Advantages of aluminium as a shipbuilding material engineering essay

The use of aluminium in any vessel involves a radical set of production methods compared to traditional shipbuilding processes. Hence, the methods used for the construction of aluminium vessels are an important factor in the feasibility study. The welding of aluminium is susceptible to hot cracking and can only be done using certain processes. It is important to employ the correct welding methods to serve different purposes. As aluminium technology matures over the years, new production methods such as aluminium extrusions were introduced in a bid to save time and which has also proven to be economical.

The use of aluminium in naval shipbuilding exists in two forms; first there is the aluminium-steel ship, where in the case, the superstructure is made from aluminium intended for topside weight saving, and the hull made from steel. Then there is the all-aluminium ship, with the purpose of achieving a considerable overall reduction in weight. It is important to understand that though both forms have their advantages, there are design issues that must be addressed related to the use of aluminium in naval vessel.

Background

1. 2. 1 Advantages of aluminium as a shipbuilding material

Aluminium’s most important characteristic is its light weight. When coupled with a reasonable tensile strength, it has grown to become the choice of material for many naval ships in the world. In a research by Wade (1996), when it comes to naval shipbuilding, mission capability is the most heavily evaluated criteria of the program. Speed is an increasingly important parameter under mission capability due to the shift in the maritime strategy of the world’s navies from blue-water operations that include traditional Anti-

Submarine Warfare, Anti-Air Warfare and Surface Action to littoral operations focusing on surveillance, mine-clearing, counter-terrorism and support for landing operations.

Ship Structure Committee (2012) suggests that there are many design parameters that can be optimized for a better performance, where structural weight is one such parameter that gives the most out of cost efficiency. According to Lamb and Beavers (2010), a decrease in weight relates directly to the reduction in material costs and operating costs throughout the service life while reduction in the power demand gives a higher fuel efficiency, higher speed, longer range and additional tonnage capacity. Also, aluminium gives additional benefits in the form of maintenance cost savings, where less painting is required.

Brown (1999) mentioned that corrosion protection offered by aluminium is around 100 times slower than structural steel. The excellent corrosion-resistance of aluminium owes its trait to the thin layer of aluminium oxide that forms immediately when the metal is exposed to air, protecting it from external elements. The use of lightweight material like aluminium can also lead to stealth improvement (International Ship Structure Committee, 2012).

In a timespan of just over a decade, aluminium high speed vessels have evolved from 30m long vessels that carried passengers and operated in littoral waters, to 120m long vessels that could carry both passengers and vehicles which operated in the open waters.

Ship Structure Committee (2012) gave an overview of the prospect of aluminium in naval shipbuilding. Aluminium is a growingly popular metal in the marine industry, typically the naval shipbuilding industry because of the wide range of physical and mechanical properties that can be created through the alloying process. Aluminium can be alloyed with chromium, copper, magnesium, manganese, scandium, silicon, silver, tin, titanium, zinc and zirconium. This wide range of alloying produces different grades of metal each with different properties.

Promising properties includes reduction in stress corrosion susceptibility, improving of toughness, strength and hardness, improving of strength without a decrease in ductility, good weldability, increase in tensile strength, elimination of hot cracking in welds, decrease in electrical conductivity and reduction in quench-sensitivity.

However, the discrepancy of the material property and behaviour of aluminium was found to vary with different sources (Sielski, 2007). The differences come as a result of different standards used for determining yield strength. Some tests were done using a 50-mm gage length that measures only weld metal and heat-affected zone, and other tests use a 250-mm gage length sample that includes the base metal. Shown in the following is one such example of aluminium’s yield strength discrepancy.

Table (1), extracted from (Sielski, 2007).

1. 2. 2 Disadvantages of aluminium as a shipbuilding material

Like any other material, aluminium also has its drawbacks. The two most important properties of a material are perhaps its yield strength and modulus of elasticity, a structure will be designed with considerations around the two properties to ensure that it is able to withstand a given load without exceeding certain permissible deflections and stress level, where the stress level is equal to the yield stress divided by a factor of safety.

Albeit aluminium alloy has a high strength-to-weight ratio, it is to be noted that for every strong aluminium alloy in terms of yield strength, there is a stronger structural steel available. In terms of Modulus of Elasticity, which is the measure of stiffness of a material, aluminium and steel measures at 69 GPa and 200 GPa respectively. Since aluminium's stiffness is only a third of steel, it will likely be deformed three times more easily than steel if put under high strain. Therefore the use of aluminium alloy is generally only limited to vessels of up to 130 meters in length (Ship Structure Committee, 2008); the longer the vessel the more stiffening is required, until a point of impracticability. The figure below illustrates the undefined yield strength of an aluminium alloy as compared to mild steel. It is important to note that for aluminium, normally 0. 2% strain limit or proof stress is used for design purposes.

Yield Strength of Steel and Aluminium

Figure (1), graph taken from (http://aluminium. matter. org. uk/content/html/eng/default. asp? catid= 217&pageid= 2144417131)

Another consideration is the low melting point of aluminium. As a naval vessel will likely be subjected to on-board fire if it comes under attack, the loss of mechanical properties of aluminium when temperature exceeds 200ËšC (Ferraris, 2005) is unfavourable. Some classification societies and navies do not permit the use of aluminium for structural applications. While

DnV, ABS and RINA permit the use of light alloy and AA5xxx series, Lloyd's register does not.

Brown (1999) noted that the cost of aluminium is roughly five times the cost of steel. Though it may be feasible to replace structural steel with aluminium alloy in view of the latter's weight-saving and corrosion resistance properties, but it might not necessarily be economical.

Table (2)

Current Methods

To determine the applicability of aluminium in naval vessels, it is important to look at the current aluminium technology available. The manufacturing and production process for aluminium is relatively new. Aluminium welding like the FSW process was invented just two decades ago at the Welding Institute in the UK. For aluminium usages to be feasible for large scale production of naval vessels, then the overall productivity must be improved. Such can be achieved through the application of aluminium extrusion and FSW as these methods offer significant cost savings (Collette et al., 2008). The existing studies on the reliability of aluminium stiffened panels can also give a clear idea of some of the impacts of aluminium usage.

1. 3. 1 Aluminium extrusions

Adding to the advantages of using aluminium is its ability to be extruded. Extrusion can allow complex design of stiffeners to be produced which can, if used appropriately; reduce the effect of stresses experienced in the mid-ship region due to hull girder bending. Collette et al. (2008) researched on the ultimate strength and optimization of aluminium extrusions. Extrusion allows a designer to replace conventional welded plates or stiffeners with extruded profiles of varying thicknesses and it can be used on decks and side shells, places with large amount of area for an increase in weight savings. This method effectively reduces the number of welds to be performed and also reduces the complexity of the overall design of the structure.

The study examined three different types of extruded stiffeners, the conventional ' T' type, the sandwich type and the hat type for use on board a high-speed vessel. The performance of all three types was found to be similar, and the study concluded that the panel should be selected based on considerations rather than which has the best strength to weight ratio. Such considerations may include cost, ease of construction and material fatigue. In the figure below, the joining of conventional plate to the stiffener requires welding while for the extruded panel, both the plate and stiffener is extruded as a single unit.

Sectional view of Aluminium Extrusion panels

Figure (2)

1. 3. 2 MIG and FSW welding

To consider the feasibility of using aluminium in shipbuilding, it is important to look at aluminium's weldability. Metal-Inert-Gas (MIG) welding, a subtype of Gas-Metal-Arc-Welding (GMAW) is the earliest form of welding for aluminium plates. In the 1950-60s, further developments gave more versatility which resulted in a highly used industrial process nowadays.

Until recently, a new and better method of aluminium welding is invented, namely the Friction-Stir-Welding (FSW). FSW is a new concept of welding where the metal is not melted for the joining process so that the mechanical properties remain unaltered as much as possible. The join between the two plates is then softened for the metal to fuse using mechanical pressure.

Kulekci (2010) notes that the FSW increases tensile, impact, and fatigue strength of the welded joint as compared to MIG process. Less hardness change and a narrower heat-affected zone can be expected in the welded material as less heat is produced from the FSW process. Higher heat intensity from the MIG process can damage the mechanical properties of aluminium. By using FSW, production rate and quality will increase and production costs will decrease.

Friction-Stir Welding Process

Figure (3), pictures from (http://www. fpe. co. uk/processes/friction-stir-welding)

1. 3. 3 Heat-Affected Zone

Mahoney et al. (1998) researched on the FSW process induced Heat-affected zone (HAZ) of the 7075 T-651 aluminium alloy. A series of tensile tests both longitudinal and transverse to the weld produced results that showed the weakest region is at the lower temperature location within 7 to 8mm from the edge of the weld area. While the average weldable aluminium alloy displays a 30 to 60% reduction in yield and ultimate strength, the loss in ultimate strength of FSW aluminium alloy is only around 25% and the yield strength at the HAZ is about 45% less than the base metal.

1. 3. 4 Strength and reliability in aluminium stiffened panels

Benson, Downes and Dow (2009) note that as aluminium alloy is an established structural material in the shipbuilding industry for high speed crafts and naval vessels, the analysis for large high speed craft operating in ocean environments have since developed rigorous methodologies for the evaluation of ultimate strength in the hull girder.

The fast increase in capacity and size of aluminium vessels has led to the demand in new engineering tools and solutions to effectively analyse the structural performance of these vessels. One of it could be the analysis on the ultimate and fatigue strength of aluminium stiffened panels. The ultimate and fatigue strength of the panels can be predicted by using the Reliability method, which consists of firstly using limit state equations to determine when the structural member has failed. Secondly, to determine the average value and the collection of random variables distribution in the limit state equation. Then the final step is to estimate the probability of a failure.

Collette (2005) researched that in the Stress-life or S-N fatigue approach, the fatigue life of a material is determined by applying continuously a varying load of constant amplitude until a crack is observed. However the main drawback is that it is not able to give feedback on the seriousness or the size of the crack. That is where the Initial-propagation of I-P method proved to be more useful. The main difference between both is that when the crack starts to form in the material, I-P method can estimate the growth using a fracture mechanics model.

1. 3. 5 All-aluminium naval ship

With all the existing technologies and methods available for aluminium shipbuilding, aluminium has the potential to replace steel in the future as the main ship construction material. Lamb and Beavers (2010) studied on the significance of an all-aluminium naval ship. It proposes two types of aluminium frigate, one with a reduced draft, the other an aluminium equivalent of a steel frigate, with identical draft and similar in weight. Aluminium ship with a reduced draft can allow for a reduction of block coefficient, thereby reducing resistance and increasing speed. With a finer hull, less power is required for propulsion, in turn cutting costs during operation.

The authors went on to conduct an analysis of steel and aluminium equivalent naval vessel design focusing on the acquisition and ownership costs. The findings showed that an aluminium ship can be constructed with just 7. 5% of the cost of an equivalent steel ship even though 50% more labour hours are required for construction of the aluminium ship. The authors highlighted that this is possible due to the overwhelming benefits of aluminium’s significantly lighter weight. Aluminium ship was also found to have operational and ownership cost advantages. Furthermore, advancement of aluminium technology in manufacturing process and design methods has closed the gap between steel and aluminium acquisition costs which in some cases, shipyards are producing aluminium structures more cost effectively than equivalent steel structures.

1. 3. 6 Hull-superstructure interaction

One of the important factors to consider when designing a naval vessel is its hull-superstructure interaction. With the aid of structural analysis software MAESTRO, Hughes and Jeom (2010) determined that Hull-Superstructure Interaction is a very complex study that can only be visualised effectively through 3D finite element model, rather than an inadequate beam theory. The vertical center of gravity for any naval vessel is critical, therefore it is important to keep the center of gravity as low as possible, either by reducing the size or using a lighter material in the superstructure.

Another important thing to note of Hull-Superstructure Interaction is the superstructure continuity with the ship side. A superstructure will participate substantially in hull girder bending in vertical continuation with the ship sides if the superstructure is long and continuous. It will undergo the same bending radius as the hull. If the superstructure rises from the same plane as that of the ship sides, then the bending will be maximal. To exclude the superstructure from any hull girder bending, it is possible to do so through offsetting it from the side sides. If superstructure is not in line with the ship sides, due to the flexibility of the deck beams, the sides of the superstructure can be subjected to a much larger radius of curvature. In the case of such design, then an intermediate transverse bulkhead must be included in amid-ship for the purpose of terminating excessive cyclic deflections and stresses in the deck structure.

The above are especially critical as a design consideration with regards to naval vessels. To further complicate matters; in a naval vessel, the amid-ship portion is used for RAS operation, or Replenishment At Sea. RAS operations are very difficult manoeuvres to execute; and it has to take place in amid-ship due to the heavier pitching motions of the vessel at both ends. In addition to that, RAS operations also require a large open deck area on both sides of the vessel. This means a reduction in the size, or width of the superstructure in amid-ship, precisely the area which experiences the largest hull girder bending.

1. 3. 7 Fatigue-induced cracking

In the case of an aluminium superstructure, the fatigue experienced will be even greater than for an equivalent steel superstructure (Grabovac et al., 1999). The cases of similar Royal Australian Navy FFG-7 class frigates which experienced fatigue-induced cracking in the aluminium superstructure were caused by a combination of applied cyclic stresses and stress concentration interacting with a region of material weakness.

This problem of fatigue-induced cracking has surfaced in almost all ships of this class. The vessel has a continuous aluminium superstructure welded atop a steel hull, which is prone to a substantial amount of hull-girder bending (Hughes and Jeom, 2010). This further reflects on how the Hull-Superstructure Interaction can affect a vessel. In the case of their study, composite material is then chosen for repairing of the cracked region by adhesive bonding, which proved to be working later on with subsequent series of assessments.

Methodology

Lamb and Beavers (2010) introduced three types of ship for their study, the baseline steel, the aluminium reduced draft and the aluminium reduced block coefficient ship for comparison. The aluminium reduced block coefficient has the same draft as the baseline steel ship but its block coefficient is much lower than the other aluminium ship.

The authors designed a 10m long mid-ship section of a naval vessel and then derived the scantlings using the ABS High Speed Naval Craft Rules. The scantlings include steel, aluminium and aluminium extrusion. Subsequently, bending moment and stress calculations were performed and the results shown were much less than the design stress of 23. 5 t/cm² for steel and 12. 4 t/cm² for aluminium. Reasons for the huge differences were given that most of the plating is based on allowable minimum thickness rather than that derived from the formulas.

1. 4. 1 Linear Stress Analysis

The structural study in the present paper will adopt the Linear Stress Analysis method. Similar to the work of Lamb and Beavers (2010), the material behaviour in this study will only be looked at in the elastic range. In the Linear Stress Analysis, the stress is assumed to be directly proportional to the strain and the structural deformations are proportional to the load. Shown below is the stress-strain graph of a material, where the limit of proportionality is the limit of the Linear Stress Analysis. Considerations will not be made for the behaviour after the limit of proportionality. Where (C) is the proof stress of the material.

Stress-strain graph

Figure (4), graph taken from (http://www. sr. bham. ac. uk/xmm/structures3. html)

In the case of Non-linear Stress Analysis, problems are solved by applying the load slowly, and then take account of the deflection with each increment. Stresses will be updated with each increment until the full load is applied. A more complex Non-linear FEA requires iterations for equilibrium with each increment; hence it is a computationally expensive approach.

1. 5 Discussion

Aluminium usage in naval shipbuilding has been increasing steadily over the years as shown in the literature above. Commercial and merchant aluminium vessels were built with different purposes and intentions in mind, some built for an increase in speed, some for more capacity and some simply for costs saving. In the case of naval ships however, they share more similarities. Common objectives would be an increase in speed and payload, if not for a reduction in draft. It is therefore important to understand what different aluminium alloys can offer for different specific function of the ship.

Aluminium alloy as mentioned earlier was found to have some discrepancies among various authorities; this might be due to the poor definition of aluminium’s yield strength due to the nature of its properties. Nonetheless, aluminium’s yield strength will be taken as 0. 2% of its strain limit.

Designing an all-aluminium vessel of a 130m in length is an inherently complex task, and the strongest design, most up-to-date methods of production and manufacturing must be adopted to reduce the risk of a structural failure. Due to the nature of the method employed in this paper, where a standard steel hull will be replaced by an aluminium equivalent, it is important to consider the application of aluminium extrusion as a more effective way to increase the stiffness of the hull to ensure no deformation takes place prematurely. As fatigue-induced stresses was found on almost all of the FFG-7 class frigates, there is a need to study the hull-superstructure interaction of the vessel and understand the effects if applied on an all-aluminium vessel.

Among the past studies, few have made comparison between a steel ship and an aluminium ship. One notable work is from Lamb and Beavers (2010), which based their calculations on a hypothesised frigate. This present paper differentiates from that in a way that it looks at the differences between the two materials if used on an existing vessel. For a ship that already has an optimum hull form, and re-designing it would be irrelevant due to specific mission capabilities, it will be useful to adopt this approach. Another way to look at it is that certain navies might prefer to build an aluminium equivalent of a steel Off-the-Shelf (OTS) ship like the FFG-7 which has proven to be a cheap and seaworthy ship, than to completely redesign an entire vessel. The design process of a new naval vessel can take up to several years.

Apart from that, the past research of the all-aluminium ship with its cost and feasibility study was found to be outdated and non-applicable to the present year. The present research will provide an up to date costs comparison between steel and aluminium, inclusive of costs incurred in the welding process, and with the additional consideration for aluminium extrusions. Also critical will be the consideration of the various methods of welding.

It is important to note that there are limitations within this feasibility study. The Linear Stress Analysis method adopted is only accurate to a certain extent and Non-linear Stress Analysis method should be adopted for any future work in this topic. Also, there are considerations which will not be covered in this feasibility study. Factors such as the lack of infrastructure for aluminium naval shipbuilding in terms of aluminium workshops and supply of aluminium panels will not be considered. Limitations may also include the lack of skilled workers and expertise in aluminium manufacturing and ship production.

1. 6 Aims and Objectives

In short, the purpose of this paper is to study the feasibility of using aluminium as a naval shipbuilding material. To achieve that, it is necessary to include the common shipbuilding material, steel, for comparison. This paper aims to give a clearer comparison, in terms of designs, methods used, costs incurred and production time of the two ships.

The US Navy FFG-7 class frigate will be used as a base ship. Designed in the mid-1970s by Bath Iron Works and partner Gibbs & Cox, FFG-7 frigate is intended to serve as an inexpensive escort ship. Its area of operations includes protecting merchant convoys, replenish groups, landing forces, submarines and carrier battle groups; also performing anti-submarine warfare or surface action. The frigate has a steel hull with an aluminium superstructure intended for weight saving.

The overall bending stress characteristics in the mid-ship section of the frigate will be presented through load, buoyancy, shear force and bending moment calculations; one with steel hull and the other, a hypothesised aluminium hull of the same dimensions. Essentially, constraining the dimensions of the hull for an aluminium equivalent will result in an increase in plate thickness due to the reduction in the section moduli of aluminium. An alternative could be the increase in the number of stiffeners to be used and ultimately, the final design of the aluminium equivalent mid-ship section should include both methods for a section modulus increment. The results produced should show that an aluminium hull would still be sufficient in terms of section modulus to keep the maximum bending stress values under the design stress of the frigate, at 131. 75 N/mm^2 (Ship Structure Committee, 2002).

All calculations in the present structural analysis will be based upon the linear elastic region of the materials only. Through the study on a mid-ship section, it can provide an idea of the stress characteristics of the entire vessel as the maximum bending moment will usually takes place in that region. Finite Element Analysis software MAESTRO will be used to model a mid-ship section of the naval vessel and give a better understanding of the structural stresses acting on the aluminium hull.

The paper will go on further to present the costs relating to the two ships, in terms of acquisition, productivity and ownership of the vessels with respect to the current steel and aluminium prices. The results from the study will be analysed and discussed, after that the conclusion will be drawn accordingly.