Chapter 1
ALUMINIUM, METAL AND THE SEA

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.

VOL. II. NEW YORK, DECEMBER

ALUMINUM: ITS ALLOYS AND THEIR USE IN SHIP CONSTRUCTION.

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

METAL AND THE SEA

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).

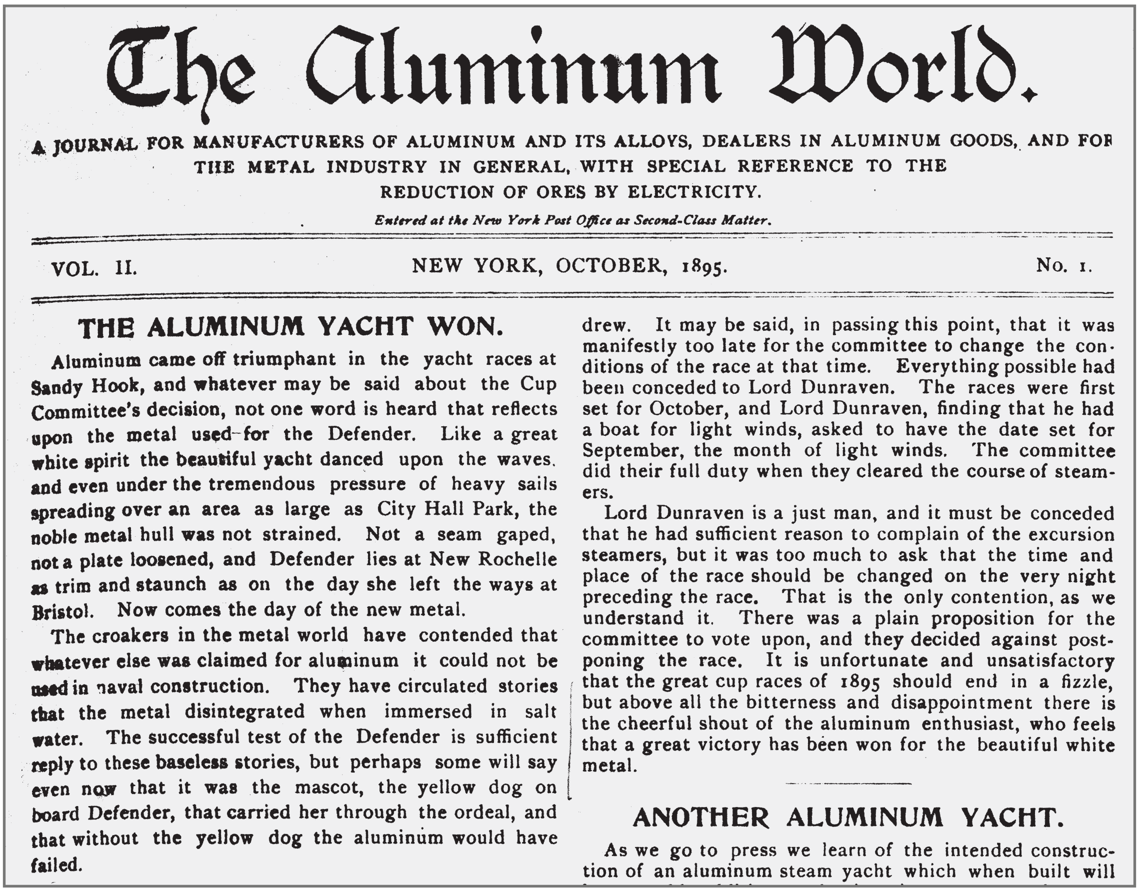
Navies too took an interest in aluminium. Thus it was that in 1894 the French navy placed an order for a torpedo-boat, "Le Foudre", with the British shipyard Yarrow & Co. This vessel had a length of 19 metres, a beam of

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.

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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*

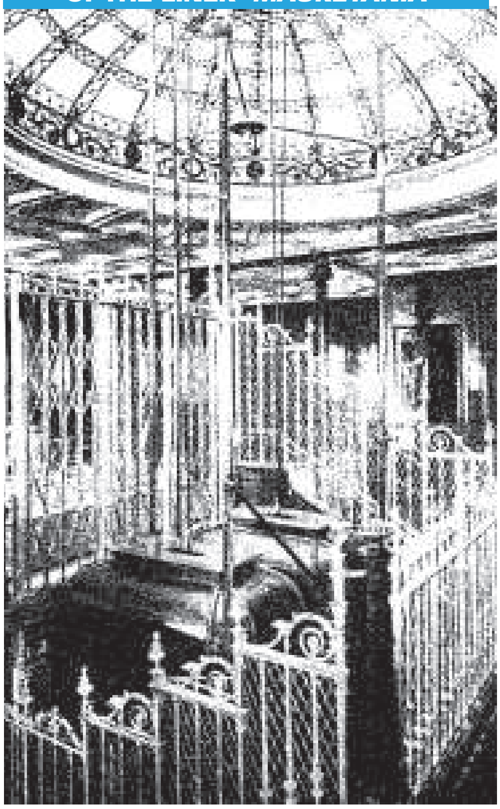

Figure 4

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

RIVETED CONSTRUCTION OF THE *DIANA II*

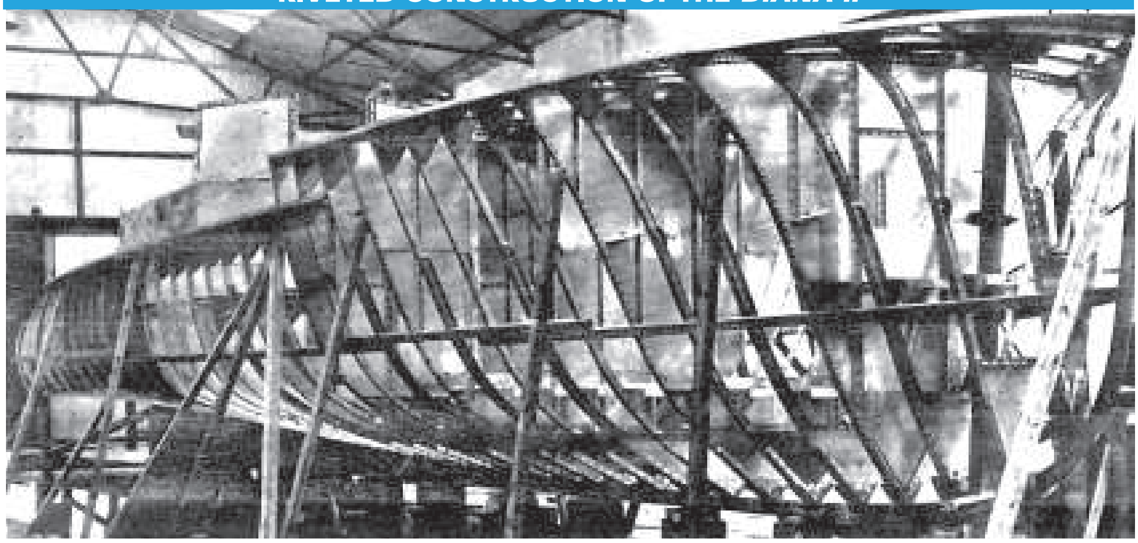

Figure 5

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.*

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