eliminate the loss of mechanical characteristics in the heat affected zone.

Methods of calculation should evolve towards the ULS (13) and LFRD (14) concepts which are already being used in aeronautics to optimise structure dimensions while combining lightness and safety.

Finally, and contrary to a received idea, there is nothing to indicate that there is a limit to the length of "all aluminium" boats - both hulls and superstructures.

In 1970 the first catamarans launched by Scandinavian shipyards were 25 – 30 metres long. By the end of the Nineties, aluminium catamarans and monohulls were achieving lengths of 120 metres and more, and their carrying capacity continues to grow (Table 2).

(13) *ULS = Ultimate Limit State Design.*

(14) *LFRD Load Resistance Factor Design.*

Bibliography

[1] "Notes on the yacht *Defender* and the use of aluminum in marine construction", Richmond Pearson Hobson, Assistant Naval Constructor, US Naval Institute, *Proceeding* 1897, pp. 523-562.

[2] "Aluminum: its alloys and their use in ship construction", *The Aluminum World*, Volume 2, No. 3, December 1895, pp. 49-56.

[3] "Le métal de l'Ange", Corine Renié and Daniel Charles, *Voiles et Voiliers*, No. 229, March 1990, pp. 70-75.

[4] "La possibilité d'application de l'aluminium et de ses alliages dans la Marine", R. Guérin, *Revue de l'aluminium* , No. 12, April 1926, pp. 204-209.

[5] "Fastest in the World", *The Aluminum World*, Volume 2, No. 1, October 1895, p. 9.

[6] "The History of aluminum as a deckhouse material", Robert A Sielski, Naval engineering Journal, May 1987, pp. 165-172.

[7] "The Aluminum yacht won", *The Aluminum World*, Volume 2, No. 1, October 1895, pp. 1-2.

[8] "100 years of the use of aluminium in shipbuilding", DJ Howarth, JC Huskins, *Lloyd's Register of Shipbuilding*, Conference Ausmarine 1994, pp. 114-126.

[9] *The Journal of the Society of Chemical Industry*, page 487/489, May 31, 1895

[10] "Aluminum for boat building", *The Aluminum World*, Volume 1, No. 11, August 1895, pp. 201-202.

[11] "L'aluminium et ses alliages dans les constructions navales", A de Biran, *Revue de l'Aluminium*, No. 42, 1931, pp. 1371-1396.

[12] "L'évolution des applications des alliages légers et notamment de l'Alpax dans les marines de guerre", R. de Fleury, *Revue de l'Aluminium*, No. 19, 1927, pp. 464-465.

[13] "Mobilier et marine", J. Dumontet, *Revue de l'Aluminium*, No. 111, 1939, pp. 1695-1699.

[14] "Notes on the development of certain materials used in ships of the U.S. Navy", Rear Admiral George H. Rock (CC) U. S. Navy, Vice President, *Transactions of Society of Naval Architects Marine Engineers*, 1931, pp. 215-249.

[15] "L'aluminium et les alliages légers dans les moyens de transport", M. Pubelier, *Revue de l'Aluminium*, No. 77, 1936, p. 32.

[16] "Aluminium and its alloys", G. O. Taylor, *The Metal Industry*, April 1943.

[17] "Le paquebot France, 1 600 tonnes d'aluminium", *Revue de l'Aluminium*, No. 297 and 299, 1962.

[18] "The applications of aluminium alloys to marine uses", *The Aluminium Development Association,* London 1948.

[19] "Sur les alliages d'aluminium et de magnésium", Note de M. Boudouard, *Compte Rendu Académie des Sciences*, Volume 132, 1901, p. 325.

[20] "Equilibrium relations in aluminum-magnesium alloys of high purety", E. H. Dix, F. Keller, *Transactions A.I.M.E.*, Vol 83, 1929, pp. 351-372.

[21] "Development of wrought aluminum-magnesium Alloys", E. H. Dix, Jr. W. A. Anderson and M. Byron Shumaker, *Technical Paper* No. 14, Aluminum Company of America, 1958.

[22] "Korrosionsversuche mit Hydrolanium", *Zeitschrift für Metallkunde*, Vol 25, 1933, pp. 252-258.

[23] "Recent developments in corrosion resistant aluminium-magnesium alloys", P. Brenner, W. Roth, *Journal Institute of Metals*, Vol 74, 1948, pp. 159 -190.

[24] "Traitements thermiques de stabilisation des alliages d'aluminium-magnésium à 5%, contre les effets de chauffage à basses températures", *Revue de l'aluminium*, 1955, Nos. 223, pp. 717-725 and 224, pp. 795-801.

[25] "Addition de chrome et de manganèse dans les alliages légers à 3 et 5% de magnésium", A Guilhaudis and R. Develay, *Revue de Métallurgie,* No. 4, 1957, pp. 288-298.

[26] "La tenue des alliages légers à la corrosion à la corrosion marine", A. Guilhaudis, *Revue de l'Aluminium*, No. 186, March 1952, pp. 85-91, No. 187, April 1952, pp. 127-133, and No. 188, May 1952, pp. 192-198.

[27] "Corrosion behaviour of aluminium alloys in seawater", H. P. Godard and F. F. Booth, *Conférence Centre Recherches Etudes Océanographiques*, Vol 6, 1965, pp. 37-52.

[28] "Etat d'un radeau en alliages d'aluminium en mer depuis 25 ans", A. Guilhaudis *Revue de l'Aluminium*, No 433, 1974, pp. 565-574.

[29] "Resistance of Aluminum-Base alloys to Marine exposure", R. B. Mears, R. H. Brown, *Transactions of Society of Naval Architects Marine Engineers*,1930, pp. 27-42.

[30] "Performance of aluminum alloys in marine environments", C. J. Walton, E. T. Englehart, Alcoa, *Meeting of The Society of Naval Architects and Marine Engineers*, Nov. 1949.

[31] "Uses of aluminum in shipbuilding", Paul V. Faragher, *Transactions of Society of Naval Architects Marine Engineers*, Vol. 52, 1944, pp. 91-113.

[32] "The Use of Aluminum Alloys in Vessels of the United States Navy", S. N. Pyne, P. W. Snyder, H. D. McKinnon, *Technical Bulletin* No. 1, 1940.

[33] "Practical Problems Relative to the Use of Aluminum Alloys in Ship Construction", C. V. Boykin, M. L. Sellers, *Transactions of Society of Naval Architects Marine Engineers,* 1953, pp. 358-409.

[34] "L'utilisation de l'aluminium et de ses allaiges en construction navale", *L'aluminium Français*, brochure 1962, p. 60.

[35] "L'aluminium et la mer", C. Vargel, Matériaux et Techniques, May 1986, pp. 233-245.

[36] "First Stena HSS 1500 delivered by Finnyards", *Fast Ferry International*, April 1996, pp. 15-24.

[37] "CFI delivers second PacifiCat to BC Ferries", *Fast Ferry International*, November 1999, pp. 15-28.

[38] "Rodriquez delivers TMV 115 Aquastrada to Spanish operator", *Fast Ferry International*, July 2001, pp. 19-22.

[39] "New Aquastrada and R&D contracts for Rodriquez", *Fast Ferry International*, November 2000, pp. 15-17.

[40] "Fincantieri delivers three MDV 1200 Monohulls", *Fast Ferry International*, June 1997, pp. 19-23.

[41] "First Bazàn Alhambra completes trials programme", *Fast Ferry International*, December 1996, pp. 15-19.

[42] Silvia Ana, Tony Wilson, Speed at Sea, Vol 3, Issue 1, 1997, pp. 8-13.

[43] "SNCM Feryterranée introduces Corsaire 11000", *Fast Ferry International*, July 1996, pp. 19-25.

[44] "New generation crew/supply vessel for the Gulf of Mexico", *Work Boat World*, Dec. 1994.

[45] "Magic Tide, 135' Aluminium Crew/Supply boat", *Work Boat World*, July 1995.

[46] "First Fincantieri Pegasus monohull leased to Stena Line", *Fast Ferry International,* June 1996, pp. 17-22.

[47] "Fincantieri Jupiter monohulls complete first season", *Fast Ferry International*, October 1998, pp. 15-20.

[48] "ALN monohulls enter service in France and Greece", *Fast Ferry International*, June 2000, pp. 22-28.

[49] "L'aluminium dans l'industrie du pétrole", *Revue de l'aluminium*, No. 243, 1957 pp. 531-534.

[50] "New uses for aluminium", B. J. Fletcher, *Petroleum Processing*, Vol 4, 1949, pp. 1105-1108.

[51] "Les tiges de forage en aluminium", M. Frossard et J. P. Lamotte, *Revue de l'aluminium,* No. 320, 1964, pp. 554-558.

[52] "Tentative recommended Pratice for Use of aluminum in Lake Maracaibo", H. P. Godard, W. L. Perkins, *Materials Protection*, October 1963, p. 105.

[53] "Engouement pour l'aluminium sur la lagune de Maracaïbo", J. J. Berreby, *Revue de l'aluminium* , No. 264, 1959, pp. 445-447.

[54] "Development of an offshore aluminium living quarter", I. Saetre, S.T. Strandlie, Statoil, *Conference Offshore Mechanics and Artic Engineering,* Stavanger, Norway, June 1991, vol. III-A, pp. 247-253.

[55] "A light weight giant", *Aluglobe*, vol. 2, 1999, pp. 10-11.

[56] "Application of aluminium to offshore topside structures", M. J. Bayley, *First International Offshore and Polar Engineering Conference,* Edinburgh UK, August 1991, pp. 11-16.

[57] "Aluminum alloys for pressure hulls", C. L. Brooks, *Metals Engineering Quarterly*, ASM, Vol 5, 1965, pp. 19-23.

[58] "Study confirms fast freight potential", *Speed at Sea*, February 1998.

[59] "Companies join forces to promote SES concept", *Fast Ferry International*, November 1998, pp. 23-26.

[60] "Mitsubishi releases details of surface effect ship range", *Fast Ferry International*, October 1996, pp. 24-25.

[61] "New alloy development at Pechiney, a new generation of 5383", Alexandre Duran, Roman Dif, FAST 2001: *Sixth International Conference on Fast Sea Transportation,* Southampton, UK, September 2001, Volume 3, pp. 223-230.



THE PRINCESS

Chapter 2
ALUMINIUM'S ADVANTAGES

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2. ALUMINIUM'S

SOMETIMES the obvious must be stated: the first advantage of aluminium is that - like steel - it is a metal.

The rules used to calculate the strength of metal materials can be applied without difficulty because semi-products made from aluminium alloys are isotropic and homogeneous in the mass. The mechanical properties of the aluminium alloys used in shipbuilding are stable over time. There is no phenomenon of "ageing" of the material's internal structure as may be the case with "plastics".

By applying the rules and practices of classical sheet metal working and fabrication, it is possible to construct ships and to repair or fit them out with no particular difficulty and in any climatic conditions (1).

Like most everyday metals, aluminium is ductile in the sense that it can sustain strains that remain elastic so long as the stresses do not exceed the proof stress.

If the stress accidentally exceeds this limit, the permanent set (due to the plasticising of the metal) absorbs the energy proportional to the hatched area in the curve in Figure 6.

UNIAXIAL STRESS STRAIN CURVES

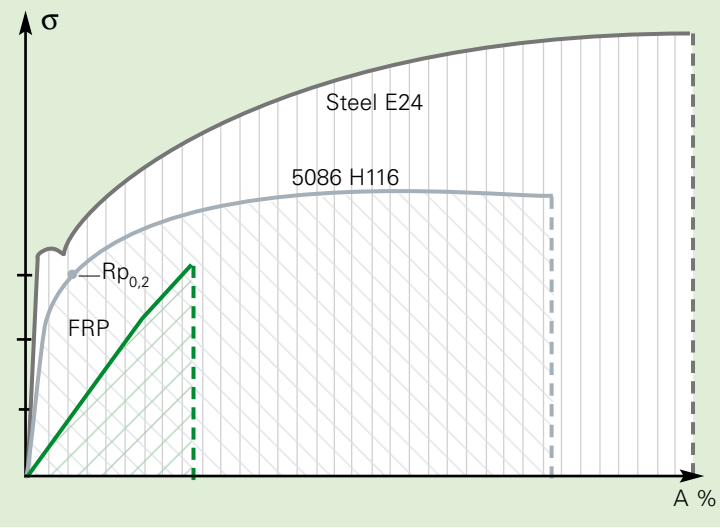


Figure 6

The result is that, in the event of an impact, all or part of the impact energy is absorbed by the deformation of the metal depending on the intensity of shock and the mass of metal at the point of impact. The fact that deformation is possible before rupture occurs is a factor of safety.

However the continuous development in the marine uses of aluminium since the Nineteen Fifties, especially shipbuilding, is explained by the specific advantages which aluminium offers:

- its lightness of weight,
- the availability and diversity of functional semi-finished products,
- its formability,
- its resistance to corrosion in marine environments,
- its environmental compatibility,
- its cost-effective recyclability.

It is for these reasons that aluminium contributes so much to the development of high speed ships and numerous marine applications.

(1) Provided the rules of welding in a controlled atmosphere are obeyed, cf. Chapter 6.

FEDERICO GARCÍA LORCA



ADVANTAGES

1. A LIGHTWEIGHT MATERIAL

Aluminium is the lightest of the common metals (table 3), its density of 2.7 being one third that of steel. Structures made of aluminium alloy will therefore always be lighter than their steel counterparts.

In theory, aluminium and steel can be compared using three criteria (table 4):

■ at equal thickness, for structures not subjected to stress, the ratio of masses is equal to the ratio of densities:

$$\frac{m_{alu}}{m_{steel}} = \frac{2,70}{7,80} = 0,34$$

such that one ton of steel is replaced by 340 kg of aluminium, resulting in a saving of 660 kg or 66% compared with a steel structure,

■ at equal rigidity, the ratio of Young's moduli is 3, and the ratio of thicknesses of the sheets will depend on the following relationship:

$$E_{steel} \cdot t^3_{steel} = E_{alu} \cdot t^3_{alu}$$

$$t_{alu} = t_{steel} \cdot \sqrt[3]{\frac{E_{steel}}{E_{alu}}}$$

$$t_{alu} = \sqrt[3]{3} \cdot t_{steel}$$

For a unit area of 1, the ratio of masses:

$$\frac{m_{alu}}{m_{steel}} = \frac{t_{alu}}{t_{steel}} \cdot \frac{d_{alu}}{d_{steel}}$$

$$\frac{m_{alu}}{m_{steel}} = \frac{2,70}{7,80} \cdot \sqrt[3]{3} = 0,499 \approx 0,50$$

is such that one ton of steel is replaced by 500 kg of aluminium. The saving in weight is 50% compared with steel.

■ at equal stress, for sheets, and on non-welded structures, the proof stress being 220 MPa for *Sealium*® and 355 for EH36 steel, it must be verified that:

$$\sigma_{steel} \cdot t^2_{steel} = \sigma_{alu} \cdot t^2_{alu}$$

$$t_{alu} = t_{steel} \cdot \sqrt{\frac{\sigma_{e\,steel}}{\sigma_{e\,alu}}}$$

$$t_{alu} = t_{steel} \cdot \sqrt{\frac{355}{220}}$$

$$t_{alu} = t_{steel} \cdot 1,27$$

The ratio of mass:

$$\frac{m_{alu}}{m_{steel}} = \frac{2,70}{7,80} \cdot 1,27 = 0,44$$

is such that one ton of steel is replaced by 440 kg of aluminium. The saving in weight is 560 kg, or 56% compared with steel.

THE SPIRIT OF ONTARIO



PROPERTIES OF SELECTED ALUMINIUM ALLOYS AND METALS IN CURRENT USE (*)

Property	5086 H111	5083 H111	*Sealium*® (**)	6082 T6	6005A T5	Steel E24	Steel E36	Stainless Steel Z7CN18-09 Annealed	Copper Annealed M20
Density (kg.m^{-3})	2 660	2 660	2 660	2 710	2 700	7 820	7 820	7 900	8 940
Fusion interval (°C)	585/640	574/638	574/638	570/645	607/654	1400/1530	1400/1530	1375/1400	1083
Coefficient of linear expansion 20 to 100°C (10^{-6}.K^{-1})	23,8	23,8	23,5	23,5	23,6	11,7	11,7	17,5	16,5
Modulus of elasticity (MPa)	70 000	70 000	70 000	70 000	70 000	210 000	210 000	200 000	115 000
Yield strength, $Rp_{0,2}$ (MPa)	120	125	220	260	260	240	360	300	70
Tensile Strength Rm (MPa)	240	275	305	310	285	410	550	660	235
Elongation A %	15	15	10	10	12	24	20	54	45

(*) The mechanical properties indicated in this table are mean values given for guidance only.

(**) 5383 H116.

Table 3

REDUCTION IN WEIGHT OF ALUMINIUM ALLOY STRUCTURES

Comparison	Criterion	Aluminium	Steel	Potential Saving
Equal thickness	Density	2,7	7,8	66%
Equal rigidity	Young's modulus	70 000 MPa	210 000 MPa	50%
Equal stress	Proof stress	220 MPa	355 MPa	56%

Table 4

In practice, when we take into account:

- the level of mechanical properties of the aluminium alloys used in marine applications (2),
- the fatigue limit of welded joints for structures subject to variable load (3),

experience shows that the weight saving on an aluminium structure is 40 to 50% compared with an equivalent structure made from E24 steel and 30 to 40% with steel with a high proof stress [1].

This saving in weight becomes more important when the properties and specificities of aluminium are taken into account by designers and constructors. Experience shows that a "literal" transposition of steel structures produces results that are average to mediocre.

Using extrusions (and aluminium alloy castings) is an excellent way of reducing the weight of sub-structures, enhancing the fatigue strength of welded joints and optimising appearance, as figures 10 to 17, pp.28-29 & figures 48 to 50, pp.66-67 illustrate.

A comparison of the weights of two high speed ships with a length of 110 metres shows that the saving in weight by an all-aluminium vessel is 214 tonnes or 34% compared with an equivalent steel ship [5] (table 5):
For an equal speed, this reduction in weight translates as a saving on the cost of the propulsion unit which requires 20% less power than for the equivalent vessel made of steel. The saving on fuel consumption will also be in the region of 20%.

The lightness of aluminium has a number of additional benefits:

- during manufacturing: at the shipyard, sub-structures made from lighter aluminium alloys are easier to handle and require less powerful handling/lifting equipment than is needed for steel. Some shipyards with substantial lifting equipment will take advantage of this weight reduction to fit out in the workshop sections of large ships that are subsequently assembled in the dry dock (4),

(2) Cf. Chapter 3, table 18.

(3) Cf. Chapter 4, figures 48 to 50.

(4) Welding zones will be carefully protected by covers positioned to prevent air currents disturbing the gases that protect the arc.

COMPARISON OF THE WEIGHTS OF 110 METRE HSS IN STEEL AND ALUMINIUM (TONS)

	Aluminium Ship	Steel Ship (*)
Hull	280	504
Superstructure	70	70
Sub-total	*350*	*574*
Insulation	60	40
Paintwork	5	15
Total	415	629
Saving in weight	**214**	

(*) Steel hull and aluminium superstructure.

Table 5

- for the nautical properties of the ship: the reduction in the weight of the ship's superstructure (whether its hull is made of steel or aluminium alloy) will improve the vessel's stability (5) and make it possible to reduce its beam, producing ships that are more slender and hence faster,

- in operation: the saving in weight of an aluminium ship translates as a significant fuel saving for the same speed. This is true whatever the size of the vessel.

This fact was confirmed by a comparative study conducted in 1990 by the Naval Hydrodynamic Laboratory of the 'Ecole Centrale' of Nantes. The study looked at two trawlers with equivalent catch capabilities, i.e. the same hold capacity, the same propulsion and the same fishing equipment. One was made of aluminium and the other of steel (table 6).

Tests in dock showed that the towing resistance of the hull below the waterline and the corresponding power are significantly less for the aluminium trawler than for the steel trawler (figure 7). The total gain in the performance of the aluminium trawler increases appreciably with the vessel's speed, and these figures also represent savings on fuel consumption per mile:

- at 8 knots the gain is 28%
- at 9 knots the gain is 39%
- at 10 knots the gain is 50% (6).

Above 100 kW, we find that the gain in speed is 1 knot with the aluminium trawler for the same towing power.
This improvement in performance is due to a combination of two effects, the direct effect of the weight reduction and the indirect effect brought about by aluminium whose light weight is utilised to design a narrower hull below the waterline. If we decouple these two effects, we find that hull slenderness accounts for half of the gain at 8 knots but 80% at 10 knots.

In addition, propulsion tests have shown that the slenderness of the hull of the aluminium trawler makes a net improvement in the wake at the propellor that can result in a 3 to 5 points increase in efficiency.

(5) A weight saving of 100 in the upper works translates as a saving of 700 on the hull.

(6) If indeed the steel trawler can attain this speed.

TOWING POWER

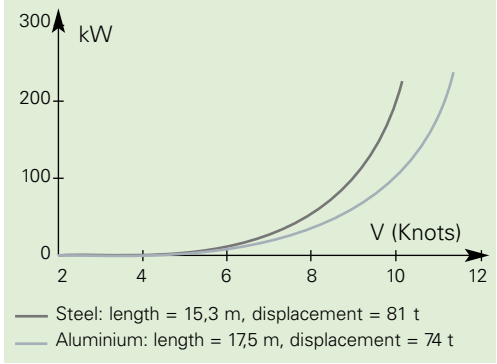


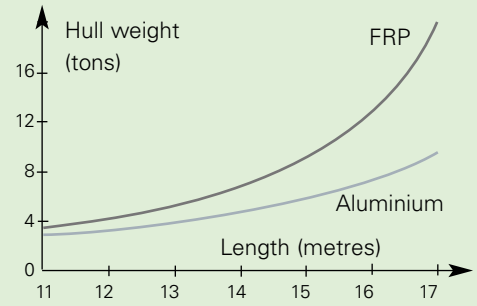
Figure 7

CHARACTERISTICS OF TRAWLERS

Characteristic	Steel Trawler	Aluminium Trawler
Length over all (OA)	15,30 m	17,50 m
Length on waterline (LWL))	13,70 m	16,00 m
Beam on waterline (BWL)	5,80 m	5,48 m
Draft	2,05 m	1,78 m
Ratio of LWL to BWL	2,36	2,52
Nominal displacement (when leaving port)	81 t	74 t

Table 6

WEIGHT OF HULL IN ALUMINIUM AND IN FRP



From Alumiage n° 97, Autumn 1984, Japan Light Metal Association

Figure 8

Regarding composite materials, aluminium alloys can only be compared with FRP (7) as this is the material most commonly used for utility boats (fishing, work boats etc.). Its density is in the region of 2.5. With this type of boat, the greater the length, the greater is the weight disparity between FRP and aluminium (figure 8).

2. DIVERSITY OF SEMI-FINISHED PRODUCTS

Compared with normal metals, aluminium is unique in offering a wide range of semi-finished products (semis) that are:

- cast in a foundry,
- rolled plate, sheet and strip, tread plate (8), pre-coated sheet and strip,
- extruded, standard or customised; it is possible to make inexpensive tools (dies) that produce shapes designed for a specific use.

2.1 Castings

Since 1950, most of the parts of the superstructure fitted to leisure craft are made from aluminium alloys with 3 or 6% magnesium: 51100 (A-G3T) or 51300 (A-G6).

In a foundry it is possible to make structural components with complex shapes in small production runs and even one-offs, from alloys such as 42100 (A-S7G03) and 42200 (A-S7G06) whose mechanical properties are perfectly adequate for structural applications. These alloys are weldable and can be joined to 6000 series shapes.

Castings can simplify assemblies through being adapted for well-defined functions in the three spatial dimensions.

2.2 Rolled semis

Rolling mills are able to supply shipyards with thin sheets (less than 12.7 mm thick) for skin, bulkheads etc., as well as thicker products for bilges, keelplates and other structural elements requiring very thick materials.

The rolling tools in our processing plants have the capacity to produce sheet up to 3 metres wide and 15 metres long. The maximum dimensions depend on the material temper; by way of example, table 7 shows the possible sizes for 5083 and table 8 for *Sealium*®.

The finishing equipment can be used to supply sheet or plate that is levelled and sawn to dimensional tolerances that meet the demands of shipbuilding, especially for the fitup of faces ready for welding, a factor of prime importance for the fatigue strength of welded joints (9).

Among the special sheets that are used in large quantities in shipbuilding (for floors, stair treads etc.) we should mention the tread plate that is available in 5083, 5086 and 5754 (figure 9).

(7) Fibre-reinforced plastic.

(8) Still called "chequer-plate" or "floor plate".

(9) Cf. chapter 6, section 7.

TREAD PLATE PATTERNS

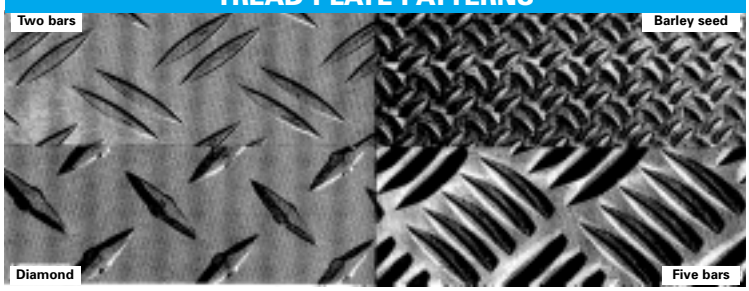


Figure 9

EXAMPLE OF SPECIFICATIONS OF 5083 SHEET AND PLATE

Thickness (mm)	Width (mm)	Length (mm)	Temper
4 ≤ t ≤ 8	2 500	15 000	F, O, H111, H112
8 < t ≤ 10	2 500	12 500	
10 < t ≤ 12,7	2 500	10 350	
3,8 ≤ t ≤ 4	1 830	15 000	H22, H32, H116,
4 ≤ t ≤ 4,2	2 100	15 000	H321
4,2 ≤ t ≤ 4,5	2 260	15 000	
4,5 < t ≤ 5,5	2 400	15 000	
5,5 < t ≤ 8	2 438	15 000	
8 < t ≤ 10	2 438	12 500	
10 < t ≤ 12,7	2 438	10 350	
4 ≤ t ≤ 6,35	2 000	15 000	H24, H34
6,35 < t ≤ 8	2 300	15 000	
8 < t ≤ 10	2 300	12 500	
10 < t ≤ 12,7	2 300	10 350	
6 ≤ t ≤ 8	2 500 à 2 800	8 000	F, O, H111,
	2 800 à 3 050	6 000	H112, H22, H24,
8 < t ≤ 10	2 500 à 2 800	9 000	H34, H116,
	2 800 à 3 050	8 000	H 321
10 < t ≤ 12,7	< 2 500	12 000	
	2 500 à 2 800	11 000	
	2 800 à 3 050	10 000	
> 12,7	≤ 3 050	12 000	

Sheets are sheared for thickness ≤ 8 mm and for length up to 15,000 mm.
Sheets and plates are sawn for thickness > 8 mm and length up to 12,500 mm.

Table 7

EXAMPLE OF SPECIFICATIONS OF SHEET IN *SEALIUM* ®

Thickness (mm)	Width (mm)	Length (mm)
3,8 ≤ t ≤ 4	1 830	15 000
4 ≤ t ≤ 4,2	2 100	15 000
4,2 ≤ t ≤ 4,5	2 260	15 000
4,5 < t ≤ 5,5	2 400	15 000
5,5 < t ≤ 8	2 438	15 000
8 < t ≤ 10	2 438	12 500
10 < t ≤ 12,7	2 438	10 350

Table 8

2.3 Extruded semis

Unlike steel, aluminium lends itself readily to forming by means of extrusion. Whereas steel shapes which are made by hot rolling have only very simple forms (angles, 'Tees', bulb flats), aluminium shapes, both solid and hollow, can assume highly complex forms that are ideally suited to their intended use.

Aluminium is extruded on extrusion presses whose power depends on the form and dimensions of the shape and on the alloys used. This is a discontinuous operation using billets whose diameter will depend on the size of the final shape.

Most shapes which are intended for use in shipbuilding and marine applications belong to the 5000 and 6000 series. Following extrusion, they undergo finishing operations (straightening, cutting to length etc.) and are heat treated if required.

The form and geometry of the shape are determined by an extrusion die through which the metal is forced. Each shape must have its own dedicated die (which is made from special steel). Contrary to common misconception, its cost is not excessive and it can easily pay for itself through savings in weight and assembly productivity.

Shapes up to 700 mm wide can be extruded with equipment that is currently available.

Aluminium shapes are coming to be used more and more in shipbuilding given the eminent extrudability of aluminium, *an attribute unique among the common metals*. They offer significant advantages in terms of weight reduction (10), time savings and assembly precision [3].

SHAPE WITH OPTIMISED INERTIA

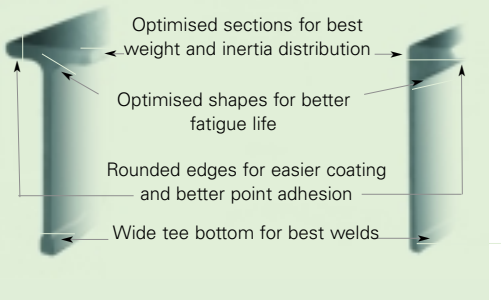


Figure 10

SHAPE WITH INTEGRAL BACKING STRIP AND STIFFENERS

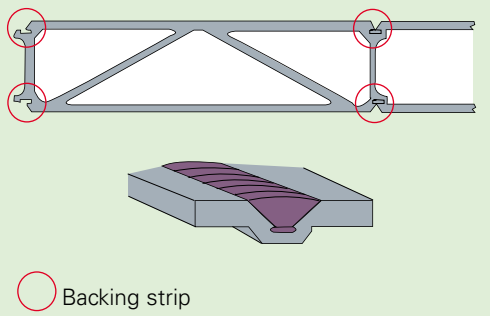


Figure 12

SHAPE WITH BACKING STRIP

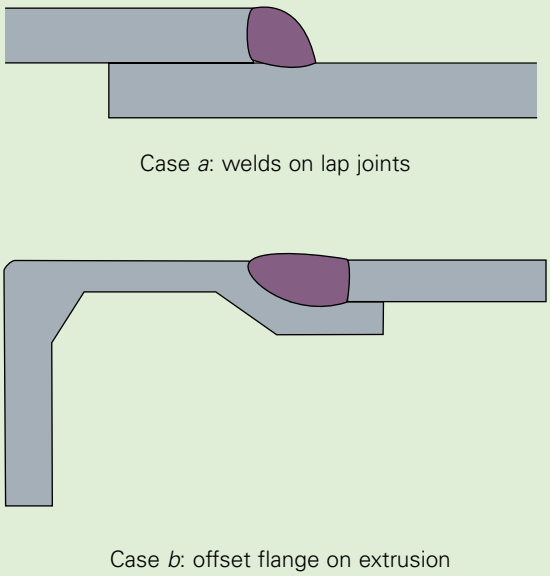


Figure 11

SLOTTED EXTRUSIONS FOR WELDING TO SHEET COMPONENTS

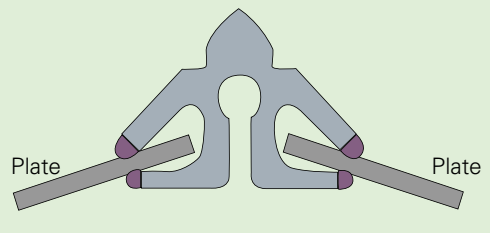


Figure 13

BULB ON EXTRUDED FLANGE FOR IMPROVED WELDABILITY

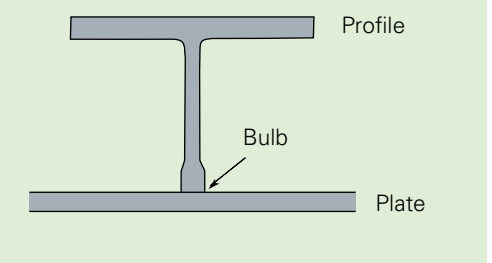


Figure 14

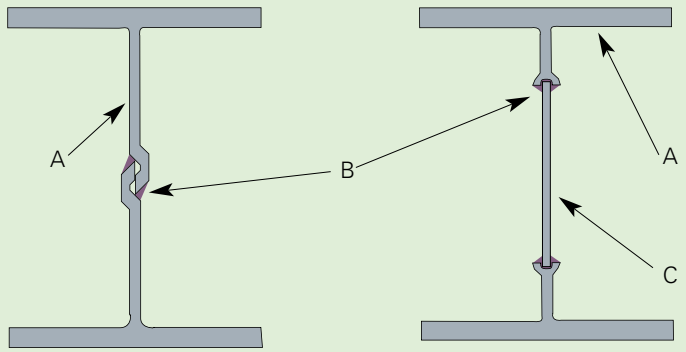
As with aluminium castings, it is possible to build particular functions into an extruded shape (but in one direction only), for example:

- masses of inertia. The ease with which aluminium alloys can be extruded is such that it is possible to distribute masses very finely so as to optimise the unit weight of the shape (figure 10),
- backing strips allow shapes to be welded to each other or to sheet. As shown in figure 11, in a shape that has a permanent backing strip it is possible to replace a fillet weld (case a) by a butt weld (case b) which has a higher fatigue limit. It is possible to combine backing strips and stiffeners in a shape (figure 12),
- locating or aligning points (figure 13),
- local bulges (bulbs) that balance the masses that are to be welded (figure 14)

Shapes can be used to "move" welds to zones of less stress (figures 15, 16 and 17), significantly improving the fatigue strength of welded joints as a result.

(10) Cf. chapter 4.

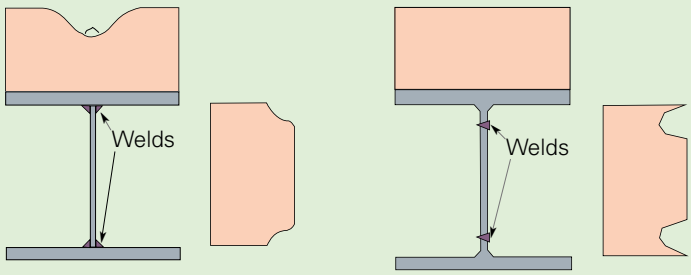
I-BEAM FABRICATED FROM SHAPES AND/OR SHEET



A: Shapes
B: Fillet weld in lap joint
C: Extruded plate or rolled sheet

Figure 15

STRESSES IN FABRICATED I-BEAMS

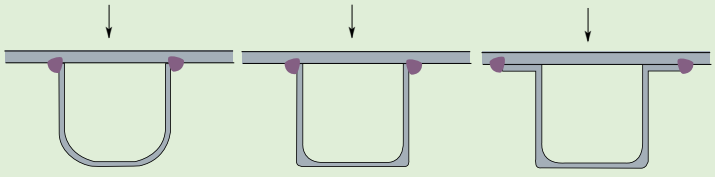


I-profile of flat plates

I-profile of two Tee extrusions and 1 plate

Figure 16

OPTIMISING STRESS DISTRIBUTION



Formed Channel | Extruded Channel | Extruded top hat

Figure 17

HONEYCOMB SANDWICH PANEL

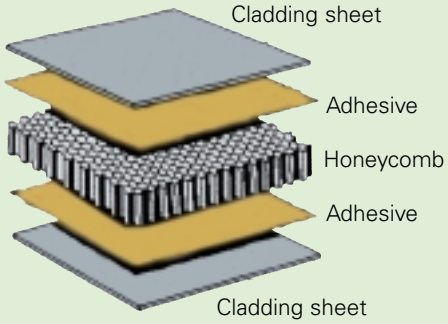


Figure 18

2.4 Special products

These are not semis in the strict sense, but aluminium alloy products shaped to a greater or lesser degree.

This category includes honeycomb sandwich panels. These products are used in shipbuilding as interior panels, curtain walls, partitions etc. [12, 13].

The panels (Figure 18) are made using cladding sheets between which the "honeycomb" - also made from aluminium alloy - is sandwiched (11). Their construction makes them extremely rigid, and under identical service conditions they can save as much as 30% in weight compared with conventional aluminium alloy panels to which stiffeners are welded.

These products cannot be welded owing to the slenderness of the constituent parts of the honeycomb and the presence of the adhesive. They must therefore be connected to their conventional substructures by means of screws, rivets etc.

(11) The parts are bonded together with an organic adhesive. Before they can be used in shipbuilding these structures must pass the fire resistance tests according to IMO resolution A.754.

3. EASE OF PROCESSING

Provided we obey certain rules that are specific to aluminium alloys, and which are discussed in the following chapters, we can process them by the normal practices of shaping and forming - bending, sheet-metal working, drawing and machining - as are used for other everyday metals such as normal steel, stainless steel etc.

Special plant or machinery is not needed to work aluminium alloys in most cases. Wherever possible however it is advisable to have a dedicated workshop for processing aluminium alloys that is separate from workshops where steel and above all copper alloys are used (12).

Just like other everyday metals, aluminium alloys lend themselves well to joining techniques such as:

- welding,
- screw fastening,
- riveting,
- snap fitting,
- bonding, etc.

Thanks to its good corrosion resistance, the surface of aluminium remains clean and will not stain its handlers.

4. RESISTANCE TO CORROSION IN MARINE ENVIRONMENTS

Marine environments are known to be very hostile to all materials. Like bronze, aluminium is one of those rare metals and alloys capable of withstanding this aggressive environment. They belong to the groups of materials referred to as being "marine grade", a label that indicates exceptional resistance to corrosion in a marine environment.

Its lightness of weight and resistance to corrosion - the main aspects of which are dealt with in Chapter 10 (13) - account for the growth in the maritime uses of aluminium over the past half-century.

The "marine" alloys of the 5000 and 6000 series combine excellent corrosion resistance in marine environments with good mechanical properties. They are therefore the most suitable for marine applications such as shipbuilding. It is also not essential to protect them by painting or anodising (14).

The excellent corrosion resistance in a marine environment has a number of important consequences for users:

- the dimensional integrity of components eliminates the need to provide a corrosion "allowance" (extra thickness) on the submerged hull,
- the service life of installations, ships etc. can be very long. It is not uncommon to find marina jetties and boats that have given several decades of service. It is obsolescence rather than corrosion which puts an end to their use,
- the appearance of installations, ships etc. is conserved far better thanks to the material's very good resistance to corrosion. The surface acquires a "patina" that blends very well into the environment without detracting from its overall aesthetic. Because the corrosion products of aluminium are white, even if the metal suffers pitting corrosion its aspect does not deteriorate as is the case with steel, whose corrosion produces rust colours,
- maintenance is minimal even when the aluminium is not protected (not painted or anodised). When it is painted, the need to repair the paint is less frequent and less urgent because the underlying metal resists corrosion.

5. IMPACT ON THE ENVIRONMENT

The issue of environmental impact is a complex one. It depends on a number of factors, including:

- the constituent material,
- how the product is formed in the workshop / shipyard,
- service conditions,
- maintenance,
- the end of the product's life.

Before a ship or installation is even built and operated, the design of the project is an important stage that will in part determine its impact on the environment. By applying design rules that are adapted to suit the material and its service conditions, we can reduce maintenance, enhance corrosion resistance etc. [6].

The construction of installations and ships using aluminium alloys is based on the classical operations of sheet metal working - cutting, forming, welding etc. - which are described in Chapters 5, 6 and 7 (15). Advances in jointing techniques and tool design are reducing the impact on the environment.

By reducing the weight of structures such as ships, aluminium can save fuel and can therefore have a beneficial impact on the level of carbon dioxide emissions.

---

(12) To avoid the attendant risks of galvanic corrosion of aluminium.

(13) Cf. page 145.

(14) However submerged structures must be protected with "antifouling" paint to prevent marine bio-incrustation.

(15) Cf. pages 73 to 128.

The excellent corrosion resistance of marine alloys eliminates the need to paint most interior surfaces of ships (16), coastal installations or offshore structures. The resulting savings on protection also greatly mitigate the environmental impact, as there is no sandblasting or discharge of volatile organic compounds (VOC).This remains true over the entire life of the vessel because surfaces that are not painted to begin with never will be painted.

At the end of their working life, aluminium ships and offshore installations can be readily recycled owing to the residual value of aluminium scrap.

6. RECYCLING

Aluminium is one of the most attractive metals for recycling in both energy and economic terms.

The most convincing proof of aluminium's eminent recyclability is the fact that you will not see aluminium equipment or scrap that has been abandoned or tipped anywhere in the world. This applies equally to marine environments.

Aluminium recycling requires just 5% of the original energy needed to produce the metal. The percentage of reclaimed aluminium has been rising constantly for 30 years to a level where it now represents 30% of the world's consumption.

Aluminium recycling has always been a highly organised industrial activity (since the Nineteen Thirties) and is profitable because aluminium waste is a valuable resource. In Europe, the value of sorted waste is in the region of at least EUR 600 per ton, whatever the fluctuations in the price of the original metal.

Aluminium is recycled at each stage of transformation (rolling and extruding) and of usage in shipyards. All workshops that process aluminium have systems for collecting offcuts and scrap from sheets and shapes which are then re-sold (17).

The dismantling of aluminium ships is not yet a widespread practice because most of these vessels are not very old - less than 30 years - but what little experience exists in this field indicates that dismantling ships made with aluminium alloys presents no particular difficulty [7]. Recycling aluminium waste should be relatively straightforward given that the alloys used in the construction of ships are the same everywhere - they belong to the 5000 and 6000 series.

7. INNOVATION

Aluminium shipbuilding benefits from the innovative dynamic of the aluminium industry, whether it be:

- in the ongoing improvement in the performance of alloys since 1990. *Sealium*® is part of this effort,
- in advanced methods of assembly such as friction welding (FSW), bonding etc.,
- in the dissemination of knowledge about the uses and processing of aluminium and its resistance to corrosion in marine environments. As part of this endeavour, this brochure and its predecessor [8] answer the needs of the professions involved, including naval architects, shipowners and yards.

Bibliography

[1] "General considerations on high tensile steel versus aluminium alloy and technical aspects related to the aluminium construction", V. Farinetti, Fincantieri, Naval Shipbuilding Division, *The Third International Forum on Aluminium Ships,* Haugesund, May 1998.

[2] "L'utilisation de l'aluminium en construction navale", Christian GAUDIN, Alstom Leroux Naval Nantes, *Conférence CETIM*, Senlis, November 1999.

[3] "Development of value added aluminium extrusions for the marine market", J. Gönner, Corus Aluminium Extrusions, *4th International Forum on Aluminium Ships*, New Orleans, May 2000.

[4] "Use of aluminium profile/honeycomb hybrid solutions in marine applications", R. J. Dean, F. Ritter, Alusuisse. *The Third International Forum on Aluminium Ships,* Haugesund, Norway, May 1998.

[5] "Aluminium honeycomb mezzanine ramps for Incat 95 metre high speed combination Ro-Pax catamarans", G. Davidson, Incat Tasmania, M. Turner, Hexcel Composites, *Third Conference Ausmarine,* Freemantle, November 1998.

[6] "Technologies for reduced environmental impact from ships – shipbuilding, maintenance and dismantling aspects", B. Hayman, M. Dogliani, I. Kvale, A. Magerholm Fet.

[7] "Research on aluminium ship recycling", N. Itoyama, Sky Alumnium Cie Ltd. *The Third International Forum on Aluminium Ships,* Haugesund, Norway, May 1998.

[8] *L'aluminium et la mer*, Pechiney Rhenalu, 1992.

(16) Only the submerged structures must be painted to prevent incrustation by marine organisms, cf. Chapter 11. It is traditional to paint all or part of the external surface of a ship in the owner's livery, but this is for decorative purposes only.

(17) In aluminium shipbuilding, the ratio of material utilisation is around 115%, i.e. only 115 kg of metal is needed to make 100 kg of ship.



HARD TOP YACHT

Chapter 3
ALUMINIUM ALLOYS IN MARINE APPLICATIONS

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3. ALUMINIUM ALLOYS

THE WROUGHT aluminium alloys (rolled and extruded) that are used in marine applications belong for the most part to two series:

- the 5000 series comprising aluminium-magnesium alloys, and
- the 6000 series which consists of aluminium-magnesium-silicon alloys.

In view of their specific aptitudes for being 'worked', most rolled semis are made from 5000 series (*Sealium*®, 5083, 5086, 5754 etc.), while extruded shapes are made from 5000 series (*Sealium*®, 5083) and 6000 series (6082, 6005A, 6061 etc.) (1).
They have been chosen for their level of mechanical properties, their ease of assembly by welding and their excellent corrosion resistance in marine environments.

The composition of wrought alloys used in marine applications is shown in table 9.

The properties of semis made from wrought alloys, including:

- their mechanical properties,
- their aptitude to cold working,
- their corrosion resistance,

depend on:

- the chemical composition of the alloy,
- the process of fabrication,
- thermal treatments which they receive during fabrication.

These properties can be significantly modified in the course of:

- cold (or hot) working,
- welding, which heats up the metal either side of the weld bead (2).

It is therefore essential to be fully aware of the influence of these operations on mechanical and other properties so as to gauge their effects and allow for them in stress calculations, for example.

This knowledge is based on fundamental notions of the metallurgy of aluminium alloys of which some of the main aspects are reviewed in the sections below (3).

(1) Sealium® is 5383 in the H116 temper.

(2) Cf. Chapter 6.

(3) For further information, refer to the brochure entitled "Aluminium semi-finished products" published Pechiney Rhenalu, 160 pages, 1997.

SEAHAWK



IN MARINE APPLICATIONS

COMPOSITION OF THE MAIN WROUGHT ALLOYS FOR MARINE APPLICATIONS (*)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Remarks (**)
5454	0,25	0,40	0,10	0,50 1,0	2,4 3,0	0,05 0,20	0,25	0,20	
5754	0,40	0,40	0,10	0,50	2,6 3,6	0,30	0,20	0,15	Mn + Cr: 0,1 - 0,6
5086	0,40	0,50	0,10	0,20 0,7	3,5 4,5	0,05 0,25	0,25	0,15	
5083	0,40	0,40	0,10	0,40 1,0	4,0 4,9	0,05 0,25	0,25	0,15	
5383 (1)	0,25	0,25	0,20	0,7 1,0	4,0 5,2	0,25	0,40	0,15	Zr ≤ 0,20
6060	0,30 0,6	0,10 0,30	0,10	0,10	0,35 0,6	0,05	0,15	0,10	
6005A	0,50 0,9	0,35	0,30	0,50	0,40 0,7	0,30	0,20	0,10	Mn + Cr: 0,12 - 0,50
6106	0,30 0,6	0,35	0,25	0,05 0,20	0,40 0,8	0,20	0,10		
6063	0,20 0,6	0,35	0,10	0,10	0,45 0,9	0,10	0,10	0,10	
6082	0,7 1,3	0,50	0,10	0,40 1,0	0,6 1,2	0,25	0,20	0,10	
6061	0,40 0,8	0,7	0,15 0,40	0,15	0,8 1,2	0,04 0,35	0,25	0,15	

(*) Taken from standard EN 573-3.

(**) Where a single value is given, it corresponds to a permitted maximum.

Table 9

THE NATALIE M



1. THE SERIES OF WROUGHT ALLOYS

There are 8 series of industrial wrought alloys, and their properties are shown in table 10.

They are divided into two categories:

- the strain hardening alloys, whose mechanical properties are determined by rolling (or extrusion) operations and by intermediate annealing (or final annealing, if any). They belong to the 1000, 3000, 5000 and 8000 series.
- the age hardening alloys whose mechanical properties are the result of the thermal processes of solution heat treatment, quenching and artificial ageing. These alloys belong to the 2000, 6000 and 7000 series.

Despite having high mechanical properties, alloys in the 2000 series with copper and 7000 series with zinc (with or without copper) cannot be used in marine applications without any special protection because of their inadequate corrosion resistance.

The 7000 series alloys without copper can be arc welded. However the high sensitivity of the heat affected zone to exfoliating corrosion demands very strict precautions for marine applications such as shipbuilding (4).

2. DESIGNATION OF WROUGHT ALUMINIUM ALLOYS

The 4-digit numerical designation of wrought aluminium alloys has acquired universal usage since 1970. New designations for these alloys were standardised by the CEN (5) in 1994.

According to standard EN 573-1 (6)(7), the first digit of the designation denotes the series of the alloy, as shown in table 10. The last 3 digits have no particular significance.

In fact the designation of a semi-finished product made from an aluminium alloy is in two parts:

- the first part – 4 consecutive digits – denotes the series to which it belongs, hence the dominant alloying element,
- the second – 1 letter (H or T) followed by one or more digits – indicates its temper (tables 12 to 15 pp. 38-39 & table18 p. 41). Each temper represents a level of mechanical properties that are guaranteed by the standards (Appendix 1).

(4) Cf. Chapter 10, section 5.

(5) CEN: European Committee for Standardisation.

(6) EN 573-1. Aluminium and aluminium alloys. Part 1: System of numerical designation.

(7) Strictly speaking, standard EN 573-1 provides for an "alphanumerical" designation in two parts, each preceded by EN AW (aluminium wrought): the first numerical part with 4 digits, and the second part based on chemical symbols (as in the ISO designation), given in [ ]. With this system therefore 3003 alloy would be written as "EN AW-3003 [EN AW-Al Mn1 Cu].

SERIES OF ALUMINIUM ALLOYS

Method of Hardening	Series	Alloying Element	Content (% by weight)	Possible Additives	Ultimate Tensile Strength Rm (MPa)
Strain hardening	1000	None		Cu	50 - 150
	3000	Manganese	0,5 to 1,5	Mg, Cu	100 - 260
	5000	Magnesium	0,5 to 5	Mn, Cr	100 - 400
	8000	Iron and Silicon	Si: 0,30 to 1 Fe: 0,6 to 2		130 - 190
Age hardening	6000	Magnesiumand Silicon	Mg: 0,5 to 1,5 Si: 0,5 to 1,5	Cu, Cr	150 - 310
	2000	Copper	2 à 6	Si, Mg	300 - 450
	7000	Zinc and Magnesium	Zn: 5 à 7 Mg: 1 à 2	Cu	Without copper: 320 - 350 With copper: 430 - 600
	4000	Silicon	0,8 to 1,7		150 - 400

Table 10

3. STRAIN HARDENING ALLOYS

These alloys belong to the 1000, 3000, 5000 and 8000 series (8). They are manufactured by a sequence of hot, then cold, forming operations (rolling for sheets) combined with intermediate and/or final annealing.

The effect of strain hardening is to modify the structure of the material by plastic deformation. It takes place when a semi-product is manufactured, during rolling, drawing or wire drawing, as well as during the processing of semis in the workshop during shape forming or bending, for example.

Strain hardening is accompanied by an increase in mechanical strength and hardness and a loss of ductility, i.e. a decrease in the material's ability to deform. The greater the amount of forming or the higher the rate of strain hardening, the greater will be these effects.

The level of mechanical properties that can be achieved by strain hardening depends on the composition of the alloy. The 5083 alloy for example which contains between 4 and 4.9% of magnesium acquires a greater hardness but a more limited capacity for deformation than the 5754 alloy which only contains between 2.6 and 3.6% of magnesium.

However the gradual rise in strength always reaches a limit beyond which further strain becomes difficult and even impossible. Heat treatment by annealing is therefore needed to "soften" the metal, if working is to be continued.

3.1 Softening by annealing

The ability of the wrought metal to "work" (deform) can be recovered by a form of thermal treatment known as "annealing".

During this treatment, which is carried out at a temperature above 300°C, the hardness and mechanical properties of the metal start by slowly decreasing - this is recovery annealing according to line A-B in figure 19. They then fall more rapidly, a process known as recrystallisation (curve B-C), and finally reach a minimum value corresponding to the mechanical properties of the annealed metal (line C-D).

These processes of recovery annealing and recrystallisation annealing are accompanied by a modification in the texture and size of the "grains" in the metal. During recrystallisation therefore, reorganisation takes place according to a new grain structure.

It is worth noting that, for the same tensile strength, ductility is greater in the recovery annealed metal (H2X) than in the strain hardened metal (H1X). The recovery annealed state will therefore be preferred when maximum formability is required.

Table 11 lists annealing conditions (treatment temperature, holding time) for some alloys.

If it is to retain its good capacity for forming, the annealed metal must not present a coarse grain (as indicated by the "orange peel" phenomenon during working operations).

There are a number of requirements for obtaining an annealed metal with a fine grain:

- The metal must have received a sufficient rate of working, corresponding to a relative reduction in section of at least 15%. If this requirement is not met, then the metal must undergo recovery annealing only (i.e. recrystallisation annealing must be avoided),
- The rate of temperature rise must be rapid, from 20 to 60°C per hour,
- Excessive temperatures, above 350 to 400°C, and excessive temperature holding times, i.e. not more than 2 hours, must be avoided.

(8) Strictly speaking, all metals and alloys strain harden, but in the metallurgy of aluminium the term "strain hardening" is restricted to the alloys belonging to series that cannot age harden.

HARDNESS CURVE DURING ANNEALING

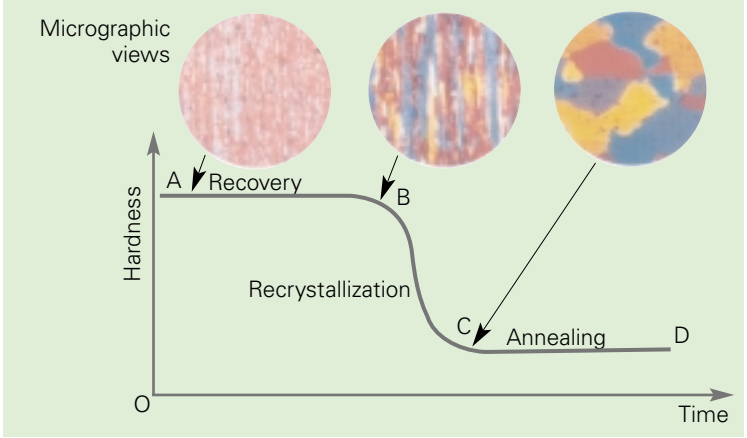


Figure 19

ANNEALING CONDITIONS				
Alloy	Recovery Annealing		Recrystallisation Annealing	
	Temperature (°C)	Time in hours	Temperature (°C)	Time in hours
5XXX	240 - 280	1 - 4	330 - 380	0,5 - 2
6060	240 - 280	1 - 4	330 - 380	0,5 - 2
6005A	250 - 280	1 - 4	330 - 380	0,5 - 2
6106	240 - 280	1 - 4	330 - 380	0,5 - 2
6082	250 - 280	1 - 4	330 - 380	0,5 - 2
6061	250 - 280	1 - 4	330 - 380	0,5 - 2

Table 11

3.2 Tempers

The strain hardening aluminium alloys are available in three basic tempers (table 12) as defined by standard EN 515 (9):

Most classical H tempers are designated by two digits whose meaning is explained in tables 13 and 14:
- the first denotes the basic temper,
- the second indicates the degree of work hardening.

Some tempers are designated by three digits, e.g. H111 and H116 (table 15):

All of these tempers imply minimum mechanical properties as laid down by EN standards, extracts of which are given in Appendix 1.

Strain hardening alloys and the most common tempers used in marine applications are indicated in table 19.

Notes: Under the new standard ASTM B 928 04 (11) relating to semis intended for marine applications and made from 5059, 5083, 5383 and 5456 alloys in the H116 and H321 tempers and semis in 5086 in the H116 temper, these materials must pass the tests of sensitivity to exfoliating corrosion according to the ASSET ASTM G66 test (12) and intercrystalline corrosion according to the ASTM G67 test (13).

Sealium® therefore undergoes these tests.

STRAIN HARDENING ALLOYS BASIC TEMPERS (ACCORDING TO STANDARD EN 515)	
Temper	Définition
F	hot rolled temper, with no guarantee of mechanical properties
O	annealed temper, with maximum forming capacity
H	strain (or work) hardened

Table 12

MEANING OF THE FIRST DIGIT OF HXX TEMPERS	
PFirst Digit H**X**X	Basic Temper
1	Work hardened only
2	Work hardened and recovered
3	Work hardened and stabilised (*)

(*) Temper stabilised by low temperature heat treatment or by heat applied during working. This temper affects mainly the 5000 series alloys.

Table 13

(9) EN 515 Aluminium and aluminium alloys – Wrought products – Designation of tempers.

(10) Cf. Chapter 10, page 162.

(11) B 928 - 04: Standard Specification for High Magnesium Aluminum Alloy Sheet and Plate for Marine Service, February 2004

(12) and with a rating better than "Pb",

(13) Cf. Chapter 10

HXXX TEMPERS (ACCORDING TO STANDARD EN 515)

Temper	Characteristics
H111	This temper differs from the O temper in that semis delivered in this temper are roller levelled after annealing to improve their dimensional characteristics such as flatness.
H112	This temper relates to semis whose level of mechanical properties is acquired by hot working or a limited amount of cold working.
H116	This temper denotes semi-finished products in the 5000 series containing 4% or more of magnesium (5083, 5086 etc.). In this temper, the semis must present a defined resistance to exfoliating corrosion in the ASTM G66 test (ASSET test) (10).
HXX4	This temper is used for "tread plate" engraved from the appropriate HXX temper.

Table 15

MEANING OF THE SECOND DIGIT OF HXX TEMPERS

Second Digit HX**X**	Meaning	Degree of Work Hardening (%)
2	Quarter hard	≈ 12
4	Half hard	≈ 25
6	Three-quarter hard	≈ 50
8	Fully hard	≈ 75

Table 14

4. AGE HARDENING ALLOYS

These alloys belong to the 2000, 6000 and 7000 series.

4.1 Principle of age hardening

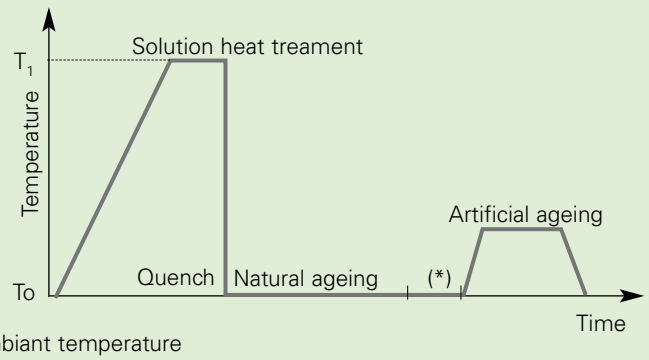
The maximum mechanical properties of these alloys are obtained by heat treatment in 3 stages (figure 20):

- Solution heat treatment is carried out at high temperature, in the region of 530°C for 6000 series alloys. While the metal is held at temperature, the alloy's constituents which are in the form of dispersed intermetallics are dissolved to form a homogeneous solid solution;

- Quenching is a process of rapid cooling normally obtained by rapidly plunging the metal in cold water when it leaves the furnace. Extruded Shapes can be "press quenched" by passing from the exit of the die into a tunnel where they are sprayed with fine droplets of water (14);

- Natural ageing or artificial ageing. The quenched metal is in a metastable state, which means that its structure evolves (15) over time culminating in a stable reorganisation in which the alloying elements are rejected from the solid solution in the form of very fine, dispersed precipitates. This precipitation increases the hardness of the metal.

AGE HARDENING SEQUENCE



To= ambiant temperature

(*) Controlled plastic deformation to obtain T 451 and T 651 is performed between quenching and artificial ageing.

Figure 20

(14) This is common practice with a number of extrusion alloys in the 6000 series (6060, 6005A, 6106) which are "press quenched" by cooling in forced air or water spray. They are designated by tempers T1 (press quenched and naturally aged) and T5 (press quenched and artificially aged).

(15) Quite rapidly, in a few hours for certain alloys.

CONDITIONS FOR SOLUTION HEAT TREATMENT, QUENCHING AND ARTIFICIAL AGEING

Alloy	Temper	Solution Heat Treatment Temperature (°C) (1)	Quench Medium	Artificial Ageing		Natural ageing minimum (days)
				Temperature (°C)	Time (hours)	
6060	T4	530 ± 5	Forced air (3) or water			8
	T6	530 ± 5	Forced air or water	175 ± 5 or 185 ± 5	8 6	
6005A	T4	530 ± 5	Water ≤ 40°C (3)		8	
	T6	530 ± 5	Water ≤ 40°C	175 ± 5 (2) or 185 ± 5	8 6	
6082	T4	530 ± 5	Water ≤ 40°C (3)			8
	T6	530 ± 5	Water ≤ 40°C (3)	165 ± 5 (2) or 175 ± 5	16 8	
6061	T4	530 ± 5	Water ≤ 40°C			8
	T6	530 ± 5	Water ≤ 40°C	175 ± 5 (2) or 185 ± 5	8	6

(1) The holding time is shown in table 17.

Table 16

(2) This treatment produces the optimum mechanical properties associated with the highest values of A %.

(3) because these alloys have a very low critical rate of quench, thin semis can be quenched in forced air.

This phenomenon is known as age hardening. It can take place at ambient temperature, in which case it is referred to as natural ageing. With some alloys, like those of the 6000 series, the process can be accelerated by holding the metal at higher temperatures (150 to 190°C), increasing its hardness as a result. This thermal treatment is performed in a furnace and is known as artificial ageing.

These thermal treatments must be carried out under rigorous conditions of temperature, time and quench rate, otherwise the final mechanical properties of the metal and its corrosion resistance may be affected.

Table 16 and Table 17 list the heat treatment conditions and the solution treatment times respectively for the main alloys of the 6000 series used in marine applications

SOLUTION TREATMENT TIMES

Thickness or Diameter (mm)	Minimum holding time at temperature in air furnace (minutes) (*)
≤ 0,5	20
0,5 - 0,8	25
0,8 - 1,6	30
1,6 - 2,3	35
2,3 - 3,0	40
3,0 - 6,25	50
6,25 - 12,0	60
12,0 - 25,0	90
25,0 - 37,5	120
37,5 - 50	150

(*) This is the minimum holding time at temperature (according to standard AMS STD-2772).

Table 17

4.2 Softening by annealing

When forming semis made from 6000 series alloys, it may be necessary to perform intermediate annealing to restore their plasticity. The temperatures and holding times depend on the alloy, and are given in table 11, p.38.

After annealing, the rate of cooling must be controlled to prevent a quenching effect.

4.3 Designation of tempers

The tempers of age hardening alloys are all designated by the letter T followed by 1 to 5 digits, a full description of which will be found in standard EN 515 (table 18).

Age hardening alloys and the most common tempers used in marine applications are indicated in table 19.

PRINCIPAL TEMPERS OF AGE HARDENING ALLOYS

Notes	Meaning	Notes
T1	T1 Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.	*This designation applies to products that undergo no cold working after the cooling process that follows hot working, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.*
T3	T3 Solution heat treated, cold worked and naturally aged to a substantially stable condition.	*This designation is used for products which, after solution heat treatment, undergo cold working to improve their strength, or in which the effects of cold working associated with flattening or straightening alters the limits of mechanical properties.*
T4	Solution heat treated and naturally aged to a substantially stable condition.	*This designation applies to products that undergo no cold working after solution heat treatment, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.*
T5	T5 Cooled from an elevated temperature shaping process then artificially aged.	*This designation applies to products that undergo no cold working after the cooling process that follows hot working, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.*
T6	Solution heat treated then artificially aged.	*This designation applies to products that undergo no cold working after solution heat treatment, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.*
T451 T651	Metal in T4 or T6 temper which, after quenching, undergoes controlled stretching to relieve internal stresses.	*This designation is used for sheet, plate, rolled or cold-finished bar, hand or ring forging and rolled ring which, after solution heat treatment or after cooling following hot working, are stretched by the amount indicated:* ■ *plate: 1.5% to 3% permanent set* ■ *sheet: 0.5% to 3% permanent set* *These products receive no further straightening after stretching.*

Table 18

RECOMMENDED ALLOYS FOR MARINE APPLICATIONS (ACCORDING TO EN 13195-1) (16)

Alloy	Sheet and Strip	Extrusion		
		Bar	Tube	Shapes
5754	O/H111 H112 H32, H34, H36	O/H111	O/H111	H112
5454	O/H111 H112 H32, H34	O/H111 H112	O/ H111 H112	H112
5086	O/H111 H112, H116 (a) H32 (a), H34 (a)	O/ H111 H112	O/ H111 H112	H112
5083 and 5383 (17)	O/H111 H112, H116 (a) H32 (a), H34 (a)	O/H111 H112	O/H111 H112	H112
6082	O (b) T4, T451 T6, T651	O/H111 (b) T4 (c) T6 (c)	O/H111 (b) T4 (c), T5 T6 (c)	O/H111 (b) T4 (c) T6 (c)
6106			T6 (c)	
6005A	T6 (c)	T6 (c)	T4 (c) T6 (c)	

(a) The 5083, 5383 and 5086 alloys made in the H116 temper as sheet, strip and plate must be tested evaluate their resistance to intergranular and exfoliating corrosion (cf. Chapter 10).

(b) This temper is not intended for any final use. The thermal treatment is applied after forming.

(c) The mechanical properties can be obtained by press quenching.

Table 19

MECHANICAL PROPERTIES FOR SHEET AND STRIP (*)

Alloy	Thickness (mm)	Temper	Rm (MPa)		$Rp_{0,2}$ (MPa)	A % (**) min	
			min	max	min	A_{50}	A
5754	3 ≤ t ≤ 50	O/H111	190	240	80	18	17
		H24	240		165	10	8
5086	3 ≤ t ≤ 50	O/H111	240	310	100	17	16
	3 ≤ t ≤ 12,5	H112	250		125	8	
	12,5 ≤ t ≤ 50	H112	240		105		
	3 ≤ t ≤ 50	H116	275		195	10	9
	3 ≤ t ≤ 50	H32 and H321	275	335	185	10	9
	3 ≤ t ≤ 50	H34	300		235	9	8
5083	3 ≤ t ≤ 50	H32 and H321	305	380	215	10	9
	3 ≤ t ≤ 50	O and H111	275	350	125	16	15
	3 ≤ t ≤ 50	H112	275		125	12	10
	3 ≤ t ≤ 50	H116	305		215	12	10
5383	3 ≤ t ≤ 50	O/H111	290		145		17
(19)	3 ≤ t ≤ 50	H116 or H321	305		220		10

(*) Taken from Table 4 of standard EN 13195-1.

(**) When they are available, values of A_{50mm} must be applied up to (and including) 12.5 mm thick and values of A above 12.5 mm thick.

Table 20

5. THE PRINCIPAL ALLOYS FOR MARINE APPLICATIONS

Most yards that build ships and equipment for coastal and offshore installations use the alloy semis as recommended by standard EN 13195-1 (16) from which table 19 is taken.

5.1 Guaranteed mechanical properties at ambient temperature

In Appendix 1 the reader will find the mechanical properties guaranteed by standards EN 485-2 and EN 1386 for tread plate (18).

Where semis are controlled by a classification society, standard EN 13195-1 specifies the minimum mechanical properties shown in table 20 and table 21 for rolled and extruded semis respectively.

5.2 Mechanical properties at low temperatures

Aluminium alloys, particularly those that belong to the 5000 and 6000 series, can be exposed to low temperatures without suffering any structural alteration (20).

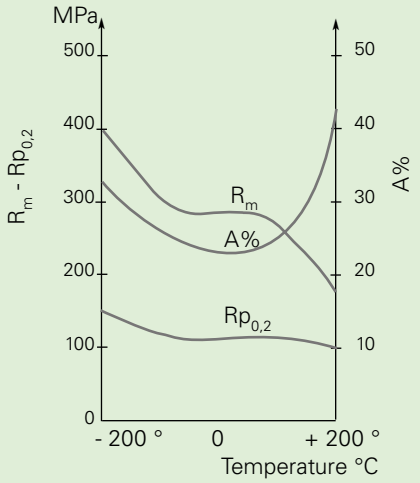
This property accounts for the growth in the cryogenic uses of aluminium, e.g. tanks in methane carriers (20), exchangers in natural gas liquefaction and regasification plants, etc.

Aluminium has also been used in the construction of a number of polar and circumpolar exploration vessels.

The change in the mechanical properties of 5083 O between –196°C and +200°C are listed in table 22 by way of example. It will be noted that the capacity for elastic deformation does not diminish at cryogenic temperatures (figure 21).

Prolonged holding at low temperatures does not modify the mechanical properties following the return to ambient temperature.

5086 O - INFLUENCE OF TEMPERATURE



Alloy 5086, O Temper

Figure 21

(16) EN 13195-1: Aluminium and aluminium alloys: Wrought products and castings for marine applications (shipbuilding, maritime and offshore), December 2002, table 1.

(17) Sealium® is always 5383 temper H116 for rolled and temper H112 (capable H116) for extruded.

(18) EN 1386. Aluminium and aluminium alloys – Tread plate – Specifications.

(19) Sealium® is always temper H116.

(20) Unlike steels, aluminium alloys have no "transition point", a temperature below which they may sustain a fragile rupture.

ALUMINIUM WATERJET LJ114E



MECHANICAL PROPERTIES OF EXTRUDED SEMIS (*)

Alloy	Form	Thickness (mm)	Temper	R_m	$Rp_{0,2}$ (MPa)	A % (**) min	
				min	min	A_{50}	A
5086	Shapes, bar, tube	3 ≤ t ≤ 50	H112	240	95	10	12
5083	Shapes, bar, tube	3 ≤ t ≤ 50	H111	270	110	10	12
	Shapes, bar, tube	3 ≤ t ≤ 50	O and H112	270	125	10	12
6060	Shapes, bar, tube	3 ≤ t ≤ 25	T5	190	150	12	12
	Shapes, bar, tube	3 ≤ t ≤ 25	T6	190	150	12	12
6061	Shapes, bar, tube	3 ≤ t ≤ 50	T5 or T6	260	240	10	8
	Profilés fermés	3 ≤ t ≤ 50	T5 or T6	245	205		4
6005A	Shapes, bar, tube	3 ≤ t ≤ 25	T5 or T6	260	215	8	6
	Closed shapes	3 ≤ t ≤ 25	T5 or T6	250	215		5
6082	Shapes, bar, tube	3 ≤ t ≤ 25	T5 or T6	310	260	10	8
	Closed shapes	3 ≤ t ≤ 25	T5 or T6	290	240		5
6106	Shapes, bar, tube	3 ≤ t ≤ 25	T6	240	195		

(*) Taken from Table 4 of standard EN 13195-1.

Table 21

(**) When they are available, values of A_{50mm} must be applied up to (and including) 12.5 mm thick and values of A above 12.5 mm thick.

5083 O CHANGE IN MECHANICAL PROPERTIES (*)

Temperature°C (**)	Rm (MPa)	$Rp_{0,2}$ (MPa)	A %
– 196	390	140	34
– 80	280	120	26
– 28	270	120	24
+ 20	270	120	22
+ 100	270	120	26
+ 150	210	110	35
+ 200	155	105	45

(*) After 10,000 hours holding at temperature.

Table 22

(**) Holding and measurement temperature.

MECHANICAL PROPERTIES AT TEMPERATURE (*) AFTER HOLDING FOR 10,000 HOURS

Alloy	Temper	20°C			100°C			150°C			204°C		
		Rm	$Rp_{0,2}$	A %	Rm	$Rp_{0,2}$	A %	Rm	$Rp_{0,2}$	A %	Rm	$Rp_{0,2}$	A %
5086	O	262	117	30	262	117	36	200	110	50	152	103	60
5083	O	290	145	25	275	145	36	215	130	50	150	115	60
6082	T6	315	280	12	300	265	14	240	220	17	130	105	28
6061	T6	310	276	17	290	262	18	234	214	20	131	103	28

(*) They are measured at the temperature indicated.

Table 23

5.3 Mechanical properties at temperatures above 100°C

The mechanical properties of aluminium alloys at temperatures over 100°C depend on the level of the temperature and the holding time as shown in figure 22 for the 6061. As temperature rises, the ultimate tensile strength Rm and yield strength $Rp_{0.2}$ decrease while ultimate elongation A% increases. The change in the mechanical properties of alloys 5083, 5086, 6082 and 6061 are given in table 23.

Hot working these alloys therefore leads to a significant drop in mechanical properties, especially among 6000 series alloys in the T5 or T6 temper.

6061 T6 – INFLUENCE OF HOLDING TIMES AT TEMPERATURE

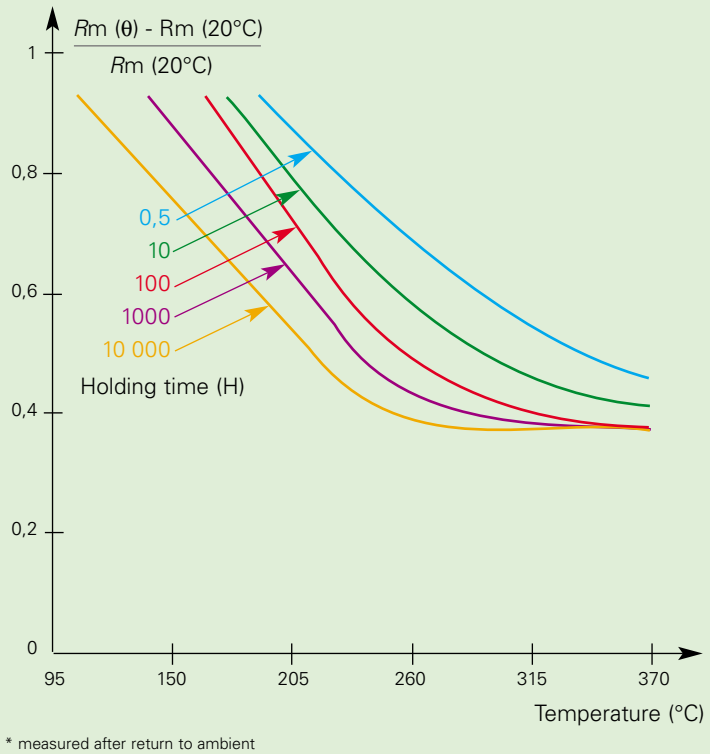


Figure 22

WELDED JOINT

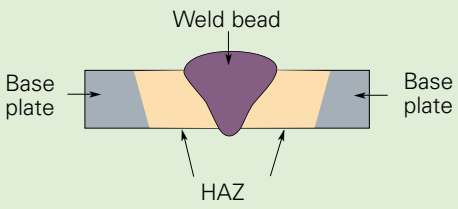


Figure 23

6. A NEW ALLOY: *SEALIUM* ®, "MARINE GRADE"

Because of the presence of the heat affected zone, a welded aluminium alloy structure is designed on the basis of the proof stress s_o in the annealed condition (O or H111) for strain hardened alloys.

Accordingly, the increase in proof stress in the heat affected zone means that for a welded structure we can either increase unit stresses for the same thickness of parent metal, or reduce the thickness for the same stress.

A welded joint consists of a weld bead and the heat affected zone on either side of it, which is itself connected to the parent metal (figure 23).

The increase in the mechanical properties of the welded joint depend on that of each of the joint's components: the parent metal, the heat affected zone (HAZ) and the weld bead, as well as on their metallurgical structure.

Research has shown that the best results are obtained with a parent metal that has a fibrous structure and a recrystallised weld bead with fine grains [1] (figure 24).

OPUS 45



To achieve this, it is necessary to control a number of more or less interdependent factors that produce a more homogeneous bond between the parent metal, the HAZ and the weld bead:

- the composition of the alloy: the principal effect of a controlled increase in the content of magnesium, zinc and manganese is to raise the level of mechanical properties of the parent metal,
- the metallurgical structure of each of the constituents: the addition of zirconium promotes the grain flow of the parent metal, and a fine grain in the weld bead helps to improve the level of mechanical properties,
- the working conditions, optimised to obtain the H116 temper.

Research by the Alcan Research Center (CRV) has led to the development of *Sealium*® (Marine Grade) which is 5383 still in the H116 temper. It meets the demands of constructors looking for high-performance alloys.

This new alloy, which is registered by the Aluminium Association under the designation AA5383, has been approved by most of the classification societies:

- American Bureau of Shipping ABS,
- Bureau Veritas BV,
- Det Norske Veritas DNV,
- Germanischer Lloyd GL,
- Lloyd's Register of Shipping LR,
- Nippon Kaiji Kyokai NKK
- Registro Italiano Navale RINA.

6.1 Mechanical properties

Publications about these new alloys report the following results:

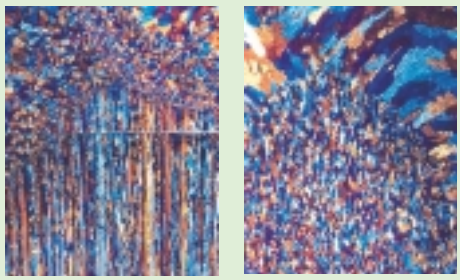
- on parent metal as sheet (table 24),
- on welded metal (table 25).
- on extruded shape (table 26)

Comparative tests have been carried out on 6 mm thick sheet in 5083 and in *Sealium*®, butt welded with 5183 filler [2].

The mean mechanical properties (five measurements) according to the DNV report (figure 25) are given in table 25.

These results show that on the welded *Sealium*®, and in the direction square to the weld, the gain in ultimate tensile is 12 MPa and in proof stress 15 MPa compared with the 5083, or 4% UTS and 11% proof stress. In the heat affected zone the gains are 20.5 and 11.6% respectively.

STRUCTURE OF WELDED JOINT ON *SEALIUM*®



Sealium® 5083 H116

Figure 24

MECHANICAL CHARACTERISTICS ON WELD

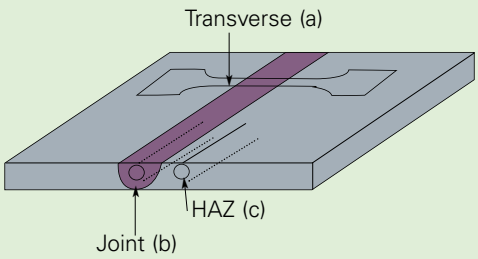


Figure 25

MINIMUM MECHANICAL PROPERTIES OF THE PARENT METAL (*) SHEETS

Alloy	Temper	Rm (MPa)	$Rp_{0,2}$ (MPa)	A %
Sealium®	(**)	305	220	10
5083	O	275	125	10
	H116	305	215	10

(*) Thickness < 20 mm. (**) Sealium® is always temper H116.

Table 24

MEAN MECHANICAL PROPERTIES ON WELDED METAL [1] SHEETS

Parent Metal	Square to the weld (a)			In the weld seam (b)			In the heat affected zone (c)		
	$Rp_{0,2}$ (MPa)	Rm (MPa)	A %	$Rp_{0,2}$ (MPa)	Rm (MPa)	A %	$Rp_{0,2}$ (MPa)	Rm (MPa)	A %
5083 H116	134	287	12,8	128	271	22,0	141	301	25,2
Sealium®	149	299	10,2	141	279	21,8	170	336	21,3
Gain in % (*)	11,2	4,2					20,5	11,6	

(*) compared with 5083.

Table 25

MINIMUM MECHANICAL PROPERTIES ON EXTRUDED SHAPES

Alloy	Temper	R_m (MPa)	$Rp_{0,2}$ (MPa)	A %
Sealium®	H112	310	190	12
5083	O	270	110	14
	H112	270	125	12

Table 26

MECHANICAL CHARACTERISTICS OF BUTT WELDED *SEALIUM*®

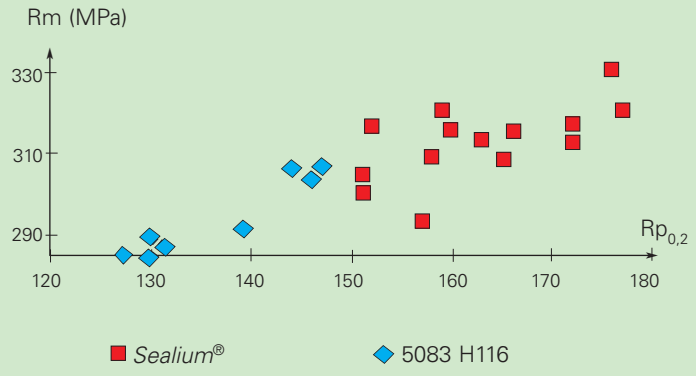


Figure 26

FATIGUE STRENGTH OF *SEALIUM*®

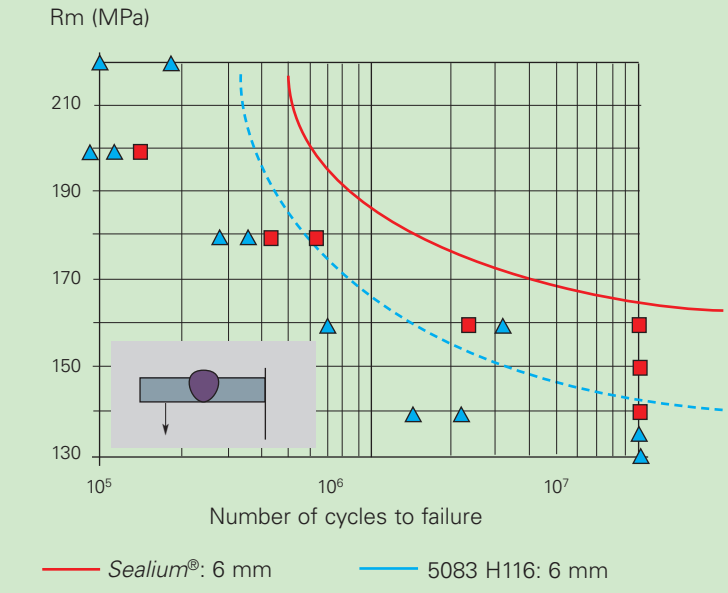


Figure 27

Generally speaking, tests across the weld seam, according to the DNV recommendations, show that the yield strength $Rp_{0,2}$ of *Sealium*® (see note (17) page 43) is always higher than that of 5083 H116 (figure 26).

These results have been corroborated by measurements carried out on welded sheet (using 5183 as filler) by a number of shipyards.

6.2 Fatigue strength

Tests have shown that the fatigue limit of butt welded *Sealium*® is approximately 20 MPa higher than that of 5083, all other things being equal (figure 27).

6.3 Corrosion resistance

Corrosion tests performed according to the specifications of standard ASTM B928 on over 50 lots of *Sealium*® manufactured by Alcan's Issoire plant have shown that its corrosion resistance is at least equivalent to if not better than that of 5083 (table 27).

To pass, a lot must be classified N, PA and PB in the ASSET test and the loss of weight in the NAMLT must be less than 15 $mg.cm^{-2}$ (21).

(21) Cf. Section 11 of Chapter 10.

RESISTANCE TO CORROSION OF *SEALIUM*®

	Exfoliating Corrosion ASSET ASTM G66 Test		Intercrystalline Corrosion Test ASTM G67 NAMLT	
	Sealium®	5083	*Sealium*®	5083
Parent metal	N/PA	PA/PB	4 $mg.cm^{-2}$	4 $mg.cm^{-2}$
Heat affected zone	PA	PB		

Table 27

7. THE SERIES OF CASTING ALLOYS

There are 5 series of industrial casting alloys (table 28). Like the wrought alloys, casting alloys have a 5 digit numerical designation according to standard EN 1706 (22). Their tempers are shown in table 29.

The potential offered by casting processes - especially for the creation of relatively complex shapes - makes it possible to use aluminium casting alloys in numerous marine applications. These include:

- ships' superstructures,
- structural components,
- assembly nodes,
- components for assemblies with mechanical functions,
- interior fitments,
- various supports.

The alloys used for these marine applications are first melt alloys, and belong almost exclusively to two series:

- the 40000 series comprising aluminium-silicon alloys, and
- the 50000 series comprising aluminium-magnesium alloys.

Aluminium-copper alloys must be avoided for marine applications unless they are well protected.

7.1 The silicon alloys of the 40000 series

These alloys have:

- excellent potential for casting, making it possible to easily design sound components with complex shapes,
- very good weldability (23),
- very good mechanical properties after thermal treatment for the age hardened alloys that contain magnesium (24),
- very good behaviour in marine environments.

Four alloys in particular are recommended:

- 41000 for components required to present a good appearance after mechanical polishing and anodising,
- 42100 and 42200 for complex components required to have high mechanical properties. These two alloys must be age hardened in order to present good mechanical properties,
- 44100 for slender chill-cast components.

7.2 The magnesium alloys of the 50000 series

The aluminium-magnesium alloys are particularly notable for their:

- excellent aspect after mechanical polishing,
- eminent suitability for anodising for protection and decorative purposes,
- good weldability: they can be joined to other cast, rolled or extruded products of similar composition,
- excellent resistance to corrosion in marine environments. They are all ideally suited to marine applications, but two alloys in particular are recommended:

- 51100, with 3% magnesium,
- 51300, with 6% magnesium.

(22) EN 1706. Aluminium and aluminium alloys. Chemical composition and mechanical properties.

(23) It is not advisable to weld 40000 series casting alloys to 5000 series wrought alloys (and vice versa. (Cf. Chapter 6).

(24) The age hardening process for the 42100 and 42200 alloys is as follows: solution heat treatment for 10 h at 540 °C, water quenching then artificially ageing for 6 h at 160°C; the process for the 41000 is the same except: solution heat treatment for 4 h at 540°C.

SERIES OF CASTING ALLOYS

Alloying Element	Designation
None	10000
Copper	20000
Silicon	40000
Magnesium	50000
Zinc	70000

Table 28

TEMPERS OF CASTING ALLOYS

Principal Thermal Treatments	EN 1706	AFNOR NF A 57 702 (*)	
None, as-cast	F	Y 20	Y 30
Solution heat treatment, quenching and natural ageing	T4	Y 24	Y 34
Solution heat treated, quenched and artificially aged to peak strength	T6 (**)	Y 23	Y 33
Solution heat treated, quenched and under-aged	T64	Y 23	Y 33

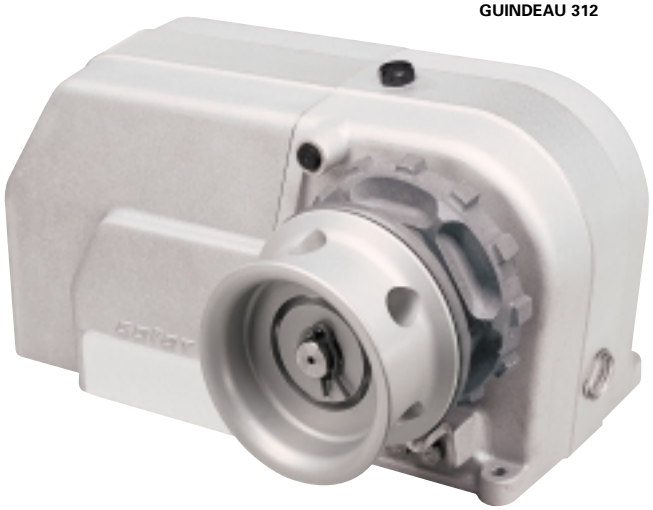
(*) Y2X denotes sand cast, Y3X denotes chill cast. (**) In practice the artificially aged T6 is never at peak strength but is always just below it to retain a minimum of elongation. T64 denotes an under-aged temper designed to promote elongation.

Table 29

8. PROPERTIES OF CASTING ALLOYS

The principal properties of the casting alloys used in marine applications are shown in the tables below.

GUINDEAU 312



8.1 Chemical composition

The chemical composition in components according to EN 1706 is given in table 30.

STANDARD COMPOSITION IN COMPONENTS (% BY WEIGHT)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Pb	Sn
41000	1,6 2,4	0,60	0,10	0,30 0,50	0,45 0,65	0,05	0,10	0,05 0,20	0,05	0,05
42100	6,5 7,5	0,19	0,05	0,10	0,25 0,45		0,07	0,08 0,25		
42200	6,5 7,5	0,19	0,05	0,10	0,45 0,70		0,07	0,08 0,25		
44100	10,5 13,5	0,65	0,15	0,55	0,10	0,10	0,15	0,20	0,10	0,05
51100	0,55	0,55	0,05	0,45	2,5 3,5		0,10	0,20		
51300	0,55	0,55	0,10	0,45	4,5 6,5		0,10	0,20		

Note: Where a single value is given, it corresponds to the permitted maximum.

Table 30

8.2 Physical properties

PHYSICAL PROPERTIES OF CASTING ALLOYS

Alloys	Density ($kg.m^{-3}$)	Thermal Conductivity at 20°C ($W.m^{-1}°C^{-1}$)	Coefficient of linear Expansion between 20 and 100°C	Solidification Interval °C	Mean Contraction (%)
41000	2700	160	22.10^{-6}	640-555	14
42100	2680	160	$21,5.10^{-6}$	615-555	12,5
42200	2680	160	$21,5.10^{-6}$	615-555	12,5
44100	2650	165	20.10^{-6}	580-575	11
51100	2670	145	24.10^{-6}	640-590	14
51300	2640	125	24.10^{-6}	625-540	13

Table 31

8.3 Engineering suitability

ENGENEERING SUITABILITY OF CASTING ALLOYS										
Alloy	Casting	Cracks Sensibility	Thin Pieces	Dimensional Stability	Machinability	Weldability (TIG and MIG arc)	Polishing	Anodizing for Protection	Anodizing for Decoration	Resistance to Corrosion in marine environment
41000	2	2	2	3	3	3	4	4	4	3
42100	3	3	4	3	2	3	3	4	0	3
42200	3	3	4	2	3	3	3	4	0	3
44100	4	4	4	4	1	4	2	4	0	3
51100	2	1	1	3	4	4	4	4	4	4
51300	2	1	2	3	4	4	4	4	3	4

0 - Unsuitable. 1 - Poor. 2 - Fair. 3 - Good. 4 - Excellent.

Table 32

8.4 Mechanical properties

MECANICAL CHARACTERISTICS ON CAST SAMPLES					
Alloy	Temper	Cast Mode	R_m (MPa)	$Rp_{0,2}$ (Mpa)	A %
41000	T6	Y23 Y33	240 260	180 180	3 5
42100	T6	Y23 Y33	230 290	190 210	2 4
42200	T6	Y23 Y33	250 320	210 240	1 3
44100	F	Y20 Y30	150 170	70 80	4 5
51000	F	Y20 Y30	140 150	70 70	3 5
51300	F	Y20 Y30	160 180	90 100	3 4

Table 33

Bibliography

[1] "High Strength Marine Grade Aluminium Alloys: a new generation of 5383 with improved properties", C. Hénon, R. Dif, A. Duran, *18th Fast Ferry Conference and Exhibition,* Nice, France, February 2002.

[2] The potential of 5383 alloy in marine application. G. M. Raynaud and Ph Gomiero, Pechiney Rhenalu, *Conférence Alumitech 97,* pp. 353-366.



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CATAMARAN UAI 50

Chapter 4
DESIGN CALCULATION OF STRUCTURES AND FATIGUE BEHAVIOUR

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4. DESIGN CALCULATION

ALUMINIUM alloy structures are designed using the rules for calculating the strength of materials.

Compared with steels, the specific properties of aluminium such as Young's modulus of elasticity, which is one third that of steel, must be calculated relative to the criterion of strain. To make up for the low Young's modulus of aluminium, inertias must be optimised to achieve a modulus of inertia I/v that is as high as possible.

Unlike steels, in aluminium alloys the heat affected zone either side of a weld is softened. The mechanical properties to be taken into consideration are the annealed condition (O) for strain hardened alloys, and the T4 condition (naturally aged at ambient temperature) for age hardened alloys.

Because of the softening process, the residual stresses from welding are lower in aluminium alloy welds than steel welds.

The fatigue behaviour of aluminium alloys depends essentially on the design of the weldments and the quality of workmanship with which they are made.

Given aluminium's specific attributes in terms of its mechanical properties and fatigue strength, experience shows that it is possible for an aluminium alloy structure to achieve a saving in weight of some 50% compared with its equivalent structure in steel.

The stress calculations of the structures of ships are based on the rules of classification societies which we shall not go into here (1). Suffice to say that these rules are based on the principles of the strength of materials, weighted by factors acquired from experience.

(1) The reader is invited to consult the relevant sources.

THE PRINCESS



OF STRUCTURES AND FATIGUE BEHAVIOUR

1. PROPERTIES OF ALUMINIUM

For all aluminium alloys that are used in shipbuilding, according to Eurocode 9 (2), structures must be calculated with the values indicated in table 34 for the basic properties.

It will be noted that whatever the alloy, Young's modulus is 70 000 MPa or one third that of steel, and that the coefficient of expansion, $23.10^{-6}.°C^{-1}$, is double that of steel. In no way is the low Young's modulus of aluminium an obstacle to designing structures normally resistant to buckling. To achieve this we just need to take advantage of the relative ease with which aluminium can be shaped and formed, especially by extrusion, and to optimise the distribution of masses as illustrated by the examples discussed in Section 3.2.

(2) Eurocode 9: Design of Aluminium Structures – Part 1-1 General rules and rules for buildings. Standard EN, ENV 1999-1-1.

PHYSICAL PROPERTIES OF ALUMINIUM

Property	Unit	Value
Young's modulus: E	$N.mm^{-2}$	70 000
Shear modulus: G	$N.mm^{-2}$	27 000
Poisson's ratio: ν		0,3
Coefficient of thermal expansion: α	$10^{-6}.°C^{-1}$	23
Density: ρ	$Kg.m^{-3}$	2 700

Table 34

2. DETERMINING THE MAXIMUM STATIC STRESS

The criteria used by most classification societies are usually based on a comparison of the calculated stress with the maximum admissible strain which is obtained from the calculation done according to the theory of the elastic bending of structures [1].

The minimum test piece sampling of a structure is determined from:

- the load to which the structure is subjected (which depends on the characteristics of the ship),
- the mechanical properties of the material,
- the design rules; these may be weighted by correction factors drawn from experience.

THE PRINCESS



2.1 The case of a plane section reinforced with stiffeners

For a thin sheet of great length, subjected to angular strain of low amplitude, the maximum stress on such a structure (figure 28) is equal to [2].

$$\sigma_{max} = pk\left[\frac{b}{t}\right]^2 \qquad [1]$$

where:
- σ_{max} = maximum admissible stress,
- p = hydrostatic pressure,
- k a correction coefficient,
- b = width of the panel,
- t = thickness.

In equation [1], thickness t of the sheet of the section is written:

$$t = b\sqrt{\frac{pk}{\sigma_{max}}} \qquad [2]$$

Compared with the yield strength $Rp_{0,2}$ of the metal, the above expression is expressed simply:

$$t = \sqrt{\frac{A}{Rp_{0,2}}} \qquad [3]$$

According to the DNV rules (3), thickness t can be calculated with the following equation:

$$t = s\sqrt{\frac{Cp}{\sigma}} \qquad [4]$$

where:
- σ = maximum admissible specific stress due to lateral pressure
- p = hydrostatic pressure,
- C = correction coefficient dependent on the geometry,
- s = space between stiffeners,
- t = thickness.

2.2 The case of a beam in bending subjected to uniform hydrostatic pressure

The maximum stress is obtained from the formula (figure 29) [3]:

$$\sigma_{max} = \frac{M\,v}{I} = \frac{M}{S} \qquad [5]$$

where:
- σ_{max} = maximum admissible bending stress,
- M = bending moment,
- v = distance from the neutral axis,
- I = moment of inertia,
- S = I/v = modulus of inertia.

Knowing the maximum admissible bending stress and the bending moment due to the load between two supports, there is:

$$S = \frac{M}{\sigma_{max}} \qquad [6]$$

As with the thickness, S depends on the yield strength of the metal:

$$S = \frac{k}{Rp_{0,2}} \qquad [7]$$

According to the DNV rules (4), the equation [6] is written:

$$Z = \frac{m l^2\, s\, p}{\sigma} \qquad [8]$$

where:
- Z = section of the stiffener,
- m = correction factor for the bending moment,
- l = span,
- s = space between two longitudinal stiffeners,
- p = hydrostatic pressure,
- σ = admissible bending stress

(3) DNV Rules, Part. 3, Chap. 3, Sec. 5, B201.

(4) DNV Rules, Part. 3, Chap. 3, Sec. 5, C100.

PLATE IN BENDING

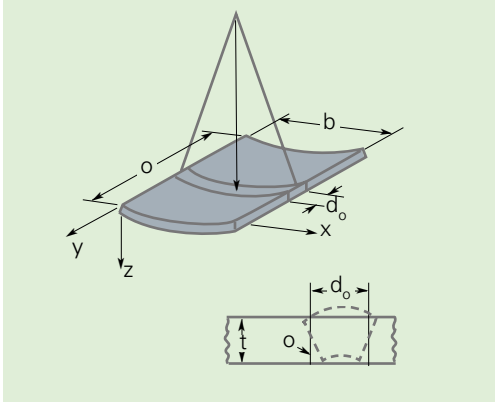


Figure 28

BEAM IN BENDING

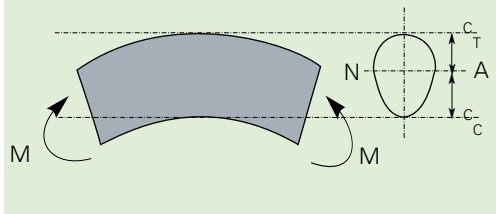
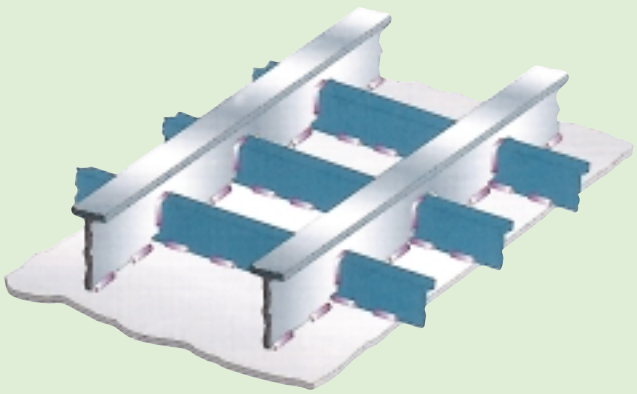


Figure 29

DESIGN OF A PLATE WITH STIFFENERS



Case (table 38)	Plate	Extruded shape
a	5083 H116	6082 T6
b	*Sealium*®	*Sealium*®
c	steel A275	steel A275

Figure 30

PRINCIPAL CHARACTERISTICS OF THE YACHT

Dimension	Value
Length OA	50,0 m
Rule Length	40,0 m
Beam	10,3 m
Draft	2,09 m
Space between frames	0,9 m
Displacement	450 tonnes
Speed	56 knots

Table 35

STRESS LEVELS

Parameters	Value
Vertical acceleration	1,5 g
Distance between stiffeners	213,0 mm
Distance between frames	900 mm
Stress on the panel	257,7 $kN.m^{-2}$
Stress on the stiffener	257,7 $kN.m^{-2}$
Stress on the frame	160,9 $kN.m^{-2}$

Table 36

3. TRANSPOSING FROM STEEL TO ALUMINIUM

Two cases must be considered :
- a plane section with stiffeners,
- a beam in bending.

3.1 The case of a plane section

The example chosen is that of a representative section of a conventional structure with sheet and stiffeners (figure 30) from the hull of a 50 metres yacht whose characteristics are shown in table 35:

The comparison relates to three cases:
- sheet and stiffeners in A27S steel,
- sheet in 5083 H116 and stiffeners in 6082 T6 extruded shapes,
- sheet in *Sealium*® and stiffeners in *Sealium*® extruded shapes,

The stresses considered are the hydrostatic pressure and the pressure due to "slamming". They are evaluated according to the DNV rules referred to in (4). Their levels are given in table 36:

The mechanical properties used are those accepted by the DNV (table 37):

The DNV design rules (5) applied to this structural element result in the test pieces shown in table 38.

Structures made from aluminium can save between 48 and 51% weight compared with steel, the combination of *Sealium*® sheets + *Sealium*® extruded shapes being a prime example (table 39).

(5) DNV Rules for Ships/High speed, Light Craft and Naval Surface Craft, January 2001.

MECHANICAL PROPERTIES OF MATERIALS

Semi Product	Alloy	Non Welded Metal		Welded Metal		
		$Rp_{0,2}$ (MPa)	Rm (MPa)	$Rp_{0,2}$ (MPa)	Rm (MPa)	Coefficient f_1
Sheet	5083 H116	215	305	125	275	0,60
	Sealium®	220	305	145	290	0,64
	Steel A27S	265	400	Unchanged		1,08
Shapes	6082 T6	260	310	115	205	0,48
	Sealium®	190	310	145	290	0,64 (*)
	Steel A27S	265	400	Unchanged		1,08

(*) The DNV rules puts the 5383 H112 in the same category as Sealium® (5383 H116).

Table 37

TEST PIECES OF STRUCTURES

Attachment	Sheet Thickness (mm)	Size of Stiffeners	Size of Longitudinals (T-shaped)
5083 H116/6082 T6	7	120 x 6 bulb flats @ 213 mm spacing	500 x 8 + 60 x 8 mm
Sealium®/*Sealium*®	7	105 x 6 bulb flats @ 220 mm spacing	460 x 8 + 65 x 8 mm
Steel A27S/Steel A27S	5	100 x 6 bulb flats @ 240 mm spacing	460 x 4 + 50 x 6 mm

Table 38

SAVING IN WEIGHT COMPARED WITH STEEL

Structural Elements ($kg.m^{-2}$)	Steel	5083 Sheet + 6082 Shape	*Sealium*® Sheet + *Sealium*® Shape
Sheet	39,2	18,9	18,9
Stiffener	36,3	11,9	9,9
Longitudinal	18,7	13,3	12,6
Total	84,40	44,1	41,4
Saving in %		47,8	51,0

Table 39

STEEL AND ALUMINIUM SHAPES

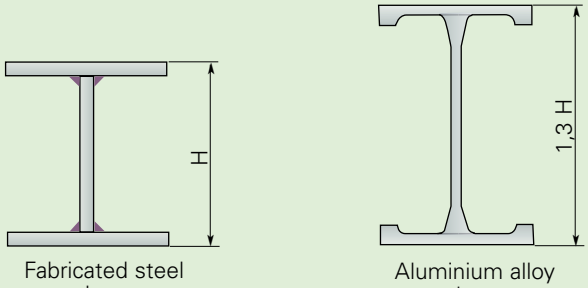


Figure 31

3.2 The case of a beam in bending

At equal strength, the following statement must be verified

$$\sigma_{e\,steel} \cdot I/v_{steel} = \sigma_{e\,alu} \cdot I/v_{alu}$$

hence:

$$I/v_{alu} = \frac{\sigma_{e\,steel}}{\sigma_{e\,alu}} \cdot I/v_{steel}$$

In that case, the transposition will be made using extruded aluminium shapes whose height is some 30% greater than the height of steel shapes (fabricated) (figure 31) or fabricated shapes.

As we have already asserted (6), aluminium's excellent extrudability makes it possible to achieve shapes that are optimised for marine applications: figure 32 and tables 41 and 42, pp. 61-62.

"TEE" SHAPE AND BULB FLAT IN *SEALIUM®*

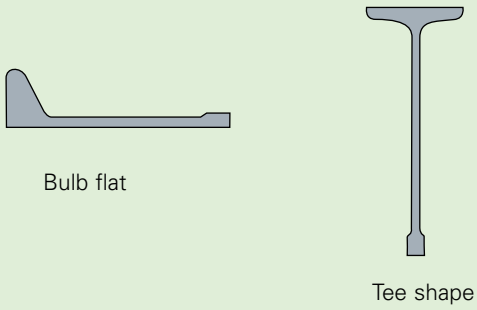
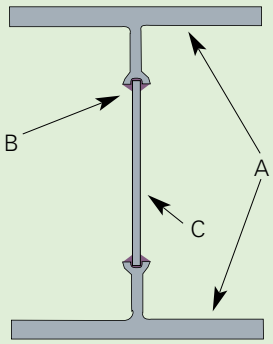


Figure 32

Calculations show that at equal strain, the weight per linear metre of a Tee shape made from *Sealium®* is half that of its hot-rolled steel equivalent with simple geometric forms (table 40).

Aluminium can be used to fabricate large shapes by the automatic welding of flanges of shapes and sheet (figure 33). This very elegant solution offers a number of advantages: it places the weld seams in the least stressed zones and allows customising.

SHAPES FABRICATED BY WELDING



A: Shapes
B: Fillet weld in lap joint
C: Extruded plate or sheet

Figure 33

(6) Cf. Chapter 2.

4. FATIGUE BEHAVIOUR OF ALUMINIUM ALLOY STRUCTURES

Until relatively recently (the end of the Eighties), problems of fatigue in aluminium ships were virtually non-existent as they were never over 50 metres long. Structures were generously designed to take local loads with no great risk of crack propagation.

Since then, aluminium ships have increased in length to 80 metres and more, and with tougher conditions of service in heavy seas combined with the frequent transport of vehicles (cars and especially coaches and trucks), fatigue behaviour has become one of the major preoccupations of naval architects and shipowners [4].

Experience shows that after more or less long periods of service these large ships can display fatigue cracks in the most stressed zones, and these cracks must be repaired.

Given the implications of fatigue behaviour for the longevity of a structure and for the cost of maintaining vessels made of aluminium

COMPARISON OF "TEE" IN *SEALIUM®* AND IN STEEL

Dimensions	Steel "Tee" P 80X5	*Sealium®* "Tee" T100 X50	*Sealium®* relative to Steel
Mass ($kg.m^{-1}$)	4,25	2,20	– 48%
Height (mm)	80	100	+ 25%
Lateral area (mm^2)	541	830	+ 53%
Moment of inertia (mm^4)	338 700	927 952	+ 274%
Moment of elastic bending relative to axis x – x (mm^3)	6 910	14 193	+ 205%
Product E x I (*)	71 127	64 957	– 9%

*(*) To compensate the differences (from 1 to 3) in elastic moduli at equal strain, the inertia of an aluminium beam must be 3 times greater than that of a steel beam. For the same load, the same length of beam and identical limit conditions, the strain is proportional to 1/E*I.*

Table 40

(or steel), this issue must be taken into account when a ship is designed and built [5].

The problem of sensitivity to fatigue is not one specific to aluminium, but affects steels just as much, especially those with a high limit of elasticity.

5. SERVICE CONDITIONS OF HIGH SPEED SHIPS

High speed ships (HSS) are subjected to cyclical stresses which are due mainly to three types of load:

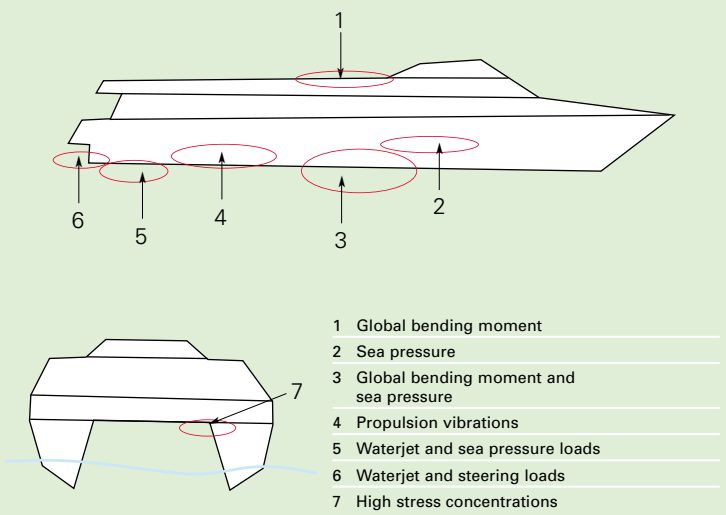
- low level loads but with a large number of cycles. These are caused by vibrations from engines, shaft lines and waterjets,
- high level loads but with few cycles. These loads are generated during vehicle loading and unloading (coaches, trucks, cars),
- medium level loads of medium frequency due to the effect of waves [6, 7].

In high speed ships, the loads due to engines, shafts and waterjets are considered to be the dominating loads in regard to the bending moment of the beam which the ship represents [8].

This means that these ships have some very highly stressed zones, as shown in figure 34.

Experience shows that the problems of fatigue are generally localised in the zones where there is a change of direction and also in doors, windows etc.

LOAD ZONES ON HIGH SPEED SHIPS



1 Global bending moment
2 Sea pressure
3 Global bending moment and sea pressure
4 Propulsion vibrations
5 Waterjet and sea pressure loads
6 Waterjet and steering loads
7 High stress concentrations

Figure 34

6. GENERAL COMMENTS ON THE FATIGUE OF METALS

Fatigue is a complex phenomenon that affects most normal metals including aluminium alloys. It occurs when structures undergo cyclical variations in load.

Experience shows that the levels of stress at which fatigue cracks (and fractures) are observed are generally much lower than the admissible stress calculated for static conditions.
Fatigue behaviour is determined by a number of relative parameters:

- the properties of the metals and alloys,
- the design,
- the workmanship,
- the loads, whose level will depend on the vessel's service conditions (its itinerary, frequency of loading/unloading and the weight of the cargo etc.).

Very many years of experience with fatigue in metal structures (steel, aluminium etc.) have shown that the two most important parameters are design and workmanship, including welding.

According to the design rules, it is only the configuration of the aluminium alloy weldment that is taken into consideration when determining fatigue life (FAT). The nature of the aluminium alloy is disregarded (7) even if its fatigue strength is known to be better, as is the case with *Sealium*® (8). The fact remains that by obeying the mandatory rules, this new alloy offers additional fatigue strength and hence enhanced safety in use.

(7) This is true for steels.

(8) Cf. Chapter 3, Section 6-2.

7. SPECIFICS OF THE FATIGUE BEHAVIOUR OF ALUMINIUM

Aluminium alloys differ from steel in a number of aspects. These include:
- Fatigue limit
- The heat affected zone (HAZ)
- Residual stresses
- Fracture mode
- Propagation threshold.

7.1 Fatigue limit

On a smooth test piece, aluminium has a linear decreasing S/N curve (figure 35). This means that the structural calculations must be verified for the level of stress below which there will be no crack propagation for a given period of time which is usually fixed at 2.10^6 cycles [9].

At this level, the fatigue limit determined on a "smooth" specimen of parent metal is 420 MPa for steel and 140 MPa for aluminium. In welded attachments, the ratio of admissible stresses (FAT) according to the calculation rules between steel and aluminium alloys is in fact closer to 2 (9) on a case by case basis.

7.2 The heat affected zone (HAZ)

Owing to the heat generated by welding, the mechanical properties of the HAZ are those of the annealed condition (O) for strain hardened alloys and of the quenched condition (T4) for age hardened alloys (figure 35), (10).

Welding has the opposite effect on steels, hardening the heat affected zone because of the rapid cooling (quench effect).

But, as with steels, welding also lowers the threshold of admissible stresses under variable loads. These thresholds (FATs) are laid down by standards, calculation rules and classification societies (11).

7.3 Residual stresses

These stresses are lower in aluminium alloys than in steel because the heat affected zone is softened by the heat generated by welding.

(9) For example, for a 100% tested butt weld, (case 211 of the IWW), the steel FAT is 125 MPa and the aluminium alloy FAT is 50 MPa, or 40% of the FAT of steel.

(10) In casting alloys, the fatigue strength of the welded joint is the same as the casting.

(11) FATs and the way in which they are determined may vary somewhat from one code or one regulation to another.

TYPICAL WÖHLER CURVES

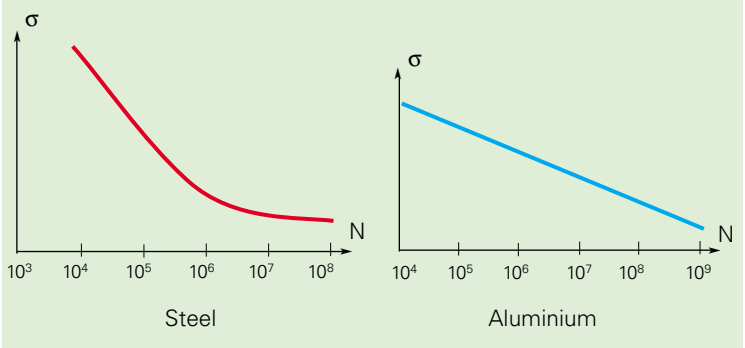


Figure 35

BULB FLATS IN *SEALIUM* ® (*)

Type	H (mm)	Tw (mm)	H1 (mm)	Tw1 (mm)	Bf (mm)	R (mm)	S (mm^2)	Weight $kg.m^{-1}$	C (mm)	I (mm^4)	Sxx High (mm^3)	Sxx Low (mm^3)
P50	50	3	9	4,5	10	4	218	0,58	21,25	57 085	2 687	1 985
P60	60	3,3	9,6	4,8	12	4	284	0,76	24,86	107 947	4 342	3 072
P70	70	3,5	10	5	14,5	4	360	0,96	27,95	186 636	6 677	4 439
P80	80	3,7	10,4	8,2	16,6	4	436	1,16	31,34	296 312	9 455	6 089
P90	100	4,2	11,4	5,7	21	4	620	1,65	38,30	659 291	17 215	10 685
P100	120	4,6	12,2	6,1	26	4	833	2,21	44,47	1 271 697	28 600	16 836
P140	140	5,1	13,2	6,6	30,5	4,8	1 106	2,94	50,31	2 267 810	45 078	25 285
P170	170	5,8	14,6	7,3	37,5	5,8	1 580	4,20	58,99	4 717 199	79 966	42 493

(*) Cf figure 32.

Table 41

TYPICAL FATIGUE CROWTH RATE CURVE

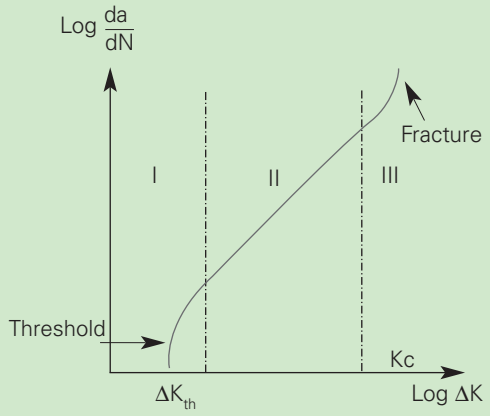
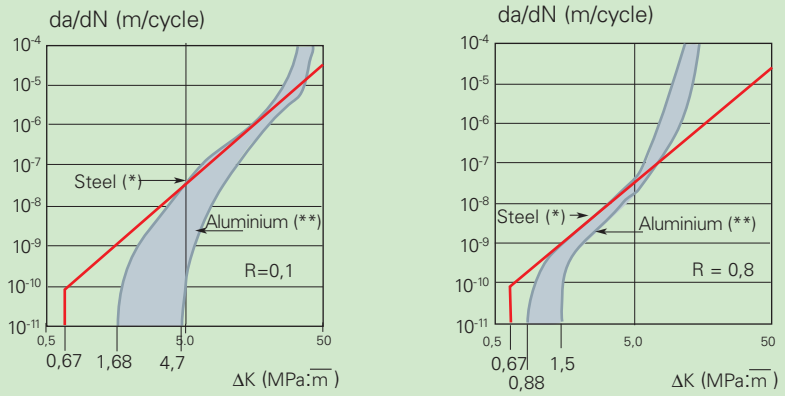


Figure 36

CRACK GROWTH RATES FOR STEEL AND ALUMINIUM



(*) Steel curve has been corrected by a factor x3 to take into account the density difference between aluminium and steel.

(**) 5000, 6000 et 7000 alloys .

Figure 37

7.4 Fracture mode

This is always ductile. Unlike steels, aluminium does not suffer cleavage fracture, for example in the weldment (under the effect of residual stresses), at low temperatures etc.

7.5 Propagation threshold

There is a threshold with the value ΔK above which a crack will start to propagate (phase II in figure 36). For an admissible limit stress of 50 MPa (FAT 50), the limit size of the incipient fault in a weld is 0.5 mm, and a well-made weld is one that is free from defects of this size.

This size limit is relatively high for aluminium alloys, much higher than for steels, all other things being equal, i.e. the mass of the structural element subjected to a load and the level of that load (figure 37).

TEE SHAPES IN *SEALIUM*® (*)

Type	H (mm)	Tw (mm)	H1 (mm)	Tw1 (mm)	Bf (mm)	L (mm)	R (mm)	S (mm^2)	Weight $kg.m^{-1}$	C (mm)	I (mm^4)	Sxx Hight (mm^3)	Sxx Low (mm^3)
T50	50	3	10	5	30	4,5	4,6	299	0,80	16,74	84 662	5 057	2 546
T60	60	3,5	11	5,5	35	5,1	5,2	402	1,07	19,94	162 062	8 126	4 046
T70	70	4	12	6	40	6,1	6	536	1,42	22,69	287 200	12 657	6 071
T80	80	4,5	13	6,5	45	6,2	6,2	650	1,73	26,55	459 564	17 310	8 598
T100	100	5	14	7	50	6,4	6,4	830	2,20	34,62	927 952	26 805	14 193
T120	120	5,5	15	7,5	5	7,7	7,8	1 091	2,90	41,01	1 735 149	42 315	21 965
T140	140	6	16	8	60	8,7	8,8	1 367	3,64	47,89	2 942 592	61 442	31 947
T170	170	6,5	17	8,5	65	10,3	10,4	1 777	4,73	58,05	5 598 542	96 440	50 010

(*) See figure 32.

Table 42

8. CLASSIFICATION OF ALUMINIUM ALLOYS

As with steels, there is no relationship between the fatigue strength of aluminium alloys and their mechanical properties: ultimate tensile strength and proof stress.

As figure 38 illustrates, tests show that the fatigue limits are of the same order of magnitude when stresses attain 10^6 cycles.

This tends to confirm what experience suggests, i.e. that fatigue strength depends on the attachment – including the configuration of the weldment – and not on the basic alloy (or its temper). This is true of the 5000 and 6000 series alloys, and applies equally to steels (figure 39).

The fatigue behaviour of metals in general and of welded connections in particular can only be measured and assessed by tests and experience [10].

The nature of the semi-finished products (sheet, shapes, forgings etc.) made from the same alloy, and their shape, has no effect on fatigue resistance [11].

Surface condition is an important parameter on the other hand: surface scoring and marks encrusted by "iron" can act as the initiation sites for crack propagation (figure 40). The same applies to edge irregularities left behind by cutting tools. Sawing is more favourable to fatigue resistance than plasma cutting because it leaves cut edges that are clean.

INFLUENCE OF THE TYPE OF ALLOY

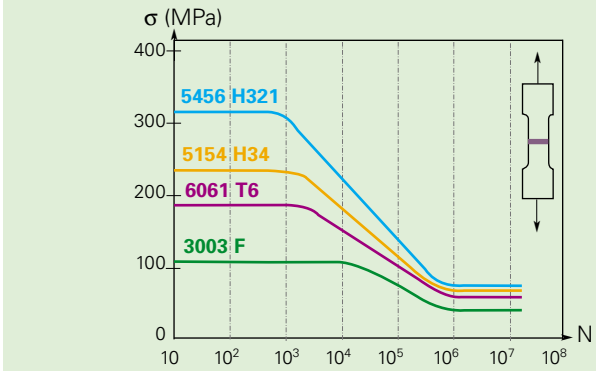


Figure 38

FATIGUE STRENGTH AT 5.10^8 CYCLES

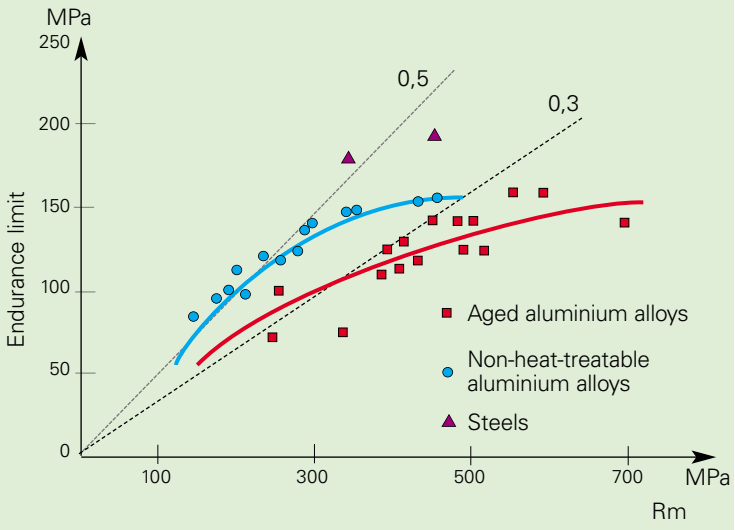


Figure 39

EFFECT OF SURFACE MARKS

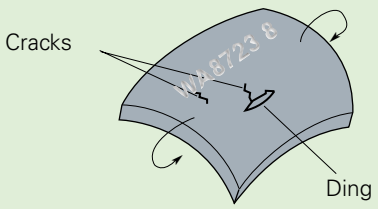


Figure 40

9. FATIGUE LIFE OF WELDMENTS

Experience shows that most fatigue cracks start from the weld bead, either at its beginning, its end or on its surface (around surface "wrinkles").The heat affected zone can also be an initiation site of fatigue cracks.

There are two main reasons for this:

- stress concentrations: the weld bead is the site of stresses due to its method of cooling [12]. Small surface craters form as the weld pool solidifies because of the decrease in volume (figure 41).
- defects (or imperfections) which form when the weldment is made. They are the site of stress concentrations (figure 42).

9.1 Weld defects

A weldment may present different types of defect (13): these can be external (misalignment etc.) or internal due to the execution of the weld (inclusions, porosity etc.), figure 43.

On principle, any defect will tend to reduce fatigue strength when it starts on a free surface and if its size - 2a - exceeds the limit above which a fatigue crack can grow (figure 36, p.62).

Calculations show that for an applied load of 50 MPa, the minimum size of the defect above which cracks grow is 0.5 mm. On weldments that have been correctly executed, the size of normal defects (porosity, shrinkage cracks etc.) varies from 0.01 to 0.40 mm (12, 13), a little less than the critical size (14).

It follows that not all of the types of defect mentioned affect fatigue strength in the same way.

(12) Cf. Chapter 6.

(13) Some of the causes of these defects are given in Chapter 6, Section11.

(14) The fatigue behaviour of a weldment depends on the growth rate of cracks (according to the laws of fracture mechanics).

CRATERS ON THE WELD BEAD

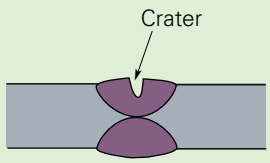
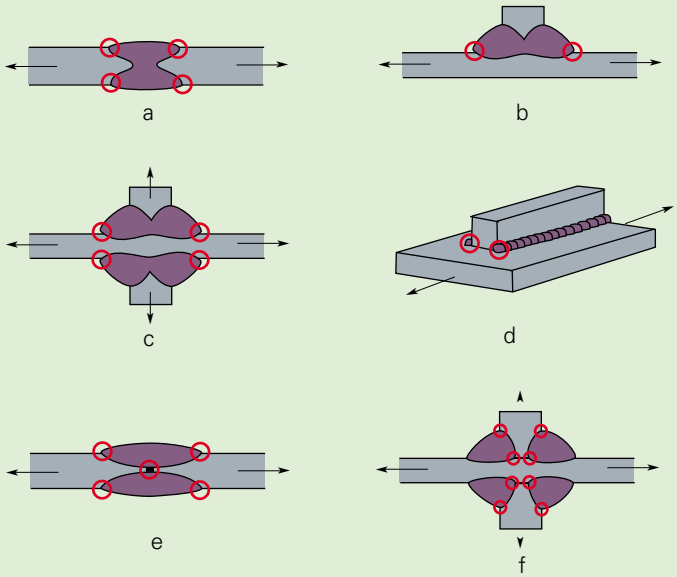


Figure 41

STRESS CONCENTRATIONS AT WELD DEFECTS



Weld toe: a, b, c, d

Weld toe + lack of penetration: e, f

Figure 42

Of the various weld defects, it is the lack of penetration (defect 5 in figure 43) which affects fatigue strength the most, which explains why the fatigue strength of fillet welds is less than that of butt welds, all other things being equal.

The toe angle "α" of the weld bead with the structure is another important factor affecting fatigue strength, for two reasons:

- geometrical, the change in direction which angle "α" marks,
- structural, due to any overfill overflowing the weld (figure 44).

The more obtuse angle "α", the greater the fatigue strength. It is at its maximum when the weld is dressed flush: α = 180°C (figures 45 and 46).

TYPICAL DEFECTS OF WELDMENTS

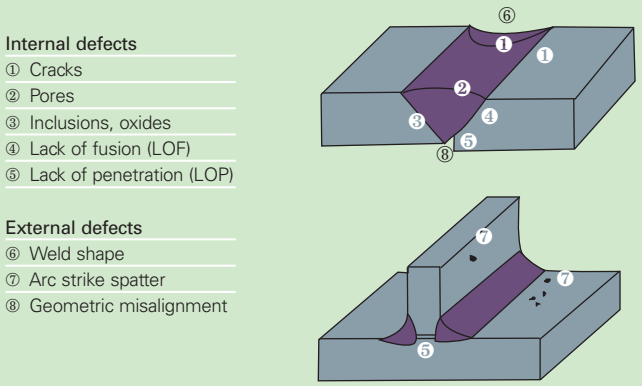


Figure 43

OVERLAP

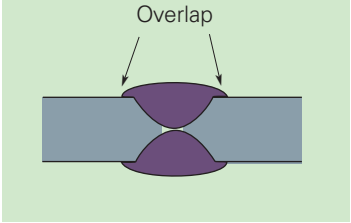


Figure 44

TOE ANGLE OF THE WELD

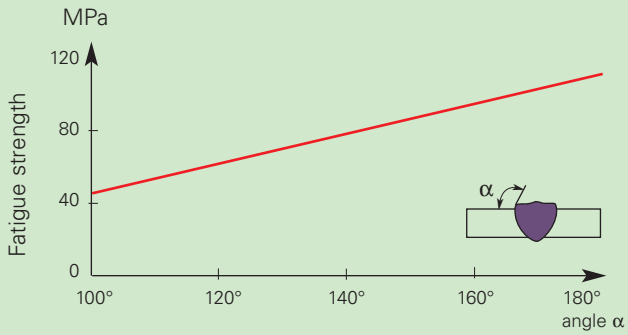


Figure 45

FLUSH DRESSING OF WELD

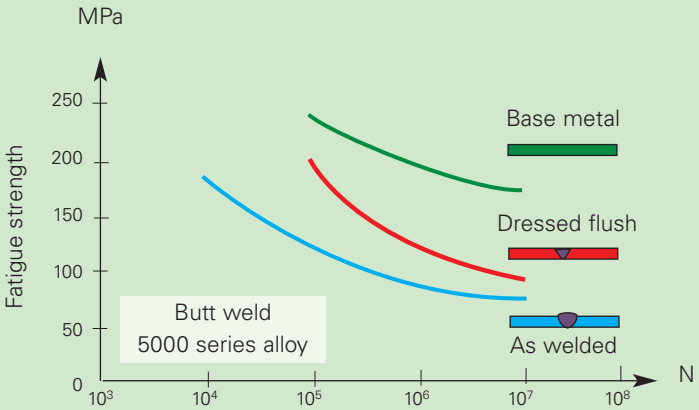


Figure 46

9.2 Classification of weldments

The limits of endurance (FAT) that are given in codes and regulations have been established on the basis of standard tests conducted on specimens taken from attachments and feedback on structures in service [14].

Eurocode 9 proposes limits of endurance (FAT 25 to 62 MPa) as a function of the size of the defects (figure 47) (misalignment, undercut, lack of root penetration, porosity, crack etc.) and the extent of controls corresponding to the desired level of FAT.

The influence of the size of four defects on the limits of endurance (FAT) is given in table 43 by way of example

Design codes and regulations confine themselves solely to the configuration of the weld to define the acceptable limit of endurance (FAT), as figures 48 to 50 illustrate.

FATIGUE STRENGTH (FAT) ACCORDING TO EUROCODE 9

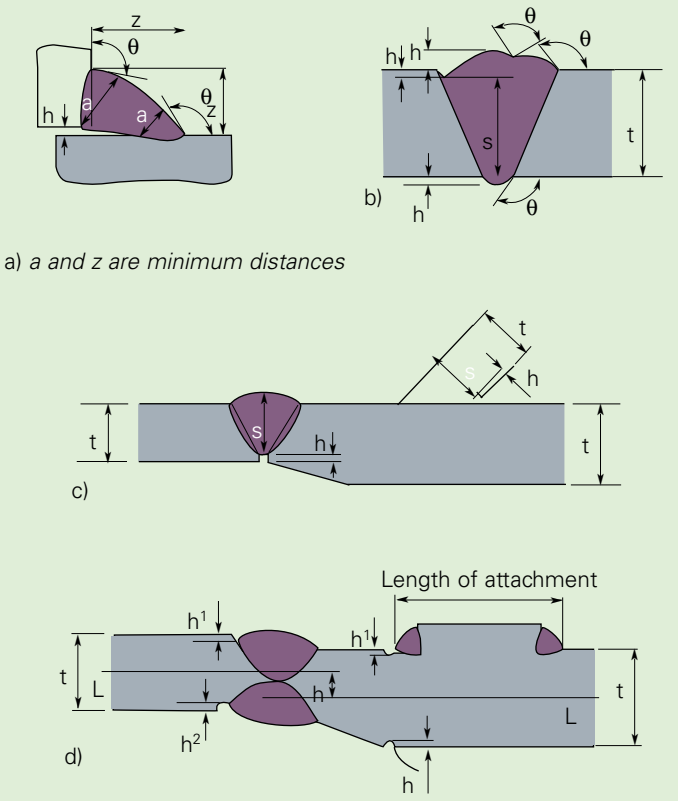
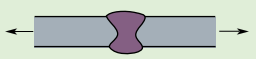


Figure 47

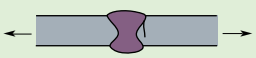
LIMIT OF ENDURANCE OF BUTT WELDS (MPa) (according to IIW Recommendations, Group XIII – XV, 1996)



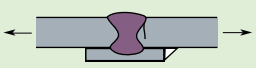
Case 211: Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT (*) 50



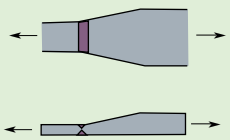
Case 212: Transverse butt weld made in shop in flat position, toe angle ≤ 30°, NDT 40



Case 213: Transverse butt weld, toe angle ≤ 50° 32



Case 215: Transverse butt weld, toe angle ≤ 50°, or transverse butt weld on permanent backing strip 25

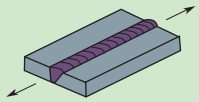


Case 223: Transverse butt weld, NDT, with transition on thickness and width
Slope 1:5 25
Slope 1:3 22
Slope 1:2 20

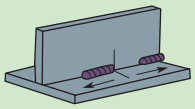
(*) Non destructive test.

Figure 48

FATIGUE STRENGTH (FAT) OF LONGITUDINAL WELDS (MPa) (recommendations of IIW, Group XIII - XV, 1996)



Case 313: Longitudinal butt weld, without stop/start positions, NDT 45
With stop/start position 36

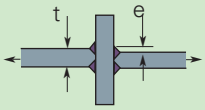


Case 324: Intermittent longitudinal fillet weld (based on normal stress in flange σ and shear stress in web τ at weld ends).

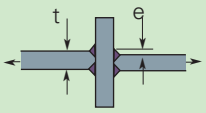
τ/σ = 0 32
τ/σ = 0,0 – 0,2 28
τ/σ = 0,0 – 0,3 25
τ/σ = 0,0 – 0,4 22
τ/σ = 0,0 – 0,5 20
τ/σ = 0,0 – 0,6 18
τ/σ = 0,0 – 0,7 16
τ/σ = > 0,7 14

Figure 49

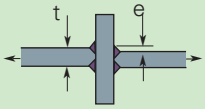
FATIGUE STRENGTH (FAT) OF CRUCIFORM WELDS (MPa) (recommendations of IIW, Group XIII - XV, 1996)



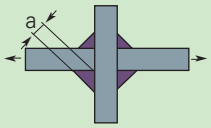
Case 411: Cruciform joint or T-joint, K- butt welds, full penetration, no lamellar tearing, misalignment e < 0,15 t, weld toes ground, toe crack 28



Case 412: Cruciform joint or T-joint, K- butt welds, full penetration, no lamellar tearing, misalignment e < 0,15 t, toe crack 25



Cas 413: Cruciform joint or T-joint, fillet welds, or partial penetrating K- butt weld, misalignment e < 0,15 t, toe crack 22



Cas 414: Cruciform joint or T-joint, fillet welds, or partial penetrating K- butt welds (including toe ground welds), weld root crack. Analysis based on stress in weld throat 16

Figure 50

ACCEPTANCE LEVEL OF INDUSTRIAL WELDS (*)

Defect	Weld	Weld direction (*)	Figures	Size of defect	FAT 25	FAT 31	FAT 39	FAT 49	FAT 62
Weld angle	all types	Transv. Longit	a, b a, b	θ ≥ θ ≥	120° 90°	150° 90°	165° 90°	175° 90°	- 175°
Excessive bead thickness	butt	Transv. Longit	b b	h ≤ h ≤	5 6	4 5	2 4	0,5 3	- 0,5
Misalignment	butt	Transv.	d	h ≤	D + 0,1 t	D + 0,05 t	D + 0,05 t	D + 0,05 t	-
Lack of root pen-tration	butt	Transv. Longit	c c	h ≤ h ≤	- D + 0,1 t	- D + 0,1 t	- D + 0,05 t	- D + 0,05 t	- -

D = dimension specified on drawings (*) From table D.2 Eurocode (9).

Table 43

10. INFLUENCE OF DESIGN AND FABRICATION ARRANGEMENTS

The fatigue behaviour of aluminium alloy ships depends:

- on the design arrangements defined by the design consultancy
- on the execution of welds in the shipyard.

10.1 Design of welded attachments

This is a very important parameter: Design engineers must propose structures in which the stress concentrations are as low as possible, while keeping within acceptable cost limits. The "hot spot" method can be used to identify the sensitive zones [15].

The influence of the design arrangements of some typical welded structures is given in table 44.

10.2 Design of bolted and bonded attachments

Bolted and bonded joints must be designed to offer good fatigue behaviour (Figures 51 and 52, p. 70). It is particularly important to ensure that the diameter of the bolts is proportional to the dimensions of the attachment.

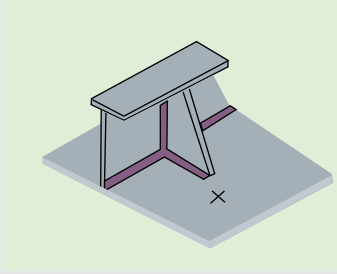
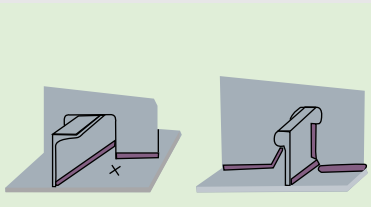
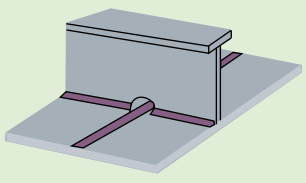
10.3 Making weldments

Experience shows that the fatigue behaviour of welded aluminium alloy structures is more sensitive to weld defects than welded steel structures [18].

This is why shipbuilding in particular, and aluminium fabrication in general, requires:

- better welding skills than are needed for steel fabrication,
- tighter control of weldments, at least those located in zones most stressed by fluctuations of load.

INFLUENCE OF WELDED STRUCTURES ON FATIGUE BEHAVIOUR [16 , 17]

Example of Structure		Remarks
Gusset of floor plate on ship bottom.		The weld bead must be wrapped at the end of the gusset to avoid crack initiation.
Path of a longitudinal through a frame.		At left, torch cannot access beneath the shape and the weld bead cannot be wrapped, so there is a risk of cracking. At right, weld is correctly made, beads do not cross over, the sheet of the frame is welded to the flat side of the longitudinal.
Path of a stiffener over skin sheet.		Correct arrangement which avoids welds crossing over (which can destroy much of the underlying weld).

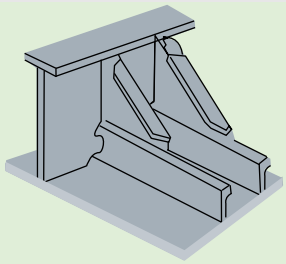
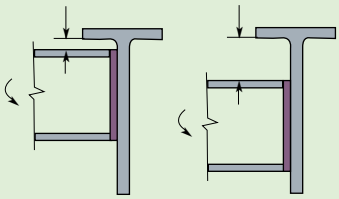
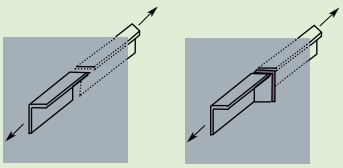
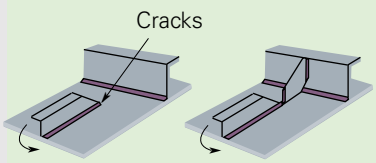
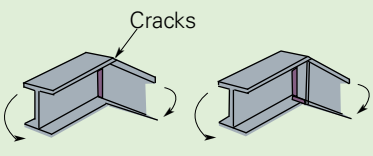
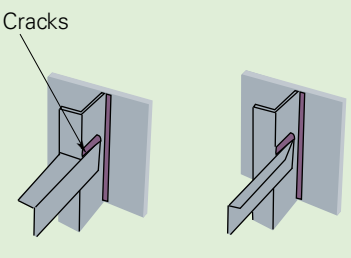
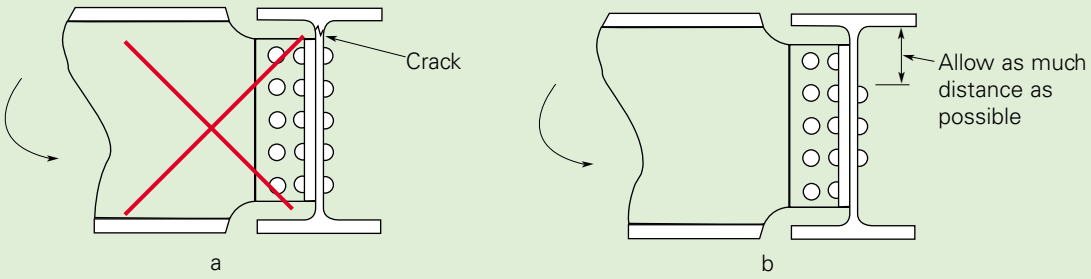
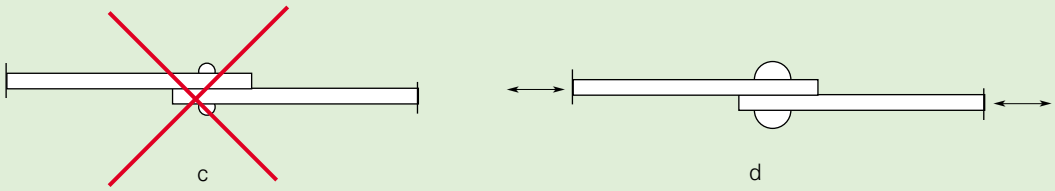
Example of Structures		Remarks
Deck flooring, junction of bar and reinforcement.		Assembly too tight, torch cannot reach the inside faces of the longitudinal reinforcements.
Connection of two shapes, e.g. longitudinal and bar.		Enough space must be left for the torch to enter everywhere and wrap around the transverse bar on the longitudinal.
Bulkhead crossing.		At left, with a shape on each side of the bulkhead, alignment will be poor and stresses will occur. At right, the shape passes through the bulkhead which is 'hung' on the shape.
Stiffeners on sheet.		At left, the stiffener stops in the middle of the sheet causing stresses, with the risk of tearing by bending. At right, the scallop in the reinforcement avoids welds crossing and distributes bending forces.
Connection of two shapes.		The change of direction creates bending and torsional stresses. These stresses are avoided by adding a plate to form a box.
Connection of a longitudinal and a bar to the sheet of the skin.		At left, the recess in the shape causes a stress concentration that is avoided by the arrangement on the right.

Table 44

BOLTED ATTACHMENTS IN SHEAR [13]



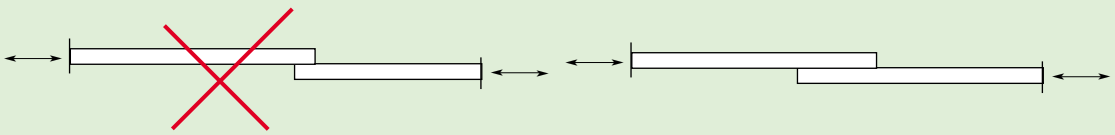
Bolts close to flange cause high local bending stresses in web (a).
A larger distance between fastener and flange allows web to flex, thereby reducing local stresses (b)



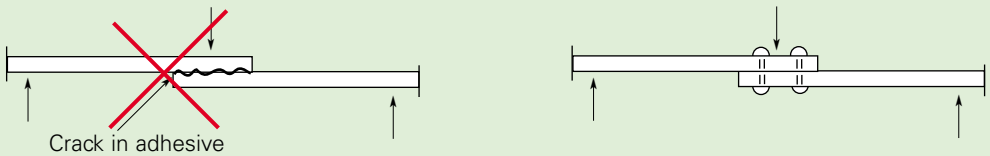
Small fastener in large parts allows fatigue failure in fastener at low nominal stress (c).
Fasteners that develop a high percentage of strength of parts shift fatigue failures to parts at higher stresses (d).

Figure 51

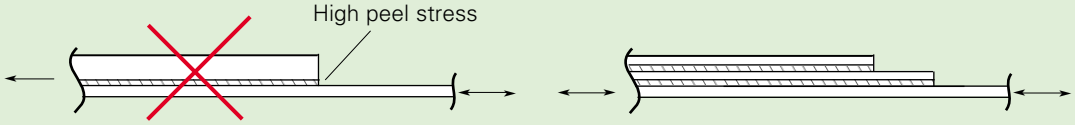
BONDED ATTACHMENTS [13]



Joints with short laps in which adhesive is stressed in inelastic range will fail at low fatigue lives. Longer laps so that adhesive is stressed elastically will result in much longer fatigue lives.



Joints with high cleavage or peel forces in the adhesive will fail at low static and fatigue loads. Use bolts or other fasteners with good tensile performance; supplement with adhesives if desired for much better fatigue performance.



Thick doublers on thin sheet causes high stress concentration at end of doubler. Stepped, thin doublers reduce stresses at end of doublers and improves fatigue.

Figure 52

11. REFERENCE STANDARDS AND REGULATIONS

Eurocode 9: Design of Aluminium Structures – Part 1 – 1 General rules and rules for buildings. Standard EN, ENV 1999-1-1, May 1998

Eurocode 9: Design of Aluminium Structures – Part 2: Structures susceptible to fatigue, Standard EN, ENV 1999-2, May 1998

Recommandations pour le calcul en fatigue de structures en alliages d'aluminium, ECCS, 1992, Institut de la Soudure

Aluminum Structures. A guide to their specifications and design. J. Randolph Kissell, Robert L. Ferry. John Wiley & Sons, Inc., 2002

British Standard BS 8118. Structural use of aluminium. Part 1. Code of practice for design, 1991

British Standard BS 8118. Structural use of aluminium. Part 2. Specifications for materials, workmanship and protection

Bureau Veritas – Rules for the classification of High Speed Craft; February 2002

ABS – Requirements for materials and welding, Part 2 Aluminum, Fiber Reinforced Plastics (FRP), 1997

DNV – Rules for classification of high speed, light craft and naval surface craft. Structures, equipment, Part 3, Chapter 3; Hull structure design, aluminium alloy, July 2002

DNV – Rules for classification of high speed, light craft and naval surface craft. Structures, equipment, Part 3, Chapter 3; Hull structure design, aluminium alloy, July 2002

DNV - Rules for classification of ships / high speed, light craft and naval surface craft. New Building, materials and welding, Part 2, Chapter 2, Metallic materials, January 2001

DNV - Rules for classification of ships. New Building, materials and welding, Part 2, Chapter 3, Welding, January 1996

Fatigue design aluminium components structures. M.E. Sharp, G. E. Nordwark, C. C. Menzer McGraw-Hill

Fatigue of aluminium structural weldments. Ship Structure Committee 2000. Rapport SSC-410, NTIS #PB2000-108442

TALAT, Chapter F2204. La conception, compiled by Steinnar Lundberg, Hydro Aluminium Structures, Karmoy, 30 pages

TALAT, Chapter F2205. Conceptions particulières, compiled by Torsten Hoglund, Royal Institute of Technology, Stockholm and Dimitris Kosteas, Technische Universität München, 27 pages

TALAT, Lecture 2301. Design of Members: Examples, prepared Torsten Hoglund, Royal Institut of Technology, Stocklom, 1999, 125 pages

TALAT, EAA, Lecture 2401: Fatigue Behaviour and Analysis, prepared by Dimitris Kosteas, Technische Universität München, 1994, 81 pages

TALAT, EAA, Lecture 2402: Design Recommandations for Fatigue Loaded Structures, prepared by Dimitris Kosteas, Technische Universität München, 1994

TALAT, EAA, Lecture 2403: Applied Fracture Mechanics, prepared by Dimitris Kosteas, Technische Universität München, 1994, 49 pages

TALAT, EAA, Lecture 2405. Fatigue and Fracture in aluminium structures, prepared by Dimitris Kosteas, Technische Universität München, 1994, 40 pages

TALAT, EAA, Lecture 2406. Fatigue and Fracture in Aluminium Structures, prepared by Dimitris Kosteas, Technische Universität München, 1999, 5 pages

TALAT, EAA, Lecture 2406, Annex 1. Fatigue and Fracture in Aluminium Structures, prepared by Dimitris Kosteas, Technische Universität München, 1994, 6 pages

TALAT, EAA, Lecture 2406, Annex 2. Fatigue and Fracture in aluminium structures, prepared by Dimitris Kosteas, Technische Universität München, 1999, 6 pages

Bibliography

[1] "Reexamination of design criteria for stiffened plate panels", Ghose D. and Nappi N, SCC382, June 1994, *Ship Structure Committee*.

[2] "Ship Structural design", Hugues, 1988, SNAME.

[3] "Engineering Mechanics of solids", E. P Popov, Prentice Hall, 1990.

[4] "Fatigue resistance poses design challenge", R. White, *Speed at Sea*, August 1998, pp. 45-46.

[5] "Fatigue design assessment of aluminium fast craft", T. Hall, F. Violette, H. Chung, *The third Ausmarine Conference,* April 1998, pp. 125-136.

[6] "High strength alloys and the fatigue life of HSLC", H. Craig, J. Donavan, A. Fredriksen, *14th Fast Ferry International Conference*, Copenhagen, February 1998.

[7] "Fatigue analysis of high speed aluminium catamarans", S. E. Heggelund, B. W. Tveiten, T. Moan, *The third International Forum on Aluminium Ships,* Haugesund, Norway, May 1998.

[8] "Fatigue assessment of welded aluminum ships details", B. W. Tveiten, T. Moan, *5th International conference on fast transportation,* Seattle, August 1999.

[9] "Fatigue of marine grade aluminium alloys" R. C. Calcraft, G. O. Schumann, D. M. Viano, *Australian Welding Journal*, Vol 42, 1997, pp. 22-25.

[10] « Fatigue crack propagation in aluminium", R. Jaccard, IIW, Document XIII-1377-90.

[11]"Significance of mechanical properties in design and applications", *Aluminum, design and applications,* Vol II, chap 4, edited by Kent R. Van Horn, ASM, 1967.

[12] Reference Jaccard IIW, Document XIII-1377-90.

[13] "Fatigue design of aluminium alloys structures", S. J. Maddox, Proceedings of the Second International Conference on Aluminium Weldments, Düsseldorf FRG 1982.

[14] "Calcul en fatigue des joints soudés", M. Bramat, *Mécanosoudage et conception,* CETIM publication.

[15] "Fatigue assessment of aluminium welded components", M. Bouet Griffon, M. Courbières, JC. Ehrström, Pechiney CRV, 1999.

[16] "Fatigue damage in aluminium ships and the betterment of details", Kazuyoshi Matsuoka, Horoshi Ishiwatat, Mantro Hirayama, Yuzuru Fujita. *The Third International Forum on Aluminium Ships, Haugesund,* Norway, May 1998.

[17] "Fatigue design aluminium components structures", M.E. Sharp, G. E. Nordwark, C. Menzer McGraw-Hill.

[18] "Fatigue of aluminium structural weldments", *Ship Structure Committee 2000.* Report SSC-410, NTIS #PB2000-108442.



STRUCTURE OF MONOHULL

Chapter 5
SHAPING AND FORMING

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5. SHAPING

THE SHAPING and forming of aluminium alloy semi-finished products for use in shipbuilding and marine applications comprises all of the operations prior to assembly by welding, riveting and bonding. These are:

- marking out prior to cutting, if required,
- cutting to shape and size before assembly,
- forming.

The development of computer software for naval architecture and ship design has made it possible to automate metal cutting operations. These operations may be carried out by the shipyard or by a sub-contractor who specialises in this activity.

This preparatory phase of forming must be conducted with extreme care, especially with regard to cutting. Cutting must be both as accurate as possible to ensure a good fitup of components that will be welded together, and as regular as possible to prevent any sites of crack initiation. Cutting quality is one of the parameters that determines the fatigue strength of welded joints.

The surface hardness of aluminium is less than that of steel. This factor must be taken into consideration when handling semis, when clamping components in machine jaws and during certain forming operations, to prevent scoring or bruising to the metal. Aluminium sheet must never be dragged along the ground, placed in the path of handling equipment such as stacker trucks, or walked on.

Aluminium alloy semis must be protected from metal particles discharged by the forming or shaping (grinding, machining etc.) of other metals such as steels or copper alloys. Such particles can cause superficial micro-pitting in the presence of moisture if allowed to become embedded in the surface of the aluminium.

The tools and forming techniques used for aluminium alloys do not differ greatly from those used for stainless steel. However certain settings (or arrangements) of tooling are different, for example bending radii or the angles of sawteeth.

1. RECEIVING AND STORAGE OF SEMIS

Packaging to the size of the finished product is made of timber or steel pallets on which sheets are stacked. These may be separated from one another by liners made from special moisture-absorbent paper.

The packs of aluminium sheet are wrapped in polyethylene film and Kraft paper and strapped to the pallet (figure 53).

COASTGUARD CP 280



AND FORMING

1.1 Receiving packs

Polymer film and Kraft paper can tear, which means that these packaging materials are not watertight and incoming packs of aluminium alloy semis must be unwrapped under cover.

Aluminium sheet must be handled with care and precautions taken to protect its clean surface condition to ensure the good quality of weldments and the general appearance of aluminium alloy structures.

1.2 Storage

There is no compelling need to remove aluminium semi products from their original packaging before they are actually needed. They just have to be protected from water and damp environments at their place of storage.

However if sheets or shapes are removed from their original packaging and stored flat, they must be placed on wooden blocks several centimetres thick to prevent any direct contact with the ground, even if this is cemented.

When sheets or shapes are laid flat without any liners between them (paper or board or even wooden blocks), whitish or greenish stains on facing surfaces will usually be observed after a certain period of time (1). These stains are due to the effect of moisture seeping in between the sheets or shapes by capillary action.

Prolonged storage of unpacked semis in the open air can lead to superficial changes on the surface of the material. These will usually be very superficial micro-pits (a few microns in size), stains or even general tarnishing (2).

While such alterations have no effect on the metal's subsequent resistance to corrosion, when they are in service on the ship they represent moisture "traps" that must be carefully removed before any welding. They will affect the general appearance of the semis however, though this is less critical when the products are painted or cannot be seen from the outside.

PACKING "MARINE" GRADE SHEET



Figure 53

Note: Ideal storage is in a covered room protected from the weather, with semis stocked upright and sheets or shapes spaced apart to prevent moisture penetrating between them. When stored flat, semis should be spaced apart using wooden blocks.

(1) These stains will have the same shape on both of the facing surfaces. They are symmetrical about the axis parallel with the sides of the sheets (or shapes).

(2) It goes without saying that these changes will be made worse in aggressive atmospheres highly polluted by industrial emissions, smoke etc.

FLYINGCAT 3



2. CUTTING TO SHAPE

The basic tools used for cutting aluminium alloys are the same as for steel. These are:

- plate or crocodile shears,
- bandsaw,
- circular saw,
- plasma,
- fluid jet.

The first three tools (and plasma) are used for manual cutting, whereas plasma and fluid jet are the preferred media when cutting is automated using programmes created with naval construction software.

The contours of the parts must first be traced on the semi before they are cut out. Metal scribing tools should not be used for tracing as they can leave marks in the material which could become crack initiation sites under the effect of stresses in service.

It is preferable to use a medium hard pencil (e.g. 5H) (3) that makes lines which are very visible and easy to erase if corrections are necessary.

2.1 Plate and crocodile shears

These shears are used for making straight-line cuts. Aluminium alloys are cut with machines of the same power as for unalloyed steel E24.

The surface condition of the edge of the shear blade must also be as clean as possible. A roughness Ra of less than 0.1 micron on a steel blade of type Z160CDV12 minimises the risks of seizing.

A suitable "cutting gap" or clearance should be set between the blade and the frame of the shear to protect sheet from distortion. The optimum setting will increase with the metal's shear strength; the gap will also be smaller for annealed sheet than for strain hardened sheet.

The use of shears to cut sheet more than 10 mm thick is not advisable in practice, as cutting introduces stresses on the sheared edges that can ultimately lead to severe pitting corrosion and also cause cracks.

2.2 Bandsaw

A bandsaw is essential for cutting sheet more than 10 mm thick and for shapes.

Sawblades used for cutting aluminium are special – their teeth have a greater pitch (i.e. there is more space between adjacent teeth) and a wider throat than blades used to saw steel (figure 54) so as to assist chip fragmentation and removal.

The pitch of the teeth must be such that two teeth are engaged in the thickness of the metal at all times, so there is a minimum thickness of material that is suitable for cutting with this tool.

The rate at which aluminium is sawn is greater than for steel, and may attain 1000 $mm.min^{-1}$. Lubrication using soluble oil or cutting oil is essential for long lengths and high cutting rates.

Sawing will produce cut edges that are clean and burr-free provided the sawblade is suitable for aluminium and the cutting parameters are set correctly.

Note: Jigsaws can be used to cut thin sheet less than 6 mm thick; jigsaws have the advantage of being very easy to handle and can be used to cut relatively complex shapes as well as straight lines.

BANDSAW

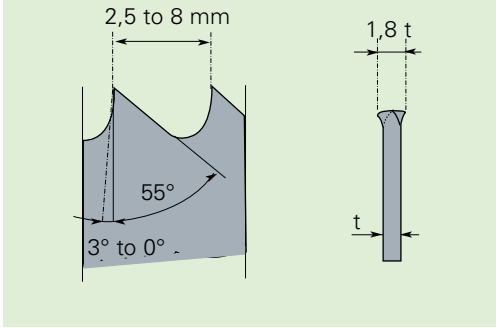


Figure 54

(3) Graphite markers should not be used on surfaces which will be in contact with water or moisture.

2.3 Circular saw

Also called a milling saw by some, it operates with an action similar to milling.

The characteristics of circular saw blades for aluminium are shown in figure 55.

With semi-finished products in the 5000 and 6000 series, cutting speeds can attain 600 to 1000 mm/min. with high speed steel (HSS) blades and 800 to 1500 mm/min. using carbide blades.

As with the bandsaw blade, lubrication is essential for long cuts and high cutting speeds.

The values of p and h will depend on the diameter of the saw

Note: Portable circular saws may be used on products not more than 20 mm thick.

2.4 Plasma cutting

The industrial use of plasma cutting for metals began in the Nineteen Fifties.

In this process, the cutting of the metal is achieved with a combination of the thermal and kinetic effects of a plasma arc which is generated by a special torch whose path follows the contours of the piece that is to be cut.

The plasma arc is obtained by passing an electric current through a stream of gas, also known as plasmagen gas, that has been brought up to ionisation temperature.

To obtain the characteristics that are required for cutting, the plasma arc is passed through a small diameter energy-cooled aperture or nozzle, the containing effect of which is to greatly increase the temperature and velocity of the resulting jet of plasma arc.

As an indication, the current flowing in the column of plasma arc can be between 10 and 1000 Amps, the diameter of the jet emerging from the nozzle ranges from several tenths of a millimetre to several millimetres, the temperature inside the jet from 15,000 to 30,000 K and the discharge velocity at the exit from the nozzle from Mach 1 to Mach 2.

The process of the plasma cutting of metal materials is based on a transferred arc, which means that an arc is established between a refractory electrode (– pole) and the piece to be cut (+ pole) (figure 56).

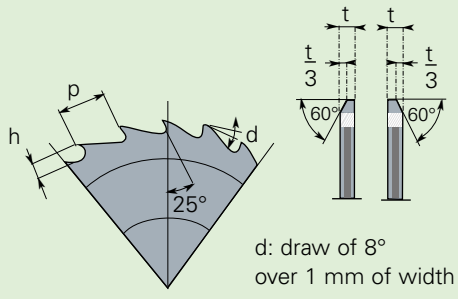
This highly rigid and extremely hot stream of plasma fuses the metal over its full thickness and ejects it outside the cut thanks to the kinetic energy generated by the plasma's very high velocity.

The choice of gas depends on the thickness of the material that is to be cut and on other criteria such as the quality of cut, productivity and running costs (table 45, p. 78).

Plasma cutting can be manual with the compressed air and argon/hydrogen processes, or automatic (on machines).

Manual plasma cutting is used primarily on site to make unplanned cuts, e.g. breaches for pipes through bulkheads, partitions etc. A template should be used for accurate cutting. Material up to 50 mm thick can be cut manually and with a limited amount of skill.

CIRCULAR SAW



d: draw of 8° over 1 mm of width

p and h are in relation with the saw diameter

Figure 55

PLASMA CUTTING

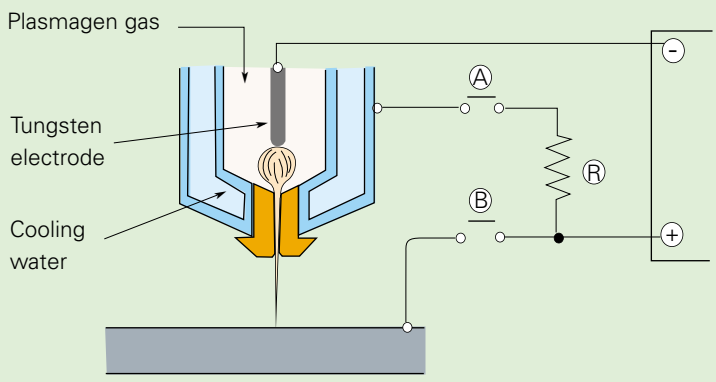


Figure 56

Automatic plasma cutting is done on straight or contoured cutting tables (such as numerically controlled (NC) X-Y machines or multiple jointed robots). The path of the plasma torch is controlled by machine axis control programmes; these run in conjunction with software that defines the geometry of the components and their interfaces with other parts so as to minimise waste by optimising both the position of the component within the sheet format and the paths of the torch.

There are two plasma cutting techniques (figure 57):

- "dry" plasma cutting on a table, in air. The draft may be as much as 5° with a plasmagen gas mixture of argon and hydrogen,

- water vortex plasma, in which the sheet to be cut is placed in a tank filled with water. The torch itself is partially submerged. The cutting draft is smaller, in the region of 2 to 3° (4).

Water vortex plasma allows higher cutting speeds than argon/hydrogen plasma cutting which is done in air. It demands more electrical power for the same thickness of cut however. Argon/hydrogen can be used to cut material thicknesses of up to 150 mm, and the geometrical accuracy of the cut pieces is in the region of 1 millimetre.

Given the high energy input that takes place during the localised fusion of the metal, heat is diffused to a width of around one millimetre on either side of the cut whatever the alloy and whatever its thickness. As happens with arc welding (5), this "heat affected zone" is annealed (in the metallurgical sense).

This zone can be removed by machining more than 2 mm from the cut edge, although this operation is obviously pointless when the piece has been cut to size and shape for subsequent arc welding.

Note: The process of oxygen cutting with the *oxy-acetylene torch* which is used widely for mild steel is not at all suitable for aluminium.

(4) During water vortex plasma cutting, the fine particles of aluminium can react with the water and give off hydrogen. It is therefore essential to avoid any build-up of this gas which can cause local explosions.

(5) Cf. Chapter 6.

PRINCIPLE OF PLASMA

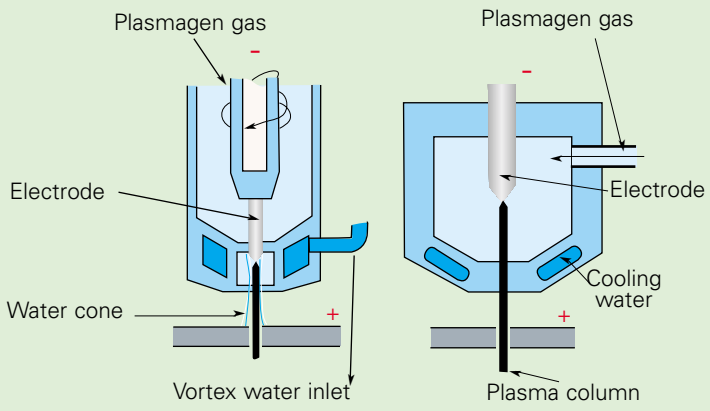


Figure 57

PLASMAGEN GASES

Thickness (mm)	Gas	Remarks
0,4 - 15	Oxygen	High cutting speeds
0,4 - 30	Compressed air	Low running costs
8 – 150	Mixture Argon (80 to 65%) / Hydrogen (20 to 35%)	Superior cut quality
1 – 70	Nitrogen + Post injection of water	Immersing the component in water reduces sources of nuisance (noise, fumes and radiation)

Table 45

2.5 Fluid jet cutting

In fluid jet cutting, the metal is cut by a calibrated jet of water charged with abrasive particles (granules of garnet, corundum or other very hard minerals). The water is projected at very high pressure - 3000 bars and more - through a nozzle onto the material which is in a tank filled with water (figure 58).

Water jet cutting produces a clean and extremely accurate cut without a draft.

On aluminium, the technique can be used to cut through thicknesses between 1 and 100 mm at speeds of 3500 and 30 mm/min respectively.

Unlike plasma cutting, there is no heat affected zone either side of the cut because no heat is transferred.

(6) For the meaning of the tempers, refer to section 4.3 in Chapter 3.

WATER JET CUTTING

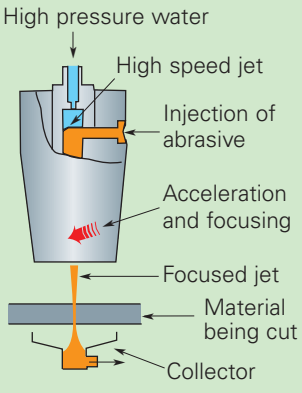


Figure 58

3. FORMING

In naval construction, forming consists essentially of the folding and forming of sheet and the bending of shapes.

Because forming requires the metal to be sufficiently plastic, it follows that the temper of aluminium alloy semis is an important parameter that must be taken into consideration for delivery and during the forming operations if these involve significant work hardening.

3.1 Influence of the temper

Most aluminium alloys used in shipbuilding and in coastal installations belong to:

- the 5000 series (aluminium-magnesium alloys), mainly in the form of sheet and plate. The most common alloys are: 5754, 5086, 5083, 5383. These alloys lend themselves very well to forming especially in the annealed tempers O and annealed flattened tempers H111. It is these tempers which should be preferred as having the best suitability for forming. This suitability decreases for the H116 temper and even more so for the H321.
- the 6000 series (aluminium—silicon-magnesium alloys), mainly in the form of shapes. The most common alloys are: 6005A, 6082 and 6061. As in all the 6000 series, these are age hardened alloys. Semis are delivered in the T6 or T5 tempers and less frequently in the T4 or T1 tempers (6). Even though these alloys lend themselves less well to forming in the artificially aged tempers (T6 or T5), they must nevertheless be formed cold and not hot. Heating would have a more or less marked annealing effect and hence a significant reduction in mechanical properties.

3.2 Sheet bending

Conventional table bending machines and bending presses are perfectly adequate provided the tools are free from unacceptable irregularities.

If for reasons of appearance the bent sheet must not display any clamp marks from the jaws, then the contact surfaces should be protected with kraft paper or plastic film.

For multiple bendings, holes should be drilled to mark their points of intersection to avoid the formation of cracks during bending (figure 59). The hole diameter will increase with the thickness of the material. It is 4 mm for sheet 1 mm thick and 6 mm for material 2 mm thick.

Aluminium alloys must never be bent at a sharp angle. The inside radius of bending is a function of the thickness of the sheet to be bent (table 46):

Note: Aluminium alloy sheet (or shapes) from which forms have already been cut out should never be formed. Cutouts must always be made after forming, using a jigsaw for example.

INTERSECTING BENDINGS

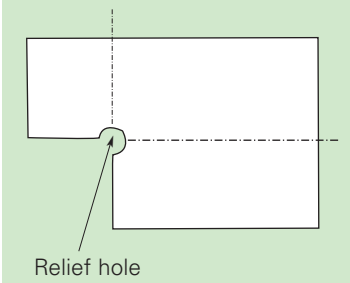


Figure 59

INSIDE RADII FOR COLD BENDING, AT 90 ° TYPICAL VALUES (*)				
Alloy	Thickness (mm)			
	Temper	1,5 - 3,0	3,0 - 6,0	6,0 - 12,5
5454	O and H111 H24 and H34	1,0 t 2,5 t	1,5 t 3,0 t	2,5 t 4,0 t
5754	O and H111 H24 and H34	1,0 t 2,0 t	1,0 t 2,5 t	2,0 t 3,0 t
5083	O and H111 H116 H24 and H34	1,0 t 2,0 t 2,5 t	1,5 t 2,5 t 3,5 t	2,5 t 4,0 t 4,5 t
5383	O and H111 H116 H24 and H34	1,0 t 2,0 t 2,5 t	1,5 t 2,5 t 3,5 t	2,5 t 4,0 t 4,5 t
5086	O and H111 H116 H24 and H34	1,0 t 2,0 t 2,5 t	1,5 t 2,5 t 3,5 t	2,5 t 3,5 t 4,5 t
6061	O T6 (**)	1,0 t 3,5 t	1,0 t 4,0 t	2,0 t 5,0 t
6082	O T6 (**)	1,0 t 3,5 t	1,5 t 4,5 t	2,5 t 6,0 t

(*) Taken from standard EN 485-2, December 2001.

(**) Sheet made from these alloys can be bent to significantly smaller radii on a "fresh quench".

Table 46

3.3 Non-developable surfaces

All scoring or clamping marks left behind after cutting must be removed from the edges of sheet material to prevent the formation of cracks at points of deep deformation.

If the material is so work hardened that shaping becomes difficult, intermediate annealing must be carried out either in the furnace or using an oxy-acetylene torch.

In this case the rise in temperature must be monitored. Tallow can be used as a temperature indicator – it turns brown around 340°C – or use thermocolour pencils that change colour as the temperature changes.

3.4 Bending tubes and shapes

Bending can be carried out manually on timber templates for slender sections or steel templates for thicker sections. If necessary, tubes are filled with sand and shapes are internally reinforced to prevent collapse or distortion.

Bending can also be done on suitable presses (three-roll bending press etc.).

6000 series alloys in the T6 temper should be bent cold so as not to affect their mechanical properties in the delivery condition. If this is not possible, they will have to be bent in the quenched T1 or T4 temper and then artificially aged under the usual conditions of temperature and time.



HIGH INERTIA BEAM FABRICATED BY WELDING SHEETS



PATROL BOATS

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6. WELDING

WELDING is the process by which two or more parts are joined by localised fusion of the metal to form a single component; the original contours of the initial parts disappear after assembly.

Arc welding is still by far the most widespread joining process and the one used most frequently in shipbuilding.

Technical advances in arc welding with pulsed MIG have helped improve the performance of welding machines and the quality of the weldments produced.

The development of other processes such as laser beam welding or friction stir welding (FSW) will further advance the design and fabrication of aluminium sub-assemblies for shipbuilding.

Whatever the welding technique that is used, the quality of workmanship of aluminium alloy weldments becomes increasingly important on very long ships as it determines the fatigue resistance of the most stressed areas of the vessel. The weld is a vital element in the fatigue strength of an assembly.

1. HISTORICAL REVIEW

The first attempts at welding aluminium were made in 1904, and gas welding was used at that time [1].

Up until the early Sixties, welding with the oxy-acetylene torch was the only method available for welding aluminium alloys. The use of this process was limited to flat welding and thin sheet.

For many years the presence of a natural oxide film on the surface of aluminium was a major obstacle to the welding of this metal. For aluminium to be welded correctly, this film must be removed and prevented from re-forming by shielding the weld pool from the surrounding atmosphere.

In oxy-acetylene welding, fluxes in the form of paste diluted in water were deposited on the edges to be welded and on the filler wire to eliminate the oxide film. These fluxes were based on chlorides and fluorides. To avoid any risk of corrosion from flux residues, these had to be removed by brushing or washing in water.

As with the arc welding of steel, rods of filler metal coated in flux for welding thicker products began to become available from 1925 onwards. One of the very first known applications of arc welding using coated rods came in France in 1934 with the construction of railway vehicles in 5056 (A-G5) alloy for the 'Cie Française des Chemins de Fer du Nord' [2]. This process was not developed to any great extent owing to the unsatisfactory quality of the weldments.

The first attempts at arc welding in a shielding gas (argon or helium) were made in the middle of the Nineteen Thirties [3]. This technique represented a major step forward, and eliminated the need for flux with its attendant risks of corrosion. It was now possible to weld at high speed and in all positions, making aluminium a "fully fledged" fabrication metal in its own right.

The industrial development of the TIG and MIG processes began in the early Fifties and advances and improvements in these processes have been made ever since. One such innovation came at the beginning of the Nineties with electronically controlled pulsed MIG welding.

WELDING A HATCHWAY FRAME



Up until the early Sixties, ships made from aluminium alloys – as well as aluminium alloy equipment on steel ships (superstructures, funnels etc.) – were assembled by means of riveting, as indeed steel ships still were.

The sailing ship "Morag Mhor", a 70 foot ketch made from aluminium-magnesium alloy (4 and 5% magnesium) and designed by a British naval architect, was the first known boat to be constructed with MIG welding in 1953 [4].

2. SPECIFICS OF WELDING ALUMINIUM

Although the techniques used for welding semi-finished products made from aluminium alloys are very similar to and even the same as those used for carbon steel, the operating conditions are rather different. This is due to the presence of the oxide film (Al_2O_3) on the surface of the metal (1) and to the physical properties of aluminium alloys which are very different from those of steels (table 47, p. 87).

(1) Cf. Chapter 10.

(2) In arc welding with the continuous TIG process, the welded piece is always connected to the minus pole (–) to remove the oxide film.

(3) Although it is an electrical insulator, the film is too thin to stop the flow of electrical current in the same way as layers of anodising whose thickness is commonly 15 to 20 microns.

(4) Greases and lubricants are carbon chains with the general formula $C_nH_{2n}O$.

2.1 The oxide film

The natural film of oxide which permanently covers the surface of the metal is 50 to 100 nanometers thick. Its melting point is very high, 2052°C, and it is insoluble in solid or liquid aluminium.

For welding purposes the film must be removed (2) and prevented from re-forming while the filler metal is being applied to the weld seam (3). This is why aluminium must be arc welded or laser welded in a controlled atmosphere consisting of an inert gas such as argon, helium or their mixtures.

Although the film is chemically stable (it is an oxide) it nevertheless reacts with its environment by adsorbing traces of rolling mill oils, shaping lubricants and the moisture present in the air. All of these elements are sources of hydrogen (4) when they are dissociated in the plasma of the electric arc.

LNG CARRIERS



2.2 Solubility of hydrogen in the fused metal

Given the very high solubility of hydrogen in liquid aluminium, it dissolves in the weld pool of the weld seam as it is formed (figure 60) (5).

However since hydrogen is not soluble in solid aluminium, if cooling is too fast it will have a tendency to become trapped in the metal forming bubbles that will be porosities in the weld seam (6).

This is why it is so important to remove all possible sources of hydrogen on the metal that are present in moisture, in traces of grease and in the shielding gases.

2.3 Physical properties

Table 47 presents a comparative list of those physical properties of aluminium and steel which affect the welding of these metals. It is the thermal properties which account for the significant differences between the welding conditions for aluminium compared with those for steel.

Aluminium has a high calorific capacity (899 $J.kg^{-1}.K^{-1}$, compared with 420 for steel) and a higher thermal conductivity (229 $W.m^{-1}.K^{-1}$, against 54 for steel). This means that much of the energy input from the arc is used to heat up the pieces that are to be welded.

Aluminium's high effusivity (7) requires a very high level of welding energy. All other things being equal, the rise in temperature of aluminium parts to be welded will be greater than for steel parts.

Heat quickly dissipates in aluminium due to its high diffusivity (8) (0.9 compared with 0.2 for steel), and this must be compensated by the input of heat from the electric arc.

Aluminium's high coefficient of expansion ($23.10^{-6}K^{-1}$), its high diffusivity and the metal's high level of temperature mean that welding is accompanied by more strain in aluminium than in other metals.

To maintain stable conditions therefore, aluminium must be welded at a rate higher than the rate at which the heat is propagated (figure 61).

If carbon steels are cooled too quickly they undergo a martensitic transformation that is accompanied by an increase in volume which in turn can cause cracks at the base of the weld seam.

SOLUBILITY OF HYDROGEN

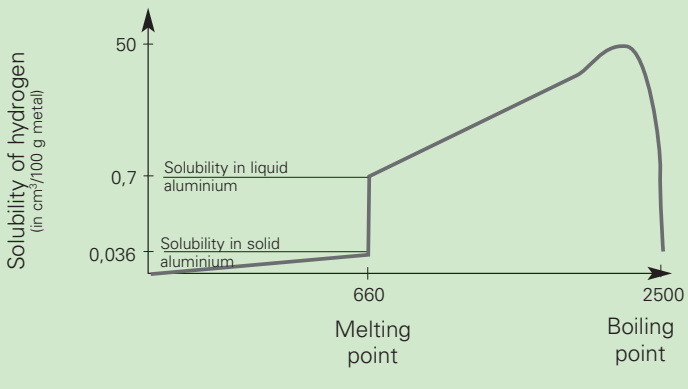


Figure 60

(5) Contrary to what happens with certain steels, hydrogen does not embrittle aluminium and does not sensitise it to stress corrosion.

(6) Cf. table 54, pp. 104-105.

(7) Effusivity "b" is the product of the square root of the product of thermal conductivity λ by density ρ and by specific heat capacity Cp:
$b = \sqrt{\lambda.\rho.Cp}$.

This variable describes the amount of heat which a heated zone receives by conduction, where:
λ = thermal conductivity
ρ = density
Cp = calorific capacity.

(8) Thermal diffusivity "a" is defined by the relation
$a = \frac{\lambda}{\rho.\ Cp}$

HEAT FLOW DURING WELDING

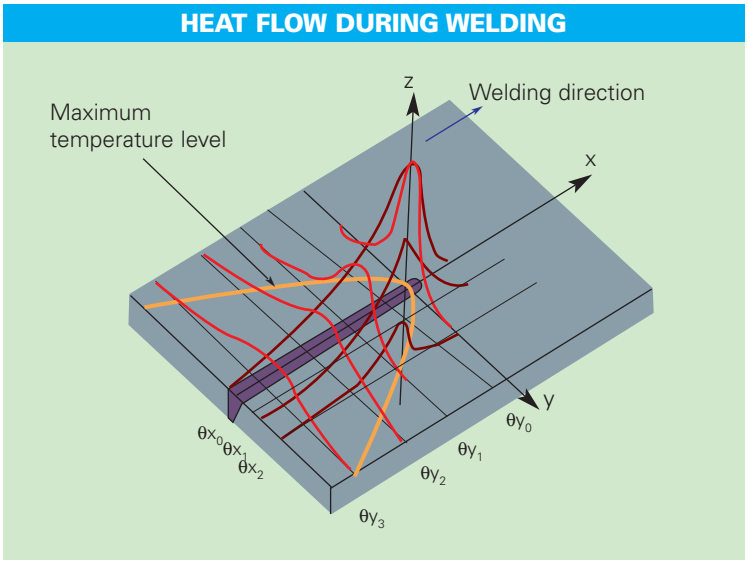


Figure 61

There are no such changes with aluminium alloys. As a result, the rapid cooling rate of the weld – between 100 and 1000°C per second – does not cause any defect in the seam.

It is therefore not normally necessary to preheat aluminium prior to welding as can be done with steel (to prevent cracks in the weldment during cooling).

All of these factors must be allowed for when designing joints and executing the actual welds. This highly important aspect is discussed in Section 3.

(9) The mechanical properties of the weld seam itself are usually superior to those of the HAZ. When there is a crack, this usually occurs outside the weld seam.

2.4 The heat affected zone (HAZ)

With steels, changes of phase cause local hardening of the heat affected zone over a width of several millimetres. In contrast, the effect of heating is to soften aluminium alloys when they are:

- in the strain hardened condition as is the case with the 5000 series alloys in the H116, H24, H32 and H34 tempers,
- thermally treated, e.g. 6000 series alloys in the T5 or T6 tempers.

As figure 62, p. 88, shows, the material's mechanical properties change gradually from the weld seam outward to the edges of the HAZ (9).

As a result, the mechanical properties of the weldment are usually inferior to those of the parent metal. They are near to the annealed condition for strain hardened alloys and to the T4 temper for age hardening alloys.

PHYSICAL PROPERTIES OF ALUMINIUM AND STEEL E24

Property	Unalloyed Aluminium (1050A)	Steel E24	Ratio Al/Steel
Fusion interval (°C)	645/658	1 400/1 530	
Melting point of oxides (°C)	2 052	900	
Solidification shrinkage (%)	1,7	1,2	1,4
Density (kg.m^{-3})	2 700	7 820	0,34
Mass heat capacity Cp (J.kg^{-1}.K^{-1})	899	420	2,14
Latent heat of fusion (kJ.kg^{-1})	385	210	1,83
Thermal conductivity (W.m^{-1}.K^{-1})	229	54	4,24
Thermal diffusivity "a" (10^{-4}.m^2.sec^{-1})	0,9	0,2	4,5
Effusivity "b" (J. m^{-2}.K^{-1}.sec $^{-1/2}$)	24 000	16 000	1,5
Coefficient of linear expansion α (10^{-6}.K^{-1})	23,5	13,5	1,74
Electrical resistivity ρ (10^{-9} Ω.m)	292	1010	0,29
Young's modulus (MPa)	70 000	210 000	0,33

Table 47

This is why for stress calculations, the design codes and regulations of the classification societies specify levels of yield strength of the annealed condition for strain hardening alloys and of the T4 temper for age hardening alloys.

In the case of butt welds, the HAZ is some 25 mm wide either side of the weld seam whatever the thickness of the parent metal and whether TIG or MIG welding is used.

The impact on the mechanical properties of the weldment must be minimised by:
- selecting the filler metal that is best suited to the parent alloy,
- establishing a welding cycle that is as rapid as possible to limit the size of the HAZ,
- designing the assembly so that the weldments are in the least stressed positions.

2.5 Weldable aluminium alloys

Most of the alloys belonging to the 1000, 3000, 5000 and 6000 series can be welded with the conventional TIG or MIG processes and by the other energy beam processes – electron beam, laser etc.

The 5000 series is the one that is most suitable for welding.

The wrought alloys *containing copper* in the 2000 and 7000 series (10) are not easy to arc weld (11). The presence of the copper causes cracking and shrinkage cracks on the weld seam.

The weldability of castings depends more on the method of casting than on the chemical composition of the alloy. Diecast parts cannot be welded as they may contain a lot of air that is introduced during the casting process.

Sand cast or chill cast parts can be welded provided they are "clean", i.e. free from porosities and shrink holes that produce blisters in the weld seam (12).

The 42100 (A-S7G) and 43300 (A-S10G) alloys can be welded with alloys in the 6000 series (13).

(10) The 7000 alloys without copper such as the 7020 can be welded but the HAZ is very sensitive to exfoliating corrosion (cf. Chapter 10).

(11) The welding regulations and construction codes such as Eurocode 9 and standard BS 8118 actually exclude these alloys from arc welded assemblies.

(12) Porosities in sand castings can be avoided by the use of metal heat sinks that improve the microstructure and prevent the formation of porosity.<0}

(13) The 5000 series cannot be welded with the 42000.

MECHANICAL CHARACTERISTICS OF THE HAZ

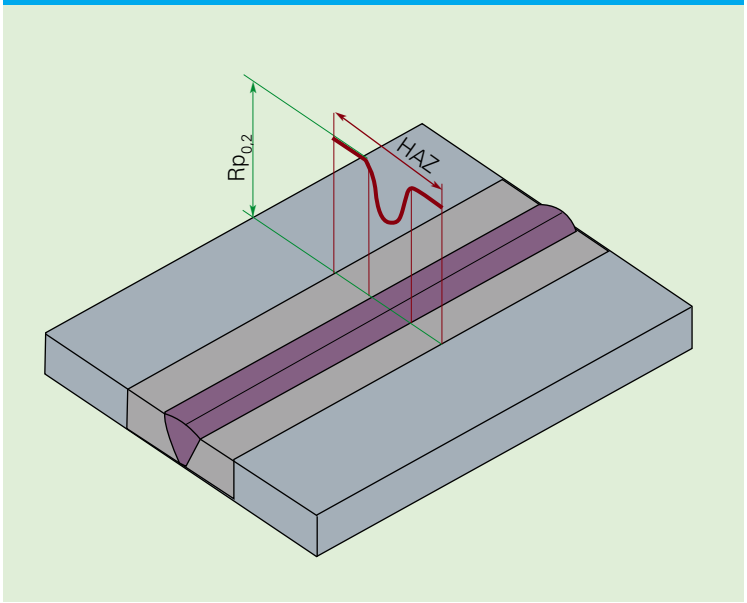


Figure 62

3. IMPLICATIONS FOR THE DESIGN AND EXECUTION OF WELDS

During welding, every point on a welded piece undergoes a heat cycle whose profile is a function of a number of parameters:

- the power of the heat source which depends on the process (MIG, TIG etc.),
- the geometry of the piece,
- the welding position (flat, vertical, horizontal, overhead),
- the diffusion coefficient of the material.

The result is a variety of different temperatures present in the component in the course of welding. These temperature differences translate into residual distortions of varying extent and which are due:

- to differences in expansion,
- to shrinkage as the weld seam solidifies.

3.1 Distortion

Distortion can be longitudinal or transverse:

- **longitudinal distortion** is caused by the contraction of the metal during the process of cooling which is not uniform. Stresses are set up along the weld seam (figure 63).

These stresses depend on the position of the weld – they are minimal or non-existent when the weld is on or near the neutral axis of the piece (figure 64) but very pronounced when the weld is asymmetrical. Concavity will follow the same orientation as the weld seams. On long components, distortion may manifest itself as a twist that will prove difficult to correct (figure 65).

As a general rule, distortion will be significant when the weld seams are asymmetrical relative to the piece.

- **transverse distortion** is due to a shortening of the weld seam – this is more pronounced at the surface of the seam than at its root and so creates a 'gripping' effect with angular deformation (figure 66).

This effect must be limited by balancing the stresses with a second weld: a double vee-groove weld on thick components and on the opposite side for fillet welds (figure 67).

LONGITUDINAL DISTORTION

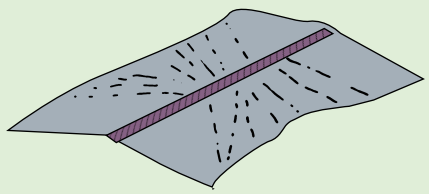


Figure 63

WELDS ON THE NEUTRAL AXIS

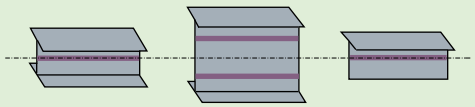


Figure 64

ASYMMETRICAL WELDS

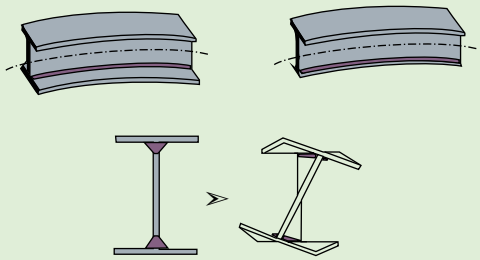


Figure 65

DISTORTION OF WELDS



Figure 66

CORRECTION OF DISTORTION

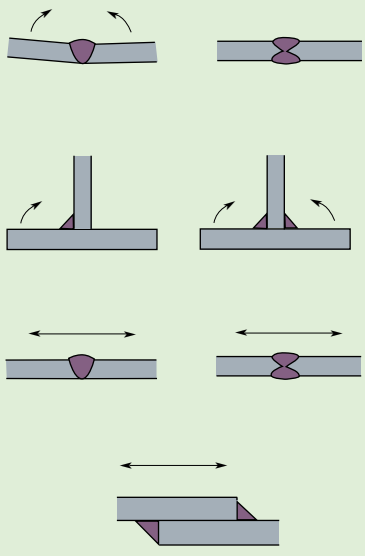


Figure 67

3.2 Stresses

Local levels of stress can exceed the yield strength of the metal, and are a function of:

- the shape of the piece,
- the layout of the weld seams,
- the weld sequence,
- positioning tools,
- clamping.

Figure 68 indicates the level of longitudinal residual stress in sections fabricated by welding.

3.3 Controlling distortion

There are a number of factors by which distortion can be controlled:

- **Joint configuration**: so far as possible the designer should position the welds in a plane of symmetry of the component and on its neutral axes (14), and use specially designed shapes (15) where possible.

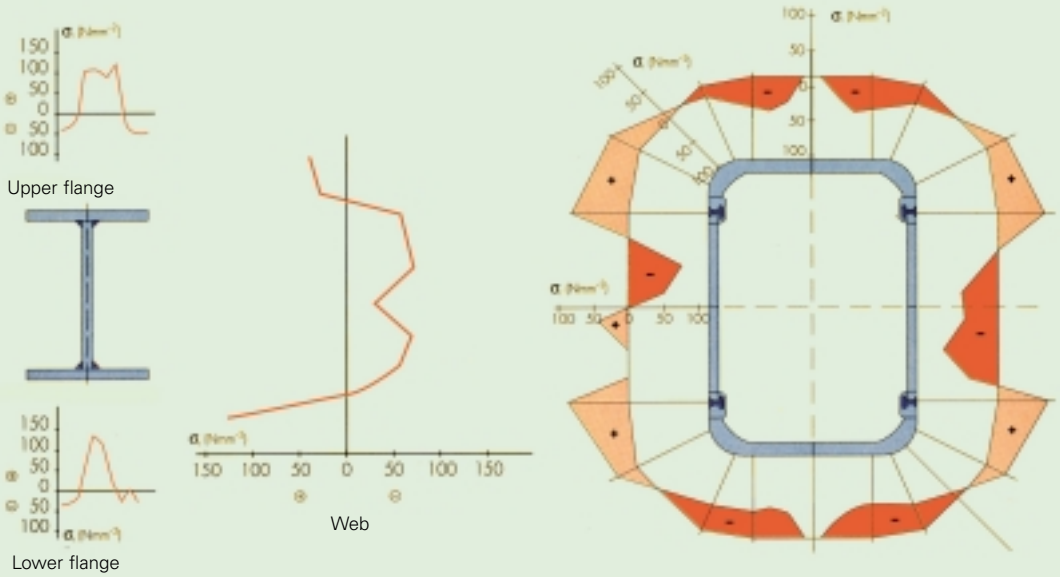
- **Careful forming** must be used to minimise clearances and offsets between the welded components and to eliminate fitup errors,

- **The welding sequence**: it is important to weld moving towards the outside edges to allow expansion to occur freely. The welds must be executed in reverse order of length, with the shortest first to better distribute any distortion. Distortion can be corrected more easily with long seams (figure 69).

Where possible, automatic welding with two torches is a very good way of reducing distortion (figure 70).

The distribution of internal stresses can be optimised by using a sequence of welds that

RESIDUAL STRESSES



Connection of plates in 5083 H111 and extruded shapes in 6082 T6

Figure 68

YACHT FRAME



WELD SEQUENCE

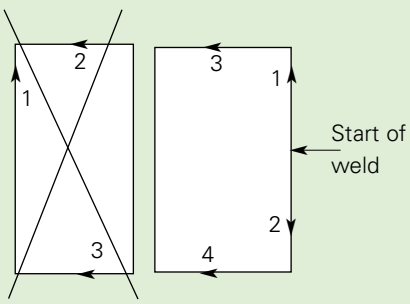


Figure 69

induces residual compression stresses in the weld seams that are stressed in tension (figure 71). This approach will very significantly improve the fatigue strength of the welded joints.

■ The purpose of **clamping** is to hold the parts in position. However clamps, fixtures etc. must not prevent expansion on the longest axes or components will be stressed (with an attendant risk of softening due to expansion Δl). Generally speaking, parts should not be clamped in the directions of greatest expansion as this will aggravate distortion square to the weld (figure 72).

On thick material, angular distortion can be avoided by attaching temporary stiffeners across the weld (figure 73).

■ **Welding parameters**: Distortion can also be caused by the solidification shrinkage of the weld seam. The greater the quantity of fused metal and the higher the temperature, the greater this shrinkage will be. Distortion can be limited by using high energy heat sources to weld as rapidly as possible – the faster the welding, the less time the heat has to dissipate

■ **Balance of heat flows:** Longitudinal distortion can be aggravated by a thermal imbalance between the welded pieces. This imbalance can be due to:
- the very different masses of the pieces that are to be joined,
- misalignment as the welding torch moves,
- poor contact with the support,
- etc.

Whenever possible therefore, the "thermal masses" must be balanced to achieve good thermal symmetry in the assembly (figure 74).

(14) This layout has a positive influence on the fatigue behaviour of the welded assembly, cf. Chapter 4.

(15) Cf. Figures 11 to 14, Chapter 2.

WELDING WITH TWO TORCHES

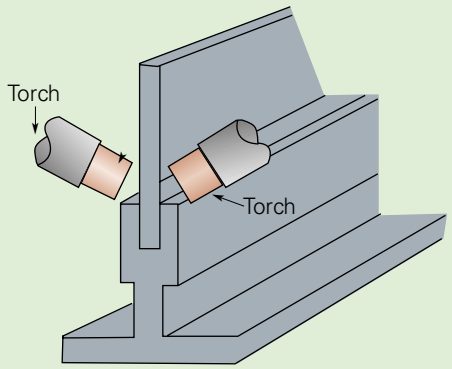
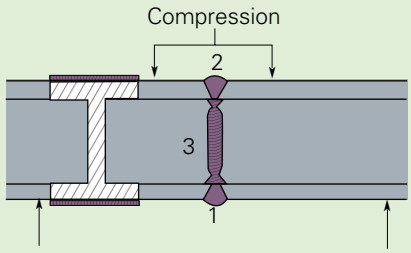


Figure 70

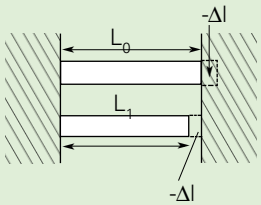
BUTT WELDING SHAPES



Weld sequence: 1, 2, 3

Figure 71

EFFECT OF CLAMPING



L_0 = Initial length
L_1 = Final length

Figure 72

THERMAL BALANCE OF A WELD

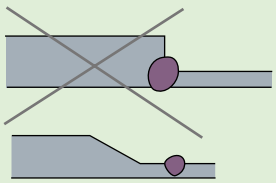


Figure 74

CLAMPING WITH STIFFENERS ACROSS THE WELD

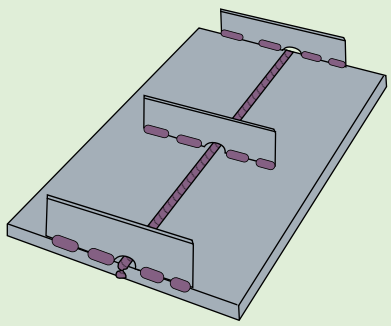


Figure 73

3.4 Use in the fabrication of a section with stiffeners

Figure 76 shows the optimum welding sequence (i.e. order in which the welds are made) for limiting distortion when welding the elements of the section illustrated in figure 75.

Welding starts in the centre of the panel and moves out towards the free edges to allow unimpeded expansion.

LIFTING ALUMINIUM SUB-ASSEMBLIES



PANEL WITH STIFFENERS

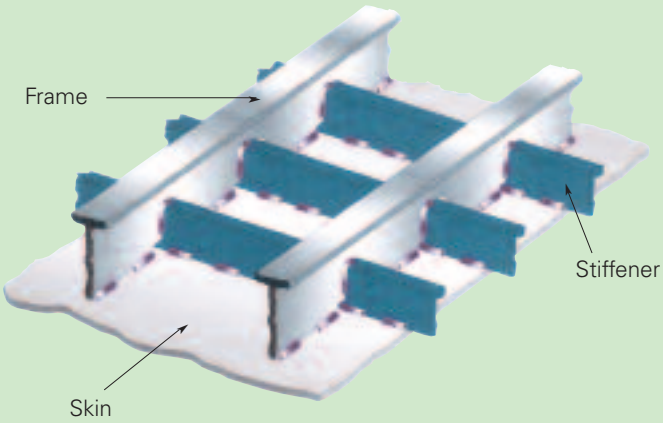


Figure 75

TYPICAL WELDING SEQUENCE OF A PANEL

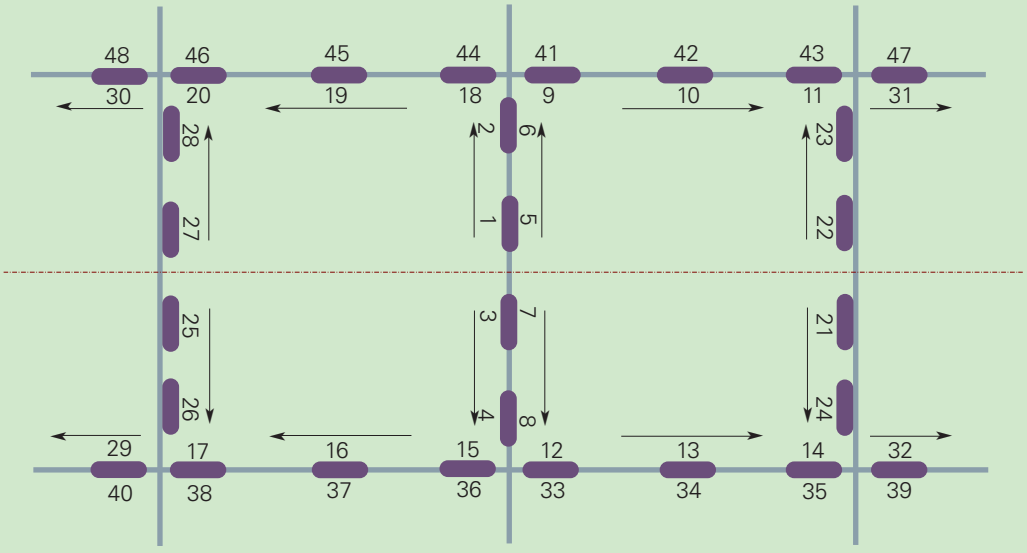


Figure 76

4. ARC WELDING PROCESSES

In arc welding, the joint between the pieces to be assembled is made by filling an appropriate shape (Vee, cross, bell) with a filler metal (rod or wire) which is melted step by step. The joint can be filled in one or more passes. As the filler metal melts, so do the edges of the components that are being joined together (unlike in brazing).

Ever since the arc welding of aluminium in inert gases (argon or helium) came into widespread industrial use, there have always been two main processes but they tend to complement rather than compete with one another (table 48, p. 97). One, TIG, is mainly manual, while the other, MIG, can be fully automated. MIG welding has advanced in great strides since the early Nineties to the point where the conditions under which aluminium is welded are now greatly enhanced.

The mechanical properties of the weld seams are identical in both processes, all other things being equal, i.e. parent alloy, filler metal and material thickness.

PRINCIPLE OF TIG WELDING

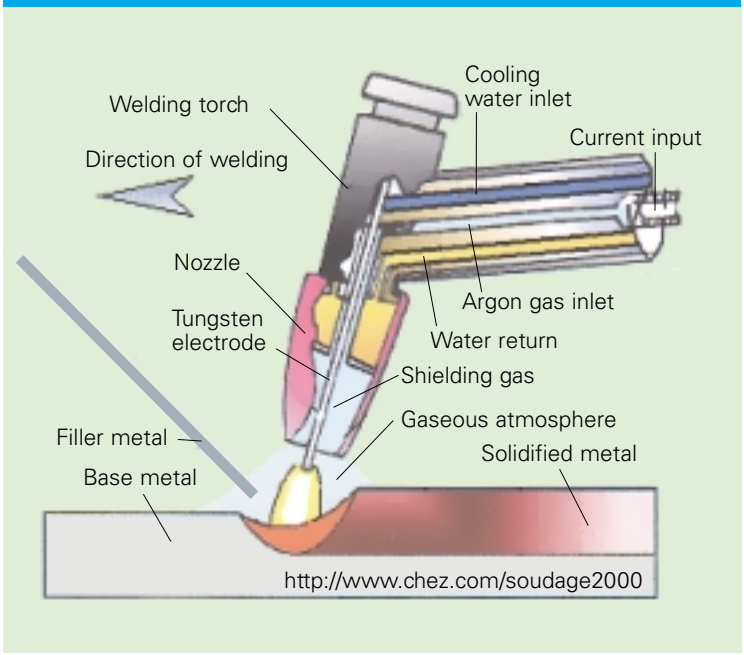


Figure 77

4.1 TIG welding (Tungsten Inert Gas)

In TIG welding (16), the electric arc forms between a refractory tungsten electrode and the piece to be welded. The shielding gas – usually argon – is blown out through the nozzle of the torch (figure 77).

In manual TIG welding, the filler metal in the form of a straightened wire rod (0.8 mm to 4.0 mm in diameter) is held manually by the welder. In automated TIG welding, the filler metal is fed automatically from a reel of wire of diameter 0.8 mm to 2.0 mm by a motorised dispenser.

Welding machines operate with stabilised HF alternating current for manual welding or continuous or pulsed d.c. current for automatic welding. Machines must be fitted with an electronic circuit board designed for aluminium welding, with a pulse arc stabiliser and an arc re-igniter.

The geometry of the refractory electrodes is an important factor influencing the quality of the weld. The electrode must be ground sharp unless the welding machine runs on a.c. current. For d.c. current, the electrode tip must be inside a cone of 30 to 60 degrees, and machining (or grinding) marks must run parallel to the longitudinal axis of the electrode (figure 78).

GRINDING OF TIG ELECTRODES

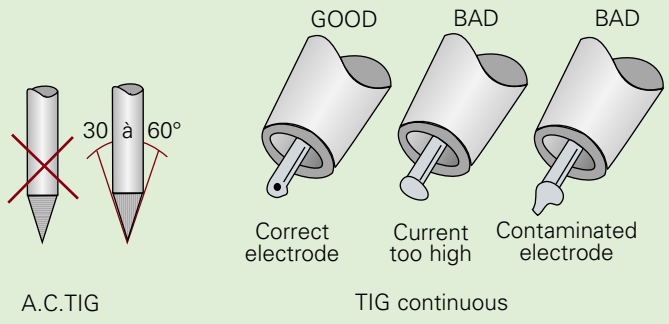


Figure 78

(16) The process is known as WIG in Germany (tungsten in German is 'Wolfram') and GTAW in America (Gas Tungsten Arc Welding).

TIG uses less power than MIG, so the heat affected zone is wider (because of the diffusion coefficient) and there is more distortion due to expansion. The rate of welding which is controlled by the welder is relatively slow, in the region of 0.2 $m.min^{-1}$.

TIG welding is above all a manual process and simple to use, allowing meticulous workmanship and precision results.

Welding is possible in all positions. It is suitable for material 1 to 6 mm thick. It can be used to weld with clearances that are over twice the thickness of components under 1.5 mm thick.

TIG is difficult to automate so is limited to use in the development of prototypes and in the repair of defective welds.

4.2 MIG welding (Metal Inert Gas)

In MIG welding (17), the filler wire also acts as the electrode supplying the power (figure 79). The wire is automatically uncoiled from a reel and fed to the welding tool (gun or torch) as it is used up.

The welding power is proportional to the amount of wire that is fed to the weld seam, and is supplied by a d.c. power source which can be continuous or pulsed. Connection is made with reverse polarity, i.e. the workpiece is always connected to the minus (negative) pole to ensure descaling of the oxide film.

MIG welding is 'self-pickling' because the transfer of electrons from the workpiece to the filler wire breaks the oxide film (provided it is very thin, several nanometers).

A thick oxide layer that has formed following long exposure to ambient humidity cannot be fully removed, and the weld seam will have oxide inclusions (defect 303, cf table 54, p. 104). Semi-finished products should therefore be stored under cover in a dry place (18).

The welding current varies from 40 to 700 Amps depending on a number of parameters such as the diameter of the filler wire, the position of the weld, the size of the components etc.

The classic MIG process using continuous current has many advantages:
- excellent productivity due to the high rate of filler metal deposition,
- good penetration,
- low splatter,
- the process can be automated.

4.3 Synergic pulsed MIG

MIG welding has made great advances since the appearance in the early Eighties of so-called "synergic pulsed current" generators in which the current is supplied by power transistors.

Prior to this, power was supplied by thyristor generators whose pulse frequency was a direct function of the mains frequency. Settings were difficult and lacked flexibility because the speed of the wire had to be adjusted according to the frequency.

Synergic pulsed current generators allow the welding cycle to be regulated (figure 80) to give:
- high current at the start of the weld to avoid lack of fusion and penetration, and
- low current at the end of the weld to prevent crater formation.

PRINCIPLE OF MIG WELDING

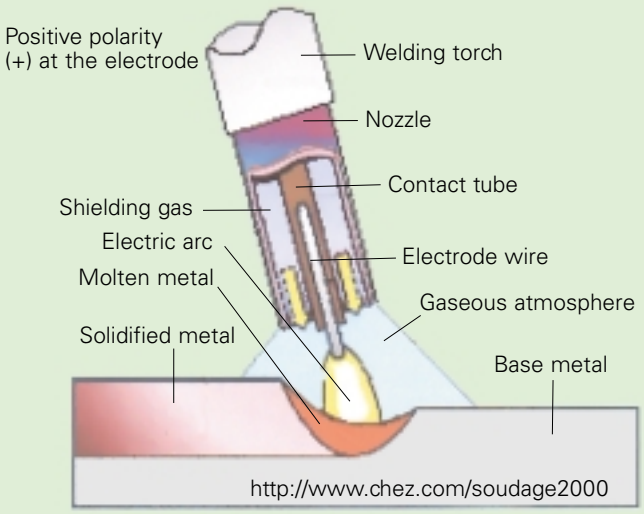


Figure 79

(17) Still also known as MAG (Metal Active Gas) or GMAW (Gas Metal Arc Welding).

(18) Cf. Section 5.

The welder can control three parameters to optimise the weld seam:

- the speed of the wire, proportional to the welding current,
- the welding speed,
- the height of the arc, proportional to the welding voltage.

With these machines, the parameters adjust automatically to the displayed speed of the wire. Settings can be refined by adjusting the height of the arc.

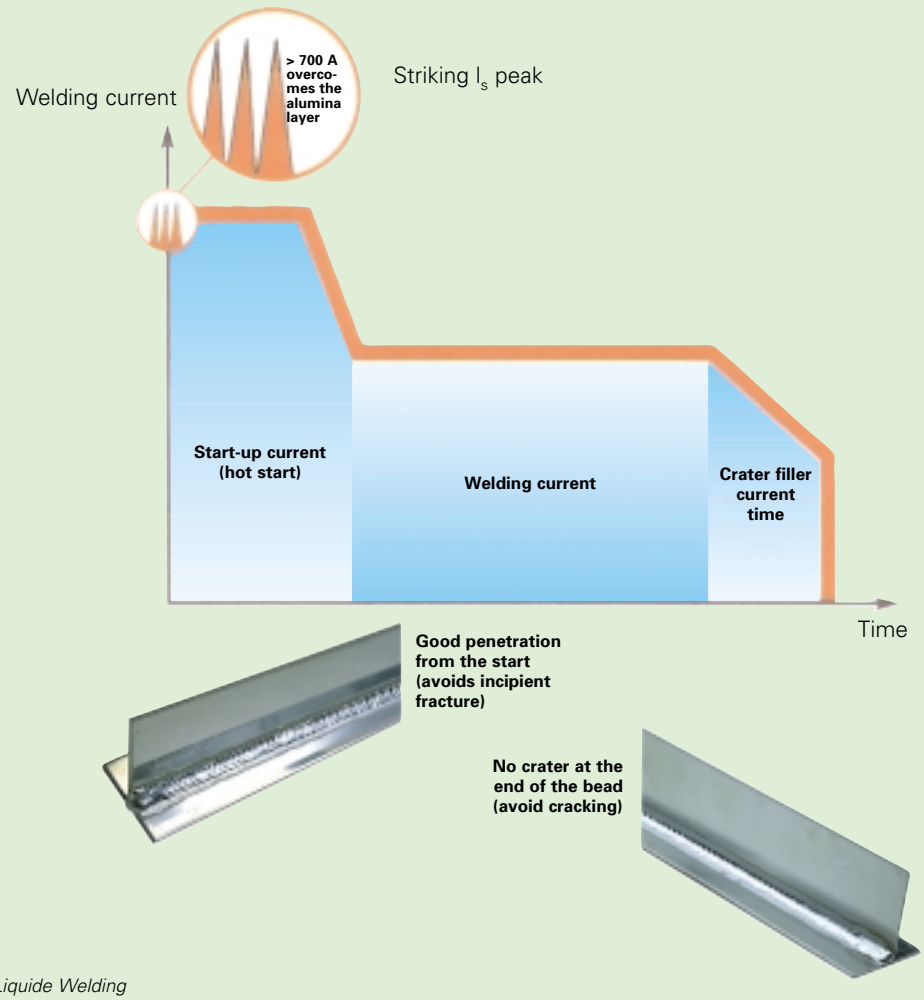
In this system, the metal is transferred "drop by drop" (i.e. one drop of metal per pulse), allowing the minimum weldable thickness to be reduced from 3 to around 1 mm (19).

Pulsed MIG offers a number of additional benefits over conventional MIG welding with continuous current:

- welds can be made in any position,
- distortion is limited (low power input),
- limited weld repairs and fewer in number,
- wide range of thicknesses with the same diameter wire,
- good joint quality and good mechanical properties,
- good appearance of the weld seam, especially with spray transfer,
- process can be fully automated.

(19) With the old-type generators the transfer of metal by spraying was only possible at 20 V and over. Below this voltage, globule or short-circuit transfer is unsuited to the welding of aluminium, which accounts for the minimum thickness of 3 mm.

SYNERGIC WELDING CYCLE



From Air Liquide Welding

Figure 80

THE SPRAY-MODAL PROCESS

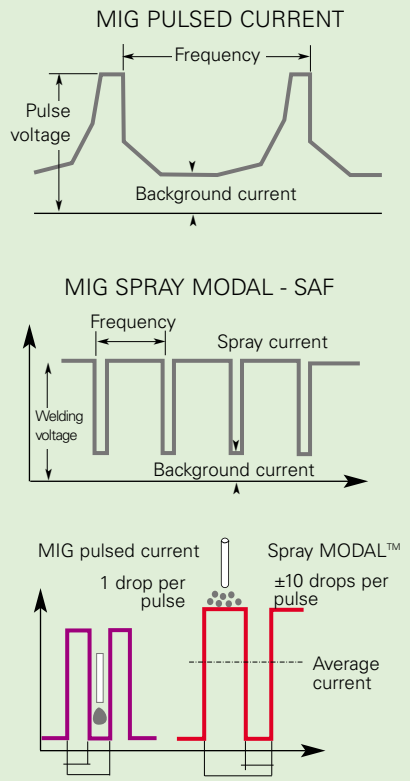


Figure 81

4.4 "Spray MODAL" synergic MIG with modulated current

There is now a variant of the synergic welding technique – the "Spray Modal" process (20). It operates with modulated current which falls very rapidly over a very short period of time (several milliseconds) with every pulse during which several drops of filler are projected into the weld pool (figure 81). These rapid variations in voltage within the arc cause the weld pool to vibrate, encouraging the evacuation of hydrogen bubbles from the metal while it is still liquid.

Compared with synergic pulsed MIG, Spray-MODAL welding

- reduces or even eliminates porosity in the weld (figure 82).
- enhances penetration,
- increases welding speed.

4.5 Filler wires

An evenly dispensed filler wire will ensure good arc stability and hence the quality of the weld.

The low rigidity of the filler wires requires the use of suitable dispensers to minimise the chances of the wire snagging in the torch tube which must be made of PTFE ("Teflon") to eliminate risks of abrasion.

A torch with a push/pull wire dispensing system is recommended to ensure optimum dispensing regularity, especially when using the 4043A wire grade and in automated welding.

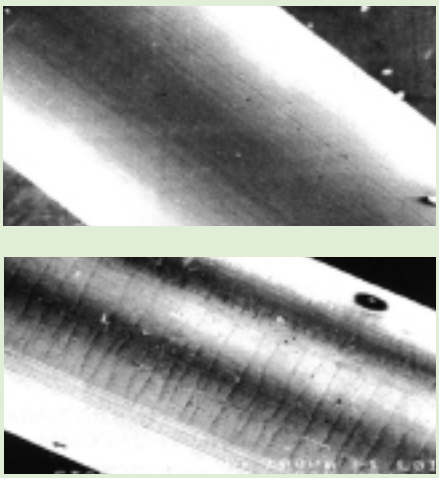
Filler wire is usually 1.2 mm in diameter, although there are also 1.6 mm gauge wires; these are more rigid and their use is growing with pulse MIG. They are also used when the rate of deposition is high.

Shaving the filler wires in the final drawing pass has a number of effects, all of which enhance the quality of the weld:

- it eliminates the outer zone which can be the site of magnesium segregation,
- it removes traces of grease,
- it 'sizes' the weld which removes surface irregularities that are areas of moisture retention (figure 83).

(20) *Patented by Air Liquide.*

SURFACE CONDITION OF FILLER WIRES

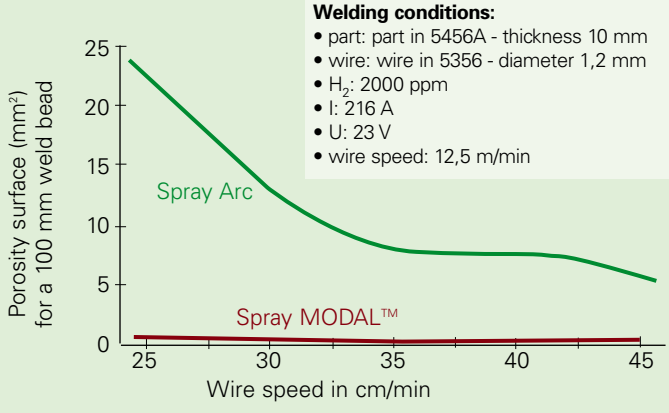


GX50

From Air liquide Welding

Figure 83

EFFECT OF SPRAY-MODAL ON POROSITY



From Air liquide Welding

Figure 82

PARAMETERS OF TIG AND MIG WELDING			
	d.c. TIG	a.c. TIG	d.c. MIG
Current source	Direct	Alternating with HF and arc decay (specially designed for aluminium alloys).	Direct, with very shallow trailing edge. A pulsed source is a good option for slender work.
Electrodes	Zirconium tungsten	Pure tungsten	Filler wire
Torch angle	80° in the direction of advance	80° in the direction of advance	80° in the direction of motion
Gas	Helium	Argon or mixture of 70% argon, 30% helium(*) Flow 10 l/min^{-1}	Argon or a mixture of 30% argon, 70% helium (*), (**) Flow 1 l/min^{-1} for a nozzle 18 to 25 mm in diameter
Welding speed	0.30 to 0.60 m/min^{-1}	Slow: 0.15 to 0.30 m/min^{-1}	Faster: 0.40 to 1 m/min^{-1}
Application	Thickness 0.1 to 10 mm Automated welding with good weld quality	Thickness 1 to 6 mm Prototypes Repairing defective welds	Thickness 1 mm and over, in several passes if necessary All welded fabrications

(*) The helium in argon/helium mixtures increases the welding speed and improves penetration.
(**) Pulse MIG and Spray MODAL™ synergic MIG methods operate mainly with argon.

Table 48

5. STORAGE OF SEMI-FINISHED PRODUCTS AND FILLER WIRE

Given aluminium's very strong affinity for hydrogen when in the liquid state (figure 60, p. 86), it is essential to remove all possible sources of that element, especially moisture which can deposit on semis and filler wire in storage and hydrate the oxide layer.

Filler wire is always supplied in sealed packs that must be stored in an enclosed, covered room that is at the same temperature as the welding shop. The packs should not be opened until required for use.

When welding operations are complete, any wire left on the reel must be stored in a cabinet maintained at a constant 40°C.

6. SURFACE PREPARATION

Other sources of hydrogen are the rolling and forming greases and oils left on the surface of the metal, and other impurities of different types, such as traces of paint.

The surface of the metal must therefore be cleaned very carefully on both sides, starting by degreasing with a non-chlorinated solvent to dissolve the greases and oils (21). Solvents are themselves hydrocarbon compounds containing hydrogen atoms, so great care must be taken to ensure no trace is left prior to welding.

After degreasing, the edges must be brushed (after chamfering as necessary) on both sides of the metal and over a sufficient width that is at least equal to the width of the heat affected zone, i.e. 25 mm. A rotary brush with stainless steel wires should be used for this.

Whatever method of brushing is used (manual or mechanical) the brush itself must be very clean and operators must wear gloves.

The "life" of surface preparation is certainly no more than one day, after which time the oxide film may well absorb moisture once more, especially in humid environments (22).

To eliminate moisture, just prior to welding an oxy-acetylene torch can be used to pre-heat the edges at a temperature above dew point in the region of 30 to 40°C.

7. JOINT PREPARATION AND SETUP

These operations are very important, and will determine the quality of the weld and its fatigue resistance. For example, excessive clearance between the workpieces can cause the weld seam to collapse and lead to the formation of undercuts that can be very detrimental to the quality of the weld and its fatigue resistance.

The type of edge preparation will depend on:

- the thickness of the work,
- the type of weld: butt, flat or fillet, vertical, overhead or horizontal,
- the use of a backing strip or bar, whether permanent or not.

As a general rule, the edges of material up to 4 mm thick are not chamfered.

Ideally, edges that are to be welded should be prepared by machining with a coarse-tooth cutter or if this is not available, manually using a coarse file. Avoid grinding with corundum or resin wheels.

Workpiece configuration is also important; this relates to:

- the clearance between the workpieces – this must be as small as possible (23) to prevent distortion,
- the size and shape of the backing bar (stainless steel).

Tables 49 and 50 illustrate a number of examples of edge preparation and configuration found in shipbuilding.

8. FILLER METAL

The filler metal must be compatible with the chemical composition of the parent alloys that are to be welded, and must ensure the best possible weldability.

The choice will also depend on the mechanical properties and corrosion resistance that the joint is required to have.

For the aluminium alloys that are used in shipbuilding (and other marine applications), the filler metals are:

- silicon alloys, mainly 4043A, 4045, 4047A,
- magnesium alloys, mainly 5356, 5183, 5556A.

Their compositions are shown in table 51, p. 100.

Table 52, p. 101 - taken from EN 1011–4 (24) - shows possible choices of filler metal according to the hierarchy of criteria used for the weld. 5183 is the best filler metal for welding *Sealium*®.

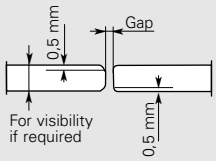
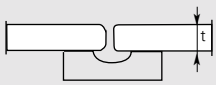
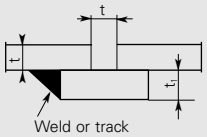
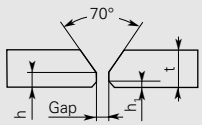
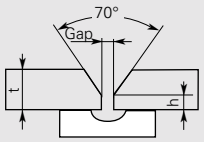
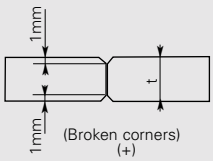
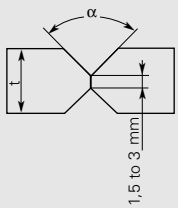
(21) Chemical pickling in alkaline baths should be avoided at all cost. Thorough washing is essential and experience shows that this is often inadequate, with a risk of subsequent corrosion by traces of the alkaline medium.

(22) BS 8118 "Structural use of aluminium, Part 2 Specification for materials, workmanship and protection" states that the time between cleaning and welding must not exceed 6 hours.

(23) Zero clearance is the ideal.

(24) Standard EN 1011-4. Welding – Recommendations for welding of metallic materials. Part 4: Arc welding of aluminium and aluminium alloys.

EXAMPLES OF EDGE PREPARATION FOR BUTT WELDING MIG WELDING

Position	Welding	Backing	Thickness (mm)	Preparation	Remarks
All	1 side only	none	3 < t ≤ 6		Max. gap 1.5 mm Back-weld advisable for t > 4 mm (*)
		temporary			Max. gap 3 mm
		permanent			t_1 = t + 1 mm with max. 6 mm
Flat, vertical, overhead	1 side only	none	3 < t < 25		Max. gap 1.5 mm Back-weld advisable for h = 3 mm (*)
		temporary			Max. gap 2 mm
Flat	2 sides alternately	none	8 < t < 30		Material over 12 mm thick should be welded automatically with a high current (+). Improvement and visibility of the weld
Flat, vertical, overhead	2 sides alternately	none	t > 10		α = 70/90° for flat and overhead welds α = 70° for vertical welds

(*) Where a back-weld is advisable, it must be welded after gouging to the base of the first pass.

Table 49

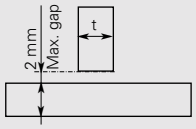
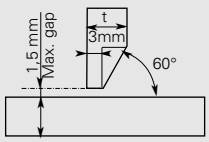
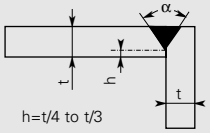
(*) Taken from standard NF 87-010 "Aluminium et alliages d'aluminium – Soudage – Préparation des bords" (Aluminium and aluminium alloys – Welding – Edge preparation).

9. FINISHING

The purpose of weld finishing operations is to:

- repair defective weldments,
- remove any black deposits left by welding,
- correct structures with excessive distortion,
- shave the seam,
- put the seam in compression by shot-peening,
- complete the concavity of the seam.

EXAMPLES OF EDGE PREPARATION FOR FILLET WELDS MIG WELDING (WELDS IN ALL POSITIONS, NO BACKING)

Welding	Thickness (mm)	Preparation	Remarks
2 sides alternately or simultaneously, automatic flat welding	t > 4		
1 side	t > 4		If possible 1 back pass on other side, 5 mm groove (*)
1 side	t > 6		α = 70 °. Back-weld if possible

(*) Where a back-weld is advisable, it must be welded after gouging to the base of the first pass.

Table 50

(*) Taken from standard NF 87-010 "Aluminium et alliages d'aluminium – Soudage – Préparation des bords" (Aluminium and aluminium alloys – Welding – Edge preparation).

CHEMICAL COMPOSITION OF FILLER METALS (*)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
4043A	4,5 6,0	0,6	0,30	0,15	0,20		0,10	0,15
4045	9,0 11,0	0,5	0,30	0,03	0,05		0,10	0,20
4047A	11,0 13,0	0,6	0,30	0,15	0,10		0,20	0,15
5356	0,25	0,40	0,10	0,05 0,20	4,5 5,5	0,05 0,20	0,10	0,06 0,20
5183	0,40	0,40	0,10	0,50 1,0	4,3 5,2	0,05 0,25	0,25	0,15
5556A	0,25	0,40	0,10	0,6 1,0	5,0 5,5	0,05 0,20	0,20	0,05 0,20
5556 (**)	0,25	0,40	0,10	0,50 1,0	4,7 5,5	0,05 0,20	0,25	0,05 0,20

(*) According to standard EN 573-3, Part 3: Aluminium and aluminium alloys – Chemical composition, except for the 5556.

Table 51

(**) According to the Aluminum Association.

9.1 Repair of defective welds

If inspection (X-ray, ultrasonic etc.) reveals unacceptable weld imperfections then the weld must be repaired.

On material under 4 mm thick, defective areas can be removed with a rotary tungsten carbide cutter mounted in a pneumatic drill. The axis of rotation of the cutter must be parallel to the axis of the weld so as to avoid incipient cracks.

For material over 4 mm thick, the defective areas should be removed with a pneumatic hammer fitted with a gouge (25).

The weld is then repaired by the same process (TIG or MIG) as was used to make the initial joint. Minor imperfections are nearly always repaired by TIG welding however, thickness allowing.

(25) Carbon arc gouging is not advisable as it may introduce carbon into the weld seam.

(26) Cf. Chapter 10, Section 10-2.

CHOICE OF FILLER METALS AS A FUNCTION OF THE ALLOY COMBINATION

Each combination has three possible choices - indicated where the lines intersect - depending on the selected criterion: Optimum mechanical properties: top line – Optimum resistance to corrosion: middle line – Optimum weldability: bottom line

The filler metal indicated is: 4 : series 4xxx → 4043A, 4045, 4047A – 5 : series 5xxx → 5356, 5183, 5556A

Alloy A					
Wrought 5000 Series Mg < 3%	5 5 (a) 4 - 5 (b)				
Wrought 5000 Series Mg > 3% (a)	5 5 5	5 5 5			
Wrought 6000 Series	5 - 4 5 4	5 - 4 5 4	5 - 4 5 4		
Wrought 7000 Series without copper	5 - 4 5 4	5 - 4 5 4	5 - 4 5 4	5 - 4	
Cast Si > 7% (c)	4 (e) 4 4	5 - 4 (e) 5 4	4 4 4	4	4 (d) 4 4
Alloy B	Wrought 5000 Series Mg < 3%	Wrought 5000 Series Mg > 3%	Wrought 6000 Series	Wrought 7000 Series without copper	Cast Si > 7% (c)

Table 52

(a) 5000 series alloys with more than 3.5% Mg are sensitive to intergranular corrosion when exposed to temperatures over 65°C and when used in certain aggressive environments (26).

(b) 5000 series alloys with less than 3% Mg and 3000 series alloys that contain magnesium may be sensitive to hot cracking.

(c) The mechanical performance of the weld depends on the internal soundness of the castings. Gassed materials and injection mouldings are considered to be non-weldable.

(d) The percentage of silicon in the filler wire must be as near as possible to that in the casting.

(e) The welding of aluminium-silicon castings (40000 series) to 5000 series alloys should be avoided where possible as Mg2Si intermetallics form in the weldment and weaken the joint.

9.2 Cleaning

Very fine black deposits of "soot" can often be seen sticking to the surface of the metal at the edge of the weld seam after MIG welding, especially when 5000 series semis are welded with 5356 alloy as the filler metal.

4043A filler wire leaves no deposits (except possibly at the start and finish of the weld) provided the welding equipment is set correctly.

This "soot" consists of particles of oxides (of aluminium and magnesium) caused by small amounts of filler metal vaporising in the arc, the temperature of the arc being higher than the boiling point of aluminium and magnesium. The vapour immediately condenses on cold parts of the sheet near to the weld.

These deposits only affect the appearance of the weld and have no impact on its mechanical properties or corrosion resistance.

This "soot" can be brushed off with a metal brush. This should be done as soon as possible after welding as it becomes much more difficult to remove if left for several hours.

9.3 Correcting distortion

Minor distortion in sheet under 3 mm thick can be corrected with a hammer or mallet.

When sheets are bulged (figure 84), the welding torch can be used to apply "shrinkage heat" as locally as possible to the bulges. The heat makes these constrained areas expand (the welded zones are shorter than the sheet), and they are compressed. Rapid cooling – with a jet of water if necessary – then causes shrinkage which places the piece under stress and so corrects the warp. "Shrinkage heat" may also be combined with hammering.

It is trickier to apply "shrinkage heat " to aluminium than to steel because of the high diffusion of heat. Unlike steel, aluminium does not change colour so the temperature must be checked with tallow or thermocolour pencils.

Shrinkage heat does not affect the mechanical properties of 5000 alloys in the O or H111 condition. However it anneals 6000 series alloys and so reduces their mechanical properties.

9.4 Flush dressing of the weld

Flush dressing of the weld seam very significantly improves the fatigue resistance of the joint provided the seam is free from internal flaws which flush dressing would expose.

According to BS 8118 for example, shaving increases the endurance limit of a seam from 24 MPa for a 120° angle to 50 MPa for a dressed flush seam (27).

Welds are normally dressed flush with a fine abrasive wheel (50 to 80 grit).

9.5 Shot-peening

Shot-peening a weld seam puts its surface in compression, neutralising internal stresses detrimental to the weldment's fatigue strength.

Different types of shot can be used – glass, ceramic or steel – but it is the latter two which significantly enhance fatigue strength (figure 85).

Although there is no way of verifying the efficiency of these treatments, they can be applied to the welds of "hot spots".

DISTORTION OF PARTS IN COMPRESSION

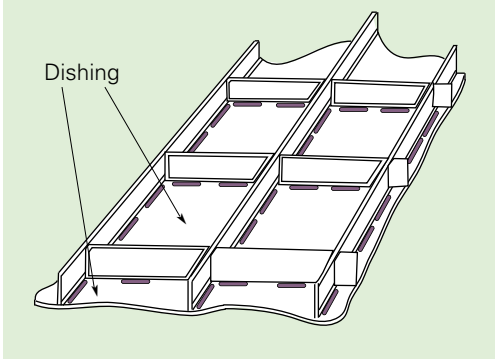


Figure 84

EFFECT OF PRE-STRESS SHOT-PEENING

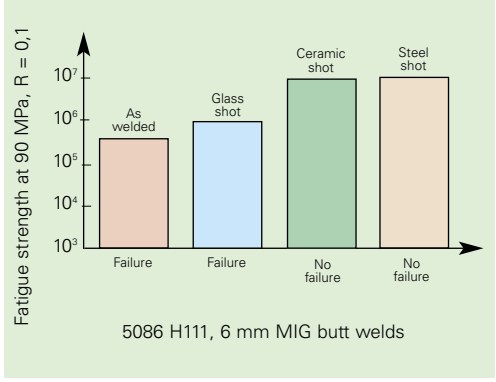


Figure 85

(27) *Cf. figure 45, p. 65.*

10. INSPECTION

The purpose of inspection is to evaluate the quality of fabricated products and more specifically to grade the quality of a weld against an acceptable level of defects.

The acceptable level of defects is determined by a number of parameters:

- the load modes and load conditions – static and dynamic,
- the levels and variations of stress,
- the safety of persons and property,
- the technical and financial consequences of failure,
- the options for routine operational inspection and control.

10.1 Approval procedures

Approval procedures are contractual but they also make reference to standards (if any) and to the regulations of classification societies, especially as regards the qualification of welders.

They may be complemented by the fabricator's own inhouse procedures, governing welding methods in particular.

Tensile and bending tests are conducted on test specimens following approval procedures laid down by the classification societies. These tests are very important as they can help:

- to detect a lack of fusion that is hard to identify by NDT testing, and
- to adjust parameters so as to limit defects.

10.2 Testing welded joints

The frequency and extent of weld testing will depend on a number of criteria, such as:

- structure,
- rate of stress,
- any loads imposed on the welds.

In the course of fabrication it is possible to perform:

- non-destructive tests including random X-ray testing (28), ultrasonic etc.,
- visual inspection and dye-penetration (29) which can be performed over the whole of some welds to detect incipient cracks,
- tests of mechanical properties and bending tests on specimens taken from batches of welded metal according to the current methods

(28) X-ray testing is not normally possible on fillet welds.

(29) According to NF A 09-120. Non-destructive tests. General principles of dye-penetration testing. June 1984.

(30) EN ISO 6520-1 Classification of geometric imperfections in metallic materials. Part 1: Fusion welding.

11. WELD IMPERFECTIONS

The causes of weld imperfections are numerous, and are a result of either the preparation of the metal or poor workmanship.

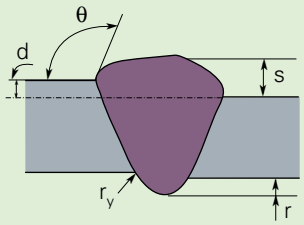
The most common defects encountered in aluminium welding are virtually the same as are found in the welding of steel: isolated cracks ('star cracks') or longitudinal cracks, incomplete penetration, poor bonding (fusion), porosity and undercuts.

Standards define weld imperfections based on measurements on a cross section (figure 86) of the weld and observations on its appearance.

An international nomenclature of defects has been established and is given in EN ISO 6520-1 (30) which lists 6 groups of imperfections, as shown in table 53, p. 104).

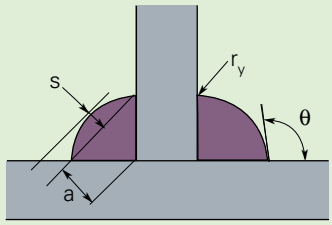
GEOMETRICAL CHECKING OF WELDS

Butt welds



Misalignment: d
Toe angles at base of bead: θ
Toe radii at base of weld: r_y

T Joint or Fillet welds



Toe angles at base of bead: θ
Toe radii at base of weld: r_y

All numerical values are expressed in degrees or mm

Figure 86

11.1 Common weld imperfections

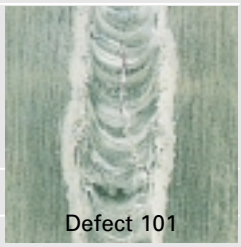
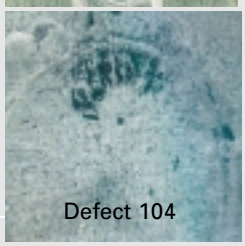
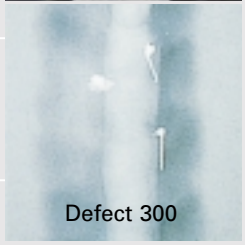
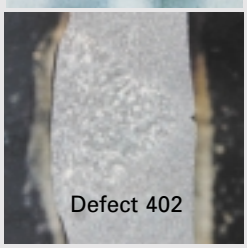
Table 54 lists the most common imperfections together with their likely causes.

GROUPS OF WELD IMPERFECTIONS

Group	Type of Imperfection
100	Cracks
200	Cavities and wormholes
300	Solid inclusions
400	Lack of fusion and penetration
500	Defects of shape
600	Sundry defects

Table 53

TYPICAL WELD IMPERFECTIONS

N°	Type of Defect	Likely Cause	Photos of Imperfections
101	Cracks	Base alloy unsuitable Poor choice of filler metal Incorrect welding sequence Excessive clamping Sudden cooling	
104	Crater cracks	Pass finished with sudden arc cutoff	
2012	Irregular wormholes	Work inadequately degreased Work and/or filler wire dirty or wet Insufficient protection by inert gas (low gas flow or leak in the system) Pass begun on cold component High arc voltage Weld cooled too quickly	
2014	Aligned wormholes	Incomplete penetration (double pass) Temperature gradient between backing and work too abrupt Excessive gap between edges of the joint	
300	Solid inclusions	Dirty metal (oxides, brush hairs)	
303	Oxide inclusions	Poor gas shielding Metal stored in poor conditions Castings	
3041	Tungsten inclusions (TIG)	Electrode diameter too small Poor handling by welder Excessive current density Poor quality of tungsten electrode	
402	Incomplete penetration	Inadequate cleaning (presence of oxide) Incorrect bevel preparation on thick work (too tight, excessive shoulder) Gap between workpieces too small (or incon-sistent) Low current, especially at the start of the seam Welding speed too fast High arc voltage	

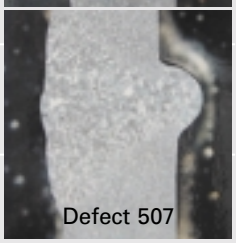
N°	Type of Defect	Likely Cause	Photos of Imperfections
4011	Lack of fusion on edges	High arc voltage Low current, especially at the start of the seam Work cold (difference in thickness between materials to be welded)	
502	Excessive thickness	Poor power control (poor U/I match) Welding speed too slow Poor edge preparation on thick work Insufficient starting current	
507	Misalignment	Work positioned incorrectly Incorrect welding sequence	
508	Angle defect	Excessive welding power Incorrect welding sequence	
509	Collapse	Wire speed too fast Torch speed too slow Poor torch guidance	
602	Splatter (or beads)	Incorrect arc control Problem in electrical contact to ground	

Table 54

11.2 Effect of weld imperfections on fatigue strength

Some weld defects have a significant impact on the fatigue strength of the weldment:

- cracks (emergent or otherwise) and incomplete penetration are very serious flaws, as shown by tests carried out on weld defects [5] (figure 87),
- defects of geometry, especially sudden breaks in curves (angle at the base of the weld seam, misalignment etc.) aggravate stress intensity factors.

BUTT WELD IMPERFECTIONS

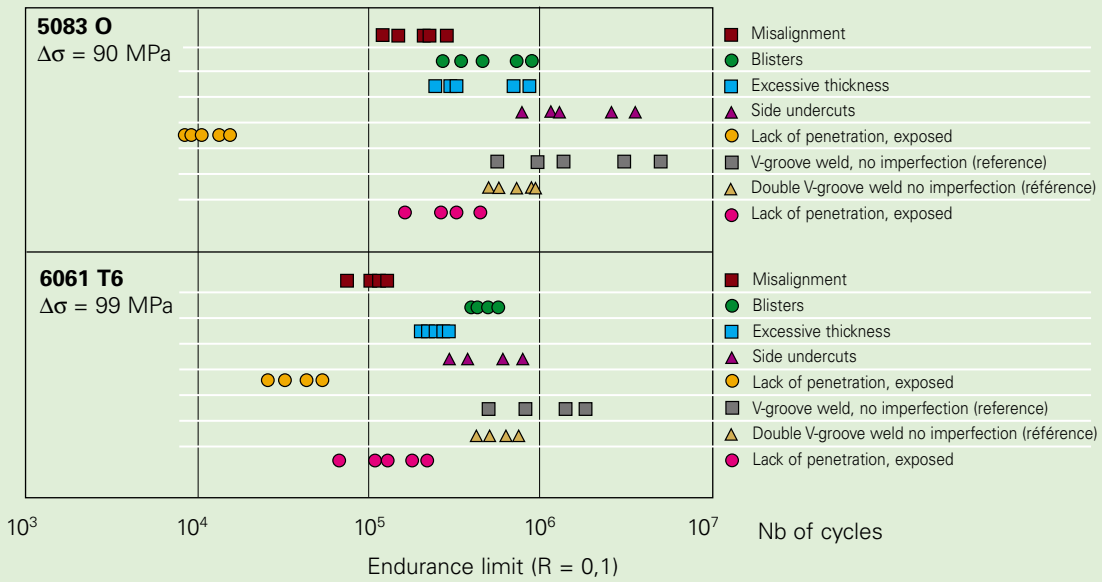


Figure 87

12. REPAIRS AND FITTINGS

European shipyards have responded to needs for the maintenance and modification of aluminium high speed ships by adapting to and specialising in this new activity [6, 7 8].

These yards repair damage to ships and modify onboard installations. The very long service life of aluminium ships means that from time to time they must be adapted in line with changing conditions of service, new equipment must be installed etc.

Work on aluminium alloy structures is based on classical sheet metalworking operations as is commonly carried out on steel ships (and their equipment), e.g. sheet and plate cutting, preparing edges for welding, making welds, correcting distortion etc.

The rules discussed previously for aluminium alloy forming and welding apply equally to these operations.

A number of basic precautions should be taken when welding items that are being repaired or modified:

- clean surfaces near to the weld with great care, using a brush to remove all traces of paint, oil or fuel that could have fouled the plates,
- dry thoroughly before welding to remove all traces of moisture,
- weld under cover of weather and away from draughts; if necessary, work under a tarpaulin when these operations are carried out in dock,
- pay particular attention to the direction in which welds are made – this will limit distortion and minimise the risks of hot cracking due to shrinkage,
- select the correct welding process: TIG (for work less than 6 mm thick) or MIG. TIG is more suitable for minor repairs where back access is difficult or impossible, being easier to use in such situations and providing better control of penetration than MIG.

For localised repairs such as a torn hull, the repair patch must be perfectly matched to the shape of the tear but will be bigger (achieved by hammering) to compensate for the contraction caused by welding. Without this precaution, the residual stress would attain a level where it would cause systematic cracking. The smaller the patch, the more pronounced this phenomenon.

Important note:
Never work with a torch or electric arc on or in any enclosed space, tank etc. that has held water (including seawater) or which has been in contact with moisture without first airing or thoroughly ventilating it to disperse the hydrogen produced by possible corrosion of the metal in contact with water. Failure to take this precaution may lead to an explosion hazard with consequences that could prove catastrophic for the operators (31). It is also a mandatory precaution for any work on fuel oil tanks.

13. LASER WELDING

Since the early Nineties, the uses of welding by laser (32) have spread widely in shipbuilding [9].

13.1 Principle of the laser

The laser is a device that generates an intense beam of coherent monochromatic radiation. In welding machines, this radiation is concentrated to obtain power densities in excess of 10^6 W.cm^{-2} which is sufficient for the industrial welding of aluminium alloys.

This power is used to generate a capillary filled with metallic vapour whose walls are lined with liquid metal in fusion. The resulting weld pool bath is displaced and the liquid metal solidifies after the beam has passed, ensuring metallurgical continuity between the workpieces (figure 88).

13.2 Welding lasers

Two types of industrial laser are used for welding metals:

- **in CO_2 lasers** the active medium is a gaseous blend of carbon dioxide (CO_2), nitrogen (N_2) and helium (H_2) at low pressure. The wavelength of the laser beam is 10.6 µm. Industrial CO_2 lasers can generate power ranging from 1.5 to 40 kW. The beam is transmitted by mirrors.

(31) The amount of hydrogen that builds up in a ballast tank can be considerable even though corrosion is only superficial. In a tank with sides 1 metre long for example, i.e. 5 m^2 of area in contact with water, superficial corrosion one micron deep releases 16.8 litres of hydrogen !!!

(32) Light Amplification by Stimulated Emission of Radiation.

■ **in Nd:YAG lasers** (Neodyme Yttrium Garnet), the active medium is a solid and the radiation wavelength is 1.06 µm, with a maximum available power of 3 to 4 kW. Despite their low power, Nd:YAG lasers offer a number of advantages over CO_2 lasers: the sources are more compact, and Nd:YAG beams can be carried by fibre optics which makes it possible to weld along complex paths using welding robots.

13.3 Laser welding of aluminium alloys

Aluminium alloys can be laser welded with no particular difficulty and at speeds as high as several metres per minute.

Laser welding offers a number of advantages:

- simplicity of preparation before welding,
- high welding speeds, several metres/minute on butt welds in 6 mm plate made from 5000 alloy,
- reduced distortion owing to the high welding speed and narrowness of the weldment,
- high penetration by the beam; it is possible to weld (CO_2 laser) 5000 series plate up to 12 mm thick in a single pass,
- high mechanical properties of the weld: nearly 90% of the parent metal on 5083 H116 and 70% for 6082 T6,
- different thicknesses can be welded,
- 'invisible' welding,
- good final condition (minimal finishing required),
- advanced automation.

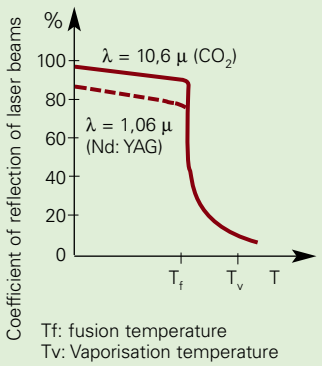
Nevertheless laser welding requires close preparation tolerances and its energy efficiency is low.

13.4 Laser weldability of aluminium alloys

Aluminium alloys have a relatively low light absorption rate in the far-infrared: 3% with the CO_2 laser and 25% with the Nd:YAG laser. However this coefficient of absorption rises rapidly above fusion temperature and is approximately 90% when the material's vaporisation temperature is reached (figure 89).

For welding therefore, vaporisation of the metal must be initiated in the laser beam. Two very different types of interaction are observed according to the power density at the surface of the material (figure 90):

COEFFICIENT OF REFLECTION OF LASER BEAMS



Tf: fusion temperature
Tv: Vaporisation temperature

Figure 89

LASER WELDING

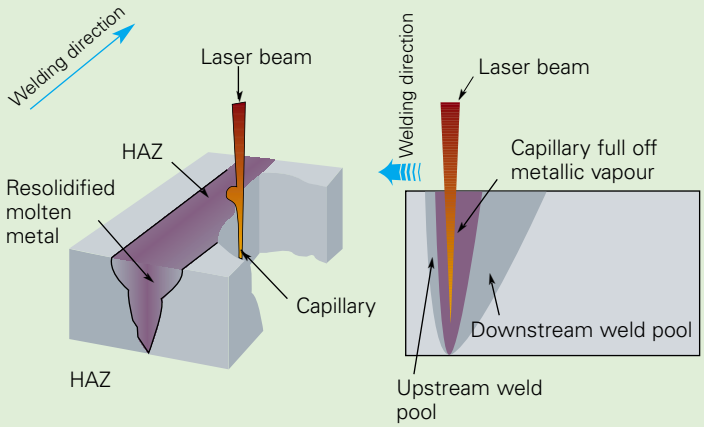
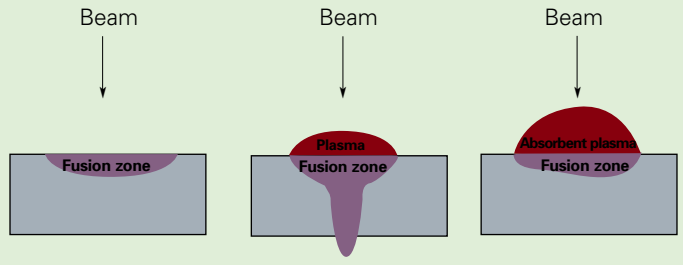


Figure 88

INTERACTION BETWEEN LASER BEAM AND ALUMINIUM



$p < 10^6$ W/cm²
Surface fusion over some tens of microns

$10^6 < p < 10^7$ W/cm²
Formation of « Keyhole » (optimum)

$p > 10^7$ W/cm²
Screen effect

Figure 90

■ at low densities, fusion is very superficial,
■ at high densities a vapour capillary forms, i.e. a narrow and deep zone of fusion in the metal. It is this interaction which is needed for welding.

The threshold of interaction, i.e. the power density needed to form a vapour capillary, is of the order of 10^6 W.cm^{-2}. The value of this threshold depends on the composition of the alloy – alloys that contain magnesium in the 5000 series (5754, 5083, 5086, etc.) have a lower threshold of interaction than other alloys (figure 91) and can be welded with less power.

It is important to note that using too high a power density is counter-productive as the metal vapours will form a plasma that acts as a shield. This is particularly true of CO_2 lasers.

A shielding gas must be used to prevent the immediate oxidation of the weld pool, and with CO_2 lasers the best results are obtained with argon/helium blends or pure helium. Argon can also be used with Nd:YAG lasers.

THRESHOLD OF LASER INTERACTION

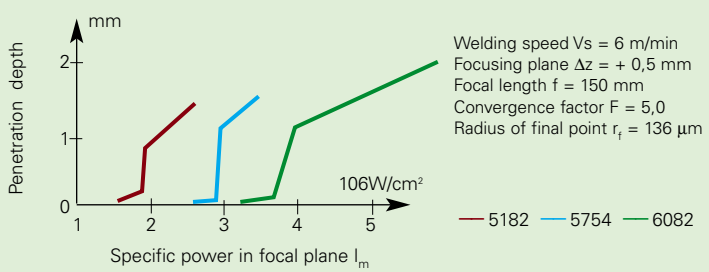


Figure 91

14. FRICTION STIR WELDING (FSW)

Friction welding with a tool (33) was invented by the TWI (34), the first patent being filed in December 1991 [10].

It is clear that this has been a decisive advance in the joining of metals in general and aluminium alloys in particular. In under ten years this new welding technique has enjoyed significant industrial development and growth in a number of sectors including shipbuilding, aerospace and the railways [11].

Since 1995 many publications have appeared and presentations given on the applications of FSW welding in shipbuilding at international conferences on High Speed Ships made from aluminium [12]. These publications reflect the obvious interest shown by naval architects and yards in this new technique, one which is already making very significant changes to aluminium shipbuilding and giving it fresh impetus [13, 14].

(33) Friction stir welding (FSW).

(34) TWI: The Welding Institute.

14.1 Principle of friction stir welding

The process is a simple one, consisting of shearing the metal without melting it (it turns 'pasty') with a rotating tool that has a 'probe' or pin on a level slightly below that of the weld. As it rotates the tool stirs the metal of the workpieces together and discharges it to the rear where the weld thus formed is softened and consolidated.

The metal is made to flow by the heat from the friction of the rotating shoulder against the surface of the metal. The shoulder, which is larger in diameter than the probe, contains the moving particles of metal and maintains a pressure that prevents the metal from being ejected outside the welded zone (figure 92).

The very significant forces that are exerted on the work mean that it must be clamped very firmly to the table of the welding machine.

14.2 Microstructure of the FSW joint

The specific properties of the FSW joint are due to its microstructure which is very different from the microstructure of an arc weld (MIG or TIG) owing to the simple fact that there is no process of fusion / solidification.
An FSW weld has four very distinct zones (figure 93) [15]:

■ **zone A**, outside the weld, is the parent metal of each of the workpieces on either side of the joint. Its structure is unaffected by welding,
■ **zone B** is the heat affected zone. It does not undergo any plastic deformation. As with the HAZ of conventional MIG or TIG welds, its mechanical properties

are low (figure 94). This zone is annealed in strain hardened alloys and over-aged in age hardened alloys (35). However no deformation occurs because the heating up of the metal and the temperature level attained are much lower than in arc welding,

■ **zone C** is the thermomechanically affected zone that has undergone plastic deformation and heating. The structure of this zone depends on a number of parameters including the type of alloy,

■ **zone D** is the "nugget" formed from recrystallised grains in which the metallurgical constituents of the parent alloys are dispersed. The grains are usually smaller than in the parent metal. This structure enhances the fatigue resistance of the welded joint.

In age hardened alloys the nugget is in a condition close to T4 (solution heat treated, natural ageing at ambient temperature) (figure 95).

14.3 Comparisons with arc welding

The FSW process operates at a temperature below the melting point of the metal, offering a number of advantages:

■ **conditions of use** are simplified: surface preparation is confined to degreasing only. Where edge preparation is necessary, surfacing is adequate. The process requires no filler metal or shielding gas,

■ **the applications** of FSW are far more extensive than with arc welding: all types of aluminium alloy products can be welded, whether castings or wrought semis,

■ **the quality of the weld:** there are no risks of hot cracking (36) or porosity as hydrogen is not formed (37),

■ **the quality of the assemblies:** distortion is minimal owing to the low temperature levels and the fact that welding takes place in a solid medium,

(35) As a result the alloys are in the metallurgical condition indicated previously.

(36) It is possible to weld copper alloys (2000 and 7000 series).

(37) If hydrogen did form it would not be dissolved because its solubility in solid aluminium is zero.

FRICTION WELDING TOOLS

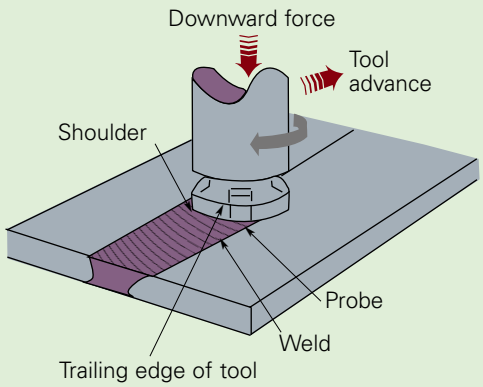
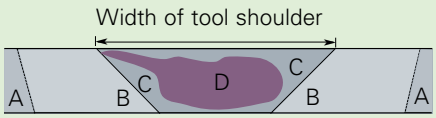


Figure 92

MICROSTRUCTURE OF THE FSW JOINT



A: Parent metal unaffected by weld
B: Heat affected zone (HAZ)
C: Unrecrystallised area found in aluminium alloys
D: Recrystallised nugget found in aluminium alloys

Figure 93

CHANGE IN HARDNESS IN THE HAZ OF 5083 [15]

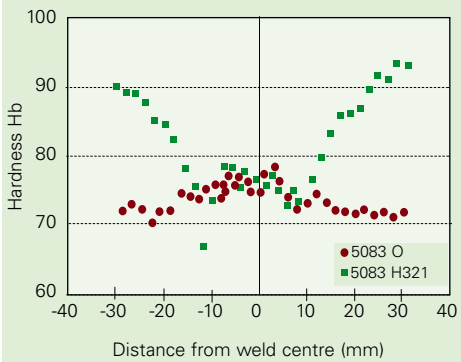


Figure 94

CHANGE IN HARDNESS IN THE HAZ [16]

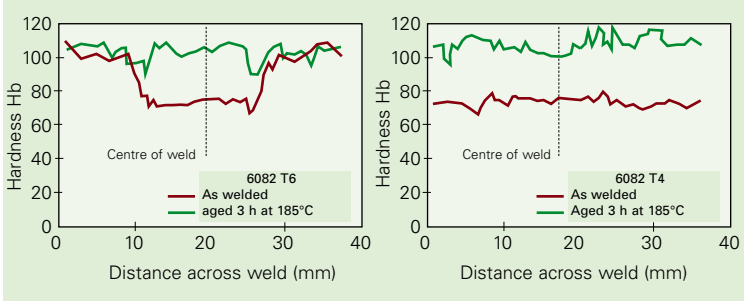


Figure 95

■ **environmental and working conditions:** there are no fumes, no flying particles of metal, no ozone emissions and no ultraviolet radiation. The process is also energy efficient, requiring about 20% of the power of MIG welding.

Its present state of industrial development makes FSW highly suitable for prefabricating sub-assemblies such as deck sections, walls, panels etc. [17] *in the workshop* for subsequent installation in ships and assembly by conventional welding techniques such as MIG (38).

A prototype "portable" machine designed by the University of Adelaide in Australia with The Welding Institute was presented recently [18]. This is in fact a tool connected to a hydraulic motor and mounted on a trolley for welding hull plates 5 mm thick. However although the tool is "portable", the components to be butt welded must be firmly fixed to withstand the forces necessary for welding.

(38) A welding code is in the process of being approved by the classification societies.

14.4 Possibilities of welding with FSW

In its present state of advance, FSW allows the welding of material up to 25 mm thick. Research into 6000 series alloys has shown that it is possible to go up to 50 mm thick with a single head (figure 96), and 75 mm with two heads (figure 97).

Given the current level of industrial development of the process, FSW can be envisaged in a number of configurations for butt welds and 'invisible' welds as shown in figure 98.

WHORL™ TOOL



Figure 96

FSW WELDING WITH TWO HEADS

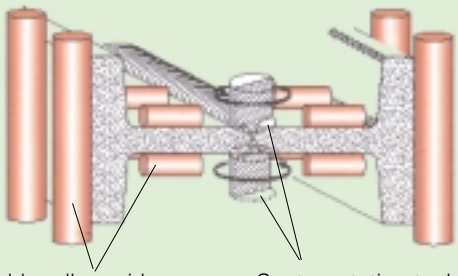
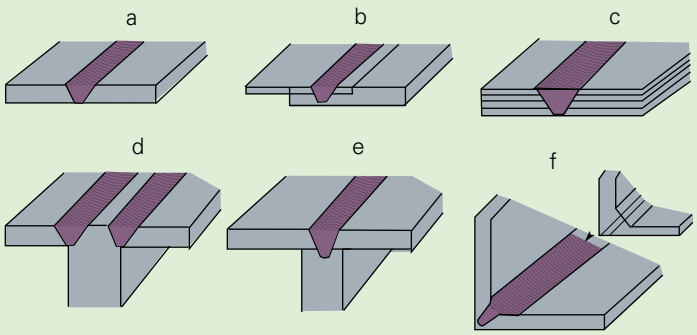


Figure 97

TYPICAL FSW WELD CONFIGURATIONS



a: Butt weld
b: Invisible weld
c: Invisible weld in several thicknesses
d: Welding brackets in Tee
e: Invisible Tee weld
f: Fillet weld inside

Figure 98

MECHANICAL PROPERTIES OF WELDED 5083 AND 5383 6 MM THICK [20]

Alloy	Welding	$Rp_{0,2}$ (MPa)	Rm (MPa)	A %
5083 H116	MIG	134	287	12,8
	FSW	157	335	17
Sealium®	MIG	150	308	13,5
	FSW	165	354	17

Table 55

LIMIT OF ENDURANCE ON 5383 (AT 10^7 CYCLES FOR R = 0.1) [11]

Alloy	Welding	Limit of Endurance (MPa)
Sealium®	Parent metal	228
	FSW	172
	MIG	144

Table 56

LIMIT OF ENDURANCE OF FSW JOINTS

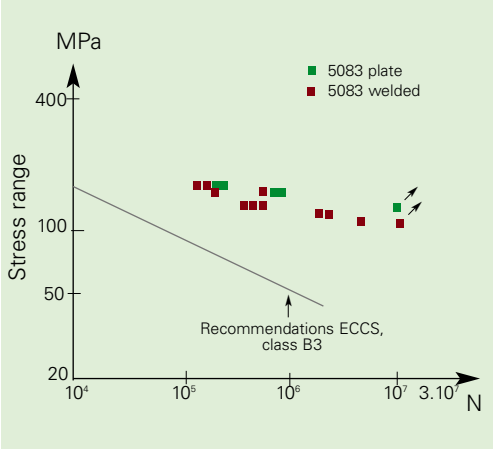


Figure 99

14.5 Performance of FSW welds

There have been numerous studies characterising the properties of FSW welds – their mechanical properties, fatigue strength and corrosion resistance of the weldment [19].

Mechanical properties

The mechanical properties of FSW welded metal are superior to those of MIG welded metal (table 55).

Fractures usually occur at the edge of the friction zone, never inside it, most probably because of the strain hardening caused by the base of the tool.

The limit of elasticity is at least 10% higher in FSW welded metal than MIG welded.

Fatigue resistance

The limit of endurance of FSW welded metal is superior to that of a MIG weld [21] (figure 99 and table 56).

The limit of endurance of an FSW weld is always superior to that of a MIG welded joint, and this is true for all alloys. This is because FSW ensures a very good connection between the joined workpieces. There is no 'sticking' (i.e. lack of fusion). It goes without saying that this applies only when the FSW joint is free from imperfections.

Corrosion resistance

Investigations carried out so far have not indicated any particular sensitivity to corrosion by FSW welds. Their resistance to corrosion is at least equal to that of MIG or TIG welds.

ENGINE AND DRIVE SHAFT BEARER



15. STANDARDS

The main standards that govern the welding of aluminium are listed in table 57..

MAIN EUROPEAN STANDARDS FOR WELDING OF ALUMINIUM

Reference	Date	Subject
BS EN 1011-4	Dec 2000	Welding. Recommendations for welding of metallic materials. Part 4: Arc welding of aluminium and aluminium alloys.
NF A 89-310	April 1973	Aluminium et alliages d'aluminium - Soudage - Assemblages élémentaires types - Critères de choix.
NF A 87-010	April 1973	Aluminium et alliages d'aluminium - Soudage - Préparation des bords.
BS EN 288-4/A1	August 1997	Specification and approval of welding procedures for metallic materials. Welding procedure tests for the arc welding of aluminium and its alloys.
NF A 89-220	April 1973	Aluminium et alliages d'aluminium - Soudage - Classification et contrôle des joints soudés.
BS 8118		Structural use of aluminium. Part 2. Specifications for materials, workmanship and protection.
BS EN ISO 9692-3	Dec 2001	Welding and allied processes. Recommendations for joint preparation. Part 3: Metal inert gas welding and tungsten inert gas welding of aluminium and its alloys. (ISO 9692-3:2000).
BS EN 12584	June 1999	Imperfections in oxyfuel flame cuts, laser beam cuts and plasma cuts. Terminology.
BS EN 30042 ISO 10042	July 1994	Arc-welded joints in aluminium and its weldable alloys. Guidance on quality levels for imperfections.
BS EN ISO 13919-2	Dec 2001	Welding -- Electron and laser beam welded joints -- Guidance on quality levels for imperfections -- Part 2: Aluminium and its weldable alloys (ISO 13919-2:2001).
BS EN ISO 6520-1	Dec 1998	Welding and allied processes -- Classification of geometric imperfections in metallic materials -- Part 1: Fusion welding (ISO 6520-1:1998).
NF EN 83-100-1	Dec 1995	Construction d'ensembles mécano soudés. Techniques de soudage. Partie 1 – Généralités: Terminologie, Classes de qualité de soudure – Etendue des contrôles.
BS EN 12062	1998	Non-destructive examination of welds. General rules for metallic materials.
BS EN 970	May 1997	Non-destructive examination of fusion welds. Visual examination.
NF A 09-120	June 1984	Essais non destructifs. Principe généraux de l'examen par ressuage.

Reference	Date	Subject
BS EN 1289	August 1998	Non-destructive examination of welds. Penetrant testing of welds. Acceptance levels.
BS EN 1712	Nov 1997	Non-destructive examination of welds. Ultrasonic examination of welded joints. Acceptance levels.
BS EN 1713	Sept 1998	Non-destructive examination of welds. Ultrasonic examination. Characterization of indications in welds.
BS EN 1714	Oct 1997	Non-destructive examination of welded joints. Ultrasonic examination of welded joints.
BS EN 1712/A1	February2003	Non-destructive examination of welds. Ultrasonic examination of welded joints. Acceptance levels.
BS EN 1714/A1	February 2003	Non-destructive examination of welded joints. Ultrasonic examination of welded joints.
BS EN 444	April 1994	Non-destructive testing. General principles for radiographic examination of metallic materials by X- and gamma-rays.
BS EN 1435	Oct 1997	Non-destructive examination of welds. Radiographic examination of welded joints.
BS EN 12517	Sept 1998	Non-destructive examination of welds. Radiographic examination of welded joints. Acceptance levels.
BS EN 287-2	June 1992	Approval testing of welders for fusion welding. Aluminium and aluminium alloys.
BS EN 287-2/A1	August 1997	Approval testing of welders for fusion welding. Aluminium and aluminium alloys.
BS EN ISO 9956-10	Nov 1996	Specification and approval of welding procedures for metallic materials -- Part 10: Welding procedure specification for electron beam welding.
BS EN ISO 9956-11	Nov 1996	Specification and approval of welding procedures for metallic materials -- Part 11: Welding procedure specification for laser beam welding.
BS EN 12345	June 1999	Welding. Multilingual terms for welded joints with illustrations.
BS EN 1792	2003	Welding. Multilingual list of terms for welding and related processes.

Table 57

Bibliography

[1] "Soudure et chaudronnerie d'aluminium", *Revue de l'aluminium,* No. 99, March 1938, pp. 1128-1135.

[2] "Le soudage à l'arc des métaux légers avec électrode fusible enrobée", Charles Guinard, *Revue de l'aluminium,* No. 167, June 1950, pp. 237-244.

[3] "Die Fügetechniken des Aluminiums im Laufe der Jahrzehnte", G. Aichele, *Aluminium,* Vol. 75, pp. 743-753, 1999.

[4] "Construction of the All-Welded Twin-Screw Auxilliary Motor Yacht", J. G. Young, *British Welding Journal,* January 1955, pp. 1-18.

[5] "Nocivité des de soudage sur éprouvettes soudées MIG" D. Albert, C. Hantrais, M. Médiouni, M. Tricot, *Rapport Pechiney* CRV 3535, December 1994.

[6] "Repair yards show their versatility", *Speed at Sea,* April 1998.

[7] "Routine repairs provide annual returns", *Speed at Sea,* January 1999.

[8] "Aluminium skills are part of routine workload", *Speed at Sea,* October 2000.

[9] "Developments in welding techniques for aluminium alloys", J. D. Russel, C. J. Dawes, R. L. Jones, TWI, *Conference Southampton* 1996.

[10] "Improvements relating to friction welding", W M Thomas, E D Nicholas, J C Needham, MG Murch, P Temple Smith, CJ Dawes, (TWI), Patent GB 91 25978.8, International PCT/GB92/02203 and European Patent Specification 0 615 480 B1.

[11] "Application of Friction Stir Welding for manufacture of aluminium ferries", S. W. Kalle, E. D. Nicholas, P. M. Burling, TWI, *4th International Forum on Aluminium Ships,* New Orleans, May 2000.

[12] "*4th International Forum on Aluminium Ships",* New Orleans, May 2000

"European Shipbuilding in the 21th Century", London, December 2000.

"The Third International Forum on Aluminium Ships", Haugesund, May 1998.

"Lightweight Construction – Latest Developments", The Royal Institution of Naval Architects, London February 2000.

[13] "Studies extend Friction Stir Welding potential", *Speed at Sea,* October 1998, p. 45.

[14] "Friction Stir benefits include cost saving", P. Hynds, *Speed at Sea,* October 1999, p. 33.

[15] "Friction Stir Welding in aluminium alloys, preliminary microstructural assessment", P L Threadgill, *TWI Bulletin,* Vol. 28 (2), March 1997, pp. 30–33 .

[16] "*Friction Stir Welding – Weld properties and manufacturing techniques",* Proc INALCO-7, Cambridge April 1998, pp. 171–181.

[17] "Application of prefabricated Friction Stir Welding panels in catamaran building", O. T. Midling, J. S. Kväle, S. Oma, *4th International Forum on Aluminium Ships,* New Orleans, May 2000.

[18] "Exploiting friction stir welding in explosevely-formed aluminium boat hull construction", I. Henderson, *Joints in aluminium,* INALCO 98, 1998, pp. 261-267.

[19] "Friction Stir Welding – The state of the art", P. L. Threadgill; *Report TWI* 7417.01/99/1012

[20] *Pechiney Report* CRV February 1999.

[21] "Friction Stir Welding aluminium alloy 5083, Increased welding speed", C. J. Dawes, E. J. R. Spurgin, D. G. Staines, *Report TWI* 7735.1/98/993.2.



MARINA AT TRINITÉ-SUR-MER

Chapter 7
ALUMINIUM BONDING AND SPECIAL ASSEMBLIES

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7. ALUMINIUM BONDING

ARC WELDING is the method of fabrication most commonly used in aluminium sheet metal working in general and in shipbuilding in particular.

However there are other methods of joining which complement arc welding, such as screw and bolt fastenings, riveting and adhesive bonding. Since these methods do not require any application of heat, they have the advantage over welding of not affecting the mechanical properties of the metal or introducing distortion.

They are essential when different materials have to be joined together, e.g. steel to aluminium (or vice versa) or polymers (or their composites) to aluminium. These "mixed" joints are found in most of the internal equipment of a ship such as the propulsion system, auxiliaries, pipework, ceilings, door and window frames etc.

Since the early Seventies, the welding of aluminium alloy structures to steel structures has been made easier by the use of aluminium/steel transition joints. One of the most common instances is that of a ship with a superstructure made of aluminium alloy and a steel hull.

This chapter deals with:

- screw and bolt fastenings,
- riveting: machine rivets,
- adhesive bonding,
- transition joint.

1. SCREW AND BOLT FASTENINGS

Unlike welding, bolting creates a joint that can be 'undone' and is used extensively to make mixed joints, e.g. steel/aluminium. This type of joint is therefore very common in connections between the structure of a ship and much of its equipment, such as engines, auxiliaries, pipework and ventilation ducts.

FELICITA WEST



AND SPECIAL ASSEMBLIES

1.1 Conventional screw fastenings

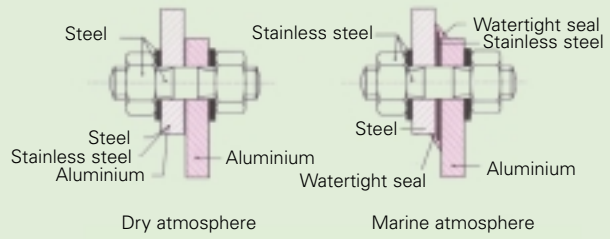
The choice of fastening will depend on mechanical considerations following a calculation of the load on the joint. Given the marine environment, increasing use is made of stainless steel fastenings that have the advantage of not rusting and so preserve their original appearance.

When the joint is subjected to extreme variations of temperature, it will be necessary to fit washers to absorb the different rates of expansion between steels and aluminium alloys.

Allowance must also be made for the risk of bimetallic corrosion of the aluminium in contact with the fastenings if they are made from mild, galvanised or stainless steel.

Bearing in mind what is said about galvanic corrosion in Chapter 10, two cases in point must be considered:

PROTECTION OF BOLTED JOINTS



From TALAT de EAA

Figure 100

■ the joint is submerged (whether permanently or intermittently) in sea water. Here, we cannot use screw fastenings made from mild or stainless steel without protecting the contacts:
- by placing insulation between the screw and the aluminium structure (figure 100),
- by cathodic protection if they are below the waterline (1).

This risk of galvanic corrosion can also be avoided by using aluminium alloy screws which are anodised to a depth of 15 microns and sealed with bichromate in 7075 T73 or 6108 T8 – their mechanical properties are shown below in table 58, p. 118. Aluminium alloy screws are 50% lighter than steel screws of equal diameter.

■ the joint is out of water: in zones that are at worst damp as opposed to actually wet, frequent use is made of screw fastenings in stainless steel or galvanised steel.

(1) Cf. Chapter 11.

FELICITA WEST



Despite the difference in potential between steels and aluminium alloys, there is virtually no risk of bimetallic corrosion to aluminium or its alloys aside from a very superficial attack limited to the contact area.

Experience shows that screws made from mild (or stainless) steel that have been screwed into aluminium are often difficult and even impossible to remove when moisture has been allowed to penetrate the thread. This is because of the bimetallic corrosion of the aluminium which, though very superficial, is enough for alumina to form and seize the steel screw.

The simplest way of avoiding this is to apply a viscous grease to the hole and the screw to create a hydrophobic environment that will prevent the ingress of moisture.

THREAD INSERTS

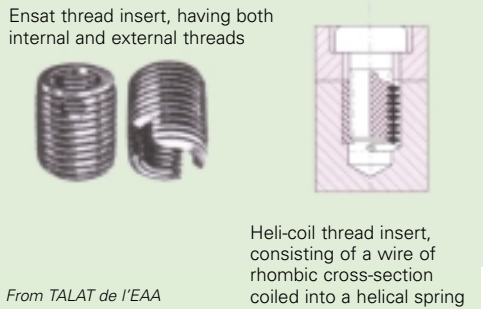


Figure 101

1.2 Thread inserts

Experience shows that threads in aluminium do not stand up well to frequent dismantling, and here the answer is to fit thread inserts made of steel into the aluminium alloy component (figure 101).
Here again, moisture must not be allowed to penetrate the thread and have the adverse effects described above.

2. MACHINE RIVETS

Originally developed for aerospace applications, machine riveting is now in widespread use in many sectors of industry, including electronics, domestic appliances and vehicles.

In shipbuilding, this method of joining is used for fixing pipe supports, suspended ceilings, interior trim (salons, lobbies etc.) and furniture.

Manufacturers of this type of rivet are now offering very reliable systems suitable for use in a wide variety of applications, and machine riveting does not require skilled operatives.

Machine riveting has a number of decisive advantages:

- Rapid fitting: Machine riveting can be very fast with the use of pneumatic or hydraulic tools. The actual rate of riveting will of course depend on the nature and configuration of the joints.
- Ease of control: Controlling the quality of a joint is made easier by the fact that the clamping force is always guaranteed and optimum because it is less than the force needed to snap the rivet stem.
- Appearance and impermeability: With some types of rivet a plastic cap can be clipped over the rivet head to enhance the appearance of the joint. This also helps to improve the structure's impermeability to air, dust and splash water.
- Mixed joints are possible: aluminium/steel, aluminium/polymer, aluminium/composite etc.

There are two families of machine rivets:

- clinch studs (or structural rivets) create the same type of connection as a conventional bolt, although they cannot be undone. Clinch bolts require both sides of the joint to be accessible,
- blind rivets are used when only one side of the joint is accessible. They too create a permanent fastening and cannot be undone.

The components are gripped:
- either by clinching a ring onto the stem of the rivet to preload it,
- or by upsetting the body of the rivet by means of the stem head to form a "counter head" on the side opposite the rivet entry.

These operations are carried out with manual riveting tool or with pneumatic or hydraulic rivet guns which are usually sold by the rivet manufacturers.

These fastenings cannot be undone, which ensures the safety of the joint but also complicates repair work. However repairs are rarely needed thanks to the mechanical performance of these rivets. This type of connection is also chosen for its permanence and "finality".

MECHANICAL PROPERTIES OF ALUMINIUM ALLOY SCREWS

Alloy	Rm (MPa)	$Rp_{0,2}$ (MPa)	A %
6108 T6	300	260	8
7075 T73	550	470	10
Steel E24	410	240	24
Stainless steel	660	300	54

Table 58

If a repair is needed, the rivets will have to be removed mechanically, e.g. by extracting the head of clinch studs, pulling out with pliers etc., and then drilling out the fixing holes to a slightly larger diameter.

2.1 Clinch studs

The components are gripped together by clinching a ring onto the stem of the stud (figure 102).

A clinch stud is fitted in a number of steps:

- the stud is inserted in the fixing hole specially drilled in the components, then the ring is placed on the protruding stem from the opposite end,
- the nose of the tool is positioned up against the ring on the stem of the rivet,
- the pull exerted by the tool squeezes the parts together, clinching the ring on the throat of the stem and leaving a permanent preload,
- the stem above the ring is then snapped off.

Because a high axial pressure is applied to the joint before the ring is clinched, no clearance is left between the joined parts and so excellent impermeability is achieved at the same time.

These rivets have good resistance to shear and vibration.

They are available in steel or aluminium alloy 7075 and 6061. For marine applications, rivets in 7075 must be supplied anodised to at least 15 microns and sealed with a bichromate.

2.2 Blind rivets

Also known as "breakstem rivets", they are used to make joints where access is only possible on one side. The parts are gripped by compressing the body of the rivet using a stem that snaps off in the head of the rivet and which may or may not remain captive (figure 103). When the stem is captive they are called "structural rivets".

These rivets can withstand significant mechanical stresses and are unaffected by vibration.

These rivets are available in steel or aluminium alloy 7075. For marine applications, rivets in 7075 must be supplied anodised to at least 15 microns and sealed with a bichromate.

2.3 Threaded inserts

Also called "lost nuts" or "blind nuts", these are threaded nuts mounted "blind" on their support, usually a sheet or shape.

Clinching is achieved by exerting tension on a threaded stem screwed into the threaded insert. This compresses the smooth section to form a 'bulb' that tightly grips the parts together (figure 104). The heads may be flat or countersunk.

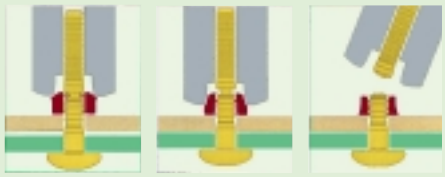
These fasteners offer significant potential by acting as lost nuts to make strong and reliable screw connections between relatively thin structures such as partitions.

2.4 Repetition fasteners

So called because they are fixed blind (by radial expansion of the stem) with a re-usable punch to which the rivets are fed from a loader (figure 105, p. 119).

These rivets have moderate mechanical strength and are only used for joints under light loads. They can be placed by continuously fed automatic riveters.

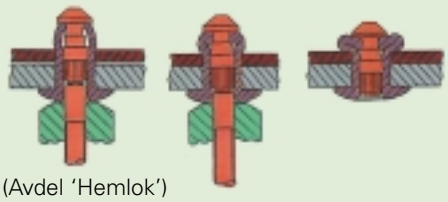
CLINCH STUD



(Avdel 'Avdelok')

Figure 102

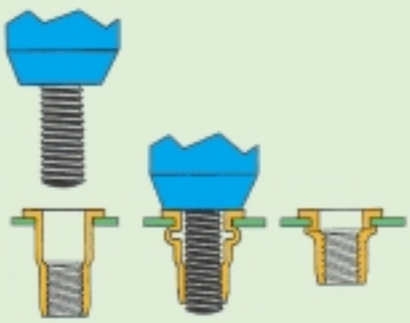
BLIND RIVET



(Avdel 'Hemlok')

Figure 103

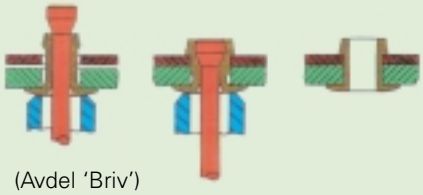
THREAD INSERT



(Avdel 'Eurosert')

Figure 104

REPETITION RIVET



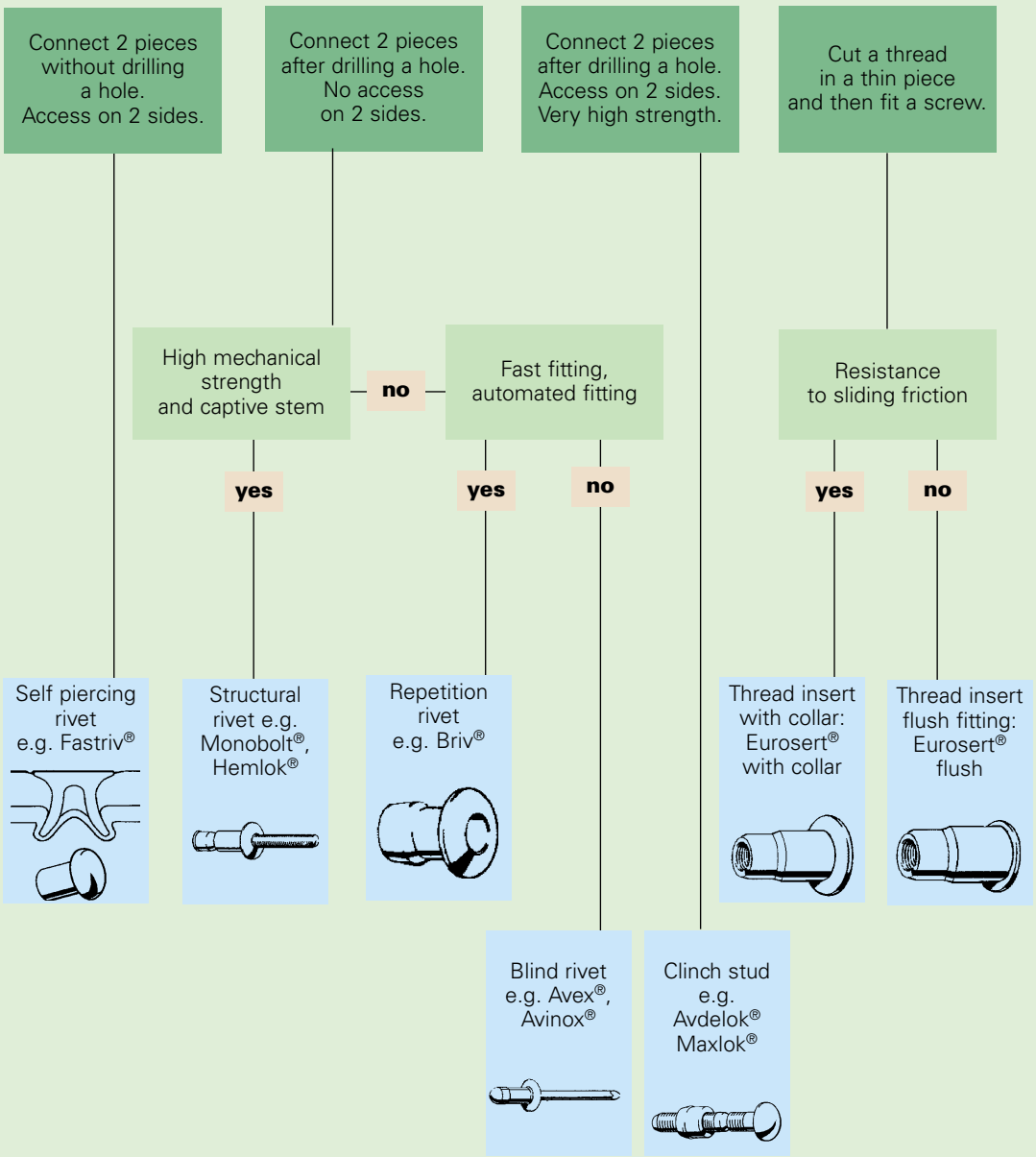
(Avdel 'Briv')

Figure 105

RIVET SELECTION CRITERIA (AVDEL DOCUMENT)

SELECTION GUIDE

YOU WANT TO



From Avdel

Figure 107

2.5 Self-piercing rivets

This is a hybrid technique that combines riveting and clinching, and requires access on both sides of the joint (figure 106).

It can be automated. The components to be joined together are not pre-drilled, and a tight seal is guaranteed as the rivet does not pierce the final layer of material.

2.6 Rivet selection criteria

The choice of rivet type depends on a number of criteria (figure 107):

- accessibility on 1 or 2 sides,
- prior drilling,
- intensity of stress on the joint, etc.

2.7 Important note

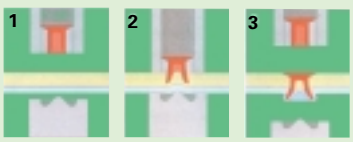
When using machine rivets made of mild or stainless steel it is essential to protect the contact zone if this will be permanently or intermittently submerged in (sea) water.

The risk of bimetallic corrosion of the aluminium can be prevented by applying a sealing compound to the contact areas between the plates and to the rivets to prevent ingress of water along the stem.

Sealing compounds must satisfy a number of requirements:

- they must be inert to aluminium alloys,
- the coating must be as thin as possible to minimise the adverse effect of the joint on the strength of the structure,
- they must have good "squeezability" around the stem of the rivet to permit close contact between the plates.

SELF-PIERCING RIVET



(Avdel 'FastRiv')

1) The tool holds the pieces between the punch and the die.
2) The FastRiv pierces the first piece and expands radially (3) in the second piece but without piercing it.

Figure 106

HYDROJET NOZZLE



3. BONDING

Industrial bonding has undergone significant development since 1960, initially in aerospace applications with honeycomb structures. In automotive, the bonding of windscreens to car bodies began in 1963 and has since spread to all types of motor vehicles. Today, all the major industries – automotive, domestic appliances, office equipment, electronics etc. – use adhesive bonding as an assembly method [1].

In marine construction, the uses of structural bonding are still limited and concern mainly hybrid joints of aluminium with glass and composites [2]. The windows of high speed ships built in Australia for example are bonded, the effect of which is to increase the rigidity of aluminium alloy superstructures [3]. The bonding of floors made of aluminium tread plate in the engine room simplifies installation and reduces the transmission of vibrations.

Bonding is used more widely in yacht building, e.g. to attach teak planking to the roof of the deckhouse, whether made of polymer or aluminium, to mount certain items of deck equipment (chain plates, winches, capstans etc.).

Ongoing technological research is aimed at significantly increasing the part played by bonding in shipbuilding, especially in homogenous aluminium/aluminium joints and mixed aluminium/steel and aluminium/composite joints [4].

3.1 Advantages of bonding

The use of bonding in shipbuilding is set to grow given the advantages it offers, particularly its ability to simplify assembly.

Compared with other joining techniques, bonding can be used to:
- connect materials of different types: aluminium to steel, aluminium to composites etc. Because adhesives also insulate, they prevent the bimetallic corrosion of aluminium in contact with the other materials in the joint,
- compensate differences of expansion in a mixed joint between different materials,
- join age hardening aluminium alloys in the 2000 and 7000 series that cannot be arc welded (2),
- enhance stress distribution (continuous joint),
- absorb vibrations, the more so the thicker the joint,
- ensure built-in impermeability,
- join sub-assemblies that are in an advanced state of completion (painting, various decorations etc.); this would be impossible with welding as the heat would damage the finishes,
- increase the tolerance of bonded joints compared with other jointing methods.

The use of bonding instead of welding avoids heating and therefore eliminates the heat affected zone, thus bonding preserves the initial mechanical properties of aluminium.

(2) Provided of course they are specially protected for use in marine environments. Stoving the adhesive (for several minutes at temperatures below 200°C) does not affect their mechanical properties.

This has two important implications:
- the thickness of components can be reduced to further save weight in bonded sub-assemblies,
- it eliminates distortion and so saves time.

3.2 Designing a bonded joint

The success of a bonded joint depends on a number of factors:
- a knowledge of the service conditions of the joints (in particular, specifications must indicate the environment),
- engineers must think 'bonding' from the design stage,
- careful surface preparation,
- correct choice of adhesive – it must suit the service conditions,
- testing to destruction before fabrication to validate the choice of adhesive, and also during fabrication if NDT testing is not possible for reasons of cost, for example,
- fabrication should be closely controlled and automated as far as possible.

There are four types of stress to which a bonded joint can be exposed (figure 108):
- shear,
- tension,
- cleaving and
- peeling.

Bonded joints do not resist well to peeling or cleaving, so should be designed to work in shear and tension.

Joints should be adequately lapped (flat geometry) or sleeved, and the influence of the materials and the thickness of the adhesive layer must also be taken into account.

To compensate for the relatively poor mechanical properties of the bonded joint, the joint's areas should be as large as possible in the usual configurations (figure 109).

The reader will find design rules for bonded joints in the specialist literature [5]. Eurocode 9 deals with bonded joints in Chapter 6-8 "Connections made by adhesive" (3).

(3) Eurocode 9. Design of Aluminium Structures. Part 1 – 1 General rules and rules for buildings.

3.3 Choice of adhesive

Although adhesives are usually classified by chemical families, their properties – especially chemical – can vary widely from one product to another in the same family.

Cold-curing adhesives are particularly suitable for shipbuilding applications owing to the large areas that have to be bonded.

STRESS MODES OF BONDED JOINTS

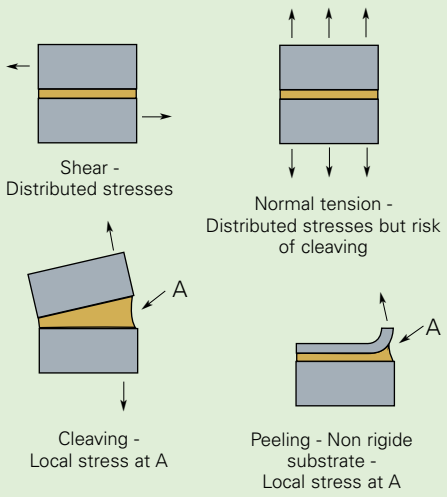
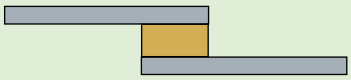
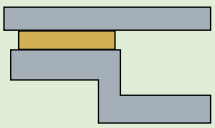


Figure 108

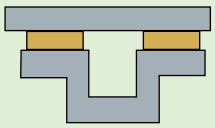
CONFIGURATION OF BONDED JOINTS



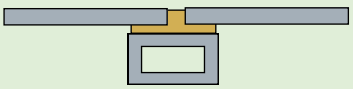
Simple lap
Configuration usually used to join thin materials as it is easy to produce and very strong.



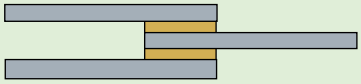
Z section
Used to stiffen large pieces.



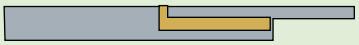
Trapezoïd section
Used to stiffen and join composite materials.



Splice joint
Often used when the surface must remain smooth, with no special preparation.



U section
Often used to increase the bonding area and reduce peeling stresses.



Edge joint
Used to pour produce a flush surface when joining two different materials, e.g. glass and a frame.

Source: Sika Industry

Figure 109

The following adhesives are worth noting in this category:

- one-component polyurethanes are particularly suitable for marine applications (impermeability); some are formulated as semi-structural adhesives. They are used widely for bonding yacht decks. Joints can be several millimetres thick,

- two-component polyurethanes are highly suitable for sandwich panels. They require the use of a primer and set within a few days at ambient temperature. The thickness of the joint sometimes exceeds one millimetre. They are inexpensive.

- two-component epoxies are highly recommended for structural bonds and go off within a few hours at ambient temperature. The ideal bonded joint has a thickness of 0.1 to 0.2 mm,

- modified acrylics go off within a few minutes. Their use is growing rapidly despite their high cost.

Other types of adhesives may also be used, e.g.:

- anaerobic adhesives for thread locking,
- one-component silicone for resolving problems of water tightness,
- one-component epoxies for joints subject to high stress levels and likely to be stoved.

Each of these families includes adhesives specially designed for marine environments.

3.4 Surface preparation

Good surface preparation is vital to ensure the quality and long life of the bonded joint [6].

Two typical procedures for interior bonds are given below:

- First procedure:

– chemical degreasing, either alkaline or acid (preferred), or using non chlorinated organic solvents like Evopred made by SID (4),
– chemical conversion – phosphoric or without chromates,
– apply a primer, e.g. an epoxy.

- Second procedure:

– degrease (as above),
– apply a wash primer.

Bonding should be carried out as soon as possible after surface preparation, but the interval can be as long as several days provided the components are stored in a clean, dry room.

There are also pre-coated sheets in which the front face is painted and the back is ready coated with a special epoxy bonding primer. These sheets are ideal for the fabrication of sandwich panels.

3.5 Industrial fabrication

As far as possible bonding should be done in a well ventilated and dust-free workshop.

It is essential to work carefully and methodically:

- wearing white gloves and safety glasses,
- in strict compliance with the adhesive manufacturer's directions, including storage instructions, e.g. time and temperature.

At each stage of production there must be proper controls of parameters such as resin/hardener ratios, duration and pressure of component fitup during adhesive curing, curing temperature etc.

Standard specimens should be tested to destruction (5) with:

- tension/shear tests with accelerated 'wet pad' ageing,
- or peel tests,

to monitor any anomalies.

3.6 Repair of bonded joints

When structures are required to last for several decades, there comes a time when they may have to be repaired because of damage or for a modification.

Joints made with rigid adhesives applied as a film are very difficult to dismantle. Joints made with flexible adhesives are easy to repair or replace provided they are at least 2 millimetres thick.

Under these conditions the joint can be easily dismantled using a metal wire or vibrating knife and without damaging the substrate.

It is not always necessary to remove the traces of the old adhesive. When treated with a suitable "activator" (which improves the adhesion of the substrate), they can form an excellent substrate for fresh adhesive of the same type.

3.7 Durability of bonded joints

The durability of bonded joints depends on factors such as:

- the chemical composition of the adhesives,
- the surface treatment of the aluminium,
- service conditions: stresses, temperature, humidity etc.

The ageing of bonded joints may be accompanied by:

- a loss of mechanical properties,
- creep under stress.

The loss of mechanical properties is due either to the transformation of the surface of the metal (a modification of the oxide layer) or to changes in the properties of the adhesive (softening, hydrolysis etc.).

Water does most damage to bonded joints by attacking the adhesive or causing surface corrosion of the metal (6).

Adhesive bonding has been used in shipbuilding for over 15 years now but our knowledge of the ageing process of bonded joints is still fragmentary.

Over 12 years of experience with marine environments indicates that the two-component epoxies display very good strength provided the joints are well designed and their surfaces are properly prepared.

---

(4) SID: Société Industrielle de Diffusion F38140 IZEAUX.

(5) According to standard EN 1465 "Adhesives - Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies".

(6) Which accounts for the importance of surface treating aluminium to reinforce the properties of the natural oxide film.

Table 59 lists some results for creep obtained from standard specimens (according to AFNOR NF T 76-107 except for thickness) made from 5754 and loaded to 25% of their initial ultimate tensile, exposed to a marine environment.

On alloys belonging to the 5000 and 6000 series, the fatigue strength of joints bonded with one-part epoxy adhesives on samples that have been alkaline degreased and then oiled is better than that of clinched or spot welded joints (figure 110).

Like all polymers, bonded joints are sensitive to the action of ultra violet (UV) rays which affect their mechanical properties. With bonded glazing, the bonded area must be protected by an opaque strip of sufficient size (figure 111).

3.8 Note

On board ships, bonded joints must comply with fire safety regulations (which in turn depend on the class of ship) [7].

Adhesives are organic compounds so could represent a "fire load" because of their organic nature. The very small amount of adhesive reduces this risk however.

Experience shows that it is possible to meet fire safety regulations with bonding assisted by riveting (or spot welding). Under these conditions, bonded joints retain their mechanical strength during an increase in temperature. At the same time, the integrity of structures must be ensured by adequate insulation that complies with fire safety regulations for ships.

(7) Fatigue tests carried out in 1995 as part of the European Brite 5656 project.

FATIGUE STRENGTH OF BONDED JOINTS (7)

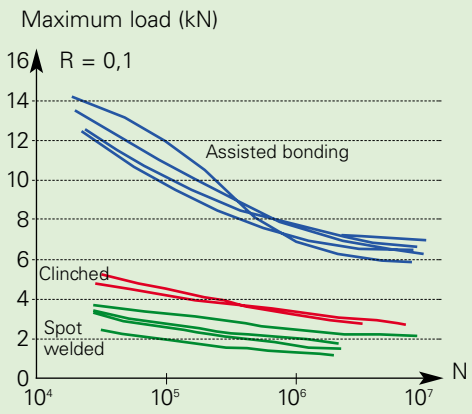
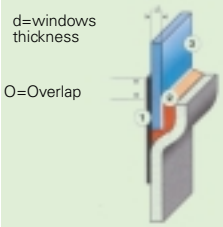


Figure 110

UV PROTECTION OF BONDED JOINTS

Minimum recommendations for protecting the joint from ultraviolet rays



$O = d\sqrt{1/(n_{12}^2 - 1)}$

n_{12} = Refractive index of glass panel

Sika Rule
0 = 2 x d
Example: if d = 8 mm, the overlap must be at least 16 mm

1 UV Protection
2 Sikaflex®-296 or Sikaflex®-265
3 Window

From Sika industry

Figure 111

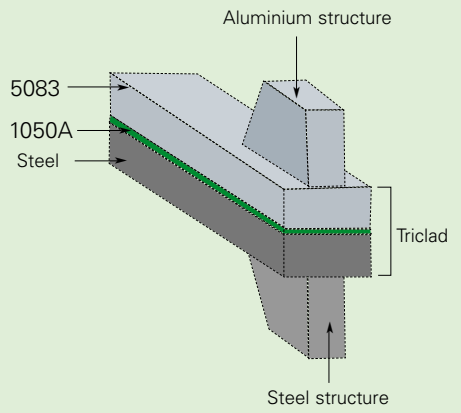
CREEP OF BONDED JOINTS ON 5754

Adhesive	Surface Preparation	Initial Load (daN)	Life in Marine Environment
One-component epoxy	MEK + Scotch Brite + MEK	147	62 days
	Phosphor anodising	161	3 specimens NR à 12,5 years 2 specimens NR à 8,5 years
Two-component flexible epoxy	Phosphor anodising	258	1 specimen NR à 12,5 years 4 specimens NR à 7 years
One-component flexible epoxy	Phosphor anodising	210	3 specimens NR à 12,5 years 2 specimens NR à 2,5 years
Reinforced acrylic	MEK + Scotch Brite + MEK	230	220 days
	Phosphor anodising	183	1 specimen NR à 12,5 years 3 specimens NR à 2,5 years

MEK: Degreasing with methyl ethyl ketone.
NR: Test specimens not broken after XX days.

Table 59

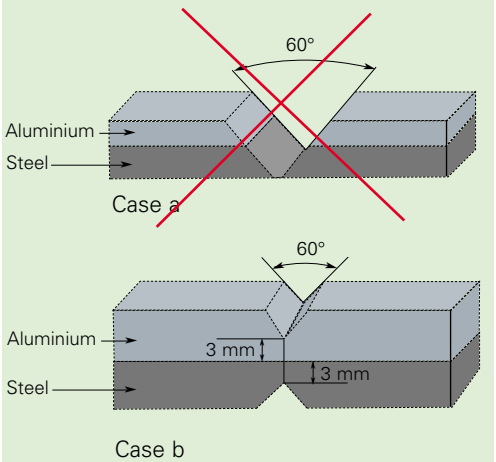
TRICLAD TRANSITION JOINT



From DMC Nobleclad

Figure 112

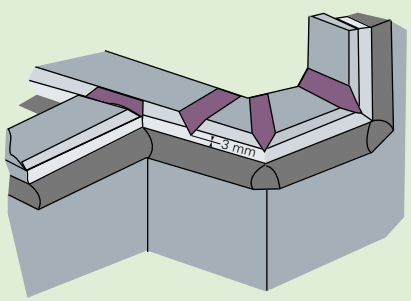
BUTT WELD WITH TRICLAD



From DMC Nobleclad

Figure 113

SQUARE AND FILLET WELDS WITH TRICLAD



From DMC Nobleclad

Figure 114

4. TRANSITION JOINTS

Introduced at the beginning of the Seventies, the transition joint is a two-metal strip used to arc weld dissimilar metals and alloys, especially when they cannot be joined together by any conventional welding process (8).

A transition joint suitable for connecting aluminium and steel can therefore be used to MIG (or TIG) weld aluminium alloy structures to steel structures on the deck of a ship or offshore platform, for example.

4.1 Parts of a transition joint

The "TRICLAD" transition joint comprises a strip of carbon steel and a strip of aluminium. The strip of aluminium is actually 2 superimposed layers, with a bottom layer of 1050 alloy in contact with the steel and an upper layer in 5083 alloy (figure 112). The three layers (1 steel, 2 aluminium) are joined by the controlled explosion of an explosive charge – explosion cladding.

Unlike the aluminium/steel hybrid joint complexes made by hot co-rolling, there are no intermetallics in the connection zone between the aluminium and the steel of the TRICLAD.

The explosion is followed by very rapid cooling (lasting approx. 1 microsecond) which prevents the formation of these intermetallics that would otherwise affect the quality of the joint between the aluminium and the steel. It is considered that "micro-fusion" takes place at the interface between the two metals over a thickness of 10 to 50 microns.

4.2 Properties of transition joints

The thickness of the components of standard transition joints, calculated not to exceed 300°C at the aluminium/steel interface (under normal welding conditions), is given in table 60.

The mechanical properties of TRICLAD are shown in table 61. On test specimens taken square to the plane of the aluminium/steel joint, 'necking' always occurs in the aluminium part beyond the connection zone between the two metals.

4.3 Conditions of use

The width of transition joints must be 4 times the thickness of welded sheets in 5083 alloy. Standard products are 25 mm wide which allows sheet up to 6 mm thick to be welded.

A number of strict rules must be followed when using transition joints to avoid irreparable damage to the connection:

- the temperature at the interface of the joint must be limited to 300°C in both metals to prevent the formation of intermetallics between the aluminium and the steel. In practice, it is advisable to do a test under normal welding conditions while checking the temperature at the interface using a thermosensitive pencil or a thermocouple,
- make chamfers in each of the metals for butt welds (figure 113a) but *avoid crossing the interface* (figure 113b) as this can damage the joint,

(8) For metallurgical reasons, the fusion of the metals creates intermetallic compounds that weaken the weld seam.

THICKNESS OF TRICLAD TRANSITION JOINTS

Type of Joint	Thickness (mm)					
	5083	1050A	3003	Steel	Titanium	Stainless Steel
5083/1050A/Steel	6	9		25		
3003/Titanium/ Stainless steel			10-12		1,50	20

Table 60

MECHANICAL PROPERTIES OF TRICLAD TRANSITION JOINTS

	5083/1050A/Steel		3003/Titanium/Stain-less Steel	
	Guaranteed (*)	Typical (**)	Guaranteed (*)	Typical (**)
Rm (MPa)	75	120 - 160	100	170 -190
Shear strength (***)	55	90 - 130		240

(*) According to MIL-J-24445A. (**) Mean figures from DMC Nobelclad. (***) At the steel interface. Table 61

- make chamfers in the strip for square joints, as shown in figure 114,
- never weld on the side face of the transition joint as this can cause irreparable damage.

Bibliography

[1] Le "collage industriel", Michel Rachline, Sika Industry, Editions Viloeco, 2001.

[1] "Blending aluminium and composites", Doug Woodyear, *Speed at Sea*, Vol 2, 1996.

[3] "Elastic adhesives used in the construction of high speed ferries", A. Van Geelen, Sika Australia Pty Ltd, *13th Fast Ferry International Conference,* February 1997, Singapore.

[4] "Research investigates bonding techniques", Paul Hynds, *Speed at Sea,* February 2001, p 47.

[5] "Elastic bonding. The basic principles of adhesive technology and a guide to its cost effective use in industry", Sika Industry, 1998, Verlag Moderne Industrie ISBN 3-478-98203-3.

[6] "Adhesive bonding of aluminium for marine applications", G. E. Judd, A. Madisson, *Conference Ausmarine 1996,* p 129-136.

[7] "Structural adhesive bonding of aluminium in marine applications". Jan R. Weitzenöck & Brian Hyman, Andreas T. Echtermeyer, Det Norske Veritas, *The Third International Forum on Aluminium Ships,* Haugesund, Norway, May 1998.

OGIA HIGH-SPEED PASSENGER FERRY





AUSSIE RULES

Chapter 8
ELECTRICAL SYSTEMS

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8. ELECTRICAL

AS WORK BOATS and passengers ships have increased in both size and complexity, the need for their on-board electrical systems to deliver more power has grown. This power is supplied as alternating current (a.c.) at voltage levels of 110, 220 and even 440 V, while certain items of equipment may also require a direct current (d.c.) supply.

Electrical systems for yachts and other pleasure craft are mostly d.c. systems supplied by batteries that are regularly charged by a dynamo connected to the auxiliary engine. The growing demand for comfort in these vessels has led to the on-board installation of standard domestic appliances (stoves, refrigerators) and air conditioning. These appliances consume a lot of 220 V a.c. power that is generated by an alternator driven by a diesel engine.

There is no reason to treat the electrical system on a boat made from aluminium any differently from that of a craft made from steel. In both cases the hulls are metal and so subject to the same risks of corrosion in the event of the flow (or leak) of current across the hull.

A.c. or d.c. current must not be allowed to flow continuously through a steel or aluminium hull that is in permanent contact with sea water.

The effect of the flow of current is to polarise the hull (as the + or – pole) and so cause the dissolution of the most negatively electrical parts of the metal in contact with water (1).

If the hull is painted, then the paint will gradually peel and become blistered.

Electrical systems on board ships are governed by international standards issued by the IEC (2) or the CEN (3), as well as by the regulations of classification societies.

All of these standards and regulations are designed to ensure the safety of personnel and the continuity of the electrical supply on board (on which the safety of the vessel depends) which are absolute priorities. They in no way affect the resistance to corrosion of the metal parts of the ship that are in contact with water.

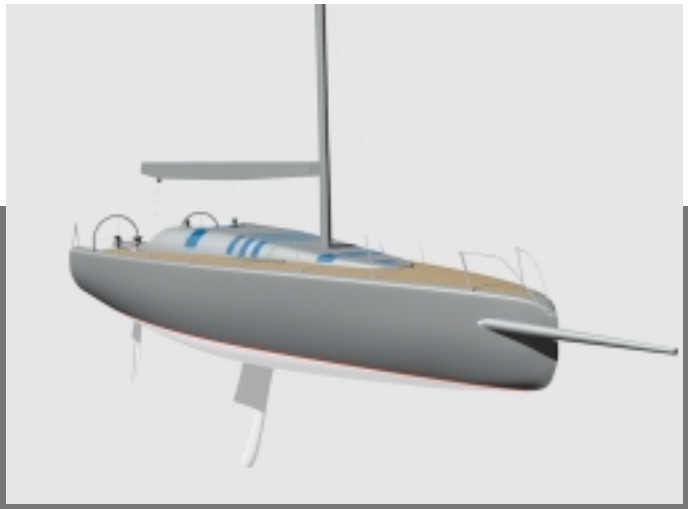
The sole aim of the recommendations that follow is to restate a number of elementary rules that, if carefully applied, will avoid the risks of corrosion to an aluminium hull. They do not contradict the standards or regulations, and most are either stated or implied in the recommendations.

(1) The anodic parts (+ pole) of the hull will dissolve, while on the cathodic areas H+ ions will be reduced to gaseous hydrogen with local alkalisation (excess of OH- ions) and attack the aluminium.

(2) International Electrotechnical Commission: Electrical installations in ships. International standard IEC 92-101.

(3) European Committee for Standardization:
Small craft – Electrical systems – Extra-low-voltage d.c. installations. Standard NF EN ISO 10133. Small craft – Electrical systems – Alternating current installations. Standard EN ISO 13297.

SLEEKER SAILING BOAT PROJECT



SYSTEMS

Current will never flow in the structures or hull of a ship provided its electrical system is installed properly in accordance with the usual codes of practice, standards and regulations governing shipbuilding and normal supervision (4), except of course in the event of an insulation fault which will be quickly identified and remedied provided regular maintenance is carried out and/or protective devices are set to the required level.

(4) In particular the monitoring of d.c. installations supplied by batteries during service and wintering.

1. GENERAL RULES

There are three rules which an electrical installation in a ship with an aluminium hull must obey:

1.1 Rule One: The hull is the earth (or ground)

The entire structure must be earthed to ensure the safety of persons (this is essential and mandatory when the supply voltage exceeds 55 V d.c. or a.c.) and the proper operation of the electrical and electronic systems. This earth is provided by the wet surface of the hull in contact with sea water (5), and is the reference potential of the system (the "earth").

Each of the earthing circuits:
- of the d.c. system, and
- of the a.c. system

must be connected to a single terminal sited in a junction box located in a dry place. The earthing circuits must be made using screened cable.

The connection to the hull is made by arc welding the aluminium conductor to a clean, unpainted area to ensure good electrical continuity. If the earthing system is made with copper cable, then the connection to the hull is made using a "bimetallic" aluminium/copper connector.

(5) Or fresh water in the case of craft used on rivers or lakes.

VICTORY LANE



1.2 Rule Two: The hull must be equipotentially bonded to all the metal structures of the electrical appliances

All the casings and enclosures of electrical units (motors, domestic appliances etc.) must be electrically connected to the hull.

There are two reasons for this:
- safety of personnel, when the power supply exceeds 55 V d.c. or a.c., and
- the operation of the electrical equipment.

In practice, equipotential bonds should be made as near as possible to the electrical items and be kept as short as possible, using cables or braids of appropriate section connected directly to the hull.

These connections must be positioned above any possible accumulation of water, as recommended by the standards and regulations.

Aluminium alloy superstructures on a steel hull

If by design, aluminium alloy superstructures on a steel ship are isolated from the hull, then electrical continuity must be ensured by conductors that are easy to inspect.

The propulsion system

Shipbuilders often install engine bearers, transmission shaft supports etc. on metal/rubber buffers or elastomer baseplates in order to absorb vibration (6).

Only the holding-down bolts will ensure electrical continuity between the engine and the hull (unless they are insulated by plastic sleeves), but this contact is not always perfect given the clearance between bolt and thread and the presence of substances such as oil, diesel etc.

While this arrangement is sufficient for protecting the aluminium from possible risks of bimetallic corrosion and reducing the intrusion of noise and vibration, the propulsion system must be equipotentially bonded to the hull for at least two reasons:
- fire safety: if the starter motor of the internal combustion engine is not "bipolar", then if it short-circuits the metal fittings on diesel or petrol supply pipes will act as a conductor for the short-circuit current and the resulting heat may be enough to ignite the fuel.
- the normal operation of the cathodic protection (7).

The metal casing of the engine must therefore be connected to the earthing system or aluminium support by means of a flexible cable.

1.3 Rule Three: The hull must never be used as an active conductor

In other words, the hull must not be used as a current return in the way that the body of a car is used.

This means that:
- in d.c. systems there must be two screened supply cables, one per pole,
- in a.c. systems there must be one screened conductor per phase and one for neutral (if distributed).

Given the aggressive nature (due to the presence of salt) of the marine environment and its inherent moisture, it is important to select equipment suitable for use in severe conditions. Particular care should be taken with connections which should have a level of IP protection that complies with the relevant standards and regulations.

Preference should also be given to engines whose electrical loads, such as starter motors and ignition, are bipolar (with return cable).

(6) This arrangement can also be used to prevent possible bimetallic corrosion of the supports: floor plates, aluminium shapes in contact with baseplates made of cast iron, steel, in the presence of water.

(7) Cf. Chapter 11.

2. DIRECT CURRENT INSTALLATION

This is the sole source of power on board most pleasure craft.

2.1 Batteries

Batteries are best accommodated in a dry, well ventilated place, usually a battery box lined on the inside with an acid-proof insulating material.

This precaution is essential both to avoid stray currents in the event of an electrolyte leak and to prevent the surrounding metal from being attacked by battery acid.

It is always advisable to disconnect both battery terminals when pleasure craft are wintered or during prolonged periods of inactivity.

2.2 Earthing

If one of the battery terminals has to be earthed then it should be the (–) pole (negative).

2.3 Insulation testing

Regular testing of the insulation of d.c. systems is highly advisable, and a simple setup (figure 115) will enable this check to be performed (8).

INSULATION TESTING

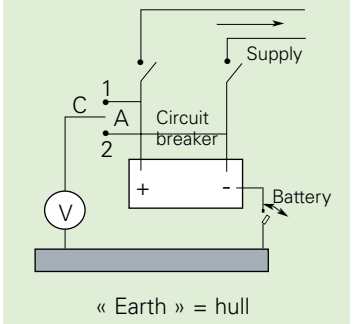


Figure 115

In normal operation the earthing strip is closed, switch C is off and the circuit breaker is closed. Routine testing is carried out as follows:

- open earthing strip,
- circuit breaker closed,
- switch to position 2 – an insulation fault in the negative circuit will cause the voltmeter to deflect,
- switch to position 1 – an insulation fault in the positive circuit will cause the voltmeter to deflect.

(8) It is although possible to use the conventional setup with indicator lamps instead of a voltmeter.

3. ALTERNATING CURRENT INSTALLATION

A.c. systems are used when high electrical power is required.

3.1 Neutral

If the neutral is not distributed and must be connected to earth (the hull), this should be done across a high impedance to limit the intensity of any fault currents.

3.2 Insulation testing

This should be done by a suitable instrument that continuously monitors the insulation of the d.c. system, in particular by calibrated circuit breakers (e.g. 35 mA).

3.3 Quayside supply

Ships often "plug in" to the on-shore mains supply when in port. The two systems, i.e. the shore supply and the ship-board system, must be separate. If they are not, then the aluminium hull and the submerged steel parts of the dock such as sheet piles, concrete reinforcement etc. will form the two poles of a galvanic cell and the aluminium will corrode.

This is because the aluminium hull becomes the anode protecting the submerged steel parts and will therefore be corroded.

This risk is easily eliminated by placing an isolating transformer at the head of the ship's power distribution system.



BOCAYNA EXPRES

Chapter 9
FIRE RESISTANCE OF ALUMINIUM

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9. FIRE RESISTANCE

WHETHER for a ship or a building on land, the resistance to fire of the materials that are used in its construction is one of the factors – without doubt the most important factor – affecting the safety of the persons who use it and of the survival of the vessel in the event of fire.

A material's behaviour in a fire is determined by its intrinsic physical properties (melting point, specific heat, etc.), its tendency to ignite and to give off smoke and fumes in the event of combustion, and changes in its mechanical characteristics. Any decrease in the latter as temperature rises will reduce the material's ability to support a load.

However fire resistance also depends on the conditions of use of the material, e.g. its position within a structure, any means of protection provided for it, its performance in a fire (retention of rigidity, extent to which it heats up etc.), generally imposed by regulations such as SOLAS and the HSC collection for high speed ships.

In shipbuilding, aluminium was first used during the period 1920 – 1930 to make furniture for passenger cabins on liners to replace wooden furniture that was considered to be dangerous in the event of a fire as it represented a fire load and its combustion gave off smoke and fumes whose catastrophic effects were already well known [1, 2].

The use of aluminium has long been challenged in a number of industries, e.g. petrochemical and offshore, that are highly exposed to fire hazards.

However despite a number of reservations relating in particular to its low melting point and the controversy that arose following the Falklands conflict in the Eighties, the marine applications of aluminium have advanced steadily since 1960 in naval construction, in passenger ships, living quarters, link bridges and in offshore structures [3, 4].

VESUVIO JET



OF ALUMINIUM

1. THE FALKLANDS CONFLICT

The resistance to fire of aluminium was the subject of much controversy during the Falklands conflict in May 1982, in which British naval forces were attacked by Argentine aircraft and nine British ships were sunk [5].

Among these nine were two Type 42 destroyers, and one of these – HMS Sheffield –was struck by an Exocet missile.

It was subsequently reported in certain sections of the media that these vessels had sunk because their aluminium alloy superstructures had caught fire upon impact from missiles or bombs dropped from aircraft.

The enquiry that followed showed that out of the nine ships damaged and sunk, only three had aluminium alloy superstructures, *and the Sheffield's superstructure was made of steel* !!!

There is nothing that establishes a cause and effect relationship between aluminium and the loss of these ships.

In a "White Paper" published by the Ministry of Defence on the 14 December 1982, the British authorities concluded that "there is no evidence that aluminium has contributed to the loss of any vessel" [6].

2. REACTION TO FIRE OF ALUMINIUM

It is now a generally accepted and established fact that "solid" aluminium (1) does not burn, does not give off smoke when exposed to fire and does not emit sparks on impact.

(1) Like most metallic powders, aluminium powder is very flammable and so hazardous to handle. Its behaviour in fire is wholly different from the behaviour of the "solid" metal covered with its natural oxide film. The solid fuel motors of rockets usually consist of a pyrophoric charge based on specially conditioned aluminium powder.

HSV2



2.1 Non-flammability

There is no evidence that solid or liquid aluminium catches fire by itself in a fire [7]. and this has been confirmed by experience and by numerous laboratory tests.

Tests have shown that in *pure oxygen*, at a pressure of 1013 bar, the ignition temperature of aluminium is above 1000°C, higher than that of other common metals such as 930°C for steel and 900°C for zinc. The level of ignition temperatures is not dependent on melting point [8]. There are metals whose ignition temperature is below their melting point, and vice versa (table 62).

The extreme difficulty in getting aluminium to burn is because the natural oxide layer inhibits the reaction of the metal with air or oxygen by "locking" the liquid metal in an envelope that provides a seal from the surrounding environment tight enough to prevent ignition (2). Put another way, we can say that there are two competing processes: the formation of the oxide layer (oxidation) and the combustion of aluminium (3).

Moreover, in mixtures of oxygen and argon, aluminium will only burn if the temperature exceeds the melting point of alumina (2250°C) and aluminium only burns by itself if the temperature attains its boiling point (3073°C) [9].

In recycling foundries, aluminium scrap of all alloys is fed into open furnaces as it is. The temperature of the melt is in the region of 750 - 800°C !

The molten aluminium can be sprinkled with jets of water. The amount of water broken down by the molten aluminium is minimal because the metal's reactivity is inhibited by the formation of the oxide film. Very little hydrogen is given off and so there is no risk of explosion.

2.2 No release of smoke

As with all common metals and alloys, aluminium does not give off any smoke or toxic gases when heated up or melted (4).

2.3 No sparking

It is worth noting that neither aluminium (nor its alloys) produce sparks upon low impact [4], which is why aluminium alloy equipment has been used in coal mines for a long time (5).



RADAR MAST

(2) Experience shows that it is impossible to set fire to aluminium cooking foil 6 to 7 microns thick with any type of flame.

(3) The oxide film can form under very low pressures of oxygen (approx. 1 millibar and less) and at high speeds of the order of 1 millisecond. This explains why the machining and sawing of aluminium present no risks.

(4) Except those from the combustion or hot decomposition of any coatings.

(5) In Europe, most road tankers that carry petroleum products have aluminium alloy tanks (made from 5083, 5186 and XTral728).

IGNITION TEMPERATURES IN OXYGEN

Metal	Ignition Temperature in Pure Oxygen (°C)	Melting Point (°C)
Magnesium	623	650
Molybdenum	750	2 620
Lead	870	327
Zinc	900	419
Iron	930	1 540
Aluminium	1 000	666

Table 62

3. CLASSIFICATION OF ALUMINIUM

Aluminium is classed as non-flammable:

- according to British standard BS 476 [10],
- according to ASTM test E136 [11].

The International Convention for the Safety of Life at Sea (SOLAS) [12] classes aluminium among the non-combustible materials, and explicitly permits the use of aluminium alloys in naval construction (6):

Steel or other equivalent material: Whenever the words "steel or other equivalent material" occur, the term "equivalent material" shall be taken to mean any non-combustible material which, by itself or with insulation, possesses properties equivalent to those of steel in regard to mechanical strength and integrity at the end of the standard fire test (e.g. a suitably insulated aluminium alloy).

4. PASSIVE PROTECTION OF ALUMINIUM

The rules for the protection of aluminium alloy structures are therefore the same as for steel structures (7), and can obviously be applied without any difficulty:

- to type A ship divisions:

- they must be constructed to prevent the passage of smoke and flames until the end of a standard one-hour fire test, according to resolution A.754 (8),
- they must be insulated with approved non-combustible materials such that the mean temperature on the unexposed surface does not rise by more than 139°C above the initial temperature, and the temperature at any point on that surface, including joints, does not rise by more than 180°C above the initial temperature, at the end of the following times:

Class A – 60	60 minutes
Class A – 30	30 minutes
Class A – 15	15 minutes
Class A – 0	0 minutes

- to type B ship divisions:

- these must be constructed to prevent the passage of flames until the end of the first half-hour of a standard one-hour fire test,
- they must have a level of insulation such that the mean temperature on the unexposed surface does not rise by more than 139°C above the initial temperature, and the temperature at any point on that surface, including joints, does not rise by more than 225°C above the initial temperature, at the end of the following times:

Class B – 15	15 minutes
Class B – 0	0 minute

More effective thermal insulation products are now used on board aluminium alloy ships [13]. These are "synthetic vitreous fibres (of silicates) of random orientation, whose percentage by weight of alkaline oxides and alkaline-earth oxides (Na_2O + K_2O + MgO + BaO) exceeds 18%". They are non toxic and conform to European directives [14].

They have an improved insulation capacity but are much thinner and so easier to apply.

They therefore represent a significant weight saving of some 40% compared with traditional "rockwool", as shown in table 63.

Experience shows that for a 40 metre passenger ship, 700 to 800 kg of INSULFRAX blanket is enough to insulate those parts of the ship that are classed type A.

EXAMPLE OF INSULATION WITH UNIFRAX FIBRES

Structure	Type	Thickness (mm)	Weight (*) (Kg m^{-2})
Deck	A30	38	3,65
	A60	50	4,80
Bulkhead	A30	38	3,65
	A60	50	4,80

(*) on a flat surface.

Table 63

(6) Solas, Chapter II-2, Rule 3, Section 7.

(7) Solas, Chapter II-2, Rule 3, Section 3.

(8) Resolution A.754: Recommendations on fire resistance tests for "A," "B" and "F" class divisions. International code for the application of fire test methods, Code FTP. IMO publications.

5. THERMAL PROPERTIES OF ALUMINIUM

The melting point of aluminium is much lower than that of steel, 666°C as against 1530°C (table 64).

The thermal properties of aluminium are distinctly superior to those of steel:

- its thermal conductivity is 3 times higher for the 5000 series alloys and 4 times higher for the 6000 series,
- its specific heat is twice that of steel.

As a result, aluminium's thermal behaviour is quite different from that of steel (9). For an equal mass of metal, far more calorific energy is needed to heat aluminium than steel; the energy is dissipated more readily because of aluminium's very good thermal conductivity. Its superior ability to conduct heat away eliminates hot spots and increases the period of serviceability.

However, in facilitating the diffusion of heat energy, aluminium will help to heat up contiguous elements (volumes or structures), and aluminium alloy structures must be insulated to avoid this.

Aluminium's reflective power is very high, 80 to 90% of incident radiation compared with 5% for painted steel and 25% for stainless steel. The effect of this high emissivity is that aluminium alloy structures that are exposed to heat radiation emitted by a fire take longer to heat up, so limiting the spread of the fire.

Aluminium's reflective power falls very little when its surface is exposed to high temperatures. For a surface temperature of between 500 and 600°C, the reflective power remains at a high level – in the region of 70% – even on surfaces that are very old and oxidized.

When the surface is painted and covered in soot, the reflective power falls very significantly to less than 20 to 30% of a clean surface [15].

(9) Cf. Chapter 6.

6. CHANGE IN THE PHYSICAL PROPERTIES OF ALUMINIUM AS A FUNCTION OF TEMPERATURE

Like most common metals, a rise in temperature modifies the physical properties of aluminium to a greater or lesser degree.

6.1 Change in mechanical properties

This is a very important parameter and one that must be taken into consideration to maintain the integrity of structures and their ability to take the initial loads.

The longitudinal modulus of elasticity of aluminium alloys decreases with temperature (table 65) [16] as shown in figure 116.

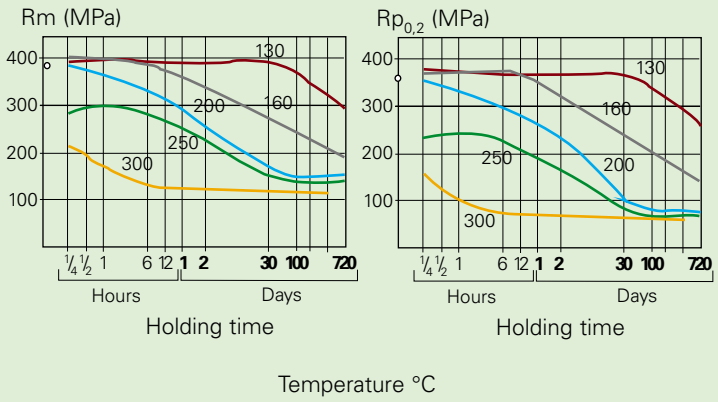
The mechanical properties of aluminium alloys, including the elastic limit, start to fall as the temperature rises above 150°C, dropping to 50% between 200 and 250°C (see table 64 and figure 118). The mechanical properties of steel also decrease with temperature, with the 50% threshold coming at around 600°C (figure 119).

THERMAL PROPERTIES OF ALUMINIUM

Property	Aluminium 1050A O	5083 O	6005A T5	Steel E24
Melting range (°C)	645/658	574/638	605/655	1 400/1 530
Boiling point (°C)	2 425	2 425	2 425	2 860
Melting heat ($kJ.Kg^{-1}$)	390	390	390	250
Specific heat ($J.Kg^{-1}.K^{-1}$)	900	900	940	420
Thermal conductivity ($W.m^{-1}.K^{-1}$)	229	117	188	54
Coefficient of linear expansion ($10^{-6}.K^{-1}$, 20/100°C)	23,5	24,2	23,6	13,5

Table 64

CHANGE IN MECHANICAL CHARACTERISTICS OF 6082



From TALAT de l'EAA

Figure 117

CHANGE IN THE ELASTIC LIMIT OF 5083 O AND 6061 T6

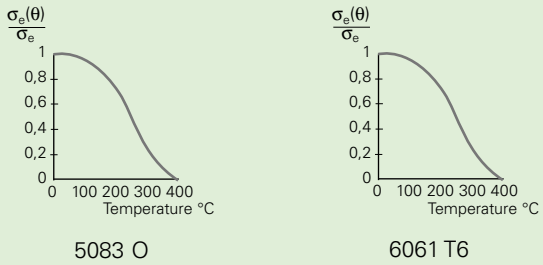


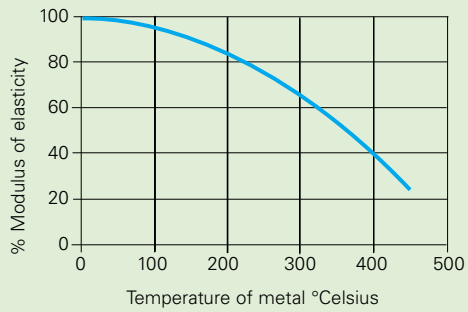
Figure 118

CHANGE IN THE MODULUS OF ELASTICITY OF ALUMINIUM ALLOYS

Temperature (°C)	Modulus of elasticity (MPa)
20	70 000
50	69 300
100	67 900
150	65 100
200	60 200
250	54 600
300	47 600
350	37 800
400	28 000
550	0

Table 65

CHANGE IN YOUNG'S MODULUS



From TALAT de l'EAA

Figure 116

The period of exposure to temperature (10) has little effect on the mechanical characteristics of strain hardened alloys when they are in the annealed condition, 5083 O and H111, 5086 O and H111, etc. However it will have an annealing effect on age hardened alloys such as 6005A, 6061, 6082 in the T6 temper when the temperature exceeds 150°C.

In practice, if a load-bearing structure made from age hardened aluminium alloys is exposed to temperatures above 150°C for several hours, then the residual mechanical characteristics of components made from alloys belonging to the 6000 series will have to be tested after the fire. The higher the temperature to which the alloy has been heated, the faster its loss of mechanical characteristics (figure 117).

(10) Cf. table 23, Chapter 3.

CHANGE IN THE ELASTIC LIMIT OF STEEL [17]

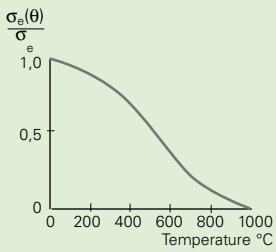


Figure 119

6.2 Change in physical properties

Aluminium's thermal conductivity increases with temperature between 0 and 400°C according to the empirical formulae (figure 120):

- λ_{al} = 0.07 θ + 190 for alloys belonging to the 1000, 3000 and 6000 series,
- λ_{al} = 0.10 θ + 140 for alloys belonging to the 2000, 5000 and 7000 series.

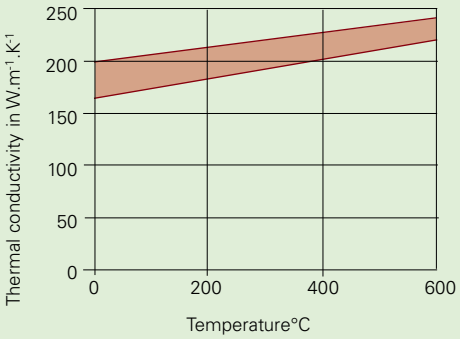
Its specific heat also increases with temperature, between 0 and 400°C, (Figure 121) according to the empirical formulae:

- Cp_{al} = 0,418 θ + 900 for the 5083 alloy
- Cp_{al} = 0,710 θ + 880 for the 6061 alloy.

Its coefficient of linear expansion increases with temperature between 0 and 500°C (figure 122) according to the formula:
$\Delta l/l = 0{,}1.10^{-7}\ \theta^2_{al} + 22{,}5.10^{-6}\ \theta_{al} - 4{,}5.10^{-4}$
with :

- l = length at 20°C,
- Δl = expansion due to temperature,
- θ_{al} = temperature.

CHANGE IN THERMAL CONDUCTIVITY



From TALAT de l'EAA

Figure 120

CHANGE IN MASS THERMAL CAPACITY

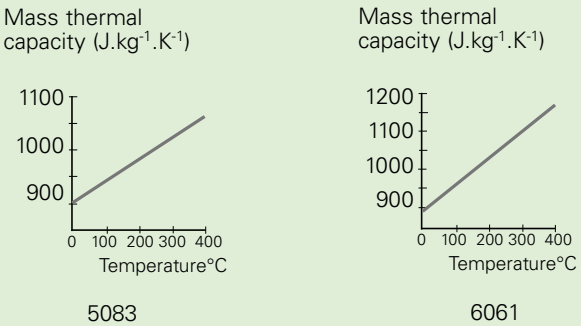
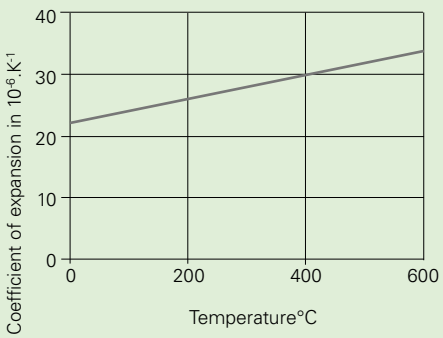


Figure 121

CHANGE IN THE COEFFICIENT OF LINEAR EXPANSION



From TALAT de l'EAA

Figure 122

Bibliography

[1]"Evolution des applications de l'aluminium au cours des cinquante dernières années [1886–1936]", *Revue de l'Aluminium*, No. 84, 1936, pp. 381-398.
[2]"Les constructions navales", P. DE LAPEYRIÈRE, *Revue de l'Aluminium*, No. 117, 1945, pp. 183-192.
[3] *Fire*, ALFED Notice, 1999 - Aluminium Federation Limited, Broadway House, Calthorpe Road, Five Ways, Birmingham B15 1TN, UK.
[4] "Application of aluminium to offshore topside structures", M. J. BAILEY, *First International Offshore and Polar Engineering Conference,* Edinburgh, 1991, pp. 265-272.
[5] "Fire Resistance and Flame Spread Performance of Aluminum and Aluminum Alloys", *The Aluminium Association*, First Edition, December 1997.
[6] "The Falklands Campaign: The lessons", presented to Parliament by the Secretary of Defence by command of Her Majesty, December 1982.
[7]"Resistance à l'incendie des constructions en aluminium", V. J. HILL, *Rapport comité International de développement de l'aluminium.* CIDA Report 7132, 1971.
[8] "Combustion of metals in oxygen", A. V. GROSSE, J. B. CONWAY, *Industrial and Engineering Chemistry,* Vol. 50, 1958, pp. 663-672.
[9] "Température de l'aluminium pendant sa combustion dans les mélanges oxygène/argon dans l'azote et dans l'air", R. BOURRIANES, *Compte rendu de l'Académie des Sciences,* Paris, Vol. 275, 1972, pp. 717-720.
[10] BS 476, Classification of Materials for Fire Resistance.
[11] ASTM, Designation E136: Standard Test Method for behavior of materials in a vertical tube furnace at 750°C.
[12] SOLAS, Consolidated Edition of 1997, Consolidated Text of the International Convention of 1974 for the Safety of Life at Sea, and of the Protocol of 1978: Articles, attachments and certificates, *International Maritime Organisation*, London 1997.
[13]"Fire insulation meets demanding standards", P. HYNDS, *Speed at Sea*, 1999, p. 31.
[14] European Directives 97/69, 80/1107, 89/391, 98/24.
[15] "Material Aspects of Fire Design", STEINAR LUNDBERG, *Hydro Aluminium Structures*, Karmoy, TALAT Lecture F2502.
[16] Eurocode 9: Design of Aluminium Structures – Part 1–2 General: Structural fire design, CEN TC 250, ENV 1999-1 2:2000.
[17]"Stabilité au feu des charpentes métalliques, matériaux de protection", C. AIMONE CAT, J. KRUPPA, G. LAMBOLEY, CTCIM BP1, F78470 Saint-Rémy-lès-Chevreuses, 1987.

INSULATION IN THE ENGINE ROOM





MOTOR YACHT

Chapter 10
CORROSION BEHAVIOUR OF ALUMINIUM IN MARINE ENVIRONMENTS

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10. CORROSION BEHAVIOUR OF

THE MARINE ENVIRONMENT is highly aggressive towards most materials, as amply demonstrated by the dilapidated state of old ships and wrecks (whether made from wood or steel) that can be seen lying abandoned around our coasts.

There are few metals capable of withstanding this hostile environment unprotected. Bronze is one of these metals, and in museums around the Mediterranean we may admire statues recovered from the ancient wrecks which they once adorned and which have lain submerged in the sea for centuries, even millennia.

Based on our very long experience of aluminium's corrosion behaviour in marine atmospheres and in sea water [1], we can now assert that the service life of aluminium in marine environments will be exceptionally long and can be measured in decades!!! We can truly claim that aluminium is the "metal of the sea" of the modern age.

Although this evidence is now widely accepted, the issue of the resistance of aluminium to corrosion in marine applications is important enough to merit a digression of some length and detail to review a number of basic principles and in doing so perhaps to prevent disappointments and avoid unnecessary protection.

Even though, around the middle of the 20th century, metallurgists and corrosion specialists perfected alloys that are "intrinsically" resistant to corrosion in marine environments – the aluminium-magnesium alloys that belong to the 5000 series –cases of corrosion still occur now and then. An examination of these cases shows that very often the cause of the corrosion lies in the design of the structure and in service conditions to which aluminium is not suited.

TRICAT 50



ALUMINIUM IN MARINE ENVIRONMENTS

1. CHARACTERISTICS OF MARINE ENVIRONMENTS

A distinction must be made between sea water and sea atmosphere.

1.1 Sea water

The sea is a liquid medium that contains the following substances in equilibrium:

- dissolved mineral salts, some 30 to 35 g per litre,
- dissolved gases, including 5 to 8 ppm (1) oxygen,
- living organisms,
- decomposing organic matter,
- mineral matter in suspension.

This mix forms a very complex medium in which the influence of each individual factor, whether chemical (composition), physical (temperature, pressure) or biological (flora and fauna), on the resistance to corrosion of metals can be neither truly isolated nor separately quantified.

The great oceans – the Atlantic, the Indian and the Pacific – which connect with one another in the southern hemisphere have a virtually uniform total salinity, 32 to 37 $g.l^{-1}$, including 30 $g.l^{-1}$ of sodium chloride or "salt".
The salinity of enclosed or isolated seas can be very different from that of the great oceans, and may vary seasonally down the year. The Baltic for example has a total salinity of 8 $g.l^{-1}$, the Black Sea 22 $g.l^{-1}$, the Mediterranean 41 $g.l^{-1}$ and the Persian Gulf 57 $g.l^{-1}$ [2].

The hostility of sea water to metals and other materials is due to its abundance of chlorides "Cl^-".

Experience and the results of corrosion tests show that aluminium's resistance to corrosion is the same whatever the sea or ocean. Comparative tests carried out on the same alloys submerged in the North Sea (16 to 17 $g.l^{-1}$ chlorides, annual temperature variation 0 to 18°C) and the Arabian Gulf (26 to 34 $g.l^{-1}$ chlorides, annual temperature variation 17 to 30°C) show that there is no significant difference between the two sites despite their difference in salinity (ratio of 1:2) [3].

The corrosion behaviour of aluminium may change when the water in a port is polluted by urban or industrial waste, provided of course the polluting elements modify the corrosivity of sea water vis à vis aluminium (2).

1.2 Sea atmosphere

The aggressive nature of sea air is aggravated by moisture and sea spray consisting of very fine droplets of sea water borne on the wind. The effect of sea air depends on the direction and strength of the prevailing winds, and is greatly diminished at a distance of a few kilometres inland.

(1) ppm = parts per million or $mg.l^{-1}$.

(2) The diluted sea water in river estuaries is usually more aggressive to materials, including aluminium, than water off shore. This paradox can be explained in various ways: the precipitations of calcium and magnesium carbonate which deposit a more or less protective film on the metal do not occur in diluted sea water. Biological activity is slower. Domestic or industrial wastes modify physical-chemical balances and may themselves contain corrosive agents.

LIVING QUARTER



2. CORROSION BEHAVIOUR OF ALUMINIUM UNDER CONTROL OF THE NATURAL FILM OF OXIDE

Aluminium owes its excellent corrosion resistance to the presence on the metal of a permanent film of natural oxide that consists of alumina (Al_2O_3) and makes the metal "passive" to the environment.

Although it is extremely thin, between 5 and 10 nanometers (3), the oxide film forms a protective barrier between the metal and the surrounding environment as soon as the metal comes into contact with an oxidizing medium such as atmospheric oxygen or water. The film forms within about one thousandth of a second and can even form under oxygen pressures as low as 1 millibar.

The physical-chemical stability of the oxide film is therefore key to aluminium's resistance to corrosion, and depends on the characteristics of the environment, such as its pH, and on the composition of the alloy itself.

SOLUBILITY OF ALUMINA

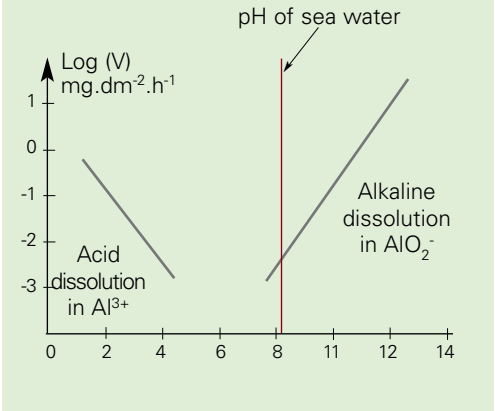


Figure 123

3. INFLUENCE OF THE PH

The rate of dissolution of the oxide film is determined by the pH of the environment (figure 123). It is very fast in acid and alkaline media and slow in media that are close to pH-neutrality (pH 5 to 9). The oxide film is therefore very stable in sea water whose pH is 8 – 8.2.

Contrary to widespread belief, the pH is not the only criterion that must be taken into account when predicting the behaviour of aluminium in an aqueous environment – the nature of the acids or bases also plays an essential part. This is very important when selecting a cleaning or pickling product for aluminium.

Thus while hydrogen acids such as hydrochloric and sulphuric are very aggressive towards aluminium (the more so in a strong solution), concentrated nitric acid has no effect on aluminium (4) and can be used in concentrations stronger than 50% to pickle aluminium and its alloys. Organic acids only have a very moderate action on aluminium.

This is equally true in alkaline environments – caustic soda and potassium attack aluminium fiercely, whereas the effect of concentrated ammonia is much less severe. The same applies to organic bases.

(3) 1 nanometer = one thousand millionth of a metre (10^{-9} m).

(4) Its oxidizing function even reinforces the oxide layer very slightly.

4. INFLUENCE OF ALLOYING ELEMENTS

Some alloying elements of aluminium alloys actually reinforce the protective character of the natural oxide film, while others weaken it. The former include magnesium, whose oxide (magnesia) combines with the alumina to enhance the protective properties of the natural oxide film, accounting for the remarkable corrosion performance of magnesium alloys in the 5000 series: 5754, 5083, 5383, 5086 etc.

Copper on the other hand is one of the elements that weaken the protection provided by the oxide film, which is why the use of copper aluminium alloys in the 2000 series and those belonging to the 7000 series with added copper is not advisable in marine applications unless special protection is provided.

GANGWAY



5. FORMS OF ALUMINIUM CORROSION

This section only deals with the forms of corrosion that might be found in marine environments on wrought alloys of the 1000, 3000, 5000 and 6000 series, and on the silicon casting alloys (40000) or magnesium casting alloys (50000).

These are:

- uniform corrosion,
- pitting corrosion,
- transcrystalline corrosion,
- intercrystalline corrosion,
- exfoliation corrosion,
- waterline corrosion,
- crevice corrosion,
- bimetallic corrosion.

5.1 Uniform corrosion

This type of corrosion is accompanied by a regular, uniform decrease in thickness over the whole surface area of the metal. The rate of dissolution can vary from a few microns per year in a non-aggressive environment to several microns per hour depending on the type of acid or base in solution in the water.

In marine environments, whether immersion in sea water or exposure to sea air, uniform corrosion is minuscule, of the order of one micron per year, and is not measurable.

We can therefore say that the service life of aluminium alloy equipment properly designed and built for use in a marine environment will not be limited by this type of corrosion.

5.2 Pitting corrosion

This very localised form of corrosion is common to many metals (figure 124) and is characterised by the formation of cavities in the material. The diameter and depth of the cavities vary depending on a number of parameters inherent in either the metal itself (type of alloy, manufacturing process etc.) or its environment, e.g. concentration of mineral salts.

Aluminium is sensitive to pitting corrosion in environments where the pH is close to neutral, which essentially means all natural environments such as surface water, sea water and atmospheric moisture.

Unlike in other common metals, this type of corrosion is worthy of our attention because the corrosion pits of aluminium are always covered by very large white blisters of gelatinous hydrated alumina $Al(OH)_3$. The blister is always much larger than the underlying cavity.

Pitting corrosion occurs at sites where the natural film of oxide is imperfect due to thinning, local rupture or gaps caused by various factors associated with manufacturing conditions, additives and so forth. Experience shows that areas which are ground or scored during sheet metal working, bending or welding operations provide ideal pockets where pits can develop during the first few weeks of immersion in sea water.

What is important for the user is to know the rate at which the pits deepen once they are initiated. Unlike other metals, e.g. zinc, whose corrosion products are soluble, alumina $Al(OH)_3$ is insoluble in water so that, once formed, it adheres to the surface of the metal inside the pit cavities. In this way, hydrated alumina considerably inhibits exchanges between the metal and sea water or atmospheric moisture.

The rate of pitting corrosion in aluminium and its alloys therefore decreases very rapidly in most media including sea water, and measurements of pit depths taken at regular intervals have shown that the rate of pitting "v" is a factor of time "t" by equations of the type $v = Kt^{1/3}$.

Many decades of experience with the use of unprotected aluminium in coastal construction (roofs, wall panels) and in shipbuilding corroborate the results obtained in the laboratory, from natural exposure or at corrosion testing stations over long periods of time: the depth of pits hardly changes once they have formed during the initial months of service.

PITTING CORROSION OF ALUMINIUM

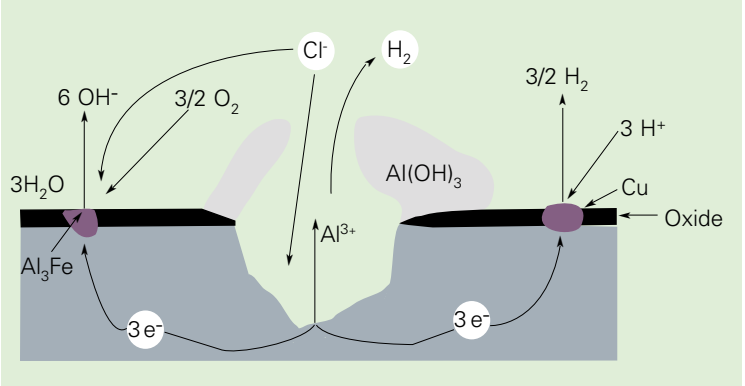


Figure 124

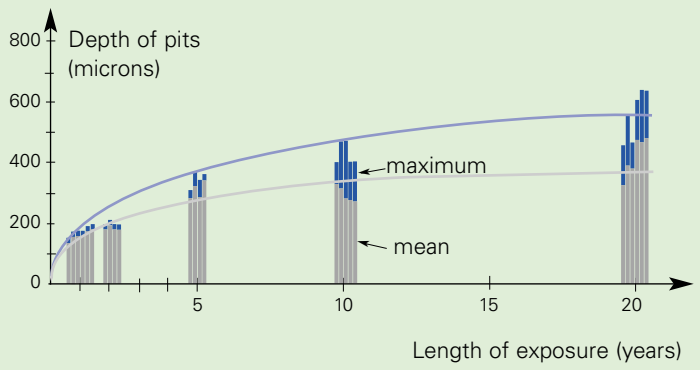
This slowdown in the rate of pitting corrosion explains the fact that aluminium equipment can be used for decades in certain natural environments (country air, sea air, sea water) without any protection. This applies as much to sea air (figure 125) as it does to immersion in sea water (figure 126). In both cases the pits are rarely deeper than one millimetre even after several years.

5.3 Transcrystalline corrosion and intercrystalline corrosion

Corrosion inside the metal, at grain level, can spread in two ways (figure 127):

- in all directions: corrosion affects all metallurgical constituents indiscriminately, it is not selective. This is transgranular or transcrystalline corrosion, so called because it spreads inside the grains,
- along preferential paths: corrosion spreads along the grain boundaries. Unlike transgranular corrosion, this type of corrosion consumes very little metal.

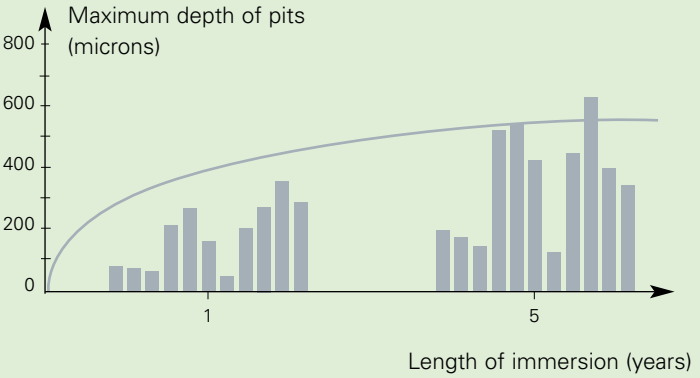
SEA SHORE EXPOSURE



Pechiney, Centre de Recherche de Voreppe

Figure 125

IMMERSION IN SEA WATER



Pechiney, Centre de Recherche de Voreppe

Figure 126

It is invisible to the naked eye, and micrographic examination is needed to detect it, usually with a magnification of 50. When it penetrates deep into the metal it affects its mechanical properties, especially elongation, and can even cause component failure.

Intercrystalline corrosion spreads from pits. There is no correlation between the depth to which intercrystalline corrosion penetrates and the diameter of the corrosion pits. In other words, intercrystalline corrosion can spread in depth from very small superficial pits.

Intercrystalline corrosion is caused by the difference in electrochemical potential that can exist between the actual grain and the grain boundary zone where intermetallic compounds, such as the βAl_3Mg_2 phase for magnesium alloys, can precipitate. The dissolution potential of this intermetallic is very electronegative: -1150 mV SCE (saturated calomel electrode) compared with the grain: -750 mV.

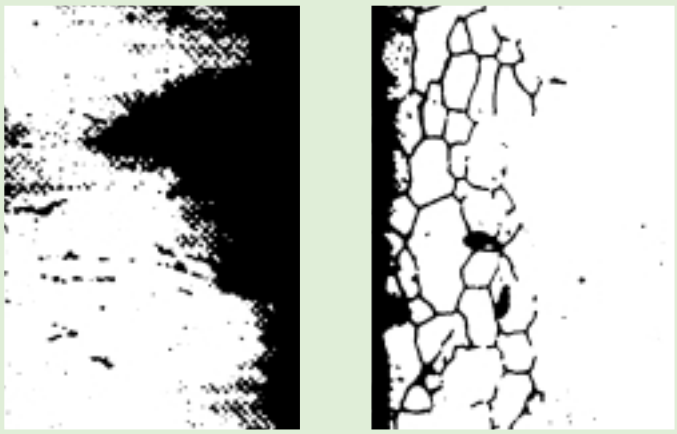
Intercrystalline corrosion can occur when three conditions come together:

- presence of a corrosive aqueous medium,
- difference in potential of at least 100 mV between the intermetallics and the solid solution,
- continuous precipitation of intermetallics in the grain boundaries.

Given the 400 mV difference in potential between the βAl_3Mg_2 phase and the grain, aluminium-magnesium alloys are sensitive to this form of corrosion under well defined and well known conditions, as reviewed in Section 10.2. They depend on the conditions of working and the conditions of service.

It is normal to quantify the intensity of intercrystalline corrosion by

TRANSCRYSTALLINE AND INTERCRYSTALLINE CORROSION



Transcrystalline Corrosion | Intercrystalline Corrosion

Figure 127

the number of grain layers that are affected by it, and it is accepted that intercrystalline corrosion is superficial and harmless when it does not spread beyond 3 or 4 layers, as is observed in the alloys of the 6000 series.

Selective tests that can be used to detect the sensitivity of aluminium alloys to intercrystalline corrosion are given in Section 11.

5.4 Exfoliation corrosion

Exfoliation corrosion is a form of corrosion that spreads along planes parallel to the direction of rolling (or extrusion). Between these planes are very thin sheets of sound metal. The build-up of corrosion products causes the corroded zone to swell, peeling away leaves of metal like the layers of an onion, hence the name "exfoliation corrosion".

The sensitivity of aluminium alloys to this very characteristic form of corrosion (figure 136, p. 162) depends on the production conditions (the rolling or extrusion process, rates of work hardening and the elongated texture of grains). In the aluminium-magnesium alloys (5083, 5383, 5086 etc.), the H116 temper, examined with the ASSET test (5), is immune to this type of corrosion.

5.5 Waterline corrosion

This form of corrosion affects semi-submerged metal structures, especially steel, in which the submerged zone close to the air/water boundary can suffer preferential corrosion that is sometimes severe (6).

In aluminium, this corrosion is due to the difference in the concentration of chlorides caused by evaporation in the thinnest part of the film of water wetting the metal (figure 128). The result is a difference in dissolution potential which can be significant between the bottom and top of the meniscus which is anodic and therefore corroded [4].

Aluminium and its alloys are largely immune from this form of corrosion in sea water, so the waterline of barges and boats with unpainted hulls is not particularly corroded by this medium. The same applies to foundation piles and the floats of landing-stages etc. in marinas.

In flowing water this effect is very weak as the meniscus is continually being renewed.

In stagnant water, the area either side of the air/water boundary line must be painted to avoid the risks of waterline corrosion.

WATERLINE CORROSION

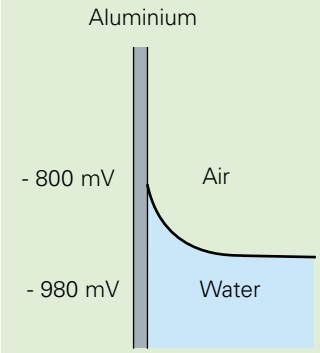


Figure 128

(5) Cf. Section 11.

(6) In steel, this form of corrosion, known as "corrosion by differential aeration", is due to the difference in the concentration of oxygen between the layer of water that is in direct contact with air – which is therefore richer in oxygen – and the layer beneath. Corrosion occurs below the waterline.

5.6 Crevice corrosion

Crevice corrosion, also known as deposit attack, occurs in tiny recesses beneath deposits where water penetrates but is not refreshed (figure 129).

The spread of crevice corrosion in aluminium is usually minimal, due no doubt to the precipitation of alumina – a product of corrosion – which quickly seals off access to the crevices. When a bolted or riveted joint that has been immersed for a very long time in sea water is dismantled, a continuous deposit of alumina is very often found between the two sheets.

When joining components however it is essential to avoid leaving recesses that might provide a foothold for corrosion in the long term. Intermittent welds on structures that are permanently or even only occasionally immersed should therefore be avoided.

CREVICE CORROSION

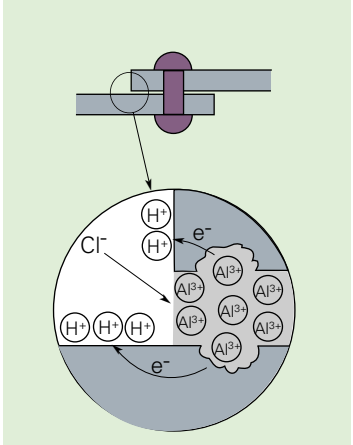


Figure 129

6. BIMETALLIC CORROSION

For a long time, the often exaggerated fear of bimetallic corrosion impeded growth in the use of aluminium, both in naval construction and in coastal equipment.

Today, after many years of experience with the use of aluminium in marine environments, we can properly assess and quantify the risks of bimetallic corrosion of aluminium in mixed assemblies between aluminium and other common metals of the type found in shipbuilding (or other applications).

Such an assessment is a necessary exercise, as it is neither possible nor even desirable for commercial and technical reasons to construct ships and equipment that are made entirely of aluminium. On pleasure craft for example, transmission shafts, screws, valves and pipes are almost never made from aluminium.

It is therefore the task of the designer and operator to ensure that contact between aluminium and other metals in marine environments cannot cause bimetallic corrosion. This is a straightforward matter provided they follow a number of elementary rules based on fundamental principles, in particular the concepts of the galvanic cell and the potential scale, and of course on experience.

6.1 The galvanic cell

When two dissimilar metals or alloys such as copper and zinc are placed in direct contact (or are electrically connected) in a wet and electrically conductive environment, e.g. a sulphuric acid solution, one of the two metals, in this case zinc, will dissolve while the other, copper, retains its integrity and appearance.

This is a battery (7) (or galvanic cell) consisting of two electrodes, each of which is a metal (figure 130):

- the one that is consumed – called the *anode* – undergoes an oxidation reaction:

$$M \rightarrow M^{n+} + ne^-$$

or

$$Al \rightarrow Al^{3+} + 3e^-$$

when it is aluminium,

- the other – the *cathode* – undergoes a reduction reaction, usually to the H^+ ions present in the water (8):

$$H^+ + e^- \rightarrow H_2$$

The amount of hydrogen that is given off bears no direct relationship to the mass of metal that is dissolved at the anode. Under standard conditions – 25°C at a pressure of 1013 mbar – it is 33.6 litres for 27 grams of aluminium.

The reactions at the anode and the cathode occur simultaneously and are balanced in electrical charges "e^-". The complete reaction for the bimetallic corrosion of aluminium is as follows:

$$Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2} H_2$$

(7) So called because the first current generator invented by Alessandro Volta in 1800 was a "pile" of zinc and copper discs insulated from one another by felt and immersed in a diluted solution of sulphuric acid.

(8) The H^+ ions are produced either by the dissociation of the water itself or by an acid dissolved in the water.

PRINCIPLE OF A GALVANIC CELL

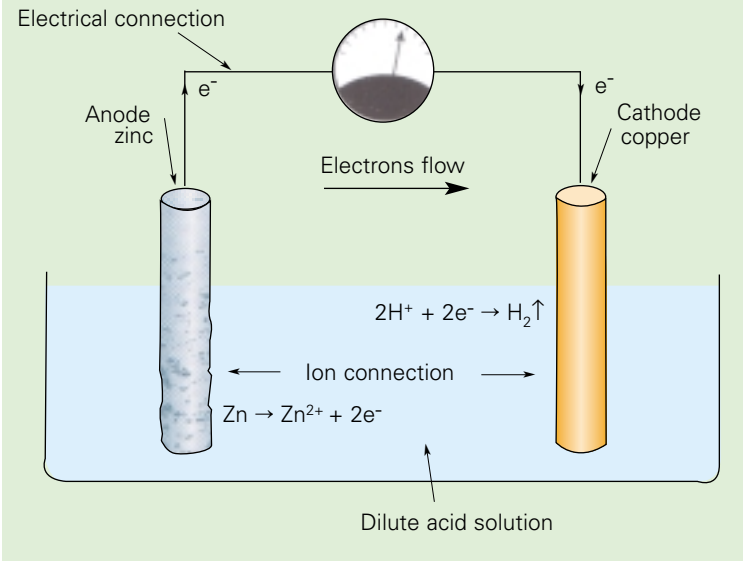


Figure 130

INSULATION OF ALUMINIUM

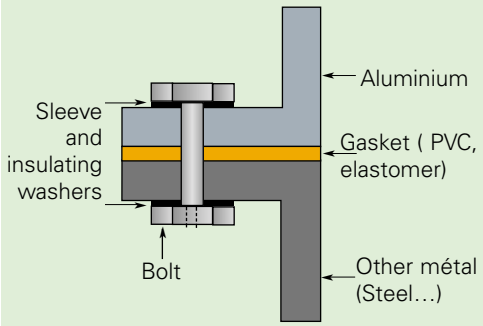


Figure 131

Hydrogen is given off (at the cathode) and aluminium (the anode) dissolves, forming alumina $Al(OH)_3$.

6.2 Conditions of bimetallic corrosion

These simplified equations show that for bimetallic corrosion to take place, 3 conditions must come together simultaneously:
- presence of an electrolyte,
- electrical continuity,
- dissimilar metals.

■ Presence of an electrolyte: the contact area between the metals must be wetted by fresh water or sea water. The more conductive the medium, the stronger the bimetallic corrosion, and it is therefore much more intense in sea water whose resistance is of the order of 10 to 25 $W.cm^{-1}$ than in fresh water (or rainwater) whose resistance attains several thousand $W.cm^{-1}$, depending on the source of the water.

■ Electrical continuity between the two metals, either through direct contact or made by means of a fastener such as clamp screws.

One simple way of avoiding bimetallic corrosion therefore is to insulate the two metals from one another as carefully as possible, and this is easily done with a high ohmic resistance, i.e. an insulating material (figure 131) such as neoprene (9).

As with any battery (or galvanic cell), anything that retards or inhibits the electrochemical reactions on the electrodes reduces its output – this is referred to as "polarisation". Applied to the case of bimetallic corrosion, the accumulation of corrosion products in the contact zone between the two metals slows down the process.

When hybrid joints made from plates of steel and aluminium alloy that are bolted together without any insulation are taken apart after years of immersion in sea water, a very dense alumina "poultice" is therefore found in the contact area. The extent of the corrosion will be limited because the alumina has significantly slowed the exchange of ions (10).

■ Dissimilar metals. This raises the concept of potential which we shall now discuss.

(9) Once a much-used technique in shipbuilding, it has been superseded by cathodic protection for immersed structures (cf. Chapter 11).

(10) It goes without saying that this initial corrosion cannot be expected to provide reliable long term protection.

6.3 Concept of potential

This is a thermodynamic phenomenon that measures a metal's tendency to oxidize. The more electronegative the potential, the more the metal tends to oxidize.

Potential is measured in millivolts (mV) against a reference electrode and in a defined medium. Corrosion specialists usually use the saturated calomel electrode (SCE) as the reference.

The result is a classification or 'potential scale' of metals and alloys; table 67 shows a part of this scale for the common metals in natural sea water in motion.

The rankings on this scale can be used to predict which of the two metals in contact with each other in an aqueous medium, or more specifically in sea water, will be attacked:

- if both metals have electronegative potential, it will be the more electronegative,
- if one metal is electropositive it will be the electronegative.

In this combination for example:

Zinc Ed = – 1130 mV
Iron Ed = – 610 mV

it is the zinc that corrodes (11).

Experience shows that bimetallic corrosion only occurs when the two metals in contact have a difference in potential of at least 100 mV.

The aluminium alloys used in marine applications have dissolution potentials that are very close to one another (table 66).

(11) This accounts for the effectiveness of coating steel with zinc, and hence the use of galvanised steel in many applications where it must be protected from corrosion.

DISSOLUTION POTENTIAL OF ALUMINIUM ALLOYS (NACL SOLUTION, H2O2, ASTM G 69)

Alloy	Potential mV SCE
1050A	– 750
3003	– 740
5052	– 760
5056	– 780
5083	– 780
5086	– 760
5154	– 770
5182	– 780
5454	– 770
5456	– 780
6005A	– 710
6060	– 710
6061	– 710
6063	– 740
42000 (A-S7G03)	– 820
51300 (A-G5)	– 870

Table 66

DISSOLUTION POTENTIALS MEASURED IN NATURAL SEA WATER IN MOTION AT 25°C

Alloy	Dissolution Potential (mV SCE) (*)
Graphite	+ 90
Stainless steel	– 100
Titanium-	– 150
Inconel	– 170
Cupronickel 70-30	– 250
Cupro-nickel 90-10	– 280
Bronze	– 360
Brass	– 360
Copper	– 360
Lead	– 510
Mild steel	– 610
Cast iron	– 610
Cadmium	– 700
Aluminium	– 750
Zinc	– 1 130
Magnésium	– 1 600

(*) mV SCE = millivolts, saturated calomel electrode.

Table 67

In a marine environment therefore there is no risk of bimetallic corrosion between these alloys. This is also true of casting alloys, and is the reason why stiffeners in 6000 alloys are frequently used welded to plate in 5000.

6.4 Practical aspects of bimetallic corrosion of aluminium in marine environments

Bimetallic corrosion is a very localised phenomenon and very often confined to the contact zone. In theory, the current density that determines the rate of dissolution of the anodic metal is a function of the relationship:

$$\frac{\text{cathodic surface}}{\text{anodic surface}}$$

Experience shows that this area relationship is of no great relevance, as bimetallic corrosion occurs primarily in or near the contact zone, and so the anode area must be judged to be more or less equal to the cathode area.

Expressed in practical terms, a small component such as a screw or probe made from copper or copper alloy and attached to a large aluminium alloy structure without any insulation – and permanently submerged – will cause severe bimetallic corrosion at the point of attachment.

Aluminium's position on the scale of potential (table 67) means that in virtually every instance in which it is joined to another common metal (12), it will be the anode of the resulting battery and so likely to suffer bimetallic corrosion if the conditions are right.

To fully appreciate the risks of the bimetallic corrosion of aluminium in a mixed joint, we must distinguish between:

- a submerged structure (quick works)
- an emerged structure (dead works) – the type of metal must also be considered in this case.

Note: Anodising affords no protection from bimetallic corrosion.

6.5 Submerged mixed contacts

As we have already shown, when contacts are submerged, bimetallic corrosion of aluminium is unavoidable when in contact with most common metals (13). The intensity of this corrosion will depend on the type of metal, on the composition of the environment and on the length of time if the contact area is submerged occasionally rather than continuously.

The aluminium structure must be protected, and there are a number of ways of achieving this:

- Insulation, by inserting plastic seals between the two metals. Taking pipework as an example, a gasket of sufficient thickness is fitted between the aluminium flanges of the pipe and the flange of a stainless steel or brass valve.
- Painting: the surface of the cathode, i.e. of the other metal, must first be masked. Painting the aluminium only is far less effective.
- Cathodic protection is the most practical solution (14) and the one used most often to neutralise the galvanic couples between a ship's aluminium hull and the propulsion system (shaft and screw) and other items attached to the hull (intake strainers, various accessories).

Note. A steel tool such as a spanner left behind in the bilge of a vessel can cause bimetallic corrosion if water is allowed to stagnate in the same area as the item made of steel (or any other metal).

6.6 Emerged mixed contacts in open air

Many decades of experience with aluminium applications in marine environments, both on board ships and in on-shore coastal installations, show that contacts with mild steel, whether bare or coated (galvanised, cadmium plated), and stainless steel cause no significant bimetallic corrosion of aluminium and its alloys (15) in the 1000, 3000, 5000 and 6000 series (16).

(12) Except cadmium, zinc and magnesium. There will be no bimetallic corrosion of aluminium in contact with fasteners made from galvanised or cadmium-plated steel. Instead, as long as there is zinc or cadmium on the steel, these metals will dissolve to protect it.

(13) This will also apply to mixed contacts in the bilges of a ship if water stagnates there.

(14) Cf. Chapter 11.

(15) For a number of reasons: a layer of corrosion products (rust, alumina) forms on the contact faces, inhibiting electrochemical reactions as we have seen.

(16) In some cases copper alloys in the 2000 and 7000 series are sensitised to corrosion on contact with steel.

As a result, such contacts are now hardly ever protected on ships (17) or in coastal installations except obviously in cases where rust discoloration must be prevented on aluminium structures (in the case of contact with steel). Today, steel/aluminium transition joints (18) are used to make welded connections between a hull and aluminium alloys.

(17) For safety reasons (cf. Chapter 9), all metal masses on board a ship or on a structure intended to house electrical installations must be equipotentially bonded. Even if contacts are insulated for reasons of corrosion or convenience, an electrical connection by means of a cable or braided wire must still be provided at one point.

(18) Cf. Chapter 9.

ATTACHMENT OF LEAD OR IRON BALLAST

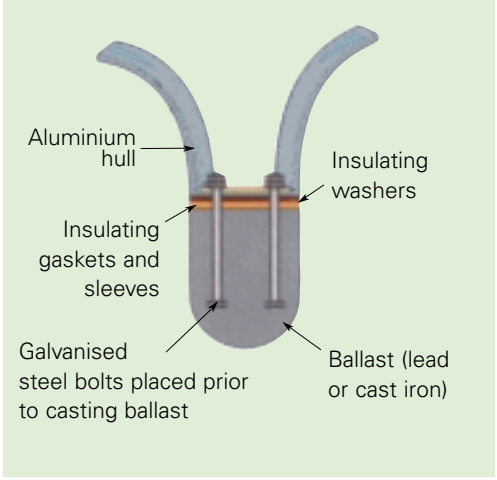


Figure 132

6.7 Influence of the type of metal in contact with aluminium

The risk of bimetallic corrosion may be greater when aluminium is in contact with certain metals and alloys.

Copper and its alloys

While contact between aluminium alloys and copper and its alloys (brass, bronze) causes no appreciable bimetallic corrosion, when emerged structures are in a wet marine environment it is advisable where possible to provide insulation between the two metals to avoid local deterioration in the appearance of the aluminium.

Verdigris however (the corrosion product of copper and its alloys) is aggressive towards aluminium and its alloys and is reduced to tiny particles of copper when in contact with them. These particles in turn cause local pitting corrosion in the aluminium, and it is therefore preferable to protect structures that are beneath an accessory that is made of copper, bronze or brass. The optimum solution is to paint them to prevent verdigris forming in the first place.

Lead

Lead is often used as ballast for pleasure craft. The combination of aluminium and lead reacts very strongly in sea water, and it is therefore essential to prevent water entering the keel if this is ballasted with lead shot or pig lead. The following procedure is usually used to prevent the risk of bimetallic corrosion which can be very severe (19):

- Carefully degrease the inside of the keel space that is accessible from the bottom of the boat,
- Apply a layer of resin 15 to 20 mm thick in the bottom of the keel,
- Once the resin has set, place the shot (or pig lead) in position, carefully avoiding contact with the aluminium edge of the keel,
- Now pack the spaces around the lead with resin up to a level 20 to 25 mm above the ballast,
- Finally, access to the keel should be sealed off by suitable means to prevent any ingress of moisture into the keel.

Lead ballast should never be laid on the bare hull, e.g. on the floor of a hold, but should be sealed in a watertight covering to prevent the bimetallic corrosion of the aluminium and the entrainment of lead salts generated by that corrosion in the presence of moisture. Lead salts will cause pitting corrosion in those areas of the hull where they are entrained by moisture.

If the lead ballast is fastened to the hull directly, it must be carefully insulated from it, as indicated in figure 132.

Lead-based paints should never be used to protect steel components on board an aluminium vessel because lead oxides, like copper oxides, cause severe corrosion to the aluminium in the presence of moisture.

Mercury

Aluminium in contact with mercury suffers very severe corrosion which takes the form of flaky white 'blooms' that spread widely where the quantity of mercury is significant or finely divided. The effect of mercury is all the more insidious as it tends to occur at low points where fine droplets of mercury accumulate.

(19) All the careful precautions taken to insulate the lead from the walls of the keel will be wasted if the keel weldments are porous! Gradual penetration of sea water through cracks due to poor welding will cause irreparable corrosion to the keel in the medium term.

It is therefore most inadvisable to carry mercury instruments such as barometers or thermometers on board a ship when spillage or breakage might cause severe corrosion of the hull.

Graphite

Although graphite is not a metal (but a metalloid), contact with it in a wet environment causes bimetallic corrosion that is more or less intense depending on the porosity of the graphite. It is therefore inadvisable to use graphite based lubricants on aluminium boats.

There is as yet insufficient experience with the use of carbon fibre equipment on board aluminium ships to be able to draw conclusions about contact between aluminium and carbon fibre composites.

Laboratory tests with immersion in synthetic sea water show that aluminium suffers a mild and very superficial attack when in contact with carbon fibre parts.

Note: When in port, craft should be moored/anchored using ropes made from hemp or synthetic fibres as this creates an 'open circuit' between the aluminium craft and the metal anchor or bollards on the quayside.

7. ALUMINIUM TARNISHING AND BLACKENING

Aluminium in a humid atmosphere or in contact with sea water or fresh water tarnishes to a degree that depends on the medium. This phenomenon, known as blackening, is not a type of corrosion but merely an alteration of the visual properties of the film of natural oxide. It does not produce any subsequent sensitivity to corrosion.

In a marine environment, blackening can be prevented on certain items by anodising or polishing them. Anodising is by far the more lasting method, and is used on boat masts.

8. ROLE AND PREVENTION OF MARINE FOULING

Unlike salts of copper (or mercury), aluminium salts are not toxic to living organisms and they can therefore easily attach themselves to aluminium surfaces where they will grow unchecked unless dislodged.

Such marine encrustations include barnacles, corals, algae, sponges etc., but cause no appreciable corrosion to the underlying metal apart from a very superficial attack to a depth of a few hundredths of a millimetre. Shells leave a virtually indelible impression on the metal.

As with other metals, antifouling paints can be used on aluminium to prevent the growth of marine encrustations (20).

However there is one very important restriction: antifouling paints based on salts of copper, mercury or lead cause severe corrosion (21) and should be avoided. This bimetallic corrosion is due to the reduction of copper, mercury and lead salts in contact with the aluminium surface and can do irreparable damage to the hull of a vessel.

(20) Cf. Chapter 11.

(21) The use of antifouling paints based on minerals salts is actually banned.

WELDMENT ON A GANGWAY



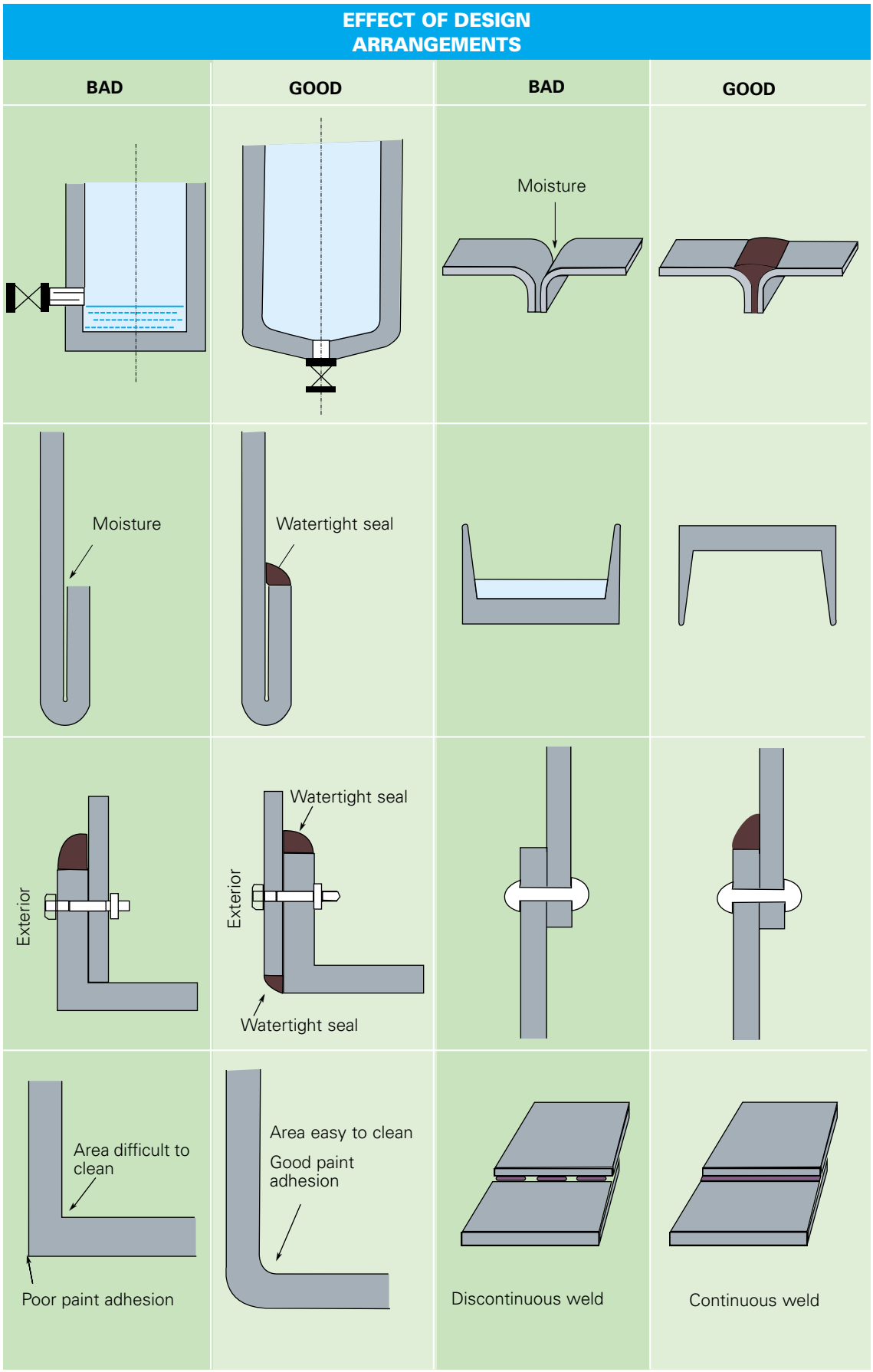

EFFECT OF DESIGN ARRANGEMENTS
BAD
GOOD
BAD
GOOD
Moisture
Moisture
Watertight seal
Exterior
Watertight seal
Exterior
Watertight seal
Area difficult to clean
Poor paint adhesion
Area easy to clean
Good paint adhesion
Discontinuous weld
Continuous weld

Figure 133

9. EFFECTS OF WELDING AND DESIGN ARRANGEMENTS

Design layouts can significantly influence the corrosion performance of aluminium alloy structures in service.

9.1 Effect of welding

Experience shows that the corrosion behaviour of welded structures made from alloys belonging to the 1000, 3000, 5000 and 6000 series is similar to that of non-welded surfaces. In other words, weld seams and heat affected zones will not be the site of preferential corrosion provided welding is done according with the relevant codes of practice and with the right filler alloys (22).

The same applies to adhesive bonding which does not affect the corrosion behaviour of components joined by this process.

9.2 Effect of design arrangements

Despite the excellent resistance to corrosion of the alloys used in shipbuilding (and in marine applications), instances of corrosion are occasionally seen in service.

An examination of these cases shows that it is most often the design layout that causes these problems. Figure 133 illustrates classic cases of design layouts that are detrimental to good corrosion performance.

Experience shows that areas where water stagnates or where dust (or soot) can accumulate can suffer very severe corrosion in the form of deep pits and even perforations.

It is therefore essential to assist the drainage of water and condensation on divisions and partitions subject to temperature variations, and to provide as much ventilation as possible for spaces that are more or less accessible (ballast tanks, holds etc.).

These areas, as well as watertight buoyancy chambers, must be regularly inspected and may require more frequent maintenance than the rest of the structure.

Finally, anything that encourages the permanent presence of moisture, such as certain types of lining, must be carefully avoided. For example, expanded foam (or insulation blankets made from rockwool or similar materials) placed against an aluminium division for thermal insulation must be positioned so that it cannot trap condensation or attract moisture.

Floor coverings should also be adhesive bonded to prevent the ingress of moisture between the covering and the aluminium "floor".

Note: Stray electrical currents can be a determining factor leading to corrosion of the hull surface in contact with sea water. As already stated (23), the hull (and any other metal structure on the boat) must never act as a return conductor for the current, whether this is d.c. or a.c.

(22) Cf. Chapter 6.

(23) Cf. Chapter 9.

10. SENSITIVITY TO CORROSION OF ALUMINIUM ALLOYS IN MARINE APPLICATIONS

Many decades of experience with marine applications of aluminium have shown that its resistance to corrosion is remarkable.

Nevertheless:

- some series of alloys are not suited to this type of application,
- production processes must be designed to avoid accidentally sensitising 5000 series alloys to structural corrosion (intercrystalline corrosion, exfoliation corrosion or stress corrosion).

Finally, service conditions must also be controlled to ensure that certain limits of temperature and time are not exceeded. The H116 temper has the advantage of undergoing mandatory inspection for sensitivity to exfoliation corrosion.

10.1 Choice of alloys for marine applications

While the 5000 and 6000 series alloys will be preferred for their resistance to corrosion, their weldability and their level of mechanical characteristics, other wrought alloys belonging to the 1000 and 3000 series are suitable for use in non-structural applications for decoration, interior fittings etc.

The use of 2000 and 7000 series alloys on the other hand must be the exception in view of their poor resistance to corrosion, and they require special protection when used in a marine environment.

The 2000 and 7000 series copper alloys cannot be welded with the classical arc processes. The 7000 series alloys without copper, e.g.

7020 or 7108, are easy to weld however, and present a high level of mechanical characteristics after welding, an attractive attribute that could be an advantage for sheet metal working in general and shipbuilding in particular.

Even so, the heat affected zone is highly sensitive to exfoliation corrosion in all environments, so much so that the development of these alloys has had to be abandoned except in very specific applications out normal fields.

In the absence of any significant progress in the control of sensitivity to exfoliation corrosion, it is not possible with our present level of knowledge (24) of the metallurgy of these alloys to use them in naval construction without special protection [5].

The casting alloys commonly used in marine applications are the 42100 (A-S7G03), the 42200 (A-S7G06) and the 51100 (A-G3).

10.2 Sensitivity of 5000 series alloys to intercrystalline corrosion

It has been well known since the early 1950s that aluminium-magnesium alloys can have a tendency to intercrystalline corrosion, the more so the higher the level of magnesium, which is why industrial alloys do not normally contain more than 5.5% magnesium.

This sensitivity is due to the changes in the distribution of the magnesium in the metal in the solid state. The solubility of magnesium in aluminium is very high at high temperatures – 15% at 450°C – but is no more than 1% at ambient.

When the temperature falls below 450°C, the magnesium precipitates in the form of intermetallics Al_3Mg_2 (or Al_8Mg_5), commonly referred to as "β phase". But when certain conditions occur these precipitates can collect on the grain boundaries, and the metal is then "sensitised". A micrograph examination soon reveals whether the alloy is sensitised or not (figure 134).

The precipitation of the β phase on the grain boundaries has a tendency to be continuous, and will be the more rapid and more dense:

- the higher the level of magnesium,
- the higher the service temperature, and
- the greater the degree of strain hardening.

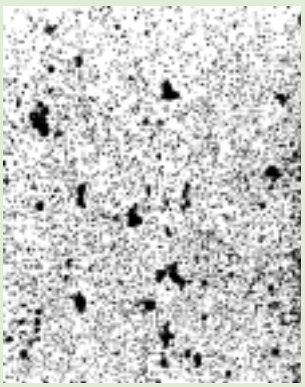
As figure 135 shows, the temperature range between 125 and 225 °C is one of high sensitisation, and sensitisation can start at even lower temperatures for the alloys with the most magnesium, over 5%.

As we have already seen, these intermetallics are anodic relative to the mass of the grain, their potential is –1150 mV SCE, a difference of some 400 mV from the solid solution, which is considerable. There is therefore a risk of intercrystalline corrosion if their precipitation is continuous on the grain boundaries and if the environment is corrosive.

MICROGRAPHIC APPEARANCE OF SENSITISED ALLOY 5083



5083 Sensitised Temper



5083 Non-sensitised Temper

Figure 134

(24) June 2003.

Temperature is not the only parameter that governs the precipitation of the β phase, as is often and mistakenly forgotten (25). Time, i.e. the period spent at temperature, is also a factor when evaluating the intensity of sensitisation. This should be obvious, as the rate at which the magnesium atoms migrate towards the grain boundaries obeys the laws of diffusion in the solid state (the aluminium matrix in this case). It is dependent on temperature according to the classic equation:

$$\tau = t \exp - (Q/RT)$$

where:
τ = the distance covered
t = time
T = absolute temperature
Q is a constant that depends on the element.

Too often, the limit at which 5000 alloys with more than 3.5% magnesium can be used has been set at 65°C (26). It is in fact the product of "Time x Temperature" that must be taken into consideration. On a 5086 for example, it will take 2 years at 65°C or several months at 100°C to cause continuous precipitation on the grain boundaries. The effect of time is cumulative.

The sensitisation of these alloys – which is always avoidable – can be due to manufacturing conditions or service conditions when they are held at temperature for long periods.

Much research has been done on all of these parameters since the 1950s [7]. Sensitisation can be inhibited by thermal treatments which cause discontinuous "pearl necklace" precipitation of the β phase on the grain boundaries [8]. For many years now, the production processes for alloys 5083, 5086 and *Sealium®* – including the H116 temper – have been specially adapted for shipbuilding [9] to avoid the supply of semi-finished products that are susceptible to corrosion. These alloys are systematically controlled by the selective tests described below.

We should remember however that the H116 temper will not prevent precipitation of the β phase on the grain boundaries when the service conditions can cause it. This temper is used very widely in shipbuilding.

SENSITISATION OF 5000 ALLOYS AND MAGNESIUM CONTENT [6]

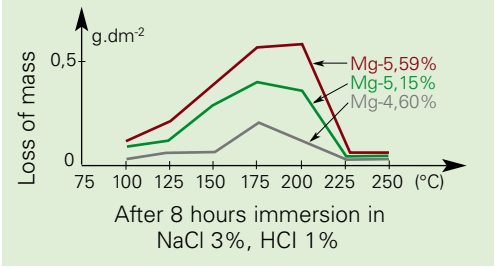


Figure 135

(25) It is not because a metal is sensitised by precipitation at the grain boundaries that makes corrosion inevitable, it depends on the environment. Experience has confirmed this at temperatures well above 65°C, including in heat exchangers operating in sea water. There are road tankers carrying heavy fuel oil, loaded at 65°C, that have been in service for 20 years or more, with 8 to 10 hours of rotation a day, i.e. at least 50,000 hours of total time at 65-70°C. But obviously sensitisation must be avoided.

(26) In the document "AD-Merkblatt W 6/1" of May 1982, published by the Vereinigung der technischen Überwachungsvereine e.V., D 4300 Essen 1, entitled "Aluminium and aluminium alloys malleable materials", the limit is set at 80°C for alloy AlMg4.5Mn, equivalent to the 5083, with tolerances of 150°C for periods not exceeding 8 hours, provided the service pressure is reduced by half and 24 hours if the service pressure is reduced to atmospheric.

MARINA PONTOON AND FLOATS MADE OF 5754



11. CORROSION TESTS

European standard EN 13195-1 (27) states that alloys 5083, 5383 and 5086 supplied in the H116 temper "in the form of sheet, strip and plate must be tested to assess their resistance to intergranular corrosion and exfoliation corrosion."

This test is either the ASSET test (ASTM G66-99) which determines susceptibility to exfoliation corrosion, or any other method agreed between supplier and buyer.

Section 9 of standard ASTM B928-04 relates to the 5059, 5083, 5086, 5383 and 5456 alloys in the H116 and H321 tempers. Susceptibility to exfoliation corrosion is measured with the ASSET test (ASTM G66-99) and susceptibility to intercrystalline corrosion with the ASTM G67 test (NAMLT).

11.1 Exfoliation corrosion testing

This is the ASSET test (28) which is conducted according to ISO 11881 (29) and ASTM G66 (30) on samples whose dimensions (length and width) are at least 40 x 100 mm. The conditions of this test are summarised below:

After surface preparation by degreasing, alkaline pickling and nitric neutralising, the specimens are immersed for 24 hours at 65 °C in the specific reagent of the 5000 series (31):

NH_4Cl - 1 M: 53 $g.l^{-1}$
NH_4NO_3 - 0,25 M: 20 $g.l^{-1}$
$(NH_4)_2C_4H_4O_6$ - 0,01 M: 1,84 $g.l^{-1}$
H_2O_2 - at 30%: 10 ml. l^{-1}

Susceptibility to exfoliation corrosion is assessed against typical images (figure 136) and result in a grading as shown in table 68.

(27) European standard EN 13195-1, December 2002, "Aluminium and aluminium alloys – Wrought and cast products for marine applications (shipbuilding, marine and offshore).

(28) ASSET = Ammonium Salt Solution Exfoliation Test

(29) ISO 11881, June 2002, Corrosion of metals and alloys – Exfoliation corrosion testing of aluminium alloys.

(30) Standard test method for visual assessment of exfoliation corrosion susceptibility of 5XXX series aluminum alloys (ASSET test).

(31)

NH_4Cl = ammonium chloride,

NH_4NO_3 = ammonium nitrate,
$(NH_4)_2C_4H_4O_6$ = ammonium tartrate,
H_2O_2 = oxygenated water.

EVALUATION OF RESULTS OF THE ASSET TEST

Evaluation	Grading
No significant attack	N
Pitting corrosion	P
Generalised corrosion	G
Exfoliation corrosion	EA, EB, EC, ED

Table 68

CLASSIFICATION OF EXFOLIATION CORROSION WITH THE ASSET TEST



From figure 6 of NF ISO 11881 Standard, June 2002

Figure 136

11.2 Test for intercrystalline corrosion of the 5000 alloys

Two tests can be used to determine the susceptibility of 5000 aluminium alloys to intercrystalline corrosion:

■ The NAMLT tests (32) according to ASTM G67 (33).

The samples are immersed in a 70 to 72% solution of nitric acid HNO_3 at 30°C for 24 hours, and weighed before and after the test.

According to standard B928-04 (34):
- the batch is passed when the mass loss is < 15 mg.cm^{-2},
- the batch is rejected when the mass loss is > 25 mg.cm^{-2},
- for mass losses between 15 and 25 mg.cm^{-2}, the form of corrosion must be determined by micrograph examination after phosphoric attack. The batch is rejected if the corrosion proves to be intercrystalline.

■ The INTERACID test according to the protocol published in the *Journal of the European Communities* on 13/09/1974, Nos. C104/84 to 89.

Here the reagent consists of a solution made from 30 g.l^{-1} of NaCl and 5 g.l^{-1} of 37% HCl (d =1.19). The samples are immersed in the reagent for 24 hours at 23°C. After determining the mass loss (weighed before and after the test), the samples are examined under a microscope with a magnification of x200.

These tests can be conducted on samples heated to 100°C for 7 days (35).

11.3 Test for intercrystalline corrosion of the 6000 alloys

These alloys are not susceptible to exfoliation corrosion. Any susceptibility to intercrystalline corrosion can be determined by the test according to ASTM G110 (36) in the reagent with 57 g. l^{-1} de NaCl et 0,3% de H_2O_2.

(32) NAMLT = Nitric Acid Mass Loss Test.

(33) ASTM G67: Standard test method for determining the susceptibility to intergranular corrosion of 5XXX series aluminum alloys by mass loss after exposure to nitric acid.

(34) B 928 - 04: Standard Specification for High Magnesium Aluminum Alloy Sheet and Plate for Marine Service, February 2004.

(35) According to the formula $\tau = t \exp -(Q/RT)$, 7 days at 100°C is equivalent to 6 months at 60°C.

(36) ASTM G110: Standard practice for evaluating the intergranular corrosion resistance of heat treatable aluminum alloys by immersion in sodium chloride + hydrogen peroxide solution.

Bibliography

[1] *Corrosion de l'aluminium*, C. VARGEL, 502 pages, Dunod, 1999.

[2] "Chemical aspects of physical oceanography", J. LYMAN, R. B. ABEL, *Journal Chemical Education*, Vol. 35, 1958, pp. 113-115.

[3] "Effect of the temperature and salt content of sea water on the corrosion behavior of aluminium", W. HUPPATZ, H. MEISSNER, *Werkstoffe und Korrosion*, Vol. 38, 1987, pp. 709-710.

[4] "Corrosion de l'aluminium sous couche mince électrolytique, corrosion à la ligne d'eau et corrosion au stockage", C. FIAUD, G. AZERAD, E. GROSGOGEAT, *Journées "Durabilité de l'aluminium et de ses alliages dans les industries électriques"*, Cefracor Paris, December 1986, pp. 33-37.

[5] "Experience from the construction and operation of the Stena HSS", H. NORDHAMMAR, STENA REDERI, *The Third International Forum on Aluminium Ships*, Hauguesund, Norway, May 1998.

[6] "Influence de la teneur en magnésium sur la résistance à la corrosion sous tension des alliages Al-Mg", A. GUILHAUDIS, *Pechiney SREPC Report*, September 1959.

[7] "Development of Wrought Aluminium-Magnesium Alloy", E. H. DIX, W. A. ANDERSON, M. B. SHUMAKER, *Technical Paper*, No. 14, Alcoa, 1958.

[8] "Traitements thermiques de stabilisation des alliages aluminium-magnésium à 5% contre les effets de chauffage à basse temperature", A. GUILHAUDIS, *Revue de l'Aluminium*, 1955, Nos. 223 and 224.

[9] "Aluminium-Magnesium alloys 5086 and 5456 H116", C. L. BROOKS, *Naval Engineers Journal*, August 1970, pp. 29-32.

NO ALUMINIUM CORROSION





CHEVY TOY

Chapter 11
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11. PROTECTION

THE ALUMINIUM alloys that are used in marine applications – essentially those that belong to the 5000 and 6000 series – have excellent resistance to corrosion in a marine environment, whether they are exposed to sea air or submerged in sea water.

Unlike other common metals such as steel, they do not need to be protected by painting or any other means. Painting only the strict minimum of a boat, i.e. the quickwork and living or reception quarters, represents a major saving on cost, including maintenance, and on weight as well.

Examples of marine applications in unprotected aluminium abound, and include oyster barges, plant and machinery rooms on passenger ships and coastal installations such as floating landing stages in marinas, road signs etc. There are also many examples of craft and coastal installations that have never been protected and which have been in service for many decades.

Aluminium and its alloys are non toxic to living organisms such as marine flora and fauna (1). Protecting the quickwork of a boat with special antifouling paint is therefore essential to prevent biofouling by deposits of an animal or vegetable origin. The same applies to submerged equipment if it is to be protected from fouling (2).

In most cases apart from the quickwork, the purpose of protection is essentially decorative and aesthetic. This is true of the protection of the dead works, the masts of pleasure craft, and the hull and superstructures of commercial vessels on which the shipowner wishes to place his personal "brand".

It has long been recognised [1] that paint lasts longer on aluminium than on steel because the substrate is more resistant to corrosion (3), and this is true in a marine environment. However painting involves the regular maintenance of the paintwork with all of the surface preparation which this entails, and while this is perfectly feasible for accessible surfaces, it is less so for ballast tanks with complex shapes or surfaces that are broken up by stiffeners, frames etc., with welds making surfaces even more irregular.

One may as well say that only accessible areas should be repaired in the shipyard, as there is often little point in attempting to paint ballast tanks, water tanks etc. – once the paint here has deteriorated, it cannot be repaired.

Three types of protection are used almost exclusively in marine applications:

- anodising,
- painting, and
- cathodic protection.

(1) This also applies to the salts and the oxide of aluminium (alumina), so even the corrosion products of aluminium are not toxic.

(2) For the effect of fouling on corrosion behaviour, refer to Chapter 10.

(3) The fact that the corrosion products of aluminium – alumina – are white, almost colourless if pitting corrosion is very superficial, has little impact on the general appearance of a painted surface on which the paint has disappeared locally under the effect of corrosion. There is no comparison with the deterioration in the look of painted steel surfaces!

YACHT MASTS



OF ALUMINIUM

1. ANODISING

Anodising is a process of surface treatment which thickens the natural oxide film and is specific to aluminium. Alloys that belong to the 5000 and 6000 series have a metallic structure and chemical composition that are suitable for anodising.

A number of anodising techniques have been developed to improve the surface properties of the metal or adapt them to particular applications: decoration, resistance to corrosion, long-lasting appearance, surface hardness, resistance to abrasion, aptitude for friction and anti-adhesion, acceptance of organic coatings (adhesives, lacquers, paints).

In marine applications, it is primarily the decorative aspect that is important. Anodising prevents tarnishing and superficial pitting corrosion. This surface treatment is applied mainly to deadworks and the masts of pleasure craft.

Sulphuric anodising is the treatment most commonly used for decoration, for obtaining hard coatings and for enhancing corrosion behaviour.

The classical treatment parameters are:

- strength of H_2SO_4: 200 ± 20 $g.l^{-1}$
- level of dissolved aluminium in the bath: 15 $g.l^{-1}$ max.
- the bath is agitated to prevent temperature exceeding 20°C
- d.c. current density: 1.5 ± 0.1 $A.dm^{-2}$

This treatment is applied discontinuously to castings (mainly for deadworks), shapes (mainly for masts) and sheet (4) or continuously to strip.

The anodic films, whose structure is determined by the type of anodising bath and the treatment conditions, consist of hexagonal cells pierced by micropores whose diameter, e.g. for a coating of 15 microns, is about one thousandth their thickness (figure 137). These porous films are ideal for absorption colouring, either by dipping in the dye or by electrolytic coloration.

(4) Surface treaments are applied in facilities with a number of treatment baths in series. The size of the tanks that contain these baths is necessarily limited, to around fifteen metres for those used to treat boat masts.

YACHT ADRIEN, GLOBAL CHALLENGE



Whether they are coloured or not, the anodic films must be sealed to close the pores and so ensure excellent resistance to corrosion. This operation is done in pure distilled boiling water containing sealing additives. The quality of the anodising, i.e. its durability, depends largely on the sealing conditions (5) (6).

Standards define classes of anodising (for building applications) as a function of thickness, and specify what classes must be used depending on the atmosphere of the particular environment (7). In practice, a minimum film thickness of 20 microns is recommended in a sea atmosphere (class 20 minimum) [2].

Provided it is regularly serviced at least once a year by removing any deposits of dust and sea salt with products suitable for anodised aluminium, the "life" of a properly sealed 20 micron film will far exceed 20 years in a marine environment.

STRUCTURE OF THE ANODISED LAYER

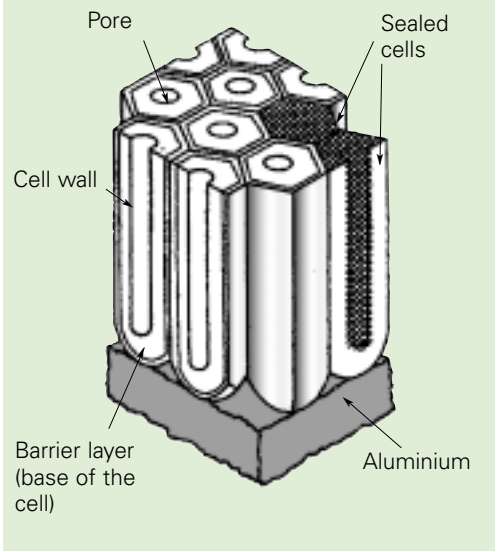


Figure 137

There are other anodising processes:

- hard anodising (with film thicknesses up to 100 microns) is normally used for technical applications as it offers good wear resistance in marine environments (8),
- thin-film phosphor anodising (a very useful surface preparation for adhesive bonding).

Note: Anodising does not remove the risk of bimetallic corrosion if an anodised aluminium piece is in contact with another metal in an aqueous medium.

(5) The anodised surface will not accept any other coating once it has been sealed – such a surface cannot be painted.

(6) In practice, the sealing time must be the same as the anodising time.

(7) Standard NF A 91-450: "Anodisation (oxydation anodique) de l'aluminium et de ses alliages. Couches anodiques sur aluminium," December 1981.

International standard ISO 7599: Anodizing of aluminium and its alloys – General specifications anodic oxide coatings on aluminium, 1983.

(8) Contrary to misconception, hard anodising is not done to protect aluminium from pitting corrosion. It offers no more protection than a conventional 20 micron film because it is almost never sealed and it is also much more expensive!

2. PAINTING

It is essential to remember that the natural oxide film which always covers the surface of aluminium prevents the adhesion of paints in particular and organic coatings in general. Its surface must therefore be prepared to create sites of adhesion – "bridges" – between the oxide film and the coating. Many years of experience show that the behaviour of coatings on aluminium depends on the surface preparation [3].

Applying paint to an aluminium alloy surface involves a number of steps:

2.1 Degreasing

The purpose of degreasing is to remove all foreign bodies, including solid particles (swarf, dust) and fatty products (oils, greases), which have infiltrated the metal's natural oxide film.

Degreasing with detergents (Teepol or equivalent type) is preferable to the use of organic solvents (9). Solvents that are too "light" such as acetone are not recommended as they are tricky to handle and highly flammable.

Degreasing should be done by treating small areas at a time, using clean lint-free cloths that are frequently replaced to ensure that impurities are removed rather than just spread around!

(9) Chlorinated solvents are used less and less for health and environmental reasons, and are likely to cause subsequent corrosion unless stabilised. They are not recommended for work in boatyards or marine applications.

2.2 Surface cleaning

There are three options:
- etching,
- cleaning with abrasive jet,
- disk grinding.

Etching

This involves chemically pickling the surface layer of aluminium so that it will accept the wash primer.

The etching medium is a phosphoric acid solution that is applied liberally to all the surfaces to be treated. It is applied with a brush, cloth or sometimes a mop, taking care to protect the operator from splashes.

After application, the medium must be left to act as directed by the manufacturer, usually for 20 to 30 minutes. The surfaces are then washed off with fresh water until the wash water returns to a pH level that is equivalent to that of water from a main.

Cleaning with abrasive jet

Cleaning with the abrasive jet (10) is carried out with an abrasive suitable for use on aluminium alloys, such as corundum or any other inert abrasive. This treatment must always be done on surfaces that are clean and dry, and be followed by thorough dust removal.

Surfaces should be painted as soon as possible following abrasive treatment to prevent the oxide film from absorbing moisture or the treated surfaces from attracting impurities.

Steel shot must not be used owing to the attendant risks of pitting corrosion. Abrasives that have already been used to treat metals other than aluminium should also be avoided for the same reason.

Disk grinding

This type of preparation is used on surfaces that cannot be treated by etching or abrasive cleaning. It must be carried out with coarse grit wheels to achieve a well keyed adhesive substrate.

However, coatings do not adhere to surfaces treated in this way as well as after etching or abrasive cleaning.

2.3 Painting

Effective protection against an aggressive marine environment is obtained by multi-layer coatings in which each coat contributes to the efficiency of the system. The types of paint most widely used at present are based on polyurethane or epoxy resins.

A typical system will consist of:
- a reactive primer, usually with a vinyl resin base and containing a certain amount of phosphoric acid. The primer ensures that the coatings adhere to the aluminium,
- finish coats whose purpose is to reinforce the water tightness of the paint system and enhance its appearance.

Finish coats should be applied with a compressed air spray gun.

(10) Incorrectly called sand or shot blasting.

(11) Due mainly to distortion caused by welding. Strict adherence to the rules governing aluminium welding as discussed in Chapter 6, will minimise the amount of filler on a hull.

2.4 Fillers

Special fillers are used to repair surface imperfections (11). Preference should be given to solvent-free epoxy fillers as these are perfectly suited to immersion and will not shrink as they harden.

Fillers should never be applied directly onto the metal but instead between successive coats of epoxy primer. Application is by spatula or more often using a float.

Once it has dried, the filler should be sanded using wet or dry abrasive paper. Some fillers may require washing with fresh water after curing, especially if this occurs at low temperature. All dust should be carefully removed from the surface before the next coat is applied.

SUNREEF 74



2.5 Antifouling paints

Aluminium and its mineral compounds such as alumina $Al(OH)_3$, the corrosion product of aluminium, are non toxic to marine flora and fauna.

The quickwork of an aluminium ship must therefore be coated with a marine antifouling paint in order to prevent deposits and encrustations of sea organisms such as mussels, barnacles and so forth.

As has been explained elsewhere (12), antifouling paints based on copper oxide must be avoided as they can severely corrode the underlying metal.

Since the early 1970s, the biocide used in most commercial antifouling paints has been based on a salt of tin, TBT (tributyl tin), which is compatible with aluminium.

In view of the toxicity of this biocide to the marine environment, on October 5, 2001 the IMO decided to ban TBT based antifouling paints from 1 January 2003, and from 1 January 2008 no vessel will be allowed to sail with its hull coated in these products (13).

A number of paint manufacturers have anticipated this ban and for several years have been making antifoul paints that are compatible with aluminium and that comply with the European Directive and the IMO's decision [4], e.g. JOTUN's ALUSEA being one of them.

2.6 Drinking water tanks

The chemical composition of the 5000 and 6000 series alloys that are commonly used for marine applications puts them among the "food-grade" materials (14).

They can therefore be used uncoated to make drinking water tanks. Before use however it is essential to thoroughly clean the walls of the tank and rinse them several times, preferably with hot drinking water.

Drinking water tanks may also be painted if desired, in which case the protection products must be supported by a manufacturer's certificate of safety.

2.7 Repairs and treatment procedures

There are two procedures to consider depending on the extent of the damage:

Procedure 1: the anti-corrosion primer has not been affected

- Degrease,
- Wash off carefully in fresh water,
- Dry,
- Apply filler to bring level,
- Sand with abrasive (grit 250-300) under water (generously around the damaged area but not down to the anti-corrosion primer),
- Re-apply the finish coat(s).

Procedure 2: the damage is more serious and bare metal has been exposed

- Degrease,
- Wash off carefully in fresh water,
- Sand with abrasive (grit 180-220) down to the metal, exposing a wide area around the affected zone,
- Apply wash-primer (reactive primer) to the areas of bare metal,
- Re-apply the complete paint system.

2.8 Application conditions, paint tests, health and safety requirements

As a general rule, paints should be applied:

- in a dust-free, draught-free environment,
- at temperatures above 15°C,
- at between 40 and 70% humidity.

Paint containers must be stored at approximately 20°C for at least 24 hours prior to use. Before commencing application it is advisable to ensure that the substrate is at least 3°C above dew point.

Painting and drying operations must be programmed as part of the overall production schedule in the same way as any other operation.

2.9 Testing paints

Paints can be tested for:

- Viscosity: This test is carried out with the flow cup according to AFNOR standard NF - T 30 070 (Ford cup No. 4) and is used to adjust the viscosity of the paint to suit the application technique (e.g. brush, spraygun) for finishing coats on dead works.
- Wet thickness: Wet film thickness is measured with comb gauges. The dry film thickness is then calculated from the result of this test and from the known dry extract by volume of the paint.

(12) Chapter 10.

(13) This decision followed on from European regulations banning the use of organostannic compounds (tin salts) since 1989 (Directive 89/677/EEC dated 21.12.1989).

(14) Standard EN 602. Aluminium and aluminium alloys – Wrought products. Chemical composition of semi-finished products used for the fabrication of articles for use in contact with foodstuff.

For example, a wet coat 100 microns thick must be applied to obtain a dry film thickness of 35 microns with a paint of 35% dry extract by volume.

If the application technique requires the paint to be thinned, then the dry film thickness will obviously be reduced for the same wet thickness. In this case it is advisable to increase the number of coats applied to achieve the total dry film thickness that is required. This point is particularly important for coats of primer.

2.10 Health and safety

In their instructions, suppliers of surface treatment products and paints indicate all of the precautions that must be taken for use and storage. They are also required by law to provide safety data sheets to any user who requests this information.

2.11 Examples of procedures recommended by Jotun

Procedures recommended by Jotun for quick work, dead work, decks and superstructures are shown in table 69 and the interior of ships in table 70.

JOTUN PROCEDURES FOR QUICKWORKS, DEAD WORKS, DECKS AND SUPERSTRUCTURE

Procedure	Quick Work	Dead works, decks, superstructure and exterior accessories
Surface preparation	Degrease with detergent (type Teepol or equivalent), Wash off with fresh water. Generally roughen all surfaces with non-metallic abrasive (corundum)*. This surface preparation must be confined to very small areas and should never be used on exterior planking.	
Primer	1 x 50 µm DFT Epoxy Primer	1 x 50 µm DFT Epoxy Primer
Finish	2 x 100 µm DFT Epoxy	1 x 100 µm DFT Epoxy 2 x 50 µm DFT Acryl Polyurethane Topcoat**
Antifouling	2 x 125 µm DFT Antifouling Selfpolishing Tin Free "special Aluminium", (non electrolytic pigments).	

** Note: Areas that cannot be roughened with non-metallic abrasive can be chemically pickled with a solution of phosphoric acid of the "deoxydine" type and then washed off.*
*** Note: A non-skid powder must be used between the two finish coats of acryl polyurethane on exterior decks.*

Table 69

JOTUN PROCEDURES FOR MACHINE COMPARTMENTS

Procedure	Ceiling divisions Interior decks	Sheet structures beneath ceilings	Sheet structures beneath engine room	Fresh water tanks
Surface preparation	Degrease with detergent type Teepol Wash off with fresh water.			
Primer	1 x 40 µm DFT Epoxy Primer			
Finishes	1 x 40 µm DFT Epoxy Undercoat White 1 x 40 µm DFT Acryl Polyurethane Topcoat		2 x 100 µm DFT Epoxy	2 x 150 µm DFT Epoxy (drinking water compliant)

Table 70

3. CATHODIC PROTECTION

This is an electrochemical form of protection in which the metal that is to be protected acts as the cathode (figure 138) on which H^+ ions are reduced (to gaseous hydrogen) according to the reaction:

$$2H^+ + 2e^- \rightarrow H_2$$

For this reaction to take place, *e⁻ electrons must be transferred to the metal*. There are two ways of doing this:

- Connecting another metal (or alloy) – the anode – whose dissolution potential is more electronegative in the particular environment, and which will oxidize according to the reaction:

$$2M \rightarrow 2M^{n+} + 2e^-$$

The electrons released in this way will flow to the cathode.

This reaction consumes the metal of the anode which is known as the "consumable" or "sacrificial" anode as a result.

On ships, anodes are usually castings designed to suit their method of attachment and their position on the vessel (photo p. 174).

- Installing a direct current source that supplies the flow of electrons needed for the reduction reaction on the metal that is to be protected. This is "cathodic protection by impressed current ".

3.1 Cathodic protection of aluminium

When it acts as the cathode, the metal's dissolution potential falls to values that are more electronegative than its normal dissolution potential. For an anode to be effective, the difference in potential between it and the metal which it must protect must be at least 100 to 200 mV. The impressed current system regulates both the required level of potential (relative to a reference electrode) and the flow of electrons.

The cathodic protection of aluminium is much more complex than that of steel even though the protection current for aluminium is one tenth of that needed to protect (unpainted) steel [5].

To protect aluminium, it must be reduced to levels of potential at which the reduction of ions H^+ accelerates. The effect of this reaction is to alkalinise the environment with an excess of OH^- ions, i.e. to cause local corrosion of the aluminium, referred to as "cathodic corrosion".

This "cathodic corrosion" (which is unwanted) has a particular appearance which makes it easy to recognise. On bare metal it generally develops as rounded craters whose surfaces can be quite shiny. If the metal is painted, the paint may blister (15).

Studies have shown that in order to obtain total protection, the potential of magnesium alloys such as 5083 or 5086 must be reduced to levels where – in sea water – cathodic corrosion develops strongly [6].

PRINCIPLE OF CATHODIC PROTECTION

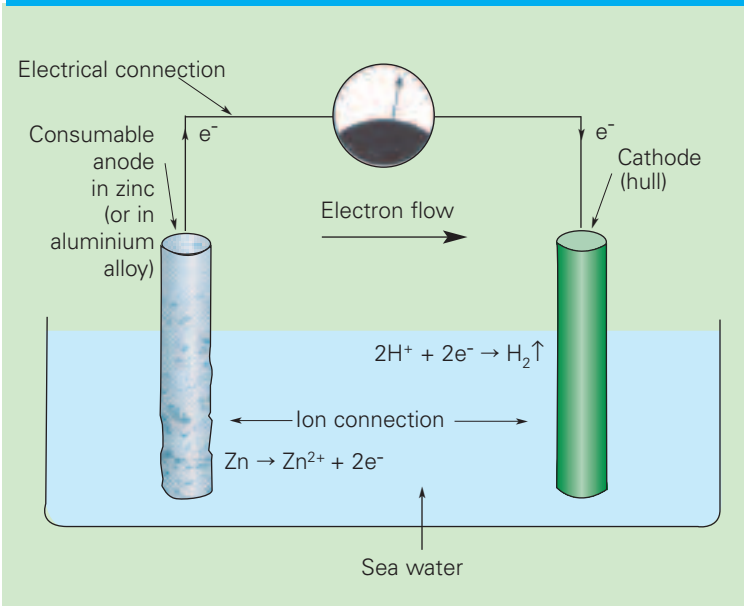


Figure 138

(15) But the converse is not true, i.e. a paint blister is not necessarily due to "cathodic corrosion".

3.2 Neutralisation of bimetallic couples

The very good corrosion resistance of aluminium-magnesium alloys of the 5000 and 6000 series in marine environments and specifically in immersion in sea water requires no protection in itself.

Whatever the vessel's system of propulsion however (conventional screw or hydrojet) cathodic protection will be needed to neutralise the bimetallic couple between the submerged aluminium alloy structure and propulsion components such as stainless steel shaft, bronze screw or steel hydrojet.

This is achieved by fitting sacrificial anodes whose weight and distribution on the hull will be determined individually for each craft by contractors who specialise in cathodic protection.

The task of these anodes is to reduce the electric potential of the bronze, stainless steel and other metals to more negative levels approaching those of aluminium (figure 139).

How the system works:
At the working point of the composite system formed by:
- the aluminium alloy hull,
- the screw and shaft (bronze and/or stainless steel) or steel hydrojet,
- the sacrificial anodes,

the anodes release a current such that the potential E_c of the metals (bronze, stainless steel) falls, as does the potential E_{al} of the aluminium. As a result, the potential of all the metals present in the vessel find a common level E_{pc}, thereby eliminating all risk of bimetallic corrosion to the aluminium alloy hull (or other structure).

Electric current flows, and so the anodes are consumed. The life of the anodes depends on a number of factors: the propulsion system, the surface to be protected, surface conditions and the temperature of the sea water, and so it is important to check the condition of the anodes whenever the boat is careened and replace them as necessary.

Choice of anodes:
The electric potential of aluminium must not be reduced by more than 200 to 300 millivolts (from its initial potential). The absolute lower limit generally accepted for the potential of aluminium is in the region of - 1100 mV SCE (16). Beyond this there is a serious risk of "cathodic corrosion".

This is why magnesium anodes should be avoided as they reduce the potential of the aluminium too far.

Anodes made from special aluminium alloys such as "Hydral" or "Mercatal" and from zinc on the other hand are very suitable and are widely used.

Notes:
For the cathodic protection of the submerged aluminium alloy structure to be effective, it is essential that:
- the boat's propulsion system is equipotentially bonded to the hull (17)
- the anodes are never painted and the anode and hull are in perfect contact.

Finally, the use of an impressed current system on an aluminium alloy ship is not advisable, as such systems are difficult to handle and pose too many risks for an aluminium hull unless they are carefully designed and correctly set up.

Everything that we have said about the cathodic protection of a ship also applies to a fixed structure that is immersed in sea water and that requires this form of protection. It goes without saying that cathodic protection will only work for the immersed part of the structure.

3.3 Quayside protection of pleasure craft

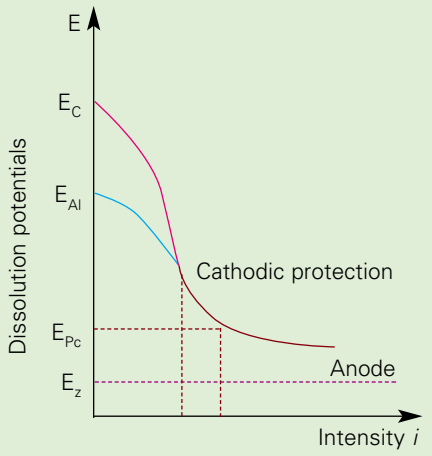
In marinas, aluminium boats may well find themselves close to or in actual contact with quays made from steel or reinforced concrete and with steel boats as well, and any sufficiently conductive contact between them can cause bimetallic corrosion of the aluminium hull.

To prevent this risk, some companies supply mobile or pendant anode systems designed to be put in place while pleasure craft are wintering. These systems are ideal for pleasure boats that are tied up at the same place for long periods of time.

(16) mV CSE = millivolts measured versus the saturated calomel electrode.

(17) Cf. Chapter 10.

NEUTRALISATION OF BIMETALLIC COUPLES



E_C = Potential of other métal (copper, stainless steel…)
E_{AL} = Potential of aluminium
E_{PC} = Potential of the cathodic protection
E_Z = Potentiel of the anode

Figure 139

Bibliography

[1] "Painting Aluminum and its alloys", J. D. Edwards, R. I. Wray, Aluminum Research Laboratories, New Kensington, Pa. *Industrial and Engineering Chemistry*, vol. 27, 1935, pp. 145-149.

[2] "Anodized Aluminium, atmospheric exposure tests", CIDA, H. Campbell, Euston 20 years, Aluminium Federation Ltd, Birmingham, report HC 8509/1, June 1987.

[3] "La protection de l'aluminium et de ses alliages par peinture", A. Guilhaudis, R. Bourbon, *Revue de l'Aluminium,* vol. 31, n° 206, 1954, pp. 7-10 et n° 207, pp. 47-51.

[4] "Effective antifouling is critical to performance", P. Hynds, *Speed at Sea,* April 1999, pp. 29-31.

[5] "Cathodic protection of aluminium in sea water", R. Gundersen, K. Nisancioglu, *Corrosion*, vol. 46, n° 4,1990, pp. 279-285.

[6] "Diagramme expérimental potentiel pH de l'aluminium pour l'eau de mer" , Ph. Gimenez, J. J. Rameau, M. Reboul, *Revue de l'Aluminium,* juin 1982, pp. 261-272.

CATHODIC PROTECTION



Chapter 12
APPENDIX

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1.1 STANDARDS OF MECHANICAL PROPERTIES

The standard mechanical properties listed below have been taken from

- EN 485 – 2: Aluminium and aluminium alloys – Sheet, strip and plate – Part 2: Mechanical properties
- EN 1386: Aluminium and aluminium alloys – Tread plate, Specifications
- EN 755 – 2: Extruded rod/bar, tube and profiles – Mechanical properties

ALLOY 5454										
Semi Products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet and Plate	O – H111	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 80	215 215 215	275 275 275	85 85 85		17 18	 16		1,5 t 2,5 t
	H24 – H34	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 25,0	270 270 270	325 325 325	200 200 200		7 5	 7		3,0 t 4,0 t
Extruded Profile	F/H112	t ≤ 25	200		85		16	14		
Extruded Tube	F/H112	t ≤ 25	200		85		16	14		
	O/H111	t ≤ 25	200	275	85		18	15		
Extruded Bar	F/H112	D ≤ 200 C ≤ 200	200 200		85 85		16 16	14 14		
	O/H111	D ≤ 200 C ≤ 200	200 200	275 275	85 85		18 18	16 16		

Table I

ALLOY 5754										
Semi Products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet and Plate	O / H111	3,0 < t ≤ 6,0	190	240	80		18		1,0 t	1,0 t
		6,0 < t ≤ 12,5	190	240	80		18			2,0 t
	12,5 < t ≤ 100	190	240	80			17			
	H24 – H34	3,0 < t ≤ 6,0	240	280			8			2,5 t
		6,0 < t ≤ 12,5	240	280			10			3,0 t
		12,5 < t ≤ 25	240	280				8		
Tread Plate	H114	1,5 < t ≤ 3,0	190	260	80		10			2,0 t
		3,0 < t ≤ 6,0	190	260	80		12			2,0 t
		6,0 < t ≤ 20	190	260	80		14	15		
Extruded Profile	F/H112	t ≤ 25	180		80		14	12		
Extruded Tube	F/H112	t ≤ 25	180		80		14	12		
	O/H111	t ≤ 25	180	50	80		17	15		
Extruded Bar	F/H112	D ≤ 150	180		80		14	12		
		150 < D ≤ 200	180		70		13			
		C ≤ 150	180		80		14	12		
		150 < C ≤ 200	180		70		13			
	O/H111	D ≤ 150	180	250	80		17	15		
		C ≤ 150	180	250	80		17	15		

Table II

ALLOY 5086										
Semi Products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet and Plate	O / H111	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 150	240 240 240	310 310 310	100 100 100		15 17	 16	1,5 t	1,5 t 2,5 t
	H116	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 50	275 275 275		195 195 195		9 10	 9		2,5 t 3,5 t
	H24 – H34	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 25,0	300 300 300	360 360 360	220 220 220					3,5 t 4,5 t
Tread Plate	H114	1,5 < t ≤ 3,0 3,0 < t ≤ 6,0 6,0 < t ≤ 20,0	240 240 240	310 310 310	100 100 100		8 10 12	 16		2,0 t 2,5 t
	H116	1,5 < t ≤ 3,0 3,0 < t ≤ 6,0 6,0 < t ≤ 20,0	275 275 275		195 195 195		4 5 6	 9		4,0 t 4,5 t
	H244	1,5 < t ≤ 3,0 3,0 < t ≤ 6,0 6,0 < t ≤ 20,0	300 300 300	360 360 360	220 220 220		2 3 4	 5		4,5 t 5,5 t
Extruded Profiles	F/H112	all	240		95		10	10		
Extruded Tube	F/H112	all	240		95		12	10		
	O/H111	all	240	340	95		18	15		
Extruded Bar	F/H112	D ≤ 250 C ≤ 250	240 240		95 95		12 12	10 10		
	O/H111	D ≤ 250 C ≤ 200	240 240	320 320	95 95		18 18	15 15		

Table III

ALLOY 5083										
Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet and Plate	O / H111	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 50,0 50,0 < t ≤ 80,0 80,0 < t ≤ 120,0	275 275 275 270 260	350 350 350 345	125 125 125 115 110		15 16	 15 14 12		1,5 t 2,5 t
	H116	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 40,0 40 < t ≤ 80,0	305 305 305 285		215 215 215 200		10 12	 10 10		2,5 t 4,0 t
Extruded Profile	F	all	270		110		12	10		
	H112	all	270		125		12	10		
Extruded tube	F	all	270		110		12	10		
	O/H111	all	270	350	110		14	12		
	O/H112	all	270		125		12	10		
Bar	F	D ≤ 250 200 < D ≤ 250 C ≤ 250 200 < C ≤ 250	270 260 270 260		110 100 110 100		12 12 12 12	10 10 		
	O/H111	D ≤ 200 C ≤ 200	270 270	350 350	110 110		14 14	12 12		
	H112	D ≤ 200 C ≤ 200	270 270		125 125		12 12	10 10		

Table IV

ALLOY 5383

Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet	O / H111	3,0 < t ≤ 6,0	290	360	145		15			1,5 t
and		6,0 < t ≤ 12,5	290	360	145		16			2,5 t
Plate		12,5 < t ≤ 50,0	290	360	145			15		
		50,0 < t ≤ 80,0	285	355	135			14		
		80,0 < t ≤ 120,0	275		130			12		
		120,0 < t ≤ 150,0	270		125			12		
	H116 (*)	3,0 < t ≤ 6,0	305		220			10		2,5 t
		6,0 < t ≤ 12,5	305		220			12		4,0 t
		12,5 < t ≤ 40,0	305		220				10	
		40 < t ≤ 80,0	285		205				10	

(*) Sealium®

Table V

ALLOY 6060										
Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	mini	maxi	mini	maxi	A_{50}	A	180 °	90 °
Extruded Profile	T4	t ≤ 25	120		60		16	14		
	T5	t ≤ 5 5 < t ≤ 25	160 140		120 100		8 8	6 6		
	T6	t ≤ 3 5 < t ≤ 25	190 170		150 140		8 8	6 6		
Extruded Tube	T4	t ≤ 15	120		60		16	14		
	T5	t ≤ 15	160		120		8	6		
	T6	t ≤ 15	190		150		8	6		
Extruded Bar	T4	D ≤ 150	120		60		16	14		
	T4	C ≤ 150	120		60		16	14		
	T5	D ≤ 150	160		120		8	6		
	T5	C ≤ 150	160		120		8	6		
	T6	D ≤ 150	190		150		8	6		
	T6	C ≤ 150	190		150		8	6		

Table VI

ALLOY 6005A										
Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Extruded Profile open	T4	t ≤ 25	180		90		15	13		
	T6	t ≤ 5 5 < t ≤ 10 10 < t ≤ 25	270 260 250		225 215 200		8 8 8	6 6 6		
Extruded Profile hollow	T4	t ≤ 10	180		90		15	13		
	T6	t ≤ 5 5 < t ≤ 15	255 250		215 200		8 8	6 6		
Extruded Tube	T6	t ≤ 5 5 < t ≤ 10	270 260		225 215		8 8	6 6		
Extruded Bar	T6	D ≤ 25 25 < D ≤ 50 50 < D ≤ 100 C ≤ 25 25 < C ≤ 50 50 < C ≤ 100	270 270 260 270 270 260		225 225 215 225 225 215		10 8 8 10 8 8	8 8 		

Table VII

ALLOY 6063										
Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Extruded Profile	T4	t ≤ 25	130		65		14	12		
	T5	t ≤ 3 10 < t ≤ 25	175 160		130 110		8 7	6 5		
	T6	t ≤ 10 10 < t ≤ 25	215 195		170 160		8 8	6 6		
Extruded Tube	O/H111	t ≤ 25		130			18	16		
	T4	t ≤ 10 10 < t ≤ 25	130 120		65 65		14 12	12 10		
	T5	t ≤ 25	175		130		8	6		
	T6	t ≤ 25	215		170		10	8		
Extruded Bar	O/H111	D ≤ 200 C ≤ 200		130 130			18 18	16 16		
	T4	D ≤ 150 C ≤ 150 150 < D ≤ 200 150 < C ≤ 200	130 130 120 120		65 65 65 65		14 14 12 12	12 12		
	T5	D ≤ 200 C ≤ 200	175 175		130 130		8 8	6 6		
	T6	D ≤ 150 C ≤ 150 150 < D ≤ 200 150 < C ≤ 200	215 215 195 195		170 170 160 160		10 10 10 10	8 8		

Table VIII

ALLOY 6082

Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet and Plate	O	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 25,0		150 150 155		85 85	18 17	 16		1,0 t 2,0 t
	T4	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5	205 205		110 110		15 14			3,0 t 4,0 t
	T6	3,0 < t ≤ 6,0 6 < t ≤ 12,5	310 310		260 255		10 9			4,5 t 6,0 t
Extruded Profile	O/H111	toutes		160		110	14	12		
	T4	t ≤ 25,0	205		110		14	12		
opent	T5	t ≤ 5,0	270		230		8	6		
	T6	t ≤ 5,0 5 < t ≤ 25	290 310		250 260		8 10	6 8		
closed	T5	t ≤ 5	270		230		8	6		
	T6	5 < t ≤ 15	310		260		10	8		
Extruded Tube	O/H111	t ≤ 25		160		110	14	12		
	T4	t ≤ 25	205		110		14	12		
	T6	t ≤ 5 5 < t ≤ 25	290 310		250 260		8 10	6 8		
Extruded Bar	O/H111	D ≤ 200 C ≤ 200		160 160		110 110	14 14	12 12		
	T4	D ≤ 200 C ≤ 200	205 205		110 110		14 14	12 12		
	T6	D ≤ 20 C ≤ 20 20 < D ≤ 150 20 < C ≤ 150 150 < D ≤ 200 150 < C ≤ 200 200 < D ≤ 250 200 < C ≤ 250	295 295 310 310 280 280 270 270		250 250 260 260 240 240 200 200		8 8 8 8 6 6 6 6	6 6		

Table IX

ALLOY 6061										
Semi products	Temper	Dimension (mm)	Rm (MPa)		$Rp_{0,2}$ (MPa)		A% min		Bending radius	
		Diameter D Thickness t Width across flats C	min	max	min	max	A_{50}	A	180 °	90 °
Sheet and Plate	O	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5 12,5 < t ≤ 25,0		150 150 150		85 85	9 16	 16		1,0 t 2,0 t
	T4	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5	205 205		110 110		16 18			3,0 t 4,0 t
	T6	3,0 < t ≤ 6,0 6,0 < t ≤ 12,5	290 290		240 240		10 9			4,0 t 5,0 t
Extruded Profile	T4	t ≤ 25	180		110		15	13		
Profile		T6 5 < t ≤ 25	t ≤ 5,0 260	260	 240	240	 10	9 8	7	
Extruded Tube	O/H111	t ≤ 25		150		110	16	14		
	T4	t ≤ 25	180		110		15	13		
	T6	t ≤ 5 5 < t ≤ 25	260 260		240 240		8 10	6 8		
Extruded Bar	O/H111	D ≤ 200 C ≤ 200		150 150		110 110	16 16	14 14		
	T4	D ≤ 200 C ≤ 200	180 180		110 110		15 15	13 13		
	T6	D ≤ 200 C ≤ 200	260 260		240 240		8 8	6 6		

Table X

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3. ENGLISH / FRENCH / GERMAN / SPANISH GLOSSARY

N°	English	French	German	Spanish
1.	As-quenched and naturally aged temper	Etat trempé mûri	Abgeschreckt und ausgelagert	Templado templado y madurado
2.	Age hardening	Durcissement structural	Aushärtung	Endurecimiento estructural
3.	Air quenching	Trempe à l'air	Luftabschrecken	Temple al aire
4.	Alloy	Alliage	Legierung	Aleacion
5.	Alloying element	Elément d'addition	Legierungselement	Elemento de adicion
6.	Aluminium	Aluminium	Aluminium	Aluminio
7.	Aluminium alloy	Alliage d'aluminium	Aluminiumlegierung	Aleacion de aluminio
8.	Annealing	Recuit	Glühung	Recocido
9.	Anodizing	Anodisation	Anodisation	Anodizacion
10.	Artificial ageing	Revenu	Warmauslagerung	Revenido
11.	Artificially aged	Etat revenu	Warmausgehärtet	Estado revenido
12.	As-quenched condition	Brut de trempe	Abgeschreckt	Bruto de temple
13.	As-quenched condition	Trempe fraiche	Frische Abschreckhärtung	Temple al agua
14.	As-quenched temper	Etat trempé	Abgeschreckter Zustand	Estado templado
15.	Bar, Rod	Barre	Stab, Stange	Barra
16.	Bending radius	Rayon de pliage	Biegeradius	Radio de plegado
17	Bending	Pliage	Falten	Plegado
18.	Bending	Cintrage	Biegen	Doblado
19.	Bevel	Chanfrein (de soudure)	Abschrägung	Chaflan de soldadura
20.	Blackening	Noircissement	Schwärzung, Trübung	Ennegrecimiento
21.	Blankholder	Serre flan	Niederhalter	Pisador
22.	Bonding	Collage	Kleben	Pegado
23.	Bow	Flèche longitudinale	Längsdurchbiegung	Flecha longitudinal
24.	Brittleness	Fragilité	Sprödigkeit	Fragilidad
25.	Brushing	Brossage	Bürsten	Cepillado
26.	Buckling	Flambement	Knicken	Flameado
27.	Buffing	Polissage au disque	Schwabbeln	Pulido al disco
28.	Burr	Bavure	Grat	Rebabas
29.	Cast	Coulée	Abguß	Colada
30.	Casting	Moulage	Guß	Fundicion
31.	Casting alloy	Alliage de moulage	Gußlegierung	Aleacion para moldeo
32.	Chemical conversion	Conversion chimique	Chemische Konversion	Conversion quimica
33.	Chemical polishing	Polissage chimique	Chemisches Polieren	Pulido quimico
34.	Clad sheet	Tôle plaquée	Plattiertes Blech	Chapa placada
35.	Cladding	Placage	Plattierung	Plaqueado
36.	Clinching	Clinchage	Clinchen	Clisado
37.	Clipping	Ebarbage	Entgratung	Desbarbado

N°	English	French	German	Spanish
38.	Coating	Revêtement	Beschichten	Revestimiento
39.	Coil	Bande	Band	Banda
40.	Coil coating	Revêtement en bande	Bandbeschichtung	Revestimiento en banda
41.	Cold working,Strain hardening	Ecrouissage	Kaltverfestigung	Endurecinento por conformacion
42.	Controlled strectching	Traction controlée	Kontrolliertes Recken	Traccion controlada
43.	Cooling	Refroidissement	Abkühlung	Enfriamiento
44.	Corrosion	Corrosion	Korrosion	Corrosion
45.	Crack	Fissure	Riß	Fisura
46.	Creep	Fluage	Plastisches Fließen	Flujo
47.	Crevice corrosion	Corrosion caverneuse	Spaltkorrosion	Corrosion cavernosa
48.	Crevice corrosion	Corrosion sous dépôt	Belagkorrosion	Corrosion por almacenmiento
49.	Critical quenching rate	Vitesse critique de trempe	Kritische Abschreckgeschwindigkeit	Velocidad critica de temple
50.	Critical strain	Ecrouissage critique	Kritischer Verformungsgrad	Endurecinento critico
51.	Crown	Bombé	Bombierung	Abombado
52.	Cutting	Découpage	Schneiden	Cortado
53.	Defect	Défaut	Qualitätsmangel	Defecto
54.	Degreasing	Dégraissage	Entfettung	Desengrasado
55.	Desensitization	Désensibilisation	Desensibilisierungsglühung	Desensibilizacion
56.	Destructive test	Essai destructif	Zerstörungsprüfung	Ensayo destructivo
57.	Die forging	Matriçage	Gesenkschmieden	Matrizado
58.	Die scores	Rayure de filière	Preßriefen	Rayado de hilera
59.	Dilatation	Dilatation	Wärmedehnung	Dilatacion
60.	Dissolution potential	Potentiel de disssolution	Auflösungspotential	Potencial de disolucion
61.	Drawing	Emboutissage	Tiefziehen	Embuticion
62.	Drawing	Etirage	Ziehen	Estirado
63.	Drawn tube	Tube étiré	Kaltgezogenes Rohr	Tubo estirado
64.	Ductility	Ductilité	Duktilität	Ductilidad
65.	Eddy current test	Essai par courants de Foucault	Wirbelstromprüfverfahren	Ensayo corriente de Foucault
66.	Edge trimming	Ebavurage	Abgraten, Entgraten	Desbardado
67.	Electrical conductivity	Conductivité électrique	Elektrische Leitfähigkeit	Conductividad electrica
68.	Electrical resistivity	Résistivité électrique	Spezifischer elektrischer Widerstand	Resistidad electrica
69.	Elongation	Allongement	Dehnung	Alargamiento
70.	Exfoliation corrosion	Corrosion exfoliante Corrosion feuilletante	Schichtkorrosion	Corrosion exfoliante/escamosa
71.	Extruded profile	Profilé filé	Vollprofil	Perfil
72.	Extruded rod/bar	Barre filée	Stranggepreßte Stange	Barra extruida
73.	Extruded tube	Tube filé	Stranggepreßtes Rohr	Tubo extruido
74.	Extrusion	Filage	Strangpressen	Extrusion
75.	Extrusion die	Filière	Preßmatrize	Hilera
76.	Extrusion press	Presse à filer	Strangpresse	Prensa extrusion

N°	English	French	German	Spanish
77.	Fatigue	Fatigue	Ermüdung	Fatiga
78.	Fatigue limit	Limite de fatigue	Dauerfestigkeit	Limite de fatiga
79.	Fatigue strength	Résistance à la fatigue	Dauerfestigkeit, Ermüdungsfestigkeit	Resistencia a la fatiga
80.	Fitup	Accostage	Anlegen	Acercamiento
81.	Flash annealing	Recuit flash	Stoßglühung	Recocido flash
82.	Flatness	Planéité	Ebenheit	Planeidad
83.	Flattening	Planage	Richten	Aplanado
84.	Flowturning	Fluotournage	Drückwalzen	Fluortorneado
85.	Forming, Shaping,	Mise en forme	Formen	Conformado
86.	Fracture toughness Toughness,	Ténacité	Bruchzähigkeit, Zähigkeit	Resistencia a la fissura
87.	Galvanic corrosion	Corrosion galvanique	Galvanische Korrosion	Corrosion galvanica
88.	Gauge	Calibre	Kaliber, Blechdicke	Calibre
89.	Gouging	Gougeage	Fugenhobeln	Acanalado
90.	Grade	Classe	Güte	Clase
91.	Grain	Grain	Korn	Grano
92.	Grain growth	Grossissement du grain	Kornwachstum	Crecimiento grano
93.	Grain size	Taille de grain	Korngröße	Tamano del grano
94.	Grinding	Meulage	Schleifen	Esmerilado
95.	Half hard temper	Etat demi dur	Halbhart-Zustand	Estado semi duro
96.	Hand forging	Forgeage	Schmieden	Forjado
97.	Hard temper	Etat quatre quart dur	Hart-Zustand	Estado duro
98.	Hardness	Dureté	Härte	Dureza
99.	Hart anodizing	Anodisation dure	Hartanodisation	Anodizacion dura
100.	Heat treatment	Traitement thermique	Wärmebehandlung	Tratamiento termico
101.	Heat-affected zone	Zone affectée thermiquement	Wärmeeinflußzone	Zona afectada termicamente
102.	Heat-treatable alloy	Alliage à durcissement structural	Aushärtbare Legierung	Aleacion tratable térmicamente
103.	Hollow shape	Profilé creux	Hohlprofil	Perfil hueco
104.	Hollow-ware manufacture	Chaudronnage	Blechverarbeitung	Caldederia
105.	Homogenization	Homogénéisation	Homogenisierung	Homogeneizacion
106.	Hot rolled sheet	Tôle laminée à chaud	Warmwalzblech	Chapa laminada en caliente
107.	Hot rolled temper (F)	Etat brut de laminage à chaud (F)	Warmwalzzustand (F)	Estado bruto de laminado en caliente
108.	Hot shortness	Fragilité à chaud	Warmbrüchigkeit	Fragilidad en caliente
109.	Impact resistance, Shock resistance	Résistance au choc	Schlagfestigkeit	Resistencia al choque
110.	Inspection	Contrôle	Kontrolle	Control
111.	Intercrystalline corrosion	Corrosion intercristalline	Interkristalline Korrosion	Corrosion intercristalina
112.	Intergranular corrosion	Corrosion intergranulaire	Korngrenzenkorrosion	Corrosion intergranular
113.	Laquering	Vernissage	Transparentlackieren	Bamizado
114.	Lateral bow, Lateral curvature	Flèche latérale	Abweichung von der Geradheit	Flecha lateral

N°	English	French	German	Spanish
115.	Length	Longueur	Länge	Largo
116.	Long transverse direction	Sens travers long	Längs-Querrichtung	Direccion transversal larga
117.	Longitudinal direction	Sens long	Längsrichtung	Direccion longitudinal
118.	Machining	Usinage	Spanabhebende Bearbeitung	Mecanizado
119.	Mechanical polishing	Polissage mécanique	Mechanisches Polieren	Pulido mecanico
120.	Mechanical properties	Caractéristiques mécaniques	Mechanische Eigenschaften	Caracteristicas mecanicas
121.	Metal	Métal	Metall	Metal
122.	Microstructure	Microstructure	Mikrogefüge	Microestructura
123.	Milling	Fraisage	Fräsen	Fresado
124.	Modulus of elasticity	Module d'élasticité	Elastizitätsmodul	Modulo elastico
125.	Natural ageing	Maturation	Kaltauslagerung	Maduracion
126.	Natural oxide film	Film d'oxyde naturel	Natürliche Oxidhaut	Capa oxido natural
127.	Natural oxyde film	Oxyde naturel	Natürliche Oxidschicht	Oxido natural
128.	Non destructive testing	Essai non destructif	Zerstörende Prüfung	Ensayo no destrutivo
129.	Over-ageing	Sur revenu	Überalterung	Sobre revenido
130.	Overheating	Surchauffe	Überhitzung	Sobrecalentamiento
131.	Packaging	Emballage	Verpackung	Embalage
132.	Painted sheet	Tôle laquée	Lackiertes Blech	Chapa lacada
133.	Painting	Peinture	Decklackieren	Pintura
134.	Partial annealing	Restauration	Anlassen auf Zustand, Erholung	Restauracion
135.	Partially annealed	Etat restauré	Rückgeglühter Zustand	Estado restaurado
136.	Penetration test	Ressuage	Penetrationstest	Resudacion
137.	Percentage elongation	Allongement pour cent	Dehnung in Prozent	Porcentaje de alargamiento
138.	Permanent set	Déformation permanente	Bleibende Verformung	Deformacion permanente
139.	Physical properties	Propriétés physiques	Physikalische Eigenschaften	Propiedades fisicas
140.	Pickling	Décapage	Beizen	Decapado
141.	Piting	Piqûre (de corrosion)	Lochfraßstelle	Corrosion superficial
142.	Pitting corrosion	Corrosion par piqûre	Lochfraßkorrosion	Corrosion por picadas
143.	Plate	Tôle épaisse	Dickes Blech, Platte	Chapa alto espesor
144.	Polishing	Polissage	Polierung	Pulido
145.	Porosity	Porosité	Porosität	Porosidad
146.	Porthole die	Filière à pont	Kammerwerkzeug	Hilera al puente
147.	Pre-ageing	Pré revenu	Vorauslagerungsbehandlung	Pre-revenido
148.	Press	Presse	Presse	Prensa
149.	Press brake	Presse à plier	Biegepresse	Plegadora
150.	Press quenching	Trempe sur presse	Abschrecken aus der Preßhitze	Temple sobre prensa
151.	Primer	Primaire	Primer	Primario
152.	Proof stress (Rp)	Limite conventionnelle d'élasticité (Rp)	Dehngrenze bei nichtproportionaler Verlängerung (Rp)	Limite elastico convencional
153.	Quarter hard temper	Etat quart dur	Viertelhart-Zustand	Estado un quarto duro
154.	Quenching	Trempe	Abschrecken	Temple

N°	English	French	German	Spanish
155.	Recovery annealing	Recuit de restauration	Erholungsglühen	Recocido de restauracion
156.	Recrystallisation annealing	Recuit de recristallisation	Rekristallisationsglühung	Recocido de recristalizacion
157.	Recrystallization	Recristallisation	Rekristallisation	Recristalizacion
158.	Recycling	Recyclage	Recycling	Reciclado
159.	Residual stress	Contrainte résiduelle	Restspannung	Tension residual
160.	Rivet	Rivet	Niete	Remache
161.	Rod	Barre ronde	Rundstange	Barra redonda
162.	Roller levelling	Planage à rouleaux	Rollrichten	Aplanado con rodillos
163.	Rolling	Laminage	Walzen	Laminado
164.	Sample	Echantillon	Muster	Muestra
165.	Sand blasting	Sablage	Sandstrahlen	Arenado
166.	Sawing	Sciage	Sägen	Serrado
167.	Scoring	Rayure	Riefen	Rayado
168.	Scrap	Déchets	Schrott	Chatarras
169.	Sealing	Colmatage	Verdichten	Colmataje
170.	Seamless tube	Tube sans soudure	Nahtloses Rohr	Tubo sin soldadura
171.	Semifinished product	Demi-produit	Halbzeug	Semi-producto
172.	Shape	Forme	Form	Forma
173.	Shear strength	Résistance au cisaillement	Kritische Scherspannung	Resistencia al cizallado
174.	Shearing	Cisaillement	Abscherung	Cizallado
175.	Sheet	Tôle	Blech	Chapa
176.	Short transverse direction	Sens travers court	Kurz-Querrichtung	Direccion traversal corta
177.	Shot blasting, Blast cleaning	Grenaillage	Strahlen	Granallado
178.	Slitting	Refendage	Längsteilen, Spalten	Cortado longitudinal
179.	Soft annealing	Recuit d'adoucissement	Weichglühung	Recocido para alisado
180.	Soft temper (O)	Etat recuit (O)	Geglüht-Zustand (O)	Estado recocido
181.	Solid shape	Profilé plein	Strangpreßprofil	Perfil macizo
182.	Solution treatment	Mise en solution	Lösungsglühen	Disolucion
183.	Specification	Spécification	Spezifikation	Especificacion
184.	Spinning	Repoussage	Flachprägen, Metalldrücken	Repulsado
185.	Spot welding	Soudage par point	Punktschweißen	Soldadura por puntos
186.	Squareness	Equerrage	Rechtwinkligkeit	Escuadrado
187.	Stabilized temper	Etat stabilisé	Stabilisierter Zustand	Estado estabilizado
188.	Standard	Norme	Norm	Norma
189.	Storage	Stockage	Lagerung	Almacenamiento
190.	Straightening	Dressage	Richten	Enderezado
191.	Straightness	Rectitude	Geradheit	Rectitud
192.	Strain	Déformation	Verformung	Deformacion en caliente
193.	Strain hardened temper	Etat écroui	Kaltverfestigter Zustand	Endurecido en frio

N°	English	French	German	Spanish
194.	Strain hardening	Durcissement par écrouissage	Verfestigung	Endurelimiento por conformacion en frio
195.	Strain-hardening alloy	Alliage à durcissement par écrouissage	Kaltverfestigende Legierung	Aleacion endurecida por conformacion en frio
196.	Streak	Strie	Streifen, Zeile	Estria
197.	Stress	Contrainte	Spannung	Tension
198.	Stress corrosion	Corrosion sous contrainte	Spannungsrißkorrosion	Corrosion bajo tension
199.	Stretching	Traction	Recken, Reckrichten	Traccion
200.	Surface condition	Etat de surface	Oberflächenbeschaffenheit	Estado superficial
201.	Surface milling	Surfaçage	Fräsung	Mecanizado superficial
202.	Surface roughness	Rugosité superficielle	Oberflächenrauheit	Rugosidad superficial
203.	Surface traitement	Traitement de surface	Oberflächenbehandlung	Tratamiento superficial
204.	Temper	Etat (métallurgique)	Werkstoffzustand	Estado (metalurgico)
205.	Tensile strength	Résistance à la traction	Zugfestigkeit	Resistencia a la traccion
206.	Tension levelling	Planage sous tension	Bandrecken, Reckbiegerichten	Aplanado bajo tension
207.	Test	Essai	Prüfung	Ensayo
208.	Texture	Texture	Textur	Textura
209.	Thermal conductivity	Conductivité thermique	Wärmeleitfähigkeit	Conductividad termica
210.	Thickness	Epaisseur	Wanddicke	Espesor
211.	Three quarter hard temper	Etat trois quart dur	Dreiviertelhart-Zustand	Estado très quarto duro
212.	Tolerance	Tolérance	Toleranz, Grenzabmaß	Tolerancia
213.	Traffic marks	Fretting corrosion	Transportscheuerstellen	Marcos de friccion
214.	Transverse direction	Sens travers	Querrichtung	Direccion tranversal
215.	Tread plate	Tôle relief	Warzenblech, Trittblech	Chapa relieve
216.	Tube	Tube	Rohr	Tubo
217.	Ultimate tensile strength	Charge de rupture	Zugfestigkeit	Carga de rotura
218.	Ultrasonic test	Contrôle ultra-sons	Ultraschallprüfung	Control ultra sonido
219.	Under-ageing	Sous revenu	Unteralterung	Subrevenido
220.	Water stain	Corrosion lors du stockage	Wasserflecken	Corrosion durante el stock
221.	Water staining	Ternissement	Trübung	Deslucimiento
222.	Weathering	Corrosion atmosphérique	Atmosphärische Korrosion	Corrosion atmosférica
223.	Weldability	Soudabilité	Schweißbarkeit	Soldabilidad
224.	Welded tube	Tube soudé	Längsnahtgeschweißtes Rohr	Tubo soldado
225.	Welding	Soudage	Schweißen	Soldadura
226.	Welding wire, Filler wire	Fil d'apport	Schweißdraht	Hilo de aportacion
227.	Width	Largeur	Breite	Ancho
228.	Work hardening	Corroyage	Verschmiedungsgrad	Fresado
229.	Working	Transformation	Umformung	Transformacion
230.	Wrought alloy	Alliage de corroyage	Knetlegierung	Aleacion de fresado
231.	Wrought product	Produit corroyé	Kneterzeugnis	Producto modelado
232.	Yield strength	Limite apparente d'élasticité	Streckgrenze	Limite elastico aparente

4. KEY AND PHOTO CREDITS



Rodriquez Cantieri Navali

Page 4

THE PRINCESS

Built by Rodriquez, Italy
Monohull HSV type
Aquastrada TMV84
Launched in 2003
Aluminium hull and superstructure
Length over all: 83.35 m,
beam: 13.50 m, draft: 1.76 m
Speed: 39 knots
Capacity: 462 passengers and
58 cars.

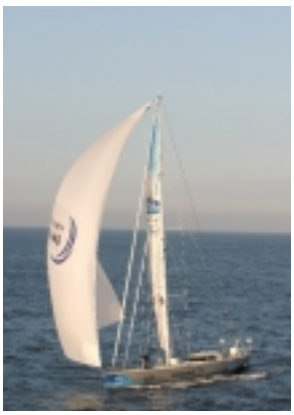


Tranz Rail

Page 5

THE LYNX

Built by Incat Tasmania PTY Ltd,
Australia
Type: HSV Catamaran
Aluminium hull
Overall length: 97.22 m,
beam: 26.60 m, draught: 3.42 m
Speed: 38 knots with a payload
of 750 t and 42 knots
with a 375 t payload
Capacity 900 passengers
Vehicle capacity: approx.
20 trucks + 80 cars, or 267 cars.



Benoit Stichebaut - DPPI Rivacom

Page 7

THE GLOBAL CHALLENGE

It is with the yacht "Adrien" that
Jean-Luc Van Den Heede beat
the record for circumnavigating
the world "the wrong way
round" in March 2004,
in 122 days, 29 days faster
than the previous record set
by Philippe Monnet.
The "Adrien" is 25.70 m long,
5.40 m wide and with a draft of
4.60 m is made from Sealium®
and 5083 aluminium alloys
supplied by Pechiney Marine.
It was built at Chantiers Gamelin
of La Rochelle (F-17000) to
drawings by the naval architect
Gilles Vaton.



Rodriquez Cantieri Navali

Page 8

THE VESUVIO JET

Built by Rodriquez, Italy
Type: HSV monohull
Aquastrada TMV 50
Launched in 2003
Aluminium hull
and superstructure
Overall length: 50.46,
beam: 8.80 m, draft: 1.35 m
Speed: 32 knots
Capacity 460 passengers
The lightness of weight due to
the 'all aluminium' construction
of this boat, and its powerful
propulsion system, enhance
the manoeuvrability of this type
of vessel. The saving in weight
allows the 'waterjets'
to manoeuvre over very short
distances.



Photo X

Page 10

THE AMPORELLE

The "Amporelle", an aluminium
monohull ferry with a length of
38.07 m and a beam of 7.46 m,
has been operated since 1992 by
the "Yeu Continent" company of
Fromentine (France) on the Ile
d'Yeu – Fromentine crossing. It
can carry up to 360 passengers.
The relatively shallow waters on
this route call for a vessel with
a draught that is equally shallow,
hence one that is light in weight.
The ferry has speed under load
of 25 knots and a top speed
of 30 knots.



SNCM post card - Photo X

Page 11

HSV ALISO

The HSV ALISO, launched
in 1996, plies routes between
France and Corsica.
This monohull ferry is 102 m long
and 15.40 m wide, with a draft
of 4.35 m.
Its speed under a load of 247 t
in calm seas is 37 knots, at 90%
power (26,000 kW installed).
It can carry 566 passengers and
146 cars.

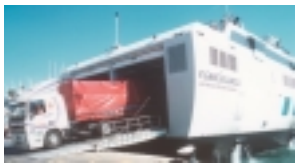


Rodriquez Cantieri Navali

Page 20

THE PRINCESS

See key of page 4.



Rodriquez Cantieri - Navali

Page 22

FEDERICO GARCÍA LORCA

Built at Rodriquez Cantieri Navali
This monohull vessel in
the Aquastrada TMV 115 series
is 115 m long and can carry
220 cars on its decks and has
300 linear metres for trucks which
gain access by means of
a retractable ramp.



Austral Ships Pty Ltd

Page 23

THE SPIRIT OF ONTARIO

Built by Austal Ships, Australia
Catamaran launched in 2003
Length: 86.60 m, draft: 3.40 m
Speed 43 knots
Capacity 774 passengers,
238 cars and 10 trucks.



Baglietto

Page 32

HARD TOP YACHT

Due for delivery in April 2004
Built by Baglietto, architect:
F. Paszkowski
Overall length 31.92 m, speed
35 knots. This fast yacht sports a
highly streamlined design for both
hull and superstructure.
In order to achieve this high
speed, the height of the yacht
has been reduced so far as
possible to minimise drag in both
air and water.



Kurt Coste & Trinity Yachts

Page 34

THE SEAHAWK

Built by Trinity Yachts, USA
Launched in 2003
3 deck motor yacht
Overall length 45.78 m,
draft 2.32 m
Passengers: 10.



Rodriquez Cantieri Navali

Page 35

THE NATALIE M

Built by Rodriquez, Italy
Launched in 2002
Monohull hydrofoil with an
aluminium hull and superstructure
Overall length 31.20 m,
width 6.78 m, draft 1.66 m
Speed 40 knots
Capacity: 240 passengers.



Rodriquez Cantieri Navali

Page 43

Aluminium Waterjet LJ114E

Built by Rodriquez, Italy
On the TMV 115 "Garcia Lorca",
each of the two motors is
coupled directly to a waterjet.
Each waterjet has sufficient
thrust to enable the vessel
to make port rapidly should there
be a problem with the other.



Photo X

Page 45

OPUS 45, under construction

Motor Yacht
Built by Koopmans Kasko's
Design: Van Witze Van Der Vzee
Naval architect: Dickkzaal
Hull and deck made from Sealium®
Length 13.75 + 0.40 m,
width 4.40 m
Speed up to 28 knots according to
motor rating.



B-Y Leglatin

Page 49

WINDLASS 312

By Goïot, of Saint-Herblain, France
This windlass is designed for use
on vessels up to 20 tonnes. All of
its components – the casing,
cable wheel and capstan head –
are cast from 51300 aluminium
alloy (A-G6).
The system has constant oilbath
lubrication to minimise the need
for maintenance.
As it is anodised, this unit will
retain its highly attractive
appearance for many years.



Rodriquez Cantieri Navali

Page 51

AQUASTRADA TMV 115
Engine room

Built by Rodriquez of Italy.
This vessel is fitted with four
Caterpillar 3618 diesel engines,
each rated at 7200 kW
(at 2100 RPM).
The engine room has been
specially designed and fitted out
to accommodate each engine
in its own fire resistant zone
so as to avoid propagation
in the event of fire.
It will be seen that that walkways
are constructed using relief tread
plate in 5XXX.



Babcock

Page 52

CATAMARAN UAI 50

Built by Babcock, Great Britain
This 50 metre long catamaran is
a variant of the 45 metre Tricat.
It has a maximum speed
of 37 knots and can carry
400 passengers.
The originality of this TRICAT lies
in the construction of its hull. The
two hulls are interconnected by
means of a transverse structure
consisting of 6XXX alloy sections
automatically welded to each
other to form an extremely rigid
cross-panel. This type of structure
is highly suitable given the fact
that on a catamaran, the greatest
stresses occur transversely
between the two hulls.
This makes it possible to increase
the vessel's level of equipment
without increasing the depth
of the hull.
The superstructure is made from
an assembly of automatically
welded stiffeners with which
large rigid panels can be very
quickly fabricated.



Rodriquez Cantieri Navali

Page 54

THE PRINCESS

See key of page 4.



Rodriquez Cantieri Navali

Page 55

THE PRINCESS

See key of page 4.



C. Vargel

Page 72

Structure of a Monohull
made from frames fabricated
in 5XXX sheet, welded
and connected using ribbands
in shapes made from 6XXX.



Rodriquez Cantieri Navali

Page 74

COASTGUARD CP 280

Special Craft CP 25
Built by Rodriquez, Italy
Length 25 m, beam 25 m
Speed 34 knots.



Babcock

Page 75

FLYINGCAT 3

Built by Babcock, Great Britain
Launched in 1998 and used for passenger transport in Greece
This 45 metre HSV catamaran is a passenger shuttle with a top speed of 50 knots and equipped with twin gas turbines.
It was constructed entirely of aluminium according to DNV rules. The Tricats are characterised by a personalised interior that is particularly stylish for a commercial vessel.



C. Vargel

Page 81

High inertia beam
fabricated by welding sheet made from 5XXX.



Austral Ships Pty Ltd

Page 82

PATROL BOATS

Built by Austal Ships, Australia
Launched in 2003
Overall length: 21.60 m,
beam 3.50 m, draft 1.50 m.
Speed: 25 knots.



Photo Derektor

Page 84

Welding a hatchway frame

Derektor Shipyards, USA.



Photo MHI

Page 85

LNG CARRIERS

Installation of northern hemisphere section of aluminium tank on a board LNG carriers built by Mitsubishi Heavy Industries, Nagasaki Ship Building.



Photo Derektor

Page 90

Yacht frame

Derektor Shipyards, USA.



C. Vargel

Page 92

Using cranes built to handle sections of ships made from steel, it is possible to lift aluminium sub-assemblies of similar size but which are already fitted out with elements of the vessel's engine room.



Photo Derektor

Page 111

Engine and drive shaft bearer

Derektor Shipyards, USA.



C. Vargel

Page 114

Marina at Trinité-sur-Mer, France (F-56470)

Marina equipment such as access gangways, pontoons and catwalks are fabricated structures welded from 6082, 6005A and 6060 aluminium sections.
The floats are watertight tanks made from welded 5754 aluminium sheet.
Neither the structures nor the floats have any protection in the form of painting or anodising.
The first marinas constructed using aluminium alloys were built in France in the early Seventies and they are still in service today.
Experience has shown that these structures show good resistance to the constant swell.



Carlo Borlenghi

Page 116

FELICITA WEST

Built by Perini Navi, Italy
Ketch launched in 2003
Length 64 m, beam: 12.72 m and draft 9.72 m.



Carlo Borlenghi

Page 117

FELICITA WEST

See key of page 116.



C. Vargel

Page 121

Hydrojet nozzle made from 5083 aluminium plate.



Benoit Stichebaut - DPPI Rivacomi

Page 127

OGIA HIGH-SPEED PASSENGER FERRY

OGIA high-speed passenger ferry operated by the Compagnie Vendéenne at Saint-Gilles-Croix-de Vie (France). Built by Gamelin at La Rochelle, France
Length 30 m, beam 7.90 m and draft 1.60 m.
Speed 20 knots, propulsion 2 X 1000 HP Cummins
Capacity: 320 passengers
In service on the Saint-Gilles-Croix-de-Vie - Ile d'Yeu crossing.



Austral Ships Pty Ltd

Page 128

AUSSIE RULES

Motor yacht
Built by Austal Ships, Australia
Launched 2002
Hull in aluminium, superstructure in aluminium and GRP composites
Overall length 69.50 m, draft 3 m
Passengers: 12.



Sleeker Boats

Page 130

Sleeker sailing boat project

Yacht 13.83 m long with a beam of 3.80 m and a draft of 2.80 m
Built by Sleeker Boats
Constructed using Sealium®
This is a high-speed competition yacht design featuring very elegant styling and a "high tech" specification.
The use of Sealium® makes it possible to reduce the vessel's weight and so increase its speed.



Kurt Coste & Trinity Yachts

Page 131

VICTORY LANE

Built by Trinity Yachts, USA
Motor yacht
Launched in 2002
Length: 37.85 m, draft: 2.02 m
10 passengers.



Austral Ships Pty Ltd

Page 134

BOCAYNA EXPRES

Built by Austal Ships, Australia
Vehicle-passenger catamaran
66.20 m long with a draft of 2.50 m
Speed 34 knots
Capacity 450 passengers and 69 cars.

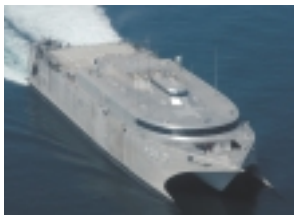


Rodriquez Cantieri - Navali

Page 136

VESUVIO JET

Built by Rodriquez, Italy
Type: HSV monohull Aquastrada TMV 50
Launched in 2003
Aluminium hull and superstructure
Overall length: 50.46, beam: 8.80 m, draft: 1.35 m
Speed: 32 knots
Capacity 460 passengers
The lightness of weight due to the 'all aluminium' construction of this boat, and its powerful propulsion system, enhance the manoeuvrability of this type of vessel. The saving in weight allows the 'waterjets' to manoeuvre over very short distances.



Incat

Page 137

HSV2

Troop transport vessel
Built by Incat, Australia
Length 97.22 m, beam 26.60 m, draft 3.43 m.
Capacity: 343 passengers.



C. Vargel

Page 138

RADAR MAST

This radar mast made of 5083 and 6082 aluminium alloys was atop a cruise ship when fire broke out while the vessel was in the final stages of outfitting in dock.
Because of its position at the top of the vessel, the mast acted as a flame duct, channelling flame and fumes generated by the combustion of cabin fittings. Temperatures must have exceeded 500°C inside the mast. Subsequent examination of the structure (which did not melt) showed that deformation was minimal and that the mast's substructures were not collapsed or destroyed.
Mechanical characteristics measured on samples taken from areas exposed to the highest temperatures had changed little (less than 10%) on the 5083 sheets. The sections in 6082 in its initial T6 temper had been annealed by the fire.



Photo X

Page 143

Engine room

Insulation in the engine room using INSULFRAX SFR, a UNIFRAX product
The flexibility of this product allows it to easily follow the contours of the floor stiffeners.



Bill Monke & Trinity Yachts

Page 144

MOTOR YACHT

Built by Trinity Yachts, USA
Launched in 2002
Length 54 m, beam 9.45 m, draft 2.26 m.
6 passengers.



Babcock

Page 146

TRICAT 50

Built by Babcock, Great Britain
Catamaran launched in 2001 and in service in Korea
Hull in aluminium, superstructure in aluminium and GRP
Length 52 m, beam 11.80 m, draft 1.60 m.
Speed 41 knots
Capacity 449 passengers.



Leirvik

Page 147

Living quarter

Built at Leirvik, Norway
Installed in the Kvitebjorn oilfield in Norway in 2002 and operated by Statoil
Weight 1200 tonnes, living area 3250 m^2
Accommodates 95 persons.



C. Vargel

Page 148

Gangway giving access to pontoons at the fishing port of La Rochelle in France, installed in the early Seventies.
The steel chain is directly attached to the aluminium structure.
Decades of experience with out-of-water joints between aluminium alloys for marine applications on the one hand and steel (mild or stainless) on the other show that no harm is done to the aluminium except for rust stains that may alter the structure's appearance.



C. Vargel

Page 157

Gangway

Weldment on a gangway at a marina.
This confirms that when they are made according to the codes of practice, TIG or MIG welds will not favour corrosion whatever the atmosphere, including marine environments.



C. Vargel

Page 161

Marina pontoon and floats made of 5754

Decades of experience have shown that aluminium alloys for marine applications suffer superficial alteration only when in contact with seawater fouling.



C. Vargel

Page 163

No aluminium corrosion

Despite being at the mercy of spray and heavy seas that constantly drench the deck, steel items such as the anchor chain shown in the photo can be left on the deck of this aluminium fishing boat that was launched in the early Eighties without corroding the aluminium that is in contact with them.
As the photo clearly shows, apart from permanently altering the aspect of the aluminium, the rust does not corrode it.



Trinity Yachts

Page 164

CHEVY TOY

Built by Trinity Yachts, USA
Motor yacht launched in 2002
Length 43.30 m, beam 8.54 m, draft 2.07 m
5 passengers.



C. Vargel

Page 166

Yacht masts

A forest of boat masts humming in the wind is a typical sight at any marina.
All of these masts are made from series 6000 alloys from which functional and attractive sections are easily extruded.
These masts are anodised to a thickness of 20 microns and with a plain or coloured coating. This anodising will retain its highly attractive appearance for many years.
The accessories that are fixed directly to these masts are usually made of stainless steel.



Benoit Stichebaut - DPPI Rivacom

Page 167

GLOBAL CHALLENGE

See key of page 7.

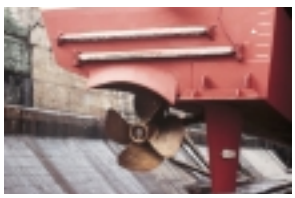


Photo X

Page 169

CATAMARAN SUNREEF 74

Built by HTEP Polska, Poland
Hull and deck made from 5083 and *Sealium*®
Length 22.5 m, beam 10.56 m
Draft 1.75 m.



C. Vargel

Page 174

Cathodic protection using sacrificial anodes at the port stern of a catamaran. These anodes neutralise the galvanic couple between the aluminium hull and propulsion components such as the stainless steel shaft and bronze screw.
The condition of sacrificial anodes made from zinc or special aluminium alloy (they must never be made from magnesium) must be regularly checked. The rate at which the anodes are consumed depends on a number of criteria including the temperature of the sea water.

5. USEFUL ADDRESSES

Alcan Marine
B.P. 130
F-63504 ISSOIRE cedex
http://www.Alcan-Marine.com

American Bureau of Shipping
ABS Plazza
16855 Northchase Dr
HOUSTON TX
USA 77060
http://www.eagle.org

Bureau Veritas BV
17 bis, place des Reflets
La Défense 2
F 92400 COURBEVOIE
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http://www.rina.org

Korean Register of Shipping KR
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Republic of Korea
http://www.krs.co.kr

China Classification Society CCS
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International Association of
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International Maritime Organization
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The Royal Institution of Naval Architects
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