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ON THE USE OF ALUMINIUM IN SHIPBUILDING

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ABSTRACT

The use of aluminium in shipbuilding dates back to 1890 and its use has increased over the years. It is now possible to make all-aluminium ships, meeting the same performance criteria as steel constructions. In a context where the total cost of ownership of a vessel prevails on the initial purchase cost, aluminium ships represent the most economical alternative. The superior mechanical properties, lightweight and corrosion resistance of aluminium alloys imposed their use in shipbuilding and in the fabrication of components for offshore platforms. By using aluminium, the naval architects can design ships and boats with high-speed capability, long life, high payloads, and low maintenance costs, as well as a high recycle value.

Keywords: aluminium, shipbuilding, technology, welding aluminium-steel

1. INTRODUCTION

Both a banal and precious metal, aluminium is one of the most important components of the planet as it represents 8% of the Earth's crust. It does not exist in pure form in nature, but is contained in ores mainly in the form of oxides. It plays a crucial role in many sectors, from the aerospace industry to robotics but also in high fashion, jewellery or contemporary furnishings.

Aluminium has proven itself as a lightweight, durable and affordable material that allows naval ships to go faster, carry bigger payloads and travel longer distances.

Ship design advancements, analysis and manufacturing methods have overcome past concerns about aluminium regarding corrosion, sensitization and repair. Acquisition costs of aluminium ships are competitive with steel ships, but aluminium ships have a clear advantage as far as the total cost of ownership is concerned.

2. USE OF ALUMINUM IN NAVAL FLEETS

In shipbuilding, aluminium is used extensively. Its first use was to alleviate the superstructure in order to down the centre of gravity. The aluminium parts were not considered as supporting parts. Then, for the design of more and more speed ships (53 knots) for the transport of passengers, it has become necessary to lighten the whole shell. Then, aluminium has become the metal used for the assembly of the support structure (High Speed Catamaran Ferry).

The introduction of the 5000 series alloys (Al Mg), during the 1920s, means that engineers and marine architects have increased the use of aluminium.

Extruded profiles, specifically studied for the envisaged application, can make the best use of aluminium. Figure 1 presents profiles used in shipbuilding (deck element, keel, bilge, element of gutter and transversal reinforcements).

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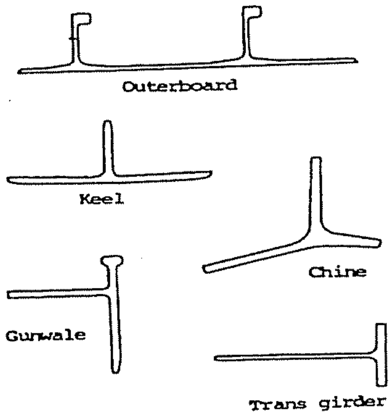

Fig.1. Examples of extruded aluminium profiles used in shipbuilding (RINA 1992)

The use of the aluminium material in the production of ships has many advantages such as the relatively high strength compared to the weight of the material, the easiness of shaping and an interesting density, but also certain disadvantages such as its purchasing cost higher than the cost of steel. Nowadays it is using aluminium 5000 series alloys for the manufacture of the hull and the deckhouse, while the aluminium alloys of the 6000 series are used typically in structures above the water line.

Table 1 Advantages and disadvantages of the use of aluminium in shipbuilding

Advantages	Disadvantages
High ratio of strength / weight	Raw material more expensive than steel
Density of one-third of that of steel	Rigidity lower than that of steel
Excellent corrosion resistance in marine environments (the 5000 series alloys do not need to be painted)	Lower melting temperature than steel - additional insulation necessary for the protection against fire (for military vessels only)
Good weldability	Lack of experience in the industry with this material
Easy forming, bending and machining	Lack of skilled welders for aluminum
Diversity and availability of semi-finished products	Reduced number of shipyards with the necessary facilities for the production with aluminum
Similarity in the structural details and design approaches	Limited number of shipyards with the facilities and experience to repair the aluminum ships
High recycling value	
Environmental compatibility	
Nonmagnetic	

The operating needs of ships, such as greater speeds and operating in shallow waters, have resulted in the fact that the use of aluminium has increased in the manufacture of ships. Also, the US Navy is interested more and more in smaller ships, more affordable and reconfigurable. To that end, vessel types LCS (Littoral Combat Ship), JHSV (Joint High Speed Vessel) and SSC (Ship to Shore Connector) use aluminium for their primary structures. Although the US Navy shifted in the 1980s from the use of aluminium as the main material for its ships because of bad experiences, recent research and developments of the Navy itself, shipyards, the American Bureau of Shipping and aluminium producers such as Alcoa should enable improved performances and costs. For this purpose, it is reported that Alcoa is working with the US Navy to understand their equipment needs and help develop a new generation of aluminium alloys optimized for marine applications.

Currently, some shipyards can produce aluminium structures for vessels at lower costs than necessary to achieve an equivalent steel ship. An aluminium designed hull with equivalent performance criteria for the strength and stiffness will be approximately 50% thicker than a steel hull, but about 50% lighter than the latter. In addition, the aluminium shell has a 30% higher resistance against bumps and a resistance at break greater than 13%. The use of aluminium in the superstructure of a vessel having a steel shell saves weight and thus improves the ship stability and ship behaviour in extreme conditions.

There is room to improve the productivity of shipyards for which the use of aluminium is a more attractive alternative. For example, a simple 10% increase in productivity would allow for savings of 6.4 million US dollars. This increase in productivity can be obtained by, inter alia, the use of advanced manufacturing technologies such as friction stir welding, the use of extruded panels, the design of modular sections, etc. The shipyards currently using this technology and methods are capable of producing aluminium structures at equal or lower cost than for an equivalent steel structure. In addition to the friction stir

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welding, fusion techniques such as the Advanced Gas Metal Buried Arc (AGMBA), the Gas Metal Arc (GMA), the Laser Beam Stir Welding (LBSW) and the assembly by adhesives and by mechanical fasteners have the potential to lower production costs and improve the quality of products manufactured by shipyards. The European Commission also funded in the early 2000s a project to adapt the joining techniques by adhesive to the needs of shipyards.

The use of advanced cutting and assembly processes helps to reduce mounting and assembling time since the distortion and residual stresses decrease with the use of these methods. In addition to enabling lower costs by improving the production method, there is also a positive impact on the sustainability of ships. The use of complex aluminium extrusions favours lowering manufacturing costs instead of requiring the realization of complex assemblies. To this end, it is possible to use extruded panels of more than 6 meters in length, which allows a great reduction of manpower that would be necessary to weld the longitudinal stiffeners of the panels consisting of assembled elements and the mounting due to the distortion produced by traditional assembly methods.

The alloys of the 5000 series are used for the manufactiring of the hull and of the deckhouse. Even if these alloys are more difficult to extrude and the equipment suppliers are more difficult to obtain, the alloys are gaining popularity. There are research studies concerned with methods for producing efficiently, economically speaking, extruded panels with stiffeners. The alloys of the 6000 series are, instead, used for the internal structure applications above the water line.

Although the initial purchase price of an aluminium boat is currently higher than the price of a steel boat, in the long term, the aluminium boat will have a lower total cost through fuel savings and less major maintenance requirements. Indeed, besides the submerged area, no paint will be required on the boat, there will be less powerful machinery to repair, less maintenance staff requirements within the crew and greater residual value at the end of its useful life.

Taking the example of a small frigate, since the boat consumes less fuel, the environmental impact will be less than for a small steel frigate. Table 2 shows the savings during the useful life of an aluminium frigate compared to a steel frigate.

Table 2 Savings related to the purchase of an aluminium frigate (25-year useful life) compared to a steel frigate

	Characteristic	Saving over 1 year	Saving over 5 years	Total savings over 25 years
Fuel	71 tons displacement	1 278 000 USD (2840 tonnes)	6 390 000 USD	32 000 000 USD
Maintenance (painting)			500 000 USD	2 500 000 USD
Total			**6 890 000 USD**	**34 500 000 USD**

Globally, a large number of high-speed patrol boats and monohull military patrols used aluminium superstructures.

Aluminium, highly resistant to corrosion, even in the marine environment, is used in the manufacture of hulls, masts and superstructures of pleasure boats, decks and superstructures of passenger ships and commercial vessels. The aluminium, because of its light weight, has allowed the development of HSV (high-speed vessels).

The HSV 120 design is based on aero-derivative techniques. Thanks to its 120 meters long hull, in aluminium and very tapered in the bow, it reaches 42 knots cruising speed (80 km/h) versus 18 knots for the conventional cargo.

The NVG 120 is expected to significantly improve the competitiveness of maritime transport. It may be used to transport passengers and thus to take the place of a ferry with a capacity of 1200 passengers and 250 cars. It may be also used for cargo ships with length up to 235 m. Finally, it is of interest also for the navy. The first civilian connections established for passenger transport should be Barcelona-Palma de Mallorca and Marseille-Alger.

Fig.2. The HSV (high-speed vessel) Source: bgv-France.com

2.1 Aluminium in Damen Shipyards

This company has thirty shipyards spread over all continents. Its products include aluminium fast crew boats, pilot boats, service boats, patrol, search and rescue boats, patrol boats, and ferries. The company has delivered aluminium patrol boats to the Royal Dutch Military Police and the Royal Netherlands Police Force. The Damen design is also used by Irving Shipbuilding of Halifax for the production of Canadian patrol vessels. Damen Shipyards Singapore manufactures and repairs fast aluminium boats.

Fig.3. Damen Stan Patrol® 6011 "Sea Axe", Source: Damen

Fig.4. Patrol craft superstructure in Damen Shipyards Galati

Based on such designs and experience, in Damen Shipyards Galati, in 2014, the process of improvement of facilities continued with an aluminium workshop, which was put into use for some yacht constructions and the superstructures for two 70-metre military patrol craft.

3. ALUMINIUM-STEEL ASSEMBLIES

The advantages of welding compared to purely mechanical assemblies or bonding are the following:

- lighter construction (non-recovery)
- lower risk of cracks that can give rise to local corrosion
- continuous transition between pieces

Many metals and combinations thereof are well weldable provided that usual procedures are taken into account. However, there are combinations of materials that are very difficult to be implemented and that could offer interesting opportunities for many companies. The welding of aluminium to steel is a very good example. The number of processes for a quality and reproducible weld is very limited. An example is welding through explosions for aluminium plating on a steel sheet for shipbuilding or for the production of transition elements (Figure 5).

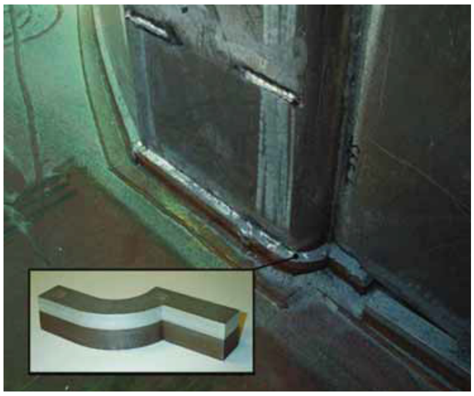

Fig.5. Transition piece welded through explosion (see detail) for the assembly of a steel deck to an aluminium superstructure in shipbuilding. Source: Triplate®

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The majority of applications where aluminium-steel joints are justified is dictated by the optimal use of the material: the use of a given material with certain properties in a specific location. One of the most important areas where the best material has to be used is "transport" in the broadest sense: automotive, shipbuilding, air and space transport, railway construction.

Important properties to be taken into account in a given application are:

- Resistance
- Rigidity
- Deformation
- Conductivity
- Corrosion resistance
- Specific weight
- Cost of the material

On some of these properties, aluminium has a much better score than steel (density, corrosion resistance, thermal and electrical conductivity) and on others it is worse (rigidity and cost).

In the ideal case, a construction satisfies all the criteria mentioned above. With the new methods of assembly, it is possible to use aluminium in combination with steel for a given application, precisely in places where their specific properties are more justified, since it is possible to assemble these materials very properly so as to form a single assembly.

3.1 Promising welding technologies for aluminium-steel connection

In the case of fusion welding processes, the steel is never melted. Due to the very high temperature, aluminium is very liquid, with all the consequences relating thereto. The much higher thermal conductivity of aluminium makes the melting of steel naturally much more difficult. In addition, the higher the temperature is, the longer the cooling time and intermetallic phases are.

In the techniques below, either aluminium is melted with a low heat input (CMT, ColdArc, laser welding), or the connection is made without melting, using plastic deformation (friction welding, friction stir welding and magnetic pulse welding).

3.1.1 CMT and ColdArc

The method called "Cold Metal Transfer" (CMT), recently developed by Fronius, is a variant of the MIG / MAG welding process. The CMT is an arc welding process in short circuit with a new method of detachment of the drops of the welding wire. By coupling the wire feed to the conduct of current and voltage, this method allows welding with a very low calorific supply.

By slightly retiring the welding wire after the contact with the work piece and limiting the welding current, the metal transfer is performed without projections. The electric arc will ignite spontaneously due to the elevated temperature and increase tension. After the transfer of metal, the wire is again fed and the current increases so that the next metal transfer can be done. With this method, the aluminium and steel can be successfully assembled (Figure 6).

Due to the low calorific intake, the formation of an intermetallic layer is limited. The cross section of Figure 6 allows to see clearly that the aluminium (above) is brazed to the steel (below).

So far, most studies have focused on the assembly of aluminium on galvanized steel, where the zinc coating improves humidifying by molten aluminium.

Fig.6. Overlapped welding made with the CMT process between an upper aluminium sheet and a lower steel sheet. Source: Fronius

The ColdArc technique by EWM is a variant of the arc welding by short circuit. With this method, the welding wire is not removed to cause the transfer of the metal (as is the case with the CMT method). The very low heat input is achieved by changing the current flow through the application of a new type of high dynamic switching (Invertor), in combination with a fast and digital process control. This technique also allows to weld aluminium to steel.

The ColdArc process may be manual or automated. The CMT process is especially suitable for automation and robotics, and soon, it could be used manually.

3.1.2 Laser assembly techniques

A laser allows welding with a very low heat input because all the energy is concentrated in a thin beam. High welding speeds can be achieved. There are different possibilities for realizing a quality laser welding between aluminium and steel.

In most laser welding processes, the aluminium is melted (with or without filler metal) and the steel is moistened by molten aluminium.

The crucial factors are the positioning of the laser beam, as well as the clamping apparatus. The laser welding methods have the advantage of higher welding speed than those obtained with the CMT and ColdArc but, on the other hand, the tolerances are very important: the gap should be as narrow as possible.

To solve the problem of the low flexibility, two welding processes of laser hybrid were developed (Hybrid Laser Welding, HLW) specifically for joining aluminium to steel, while maintaining the productivity of the laser welding: the laser-MIG hybrid welding method and the laser-plasma hybrid welding process.

With the hybrid welding process laser-MIG, 2 mm aluminium can be welded end to end to steel with a welding speed of up to 4 m/min. Moreover, this method allows a welding chamfer of up to 1 mm. The exigencies are significantly lower and can thus be raised at the joint preparation.

In addition to the production of flat sheets of different thicknesses or different materials which are welded before stretching to the automotive industry, it also has application possibilities in shipbuilding, among others.

It is also worth mentioning the "Fluxless Laser Brazing", which was recently developed by Corus. With this method, as in the case of the CMT, the aluminium side is melted with the filler metal, while the steel side is brazed (Figure 7).

The intermetallic layer from the steel side has a thickness of about 1 µm. The advantage of this technique compared to the conventional laser welding is that no flow should be applied which would have been a source of corrosion. This is better than the methods of hybrid laser welding. With the free soldering flux, Corus is addressed in particular to the automotive industry.

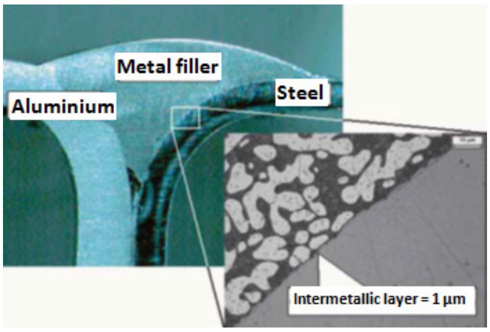

Fig.7. Aluminium-steel connection made with "flux less laser brazing" Source: Corus

3.1.3 Friction welding

In the case of conventional friction welding by rotation, two parts (at least one of rotationally symmetrical geometry) are pressed against each other. One of the pieces is rotated such that the latter is heated by friction to a temperature below the melting point and then subjected to forging. The bottom line here is the relatively low temperature that the material reaches. What

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is specific in the aluminium-steel welding is that the formation of the intermetallic layer is limited, such that eligible mechanical proprieties can be obtained.

In addition to the friction welding by rotation, there is also the orbital welding and linear friction where it is not mandatory that a piece has a circular section.

3.1.4 Friction stir welding

During the friction stir welding (FSW), the work piece is heated by friction, as is the case with the friction welding. But, in the case of FSW, frictional heat is generated between a reusable rotary tool and the surface of the parts to be assembled. The part of the tool inserted into the material (the pin) provides further mechanical mixing of the parts to be welded. During FSW, no fusion appears, such that the formation of intermetallic phases is limited.

Welding by conventional friction is limited because at least one of the two parts must be symmetrical in rotation while the FSW can weld the sheet and profiles in end to end with an overlap.

Spot welding is also possible with the FSW. This technique is already applied on an industrial scale at Mazda. For spot welding aluminium, Mazda declares a 40% lower investment cost compared to the resistance welding, as well as a 99% reduction in energy consumption during the welding.

The zinc layer on the steel, in addition to the limitation of galvanic corrosion, has a positive influence as far as the formation of harmful intermetallic phases is concerned.

3.1.5 Magnetic pulse welding

In contrast to the techniques mentioned above, apart from explosion welding, the magnetic pulse welding (MPW) does not use heat to perform welding. During the MPW, a spool is placed under the parts to be welded but without being in contact with them. During the welding cycle, a very large amount of electrical energy is released in a very short period of time. This high flow of energy through the spool and the discharge current induces eddy currents in the outer part. The repulsion between two magnetic fields develops a force that gives a very high speed (> 1000 km/h) to the outer part towards the inner part. This causes a residual deformation, without a return of the piece to its original shape. The method is suitable for joining tubular products in an overlapping configuration.

4. CONCLUDING REMARKS

The progress and enrichment of different families of aluminium alloys improved design techniques, manufacturing, while technological advances in methods of assembly and the production of semi-finished products have opened the door to an increased use of aluminium. It is now possible to make boats, all-aluminium, meeting the same performance criteria as steel boats. Several countries have aluminium boats: the US, Japan, the Republic of Yemen, Australia, Russia, etc. Other countries have acquired boats combining steel and aluminium.

The design is a key element in achieving a high performance aluminium vessel. Some approaches used in the design reveal that some of the rules are too conservative and some are not conservative enough when it comes to aluminium design. In 1975, ABS has published "Rules for Building and classing Aluminium Vessels". Although this document is still valid, designers must also seek to optimize structural details according to the selection of alloys. ABS offers a classification and certification service for government ships, Navy, Coast Guard, etc. from around the world. In addition, the US Navy has also published the Naval Vessel Rules, providing additional information. It is important to understand the needs translated beyond the specifications of the applicant organization and the desired design in order to develop appropriate design procedures and specific alloys are developed as needed.

It is known that shipyards have traditionally developed their skills around

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steel. Several shipyards now tend to address their shortcomings and learn the working procedures related to aluminium, in order to know the modern manufacturing techniques for aluminium. This fact has to be considered since the lack of knowledge of current technologies does not help the cause.

Availability, training and retention of skilled welders for aluminium are also among the issues to take into consideration, since steel is still the prevalent material. There is a need for education and training of staff in order to develop skills and investment will be required from shipyards in this direction. Automation also makes sense given the situation. Thus, a lot remains to be done in the context of an increased use of aluminium.

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