Chapter 2
ALUMINIUM'S ADVANTAGES

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.

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

UNIAXIAL STRAIN CURVES

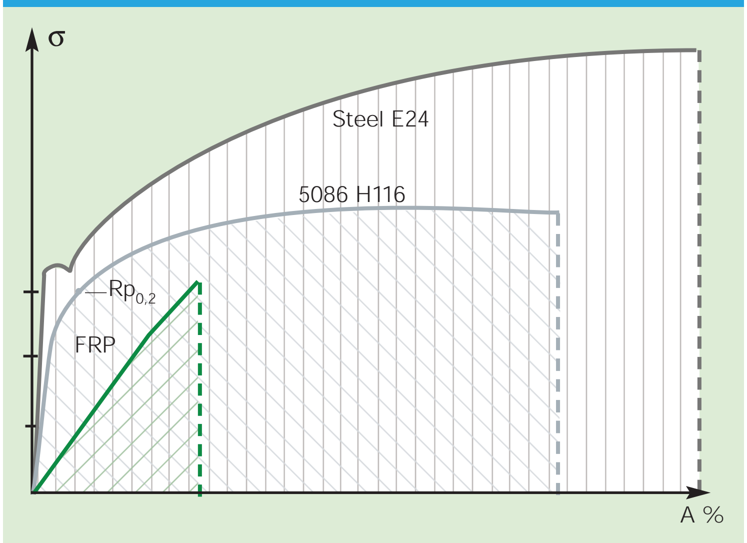


Figure 6

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.

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 tonne 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:

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

$$\frac{m_{alu}}{m_{steel}} = \frac{2,70}{7,80} \cdot \sqrt[3]{3} = 0,499 \approx 0,5$$

is such that one tonne 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:

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

$$t_{alu} = t_{acier} \cdot \sqrt{\frac{\sigma e_{acier}}{\sigma e_{alu}}}$$

$$t_{alu} = t_{steel} \cdot \sqrt{\frac{355}{220}} = 1,61$$

The ratio of mass:

$$\frac{m_{alu}}{m_{steel}} = \frac{2,70}{7,80} \cdot 1,65 = 0,57$$

is such that one ton of steel is replaced by 570 kg of aluminium. The saving in weight is 430 kg, or 43 % 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 à 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 tale 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	215 MPa	355 MPa	43 %

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 substructures, 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 manufacture. 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 (TONNES)	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

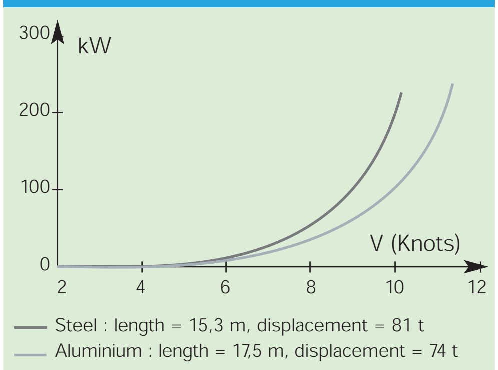
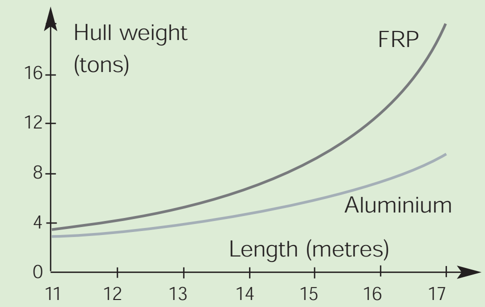


Figure 7

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 sheet (less than 12.7 mm thick) for skins, 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. Table 7
Sheets and plates are sawn for thickness > 8 mm and length up to 12,500 mm.

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

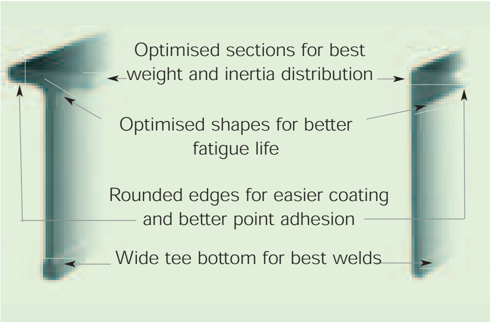


Figure 10

SHAPE WITH BACKING STRIP

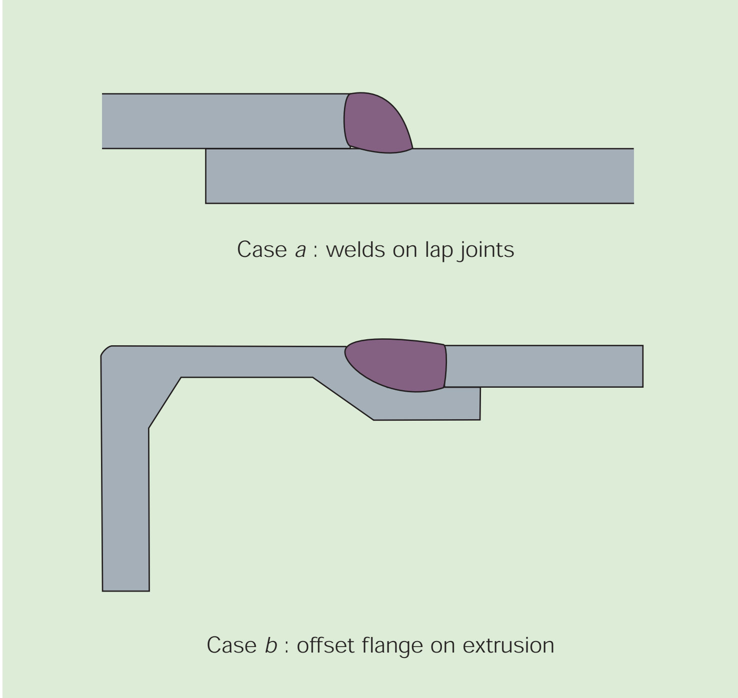


Figure 11

SHAPE WITH INTEGRAL BACKING STRIP AND STIFFENERS

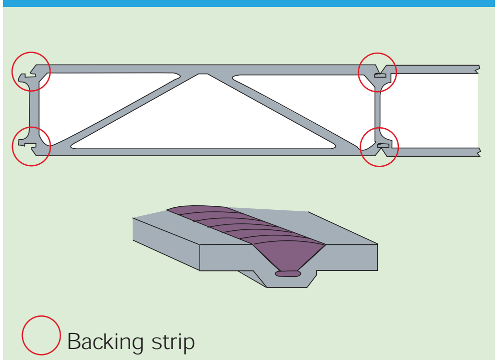


Figure 12

SLOTTED EXTRUSIONS FOR WELDING TO SHEET COMPONENTS

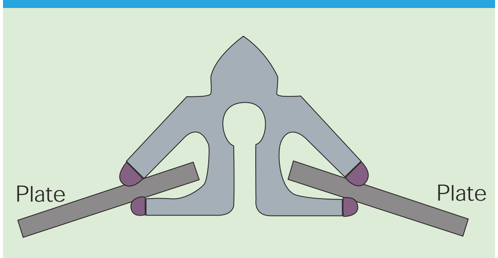


Figure 13

BULB ON EXTRUDED FLANGE FOR IMPROVED WELDABILITY

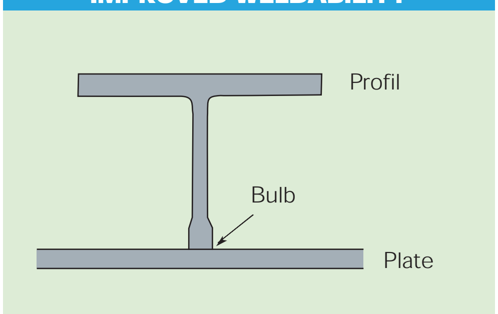


Figure 14

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

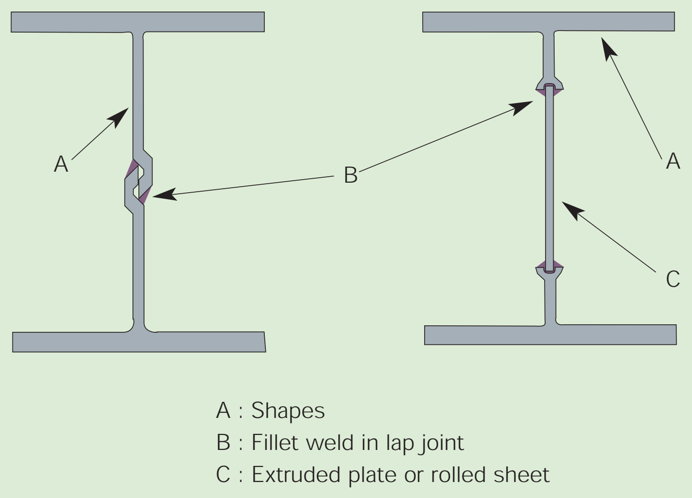


Figure 15

STRESSES IN FABRICATED I-BEAMS

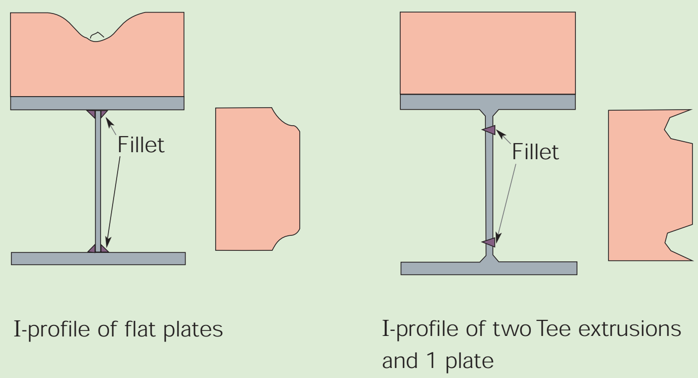


Figure 16

OPTIMISING STRESS DISTRIBUTION

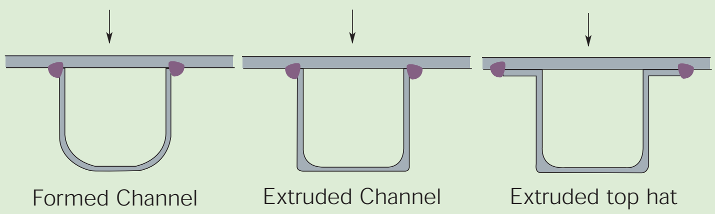


Figure 17

HONEYCOMB SANDWICH PANEL

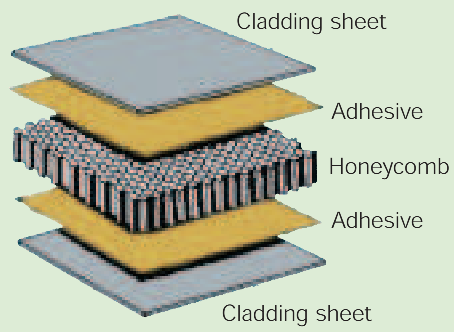


Figure 18

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.

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(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 tonne, 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.

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

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(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