THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

(AUSTRALIAN BRANCH)

ALUMINIUM IN SHIPBUILDING

BY

MR. COLIN. B. JAGGER M. Sc.

SYDNEY

9TH JULY 1975.

484.

G.B. JAGGER
1975

SUMMARY

ALUMINIUM IN SHIPBUILDING

The paper provides a review of the marine applications for aluminium and the potential growth areas. Attention is focussed on some of the problems encountered by shipbuilders and means by which more effective use may be made of aluminium are examined.

The characteristics of aluminium as they relate to the selection of alloys, strength problems and the special features of welding aluminium, are discussed and an attempt is made to place welding defects and distortion problems in perspective.

The importance of a clear understanding of the economic aspects of the use of aluminium, in addition to technical expertise is stressed and the way in which the increasing use of the computer by shipbuilders will enable aluminium to be evaluated as an alternative material in a more comprehensive manner is outlined.

INTRODUCTION

The major advantage of aluminium over traditional building materials, its light weight, was utilised as soon as the material became commercially available and a number of aluminium craft were built in the 1890's in both Europe and America. These early examples of aluminium boatbuilding, constructed of pure aluminium, possessed excellent corrosion resistance in sea water but did not have the strength required for marine service.

The early higher strength alloys using copper as their main alloying element were developed in other industries and while there were a number of isolated vessels built, they did not have adequate corrosion resistance and it wasn't until the magnesium-manganese alloys were developed in the 1930's that the potential for aluminium vessels was established.

The steady growth in marine applications for aluminium was confined to rivetted small craft until the navy began using aluminium alloy in both submarines and large surface vessels. The first extensive use of part aluminium superstructures was in the 'Weapons' class destroyers in 1947.

Increased stability requirements for passenger ships demanded by the Safety of Life at Sea Convention in 1960 encouraged designers to re-appraise the advantages of using lightweight aluminium superstructures as an alternative to the additional permanent ballast or increased beam found to be necessary to achieve the required standards. The first really big step forward for aluminium in this field was made when over 1000 tonnes of aluminium were used in the rivetted superstructure of the S.S. "United States".

Modern useage of aluminium in the shipbuilding industry began in the 1950's with the development of the metal inert gas process of welding. For the first time welds of a consistently high standard could be made economically and the way was open for designers to take advantage of the high strength, light weight and corrosion resistance of this versatile material.

Aluminium can be used to improve stability, increase deadweight capacity, reduce draft, increase speed and minimise maintenance. This paper will show that aluminium alloy has a place in shipbuilding by relating its characteristics to marine applications, setting out its proven fields of use and indicating growth areas. It will discuss problems facing the shipbuilder and, particularly in the field of welding, will provide guide lines for the more effective use of aluminium.

MARINE APPLICATIONS FOR ALUMINIUM

The best known application for the layman would be aluminium small craft. A tremendous rise in the numbers of cartop dinghies and other light trailable boats demanded by an affluent society made quantity production viable and stretch form techniques, coupled with well-developed welding processes, enabled manufacturers of aluminium boats to compete very favourably with those using fibreglass and other established materials. There is an economic limitation on a middle range of boats as aluminium construction is essentially 'one off' type of production and the need for rigid panels, limits the saving in weight that can be gained. The favourable weight/ballast ratio obtainable for larger aluminium hulled yachts has made this material first choice for ocean racers. The reduced maintenance and clean appearance has further enhanced its reputation.

Aluminium has been used in the construction of hydrofoils more from necessity than from choice and consequently few writers have bothered with the economic aspects. Weight must be substantially reduced to gain a power/weight ratio sufficiently high for the vessel to develop power 'over the hump' that is, to lift the entire planing hull clear of the water. The hull must be both strong and resilient to enable it to withstand the acceleration and re-entry forces. A number of alloys with the required characteristics to meet these demanding criteria were available at the time hydrofoils were commercially developed and in addition the technology for satisfactory welding and fabrication was already established.

Hovercraft have complemented some of the services performed by hydrofoils as the inability to carry weight is not present to the same extent. Aluminium is first choice in this unique type of construction for both strength members and shell panelling. By 1968 the Mountbatten class were developed which could carry 250 passengers and 30 cars, one British company alone has up to 60 amphibious hovercraft on its production line.

The changing role of the navy and the changed types of ships in service have made at least partial aluminium construction the normal rather than the exception. Capital ships have been phased out and their relatively small replacements have practically the same amount of tracking and detection equipment. The scanners and other weights high in the superstructure have made aluminium superstructures a must for stability requirements. Light displacement missile vessels and patrol craft which make up the bulk of any modern fleet require fine lines for speed and can make the most use of aluminium's obvious assets, light weight, high strength, good formability and excellent corrosion resistance for reduced maintenance.

Fishing boat design must be firmly based upon purely commercial considerations and although owners are traditionally very conservative, more and more fleets are turning towards aluminium construction. Light planing hulls capable of lifting up to two tonnes of catch have been in service in the in-shore fishing industry for some years and a comprehensive economic study sponsored by the Aluminum Association of the U.S.A. several years ago domonstrated a substantial financial gain for aluminium trawlers engaged in a wide variety of fishing. The investigation showed that aluminium hulls made possible higher cargo/hull weight ratios with savings in fuel consumption, allowed larger vessels to be powered by the same unit or gave increased speed and greater range thus cutting down 'dead time' moving to the fields. There is negligible cleaning and maintenance in the fish holds in which no linings need be provided.

Design features minimising first cost and reducing fabrication difficulties have been the final break through. The economic gains have been demonstrated and the demand which followed has been increasingly met by aluminium vessels which make full use of the desirable characteristics of aluminium.

The final marine application to be discussed, containment systems for liquid natural gas carriers, is also the most spectacular growth area for aluminium. The first quite small LNG carrier went into service in 1959, by 1973 there were 2.4 million tonnes of new construction on world order books representing 3.8 million cub metres capacity. Aluminium alloys with the required cryogenic properties were available and the technology was already developed ready to meet the demand created by changes in the use of energy resources.

Liquid petroleum gas containment systems with temperature ranges to $-82^{o}c$ use both aluminium and a variety of alloy steels in direct competition but the LNG field, with temperatures down to $-162^{o}c$, is dominated by aluminium alloys. The reason is relatively simple, there are few changes in the composition of aluminium alloys for the more severe service and thus few changes in the fabrication techniques whereas the high alloy steels necessary for the very low temperature gases require very much more sophisticated welding and fabrication methods.

These are the common marine applications, aluminium is used in some of them from necessity and in others for purely economic reasons. Some are static, some are expanding rapidly, in all areas aluminium is gaining steadily wider acceptance.

There are problems encountered by shipbuilders using aluminium and in the next sections some of these will be examined, however the overall picture is clear, aluminium has a place in shipbuilding and will gain much wider acceptance.

THE CHARACTERISTICS OF ALUMINIUM ALLOYS

The inconsistent results obtained when welded aluminium structures were first introduced could be blamed on deficiencies in the welding processes but the poor performance in aluminium construction which has led to considerable financial loss by some shipyards in recent years can largely be attributed to a lack of appreciation of the special characteristics of aluminium alloys.

The situation has occurred because designers who have a high degree of competency when working with steel have not been aware that minor changes in the chemical composition of the selected aluminium alloys may have only a marginal influence on strength and corrosion resistance, but could have serious consequences in the production processes.

These difficulties need not arise as there is reliable data available for both design and production. However, to make full use of this information the designer must understand something of the inter-actions between chemical composition, heat treatment, physical properties, and the requirements of the welding process.

THE RANGE OF ALUMINIUM ALLOYS.

Commercially pure aluminium is soft and ductile. The increased strength required for commercial uses is achieved by the addition of such elements as copper, zinc, magnesium, manganese and silicon to produce various alloys. These either singly or in combination impart strength to the metal.

The two basic types of aluminium alloys are referred to as heat-treatable and non-heat-treatable. A heat-treatable alloy is one which, during its process of manufacture, has been subjected to a carefully controlled thermal treatment in order that its strength may be improved. A non-heat treatable alloy depends upon the hardening effect of alloying elements for its initial strength and further strengthening is made possible by various degrees of cold working.

A wide range of alloys with vastly different properties are available. Strength varies from about 13000 psi. for commercially pure aluminium to tensile strengths approaching 100,000 psi. in the zinc based alloys.

The poor corrosion resistance of the copper based alloys was mentioned in the section reviewing marine applications, and it was stated in general terms that a number of other groups of alloys are also unsatisfactory for a variety of reasons. The very high-strength alloys with zinc as the major alloying element cannot as yet be readily welded thus have very limited use and, while the alloys containing appreciable amounts of silicon are in demand for architectural applications, they have no advantages applicable to shipbuilding.

Although these groups of alloys will not be discussed further, a general knowledge of their characteristics is useful, as most texts dealing with the metallurgical aspects of alloys use them to illustrate points concerning the magnesium and magnesium-silicon alloys commonly used for marine applications.

It is not within the scope of this work to study the metallurgical aspects of alloys however some general comment on their chemical composition and thermal treatment will emphasise the need for attention to detail if they are to be used effectively.

THE EFFECTS OF CHEMICAL COMPOSITION, THERMAL TREATMENT AND STRAIN HARDENING

The method by which increased strength is obtained varies with the alloying elements used and the way in which they are dispersed within the matrix of the material.

Heat treatable alloys are better described by the common alternative name 'precipitation - hardenable' alloys as they are those containing appreciable amounts of the elements that are soluble in aluminium. Copper, magnesium, silicon and zinc. The first step in solution heat treatment is designed to put the soluble elements into solution and this is followed by quenching. The precipitation hardening continues by holding the alloy at only slightly elevated temperatures to allow the constituents to precipitate from the supersaturated soln with considerable increase in strength. This latter process is known as artificial ageing. With alloys containing magnesium and silicon or magnesium and zinc, age hardening continues at ambient temperature for a considerable time.

Combinations of alloying elements have different effects on the strength depending on the total alloy content. For example an excess of magnesium in the low magnesium-silicon alloys increases the strength but the opposite is true for the higher magnesium-silicon alloys in the same series. Minor changes can have a tremendous effect on the characteristics.

The initial strength of non-heat treatable alloys depends on the hardening effect of elements such as magnesium which is largely held in solid solution and manganese which is in the main, out of solution and distributed as a finely divided, dispersed constituent. Further strengthening is made possible by various degrees of cold working. This has the effect of breaking down the cast structure, which consists of soft crystals surrounded by a brittle network of constituents, into a more homogeneous structure where the insoluble constituents are dispersed as inclusions in the mass. Alloys containing appreciable amounts of magnesium are usually given a final heat treatment called stabilizing to ensure stability of properties. The final strength attained is denoted by the H series of tempers.

Chemical composition and thermal treatment may be used in combination to attain desired physical properties. Compromise is frequently necessary for the conflicting requirements of marine alloys. Formability is reduced by the addition of both magnesium and manganese which are the constituents increasing strength. Welding is difficult with magnesium content less than 3.5% and there is a greater likelihood of stress corrosion with increasing concentrations.

Two features gave aluminium the reputation of being a key ingredient in losses suffered by some British shipbuilders in the 1960's. One was a lack of appreciation of the ways in which aluminium could be economically used within the framework of regulations, particularly those dealing with structural fire protection, primarily written for steel vessels. The second was the wide composition limits for the alloys commonly used in the marine field at that time. When the importance of close tolerances in chemical composition was recognised a number of alloys, including N5/6, were eliminated. Further rationalisation in the British aluminium industry which remained static even though the world average growth rate was in excess of 9%, reduced the number of available alloys still further.

The necessary limitation on chemical composition has been achieved by the Americans without limiting the number of alloys available. Recognising that a wide range of alloys presents basic problems in nomenclature and rationalisation they initiated a standard alloy designation procedure with precise boundaries within a comprehensive system. Manufacturers are not restricted in any way but their product is classified very accurately.

ALLOY DESIGNATION.

The Aluminum Association designation system is simple yet comprehensive and it can be conveniently used for describing groups of alloys in a general discussion or for a precise specification. Alloys are identified by a four figure group. The first digit in the group is the identification of the series to which the alloy has been assigned and as this depends on its principal alloying constituent, the series immediately suggests the broad alloy properties and characteristics. The temper designation follows the alloy designation, the two being separated by a dash. They designate specifi sequences of basic treatments and the final degree of strain hardening.

The Aluminium Development Council has adopted a system using four digits with the same significance as the above system and an additional letter prefix to distinguish Australian alloys. An adequate description of the system is given in Part 1 Standards for the Australian Aluminium Mill Products.

The British method of assigning arbitrary numbers for alloys and giving full details of composition, properties and thermal treatment in a Code of Practice is satisfactory for manufacturing purposes but is of little use when comparing alloys. Many alloys produced in other countries have no exact British equivalent.

STRENGTH PROBLEMS

The first problem confronting the designer when economic or technical considerations dictate the need for aluminium construction is the choice of an appropriate standard and allowable stress values which may be used for a particular application. The difficulty lies in correlating information found in manufacturing specifications, design manuals or individual specifications relevant for the task in hand. This problem does not arise to the same extent for steel construction as naval architects work to a large extent to Classification Society rules. At the present time these rules are of use only as a basic guide for aluminium construction, the designer would normally submit his own proposals to the Societies for their consideration.

The second fundamental problem is one which embraces the overall design approach. Scantlings may be based on the yield or ultimate strength of the material, static or dynamic loading may be considered, and either a limiting stress or deflection may be used as the criteria. The problem is aggravated for aluminium construction by two factors. The wealth of service experience upon which many of the steel rules are based is still lacking for aluminium construction and many alloys with similar physical properties have different fabrication characteristics.

Finally the as-welded strength of aluminium alloys compared with parent plate strength varies considerably and welded joints must be considered at all stages of design.

Unfortunately many designers who are familiar with steel continue to base their work on steel practice. It will be useful to 'spell out' the ways in which the different properties of steel and aluminium significantly affect design.

DESIGN CONSIDERATIONS

There are three main differences between the design of aluminium and steel structures.

1. Deflection has far more significance for the design of aluminium members Because the modulus of elasticity is about one third that of steel, the design of aluminium members is often governed by deflection. Some deflection is of course acceptable but it is limited by the requirement that it must not be such as to impair the strength, function, or appearance of any part of the structure. Acceptable limits vary among authorities, for example, some Classification Societies set an arbitrary value as some proportion in excess of that allowed for a steel structure while others merely state that it must not be excessive. Specific limits for separate categories of members are laid down in British Standards on the structural use of aluminium.

2. The buckling characteristics of aluminium structures in compression must be specially considered.
The modulus of elasticity is again the important influence. The buckling strength of stiffened panels and aluminium decks is lower than that for steel and an increase of up to thirty percent may be required above steel scantlings to give the same resistance to buckling in an aluminium structure.

3. More attention has to be given to the fatigue strength of marine alloys.
Some metals possess a stress level such that it is possible to apply an infinite number of stress cycles without causing failure. Aluminium alloys do not possess this fatigue limit although the number of cycles before failure increases considerably with reduction in stress.

These are the changes in overall design concepts for aluminium demanded by the widely different physical properties of aluminium and steel. There is another fundamental change required if these properties are to be utilised to attain an efficient design. This is in the design and disposition of stiffeners and built-up members. Sectional material in aluminium is almost invariably produced by the extrusion process thus providing in a single operation, sections with intricate shape which would be unobtainable by the rolling process normally used for the production of steel sections.

ALLOWABLE STRESS VALUES FOR MARINE ALLOYS

Aluminium alloys, like steel, behave elastically over a considerable range of stress. The onset of plasticity is roughly defined by the 0.2 % proof stress, corresponding to a permanent strain of 0.002. This stress is analogous to the yield stress of structural steel, however, the overall stress-strain characteristics of steel and aluminium are entirely different. Although scantlings relative to steel are usually based on ultimate tensile strength, yield strength is the governing factor for most aluminium alloys.

It is important to recognise the essential difference between ultimate and yield strength as the basis for design. Ultimate stress is that which causes rupture but the percentage elongation of aluminium is so large that the structure usually becomes useless long before the ultimate strength of the material is reached.

GUARANTEED MINIMUM STRENGTH

Tables printed in technical papers listing the physical properties of aluminium alloys usually contain guaranteed minimum values derived either from the minimum specified properties set out in manufacturing standards, or from commercial limits reported in the literature of aluminium suppliers

National standards give details of the limits of composition, properties and tolerances. The wealth of information, necessary for the purpose for which the standard was written, is excessive for design purposes.

Codes of Practice list acceptable properties for alloys relevant for the required services and although these are taken from standards, they are limited in scope. Alloy 5083 (N8) for example is listed in the structural code (4) in only two temper conditions F and O yet the minimum yield strength rises from 124 MN/m^2 in these conditions to 24MN/m^2 in the H321 temper recommended for marine platework. The ultimate strength has a more modest increase from 277 MN/m^2 to 345 MN/m^2.

Values for guaranteed minimum strength are satisfactory for comparisons between alloys but are of limited use for design purposes as they are derived from machined test specimens tested under laboratory conditions. They are utilised in a number of ways to define allowable stress levels for loaded structures.

PERMISSIBLE STRESSES FROM CODES OF PRACTICE

Standards for special purposes such as the ASME.Boiler and Pressure Vessel Code are complete in themselves and contain specific permissible stresses for alloys but these values are of limited use for more general applications. At the other end of the scale the basis of many of the tables found in general texts on aluminium design is not clearly defined and limitations on the conditions under which they may be used, are not stated. Basic static design strength is frequently taken as

$$\frac{\text{ultimate tensile strength}}{2} \quad \text{or} \quad \frac{\text{yield strength}}{1.65}$$

and even these two are not necessarily derived from manufacturers' guaranteed minimum values but 'suggested reliable figures that a designer may use'. While they may be adequate for most purposes, designers will have trouble justifying them to the satisfaction of statutory bodies.

A method which is considered to be a genuine attempt to relate the guaranteed properties of alloys to the behaviour of structures, and one which is suggested as being acceptable to most authorities is set out in Appendix D of the structural code (4). Permissible axial, bending, shear, and bearing stresses are derived from formulae combining both 0.2% proof stress (yield) and ultimate tensile strength. They apply to unwelded members under static loading when buckling need not be considered. The general increase in static permissible stresses over the recommendations of an earlier report (1962) by the Institution of Structural Engineers, is supported by the inclusion of specific rules for the design of members subject to fluctuating loads. Brief mentionof these rules will be made when discussing methods of dealing with welded joints. It is important not to regard allowable stress as a fixed value suitable for all loading conditions.

There are many ways of arriving at a satisfactory allowable stress for various applications and provided their basis is known, they can readily be evaluated in the light of the foregoing comments. However thereis a further aspect which requires clarification. The factor of safety which must be applied for specific design conditions.

FACTORS OF SAFETY

The controversy over appropriate factors of safety is a live issue among naval architects and little guidance is given by statutory authorities. There are a number of ways of approaching the problem and themethod adopted depends to a large extent on the conditions of loading.

When designing for static loads the allowable stress is some fraction of the yield or ultimate strength of the material. This ratio is the safety factor. For dynamic loading where the forces acting on the structure are due to acceleration or movement in a seaway a design allowance is made by applying dynamic factors to the stresses induced by the normal loading conditions. Fatigue loading requires an entirely different approach which will be discussed separately.

THE CHANGES REQUIRED FOR WELDED STRUCTURES

So far the discussion on strength problems has been confined to the properties of unwelded parent plate. A study of tables of typical ultimate and yield strength before and after welding will show that the mechanical properties of the common alloys are affected to varying degrees by welding. The lower strength of weldments compared with the parent plate is one of the principle reasons for the different approach to design required for aluminium structures.

THE STRENGTH OF WELDMENTS

There are two essentials in the design of aluminium weldments, an understanding of the variation of yield and ultimate strength when the various alloys are welded, and reliable values for as-welded strength. Neither of these are straight-forward. The first is complicated by the different magnitude of change from the as-welded to welded condition with alloys having only minor differences in chemical composition or different temper condition and the second has the added difficulty of making provision for a number of welding processes and procedures.

All fusion welds in aluminium have a heat affected zone adjacent to the deposited weld metal in which one or more of the following metallurgical changes in various degrees and combinations takes place:

A softening of previously work hardened parent plate.
Recrystallization of the base material immediately adjacent to the weld.
Melting of the low melting temperature phases in the heat-affected zone, which may result in microfissures from cooling stresses.

The extent of the zone is approximately 25 mm on both sides of the centreline of the weld regardless of the plate thickness.

It would be inefficient to completely disregard the higher strength of the parent plate and use as-welded strength for the allowable design stress but it could equally well be argued that welding may be carried out on highly stressed members with a serious risk of failure if parent plate strength is used for design. Clearly a way must be found for dealing with the problem of two strength levels within one member.

The draft Australian Standard DR75029 provides part of the answer. Tables of prequalified procedures are given. Considerable relaxation of the qualification requirements is permitted in procedure testing if the welding parameters specified in the code are adhered to. A weld quality level is selected most appropriate for the service to which the weld will be subjected and specified on the drawing. Limits are set for variation from parameters, and minimum tensile test requirements are given which are known to be consistently obtainable using the given procedures.

Welding position has little effect on weld strength and no appreciable differences are found between the manual or automatic MIG processes.

Tables are readily available for reliable allowable strength of fillet welds and these can be used to advantage as fillet welds have become one of the most commonly used methods for joining members and account for a considerable amount of the routine calculations for aluminium design.

FATIGUE STRENGTH

Although the fluctuating loads affecting the entire ships structure would normally not be of such magnitude or of sufficient frequency to warrant using fatigue strength as the design criteria, individual members may be subjected to high reversals of stress and their failure under fatigue conditions could have serious effects on the whole structure. It is for this reason that designers need to be able to accurately assess the fatigue strength of aluminium structures.

In high-speed small craft the stiffened panels of shell plating forward and those adjacent to the propellers are subjected to repeated slamming pressures and the high number of cycles encountered in a relatively short period has frequently led to failure of the welded joints between stiffeners and shell plating, and in the shell plating itself. Stiffeners frequently have intermittent welds in order to reduce distortion and this type of joint, having approximately 50 percent of the fatigue strength of an equivalent continuous fillet weld, is particularly prone to failure.

The aluminium industry uses endurance limit as the measure of the ability of an alloy to withstand fatigue. This limit is obtained from tests which subject a polished specimen of the alloy to 500,000,000 cycles of completely reversed stress (tension and compression) without failure using the R.R. Moore rotating beam type machine. Although these fatigue endurance tests indicate the relative fatigue-load strengths of alloys it is rarely that the derived endurance factors are usable for design. The customary problem facing the designer takes the form:- 'what stress is allowable if it is assumed that there are x number of cycles in the lifetime of the member and the average stress cycle comprises a specified variation in loading.'

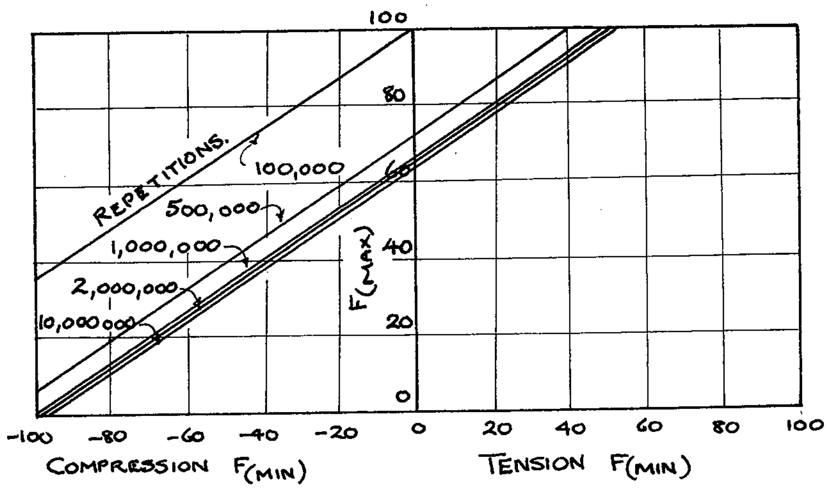
The fatigue behaviour of a component is dependent on the mechanical properties of the material and the details of the component itself.. Stress concentrations play a dominant role as fatigue life is dependent on themaximum local stress, not the average stress as is usual under static loading. Environment is important as pitting of a surface can reduce the fatigue life of a member and there is also a possibility that stress corrosion may lead to fatigue failure in thehigh magnesium alloys.

As the fatigue life of a structure is determined more by the joint configuration of the connections than by the fatigue limit of the parent alloy, codes of practice are based mainly on the results obtained from practical tests on the particular joints involved.

The British structural code CP118: 1969, (4) sets out curves and tables giving maximum permissible stress versus stress ratio for a varying number of cycles of stress and covering 9 classes of joint. Thus the permissible value of any one of the three quantities can be obtained where the other two are known. This data is appropriate for the normal alloys used in shipbuilding and a full description of the classes of joint covered in descending order of fatigue strength is given.

A more general method than that used in the structural code is given in the ASCE: 1962 specification. A chart as illustrated in Figure 2 (10) is used to express the maximum allowable tensile stress in net section as a percentage of the allowable stress in the heat-affected zone of the parent-metal alloy. Separate charts are available for butt welds and fillet welds.

fig. 2.



This method is well suited for marine applications as reliable information on the strength of aluminium joints welded in shipyards is available (18.).

Care must be taken not to over estimate the number of cycles for a given load condition. The number of cycles of load encountered in a ships' structure is usually very small as compared with machine-part cycles which are the main consideration in other industries. As a general guide it can be assumed that well fabricated structures, designed within static working stress levels will withstand 100,000 repetitions of the design load without failure, even the most conservative authorities do not consider fatigue to be an important consideration for welded members subjected to less than 20,000 repetitions. A design value of 10^9 reversals is normally used for railway rolling stock and 10^7 reversals for road transport applications. This would be considerably higher than normal values encountered in ships structures. Even 10,000,000 cycles represents 20 cycles every hour for 57 years.

Alloys of about the same parent-metal yield strengths have the same fatigue endurance limits below about 10 million cycles. Above this number there is not quite so much agreement.

Generally the fatigue strength of a butt weld is superior to that of a fillet weld. Simple double butt welds, with the beads ground flush, approach the fatigue properties of fillet welds in mild steel. This is significant since an aluminium extrusion may often be designed to accommodate a butt weld in a lowly-stressed area such as the web in a built-up member, whereas the use of steel plate to form a built-up steel beam would involve fillet weld in regions of high strength.

Careful attention to details of design and fabrication pays big dividends in fatigue life. When a fatigue failure occurs in a structure, it is often a point of stress concentration where the state of stress could have been improved with little or no added expense.

CONCLUDING REMARKS

As stated at the outset, it is important that a thorough stress and deformation analysis is carried out in the early stages of design. The foregoing comments have concentrated on specific aspects exclusive to the use of aluminium in ship construction and on the sources of information from a number of related fields which are of use to the naval architect. Design for static and dynamic loading is only one aspect, it must be complemented by a careful consideration of the factors affecting the fatigue strength of the structure. The aim of the discussion was to clarify the bond between the many sides of design.

WELDING ALUMINIUM ALLOYS

The development of satisfactory welding processes has been a key factor in the acceptence of aluminium in shipbuilding. Although there is no latitude in the welding process, aluminium can be used successfully if its special requirements for welding are analysed and related to the equipment and procedures used.

THE CHARACTERISTICS OF ALUMINIUM RELATED TO WELDING

The high thermal conductivity of aluminium has an important influence on its weldability. A large amount of heat must be concentrated on the joint area in a short time to effect fusion. Even though the melting point of most common alloys is approximately 660°C. or roughly half that of steel, the higher thermal conductivity and specific heat of aluminium more than offset the difference, and more heat is required to weld aluminium than for an equal thickness of steel.

THE FILM OF ALUMINIUM OXIDE

A dense oxide film on the surface of the alloys begins reforming again instantaneously after its removal. Means must be provided to remove this tenacious film which has a melting point far in excess of that of the parent plate, while fusion is in progress. A brief note on the interactions which take place during the transfer of metal across the arc is necessary in order to understand the cleaning action and the gas shield.

One school believes the oxide film is broken up by the complex series of branched tracks generated by the multiple cathode spots characteristic of aluminium. Electrons are emitted from the cathode with current densities in the order of 10^4 to 10^5 amperes per square centimetre and transferred through the region of hot ionised gas to the anode where they are absorbed.

The spread of the arc from the wire to the plate, irrespective of polarity, results in a plasma jet which is maintained by electro magnetic forces. This jet flows at a very high velocity and the cleaning action of the arc is attributed by some authors to ionic bombardment breaking up the oxide film.

Whether the film is removed in this way or entirely by electrons breaking up the surface as they leave the base plate is still debated but it is recognised that a DC power source with the electrode positive has an oxide cleaning action which DC electrode negative does not have.

The need to remove the tenacious oxide film and prevent its re-formation during the fusion process and the need to provide an intense localised heat source to overcome the adverse thermal characteristics of the metal are the two major factors which have an influence on the welding process. However, other variables common to all fusion welding such as the type of joint, accessibility, section thickness and required mechanical properties, must also be considered.

THE WELDING PROCESS

At the present time the only methods of welding aluminium considered to be economic, consistent, and capable of producing welds of the required standard are the metal-inert-gas (MIG) and tungsten-inert-gas (TIG) processes.

The outstanding advantage of the inert gas methods of welding over those formerly used, is the absence of any kind of flux. Flux was used to chemically break down the oxide film whose melting point is far higher than that of the alloy beneath. It is highly corrosive and needs to be completely removed after welding. This is a time-consuming and expensive procedure.

PULSED ARC PROCESS

Pulsed arc welding is a recent development ofthe MIG process for applications at the opposite end of the scale from the High-Current process. It is used for manually welding thin materials and for greater flexibility during positional welding.

Pulsed arc control of metal transfer at the lower heat input levels permits the use of lower current for a given electrode diameter by providing the total welding current as two components. The first component is a low background current supplied by a normal DC MIG power source which supplies the bulk of the heat input to the weld and electrode. The second current component comes from a pulse generator, connected in parallel with the MIG power source. This source supplies curre pulses, regulated in amplitude in relation to the electrode sizes, which momentarily increase the current density at the electrode tip and cause controlled droplet transfer

Transducers or magnetic amplifiers are no longer considered to be satisfactor even though they are cheap. Solid state transistors are used in the pulse generator to give a pre-determinable wave form. The ideal wave form tails off steadily to reduce the possibility of crack formation and has an initial overshoot for deep penetration. The transducers and magnetic amplifiers originally used are not capable of producing these conditions.

POWER SOURCES FOR INERT-GAS WELDING PROCESSES

Confusion as to the type of power source to be used for the inert-gas welding processes is brought about to some extent because the recommended source for semi-automatic MIG welding is different from that recommended for the same process when it is mechanised and an entirely different source altogether is required for the TIG process.

POWER SOURCE REQUIRED FOR TIG WELDING

Conventional TIG welding of aluminium is performed with AC current. This is suitable for both manual and automatic welding, and provides ease of arc control, good arc cleaning action and good current carrying capacity without electrode overheating.

A high frequency generating unit is coupled to a normal AC welding transformer of suitable capacity to impose a high-voltage, high frequency current in phase with the welding current to assist in starting and stabilising the arc. A surge injection method may be employed to achieve the same result.

POWER SOURCES RECOMMENDED FOR MIG WELDING

The direct current required for MIG welding of aluminium can be obtained from either a motor generator or a transformer-rectifier. A transformer rectifier is sensitive to primary voltage fluctuations but is normally preferred for its low noise level of operation and negligible maintenance.

Each of these power sources can be designed to give a drooping (constant current) output or a flat (constant potential) output and the selection of the correct characteristic is vital. The comparison between these two volt-ampere characteristics, given in table 2.2 will enable the areas of application for which each is best suited to be readily seen.

TABLE 2 VOLT-AMPERE CHARACTERISTICS

	drooping characteristic (constant current)	flat characteristic (constant Potential)
Stability of welding current with variation in wire feed and torch to work distance	good	good
stability of arc length with variation in wire feed and torch to work distance	poor	good
stability of arc length with variation in joint configuration	good	good
ease of setting to welding procedures	fair	good
suitability for use with running start	poor	good

It should be made clear that successfull welds can be made under laboratory conditions with other power sources. However, welding procedures must be strictly controlled if consistent results are to be achieved and this is difficult under the conditions normally encountered in shipyards. Power sources recommended for production work should be used unless a good reason can be shown for departing from them.

WELDING DEFECTS

Shipyards must maintain schedules under working conditions which are not always ideal therefore defects will occur. Their incidence must be kept below a level where routine rectification will not disrupt work in progress or detract from the efficiency or appearance of the completed vessel.

In many cases defects may be attributable to a number of causes and may not fit well-defined categories. However the three basic types of defects are as follows:-

1. CRACKING

Centre cracking, transverse cracking, edge cracking and crater cracks are all relatively common and equally unacceptable. They may act as stress raisers, particularly where they occur near the end of a joint.

Centre cracking originating from the underside of the weld bead is generally caused by too large a weld pool, and that originating from the top of the weld bead is usually due to the incorrect choice of filler alloy. When cracks originate near the start of the weld they may be caused by excessive restraint, i.e. the stress resulting from the contraction of the solidifying weld pool is greater than the yield strength of the solid metal already deposited.

Edge cracking may be in the weld bead or in the heat affected zone of the parent plate itself, and is caused by incorrect choice of filler alloy. Many of the secondary phases which form in weld metal have relatively low melting temperatures and in multi-pass MIG welding the heat of subsequent beads results in remelting of the low melting phases in previous passes. Under the stress imposed by the resulting weld shrinkage micro-fissuring can occur. This is a serious problem only in the higher strength alloys and is closely related to ductility in the completed weld. Reference (10) gives the metallurgical aspects of this defect.

Transverse cracking in the under-weld bead of a butt joint can be caused by using a backing bar with a groove which is too deep and narrow. Transverse cracking on the upper surface of the weld is usually the result of longitudinal restraint. These cracks are commonly found when light plate is butt welded to a substantial extrusion such as those frequently used for combined spray and chine bars on small craft.

Crater cracks are common and their rectification can be troublesome. They can be avoided in butt welds by the use of run-on and run-off plates but operator skill is necessary to minimise their occurrence in fillet welds - for example by adopting a technique of back-stepping over the crater before extinguishing the arc. Intermittent welding is desirable to minimise distortion but this places a burden on the operator as there is a possibility of crater cracking at every stop. The only successful repair is to back chip the crater and reweld.

In general the incidence of cracking may be reduced by using higher welding speeds, changing the joint design, minimising restraint, or selecting a more compatible filler alloy. At higher welding speeds, shorter lengths of weld are at any one time in a temperature range susceptible to cracking and the already solidified metal is able to take a portion of the load which would otherwise be imposed on the cooling metal. In addition the faster cooling rate of higher welding speeds results in a finer dendrite structure which exhibits less susceptibility to cracking.

2. POROSITY

This is one defect in aluminium welds which is a constant source of contention between inspecting authorities and shipbuilders.

Some of the causes include insufficient cleaning of the plate, the surface condition of the filler wire, inadequate gas coverage and erratic operating conditions. However, in general, porosity is caused by the absorption of hydrogen in the molten weld pool.

It will be noted that the solubility of hydrogen in aluminium rapidly increasss above the melting point of the alloy. If hydrogen is present during the welding of aluminium it will dissolve in the molten weld pool and will be rejected when the pool solidifies owing to the relatively low solubility of hydrogen in solid aluminium. Because of the rapid freezing of the weld pool the rejected hydrogen has little time to rise and escape by way of the surface, and therefore, is trapped in the weld bead in the form of small pores or pockets.

To attain porous free welds one must ensure that hydrogen is not present. In this respect it is not always appreciated why degreasing and wire-brushing of the surfaces prior to welding is recommended. In the first place, wire brushing removes the oxide film thereby assisting the cleaning action of the arc, which only has to remove the thin film formed between brushing and welding. This, however, is not the prime reason for scratch-brushing, because aluminium can be welded by the TIG and MIG processes without this being carried out. The chief reason is that the aluminium oxide can change in form to hydrated aluminium oxide in the presence of moisture and the very high temperatures during arcing decompose the water molecules making hydrogen available to produce porosity.

As well as on the surface of the plate this hydrate may also be present on the surface of the filler wire. The high surface area of the wire compared with the volume of the deposited metal makes it imperative that the desired clean surface of the wire is obtained. Therefore the last operation of the drawing process before the filler alloy is packed in polythene bags with silicagel is to shave off the outer surface of the wire by pulling it through a shaving die.

The basic cause and what could be described as the mechanism of the formation of porosity has been discussed at length because it is a continuing problem. The mechanism of the formation of porosity is the same no matter what the cause may be and therefore it is difficult to isolate any one cause in order to minimise its effect. There is no real agreement on the effect that various levels or porosity have on the physical properties of weldments as the effect varies with the type of loading. Because it is not practicable to eliminate the defect entirely, agreement must be reached between the client and the shipbuilder on detailed acceptable standards before work commences. If this is not done there will be continuous dispute as inspection proceeds and possibly unnecessary rework for the builder. The classification system for distributed porosity set out in References (@) could form a satisfactory basis for agreement.

3. LACK OF PENETRATION:

In general terms lack of penetration applies to side-fusion, inter-run fusion and incomplete penetration. Lack of fusion may be caused by the presence of oxide films unsatisfactory machine settings or unsuitable weld preparation.

Sufficient cleaning before welding and between passes eliminates the oxide film but faulty welding techniques can combine with incorrect settings to give inconsistent results. They may also depend on the edge preparation, for example, a large welding pool resulting from high current may flow over the parent metal before the cleaning action of the arc takes place.

Lack of penetration reduces the cross section and thus the strength of the weld and when it breaks the surface the bending strength is reduced to an unacceptable degree.

@ **Classified radiographs for Defects in Aluminium Fusion Welds British Welding Research Assn. Cambridge. Houldcroft & Young.**

DISTORTION PROBLEMS

Shrinkage and distortion are essential features of any welding. They occur because of stresses set up during contraction of the solidifying weld pool. Although there is no general formula for eliminating distortion steps can be taken to minimise its effect.

High heat inputs are required for successful fusion in the aluminium welding processes and this, coupled with its high coefficient of expansion and a thermal conductivity four times that of steel, makes distortion an ever present problem. However the effect of the properties of the material are offset to a large extent by the MIG welding process. The heat source is very intense, the speed of welding of welding can be very high and it is a continuous process.

The strength of even the non-heat treatable alloys is affected by temperatures above 400°C thus it is not practicable to rectify distortion using thermal methods without affecting the structural strength. It is just this difficulty of removing distortion from aluminium structures which sets it apart from steel at the present time. 'Line heating' methods of straightening distorted steel plate and members are so much an accepted part of steel fabrication that one tends to lose sight of the fact that the distortion, which looms so large in discussions on aluminium, is initially present to the same extent in steel. Greater efforts must be made at each stage from design to completion to prevent distortion in aluminium.

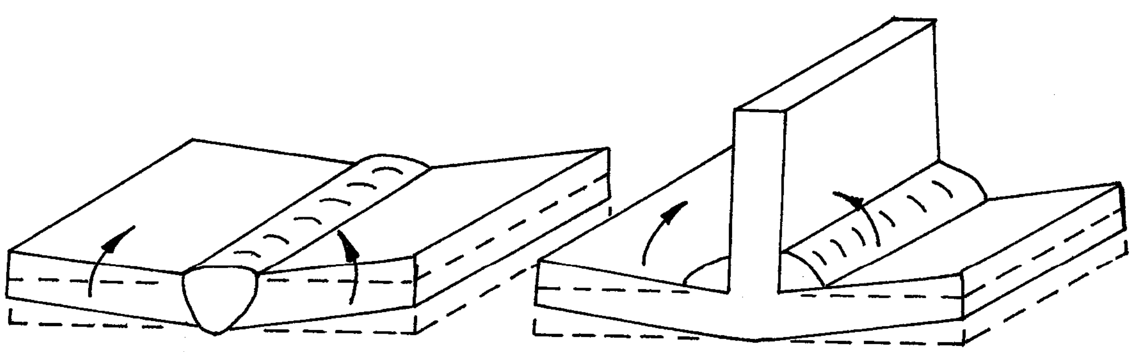
DISTORTION CONTROL DURING FABRICATION

Distortion, which is the result of eccentricity of thermal disturbance in welded joints, can be classified into three types and although they all may be found in one member, suggestions aimed at minimising their effect would be made clear by treating each one separately.

1. Longitudinal distortion: This is a problem encountered when flat plates are butt welded prior to further fabrication and assembly. If the material is thin, edge waviness may result or the joint may be bowed. Prevention is by using high welding speeds and a correct sequence of welding. Rectification can be carried out by mechanical stretching of the weld area.

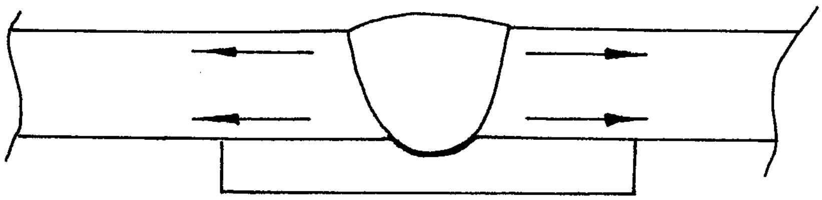
2. Transverse distortion; The width of the plate is reduced by contraction across the weld. Dimensional allowance should be made to offset the effects of transverse distortion in addition to the liberal use of tack welds for holding the job in position and using high welding speeds.

3. Angular distortion: The tendency of the plate to rotate about the longitudinal axis of the joint and is the result of transverse shrinkage being eccentric to the neutral longitudinal axis of the deposited weld metal. This is the most common distortion found in welded assemblies.

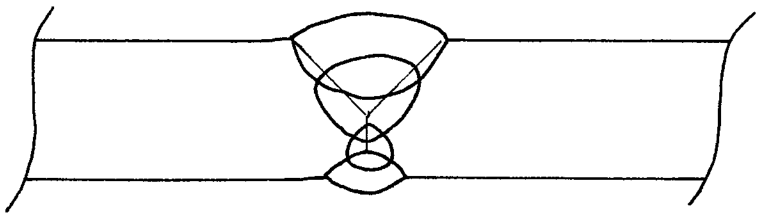


Angular distortion from butt welds is minimised by reducing the eccentricity of the contraction stresses. If the butt weld is completed in one run using a grooved backing bar to support the run on the underside as shown in Fig. 4, there will be relatively uniform heating and shrinkage on opposite sides of the neutral axis of the weld.

fig. 4



If the number of runs used on each side of multi-pass butt welds are equalised a fairly effective control of angular distortion may be maintained. The weld preparation should be arranged so that a greater amount of metal is deposited in the downhand position using high currents and so that only the same number of runs are necessary in the overhead position.



Within practical limits the angular distortion is more a function of the number of runs deposited than the current used.

In fillet welds the form of the joint does not permit concentricity as in a butt weld. The smallest fillet consistent with design requirements should be used. Wherever possible weld simultaneously from both sides of a joint to equalise contracting forces and use as few runs as possible. Rigid jigging and pre-setting assist in prevention and mechanical straightening is necessary for removal.

THE DESIGNER'S ROLE IN DISTORTION CONTROL

A number of general rules can be used at the design stage to minimise distortion:-

1. Keep the amount of welding to a minimum. Joints may be replaced by formed or extruded sections. Butt welds should use a minimum of edge preparation and root opening. All welds should be as small as possible.

2. Specify intermittent welds rather than continuous ones if they are satisfactory from other points of view such as fatigue, strength and cost.

3. Specify methods and conditions which give the highest possible welding speeds e.g. MIG welding, machine welding, flat position welding.

4. Specify competent jigging.

5. Specify that joints be located to cause least distortion e.g., at neutral axes or disposed so that weld contraction stresses balance each other.

6. Specify welding sequence and/or assembly sequence to reduce distortion.

7. Specify presetting of members to compensate for distortion.

8. Design for sub-assemblies which can be fabricated under preferred welding circumstances.

In summing up it can be said that, although distortion will always be a problem, it can largely be overcome if it is attacked in a systematic manner at all stages of design and construction.

. THE ECONOMIC EVALUATION OF ALUMINIUM IN SHIPBUILDING

Many papers on the applications for aluminium in the marine industry only briefly mention finance when justifying the use of the material. Very few authors have examined the economic aspects in depth. To use aluminium effectively in shipbuilding a detailed technical knowledge of the material is essential. It is equally important to demonstrate clearly its economic advantage.

In this section an attempt will be made to show that it is now possible with the aid of the computer, to make a satisfactory economic evaluation of aluminium construction.

THE EARLY ECONOMIC STUDIES ON THE USE OF ALUMINIUM

Early economic studies on the use of aluminium dealt mostly with conventional ships or those for specialised services such as the carriage of corrosive cargoes. Hypothetical steel and aluminium vessels were compared or an equivalent aluminium design for an existing steel ship was used to demonstrate changes in overall dimensions, capacity, powering or speed.

The study by Lengham (6) could be considered as representative of those published in the 1950's. He investigated the replacement of the midship and poop superstructures of a 600 ft bulk ore carrier by equivalent aluminium structures without altering the dimensions of the ship. No account was taken of the time value of the investment and a hypothetical charter was used as a reference. In the same work the increase in beam and power for a 23,000 ton all-steel passenger ship meeting the same stability and speed requirements as one with an aluminium superstructure were calculated and a comparison made of initial and running costs over a 20 year period.

The accent later moved towards quantifying tangible benefits, such as increased capacity, and including more operational factors. By the mid 1960's hull life, scrap value and maintenance wereincluded in the calculations for a variety of vessels. On e of the more comprehensive design studies aimed at increasing efficiency in the United States shrimp industry was sponsored by the Aluminium Association.

A trawler was designed to engage in several types of fishing and to operate at long range. Actual costs for construction and operation of an equivalent steel trawler and a smaller wooden vessel were used for comparison and data which included average catch and operating conditions for four widely different fishing grounds, was compiled in collaboration with the United States Department of the Interior. Depending on the trade considered, the additional first cost for aluminium construction was found to be recovered in one to three and a half years. A clear advantage for the aluminium vessel in all fields was demonstrated.

The technical reasons for using aluminium in the construction of lightweight hydrofoils and air cushioned vehicles developed in the 1960s far outweighed the economic considerations and very little was written about the competitiveness of the material selected. Their rapid growth and future prospects were reviewed (16) with hardly a mention of cost. Similarly, aluminium construction was accepted as being the natural choice for the superstructures of passenger liners built at this time and most papers on their design and construction covered the economic aspects only in general terms.

CHANGES MADE POSSIBLE BY THE USE OF COMPUTER PROGRAMMES

Studies of the type outlined above involving an increasingly wider range of factors were genuine attempts to look at the problems objectively and the inadequacies of studies which compared equivalent vessels by means of service parameters only, were recognised. It was only when greater use of the computer enabled designers to include structural detail and production costs in their calculations that the way was open to begin evaluating alternative materials in a more comprehensive manner.

With the wider use of computers, factors related to the trade, to finance and to the design of the ship can be integrated. It is no longer necessary to balance cost savings on alternative designs in isolation and the designs themselves can be evolved with alternative materials considered in every phase.

Structural design and analysis programs enable a more efficient use to be made of the properties of aluminium. Design can be developed from first principles without the need to substitute aluminium directly for steel members. The way is open for production and design to be integrated and detailed procedures necessary for the efficient fabrication of aluminium may be held in data banks accessible to production personnel.

A brief review of some of the programs already in use will show that the changes noted above are already part of current practice in shipbuilding although their implications for the further use of aluminium have not yet been fully realised.

COMPUTER AIDED METHODS OF ECONOMIC EVALUATION

The results of the first preliminary design study to make extensive use of the computer were published in 1965, (14). Considerable manual interface was required between various phases in the computing procedure which dealt only with ship parameters. By 1970 computer techniques had advanced to the stage where cost relations and financial criteria could be directly used for optimisation, and calculations included port development and building facilities as well as trade parameters (8).

The central feature of any economic study is the total value of the investment for the owner. This holds irrespective of details of cost-savings, whether they be gained from a greater deadweight capacity resulting from the use of aluminium or a faster turn-around resulting from a better matching of vessel size and port facility.

To optimise the many factors involved in the total value of the investment, general concepts must be translated into specific criteria, e.g. required freight rate, which depends upon the known facts or the assumption made. This task has already been tackled successfully in a number of different ways in computer programs developed for preliminary ship design, it only remains for the designer to relate the characteristics of aluminium which have the greatest economic impact, its light weight and corrosion resistance, to these existing programs.

THE SCOPE OF EXISTING PROGRAMS

Little would be gained by tracing the development of computer programs but an examination of the scope of several existing programs will illustrate how the recent rapid advances will significantly affect the future role of aluminium in shipbuilding.

One of the most comprehensive studies on preliminary design is that made by Buxton in 1972, (5). The reasons for using the computer approach were covered in detail and the role of the builder in preliminary design was defined. Higher unit value, complexity of financial arrangements and the ease of merging technical and economic criteria were used in an overwhelming case for integrating all phases of design and production by means of the computer. General bounds for detailed parameters with respect to the ship, the service and the investment were fixed by means of statistical methods. Data banks were built up and cost comparisons made of income accruing from various methods of charter or owner operation. Sensitivity tests for changes in parameters were an integral part of the program.

While this development was taking place in the preliminary design field similar progress was being made on structural design programs. By the mid 1960's the C.B.C. program developed by Det Norske Veritas enabled designers to input main dimensions, type of stiffening and arrangement of primary members, and read out scantlings of beams, girders, shell, decks, weight of parts, centres of gravity and total weight. A large choice was given for structural elements and grades of steel. Restrictions on the sections of structural members were accepted.

Program packages became available which enabled designers to use finite element analysis techniques without the need for volumes of preliminary work and an analysis-redesign method using first principles was developed whereby, starting with a simplified geometric definition of the midship section, the hull girder area, neutral axis and inertia were calculated.

STUDIES DIRECTLY CONCERNED WITH ALUMINIUM

Structural weight and the cost of construction were seen as major design decisions for conventional ships by Evans (7). He was concerned primarily with the affects that a number of grades of steel, variation in frame spacing and longitudinal or transverse framing systems had on these two factors but a comparison between aluminium and steel construction was included. This was based on the standard 'Mariner' class cargo vessel and aluminium cost data from typical American shipyards. This study gives some idea of the way in which the integration of design and production allows aluminium to be correctly assessed.

Linear Programming Methods were used by Caldwell (6) to illustrate the required percentage saving in weight to offset increased initial cost for bulk-carriers. A number of parameters were used to define the weight -cost interaction as a utility function which was then optimised.

These programs would enable the true relationships between higher initial cost, annual charges, earning capacity and weight saving to be found. Additional factors such as reduced maintenance, reduced cleaning time between cargoes and higher resale value can be given their true weight. However, there is still a considerable amount of work to be done to integrate the particular problems related to aluminium construction into the more general programs available. These are no longer hypotheticalstudies to sell the idea of aluminium, they are examples of the way in which alternatives must be evaluated if the shipbuilder is to remain competitive.

5. IS THERE A FUTURE FOR ALUMINIUM?

This is a valid question and one which cannot be answered by merely restating the growth potential in a particular industry or showing how the physical properties of the material may be used to advantage.

The refining process for the production of aluminium requires large quantities of electric power and fears have recently been expressed that the growing world energy crisis will place the future of aluminium production in jeopardy. These fears are unfounded. If the present fuel problems are not overcome there will be no future for any of the industries upon which our present economy is based. Aluminium is established as part of a way of life and its products are found in the home and in every facet of industry. Per capita annual consumption of aluminium products in the USA is already over 22 kg and increasing at an average yearly growth rate of 8.7 percent (2), applications are evident all around us.

There is little possiblility of aluminium being superseded by other materials in the forseeable future as it has been established in this generation in the face of competition. Unlike other industries which have their future profitability in the balance as a result of disposal problems and environmental protection measures, the recycling of used products is already profitably established in the aluminium industry.

The vast known reserves of bauxite, the ore of aluminium, are found in a wide belt around the world centred principally on the tropical-sub-tropical zones. Being a surface earth, the mines are open cut and readily accessible. They are not unduly influenced by politically unstable economies, Australia ranking equal first with Guinea in her reserves of bauxite which are now being actively worked to supply the refining and semi-fabricating complexes established throughout the country.

The confidence of the shipbuilding industry in the future of aluminium is reflected in the massive investment already taking place. The Japanese shipyards which are being modified in order to specialise in liquid-natural-gas carriers plan complete air-conditioned factories to house the production lines for aluminium containment systems and have already developed welding equipment and procedures specifically for these vessels.

Aluminium technology has advanced rapidly in recent years. Joining aluminium to other metals has been a problem in most industries particularly in shipbuilding. Even carefully painted and insulated mechanical joints between aluminium and steel were subject to extensive galvanic corrosion. Random areas become exposed to the corrosive marine environment where slight shifting of the structures creates localised insulation failures and the presence of a crevice as well as the significant galvanic potential between aluminium and steel promotes rapid and extensive corrosion. Explosio bonding of dissimilar metals discovered very recently is providing the answer to this problem.

In 1967, after considerable experience had been gained in cladding metals for the chemical process industry, a program was initiated to develop an explosion bonde transition joint suitable for the connection between aluminium superstructuresand steel hulls.

Explosion bonded strip is now available which allows both aluminium and steel to be welded to the respective faces of the transition pieces by standard welding techniques. Corrosion resistance is excellent, the strength is greater than that of the weaker of the two materials and it is competitively priced. All shipyards working with the explosion bonded transition joint have found it easier and more economical to install than mechanically fastened systems and there is no maintenance required after installation.

An excellent description of the bonding process and a review of some of the applications are given in reference (12). Transition strips are already being extensiv ly used in U.S.A. and they are available as tailor-made blocks in Britain. This is one further example of the way in which a rapidly developing technology is overcoming the few remaining problems standing in the way of a full acceptance of aluminium.

Whether the short term aspects such as the current shipbuilding programs are examined or the very existance of aluminium in future industry is questioned, one thing becomes abundantly clear. Aluminium is a part of modern technology and it has an assured future.

CONCLUSION

For a number of marine applications the use of aluminium is the only practical and economic way of meeting design and operational criteria and growth rate in these fields is restricted only by the number of vessels required. In other areas the advantages have been demonstrated and acceptance is growing. The more extensive use of the computer for detailed studies in both preliminary and structural design will enable the true potential for aluminium to be evaluated and many more shipyards will be involved in the use of this material

Shipyards regularly working with aluminium have realised that a different approach from that being used for steel is necessary. The difficulties are not in the new fabrication techniques but in recognising the changes in process variable that requires their adoption. Modern cutting equipment, in particular the rapidly developing plasma arc machines, will continue to reduce fabrication costs and the wider use of explosive bonded transition joints will virtually eliminate one of the last remaining problem areas, the ever-present hazard of electrolytic corrosion between dissimilar metals.

12 REFERENCES

1. Aluminium Development Council of Aust. "Aluminium Technology" Aluminium Development Council of Aust. Sydney.

2. Aluminium Federation Ltd. "European Aluminium Statistics 1971" Aluminium Federation Ltd. Birmingham.

3. Allday, W.J. "Aluminium for Small Craft" Symposium on Small Craft. Southampton September 1971. The Royal Institution of Naval Architects.

4. British Standards Institution. "The Structural Use of Aluminium" B.S.Code of Practice CP118: 1969.

5. Buxton, I.L. "EngineeringEconomics Applied to Ship Design" Transactions. The Royal Institution of Naval Architects Vol. 114 1972.

6. Caldwell, J.B. "Structures and Materials : Progress and Prospects". Philosophical Transactions of the Royal Society, Series A Volume 273 1972-3.

7. Evans, J.H. "Optimising Ship Structural Design Through the Choice of Materials" Journal of the Society of Naval Architects of Japan Vol. 128. Dec. 1970.

8. Fisher, R.W. "Economic Optimisation Procedures in Preliminary Ship Design" trans. The Royal Institution of Naval Architects. Vol. 114 1972.

9. Flint, A.R. "Riveted Joints in Aluminium - alloy Ships Plating" Report No. 163 (RB 987) 1955. The British Ship-building Research Assn.

10. Knight, J.W. "Welding, Kaiser Aluminium" Kaiser Aluminium of Chemical Sales Inc. California.

11. Macy, R.H. "Design Criteria and Economic Study - All-Aluminium Trawler" Aluminium Assn of the USA.

12. McKenney, C, Banker, J. "Explosive Bonded Metals for Marine Structural Applications" Marine Technology. Vol. 8 No. 3 July 1971.

13. Muckle, W. "The Design of Aluminium-alloy Ships' Structures". Hutchinson Eboy (Publishers) Ltd., 1963.

14. Murphy, Sabat, Taylor. "Least Cost Ship Characterisation by Computer Techniques".

15. Paffett, J. "Hydrodynamics and Ship Performance" Philosophical Transactions of the Royal Society Series A. Vol. 273 1972-3.

16. Shepheard, R.B. "The Challenge of Our Marine Environment". Trans. North East Coast Inst. of Engineers and Ship-builders. Vol.85. 1968-69.

17. Technical Services Dept., Comalco "Practical Welding of Aluminium". Comalco Ltd., Sydney.

18. The Society of Naval Architects and Marine Engineers. "Report of Aluminium Weld Test Program". Technical and Research Bulletin No. 2-13 The Society of Naval Architects of Marine Engineers.

19. The Society of Naval Architects and Marine Engineers. "Guide for the Selection of Wrought Aluminium Plate and Shapes for Ship Structure". Technical and Research Bulletin No. 2-15.

APPENDIX 4. PHYSICAL PROPERTIES.

1. COMMERCIALLY PURE ALUMINIUM.

Density (solid) 2.698 Grams/cubic cm @ 25°C
(0.0975 lb/cu @ 77°F)

Linear Coef. of Thermal Expansion 22.5×10^{-6} cm/cm/°C
(12.5×10^{-6} ins/in/°F)

Thermal Conductivity 0.59 Cal/sq cm/cm/sec/°C @ 25°C
(142.7 Btu's/sq ft./hr/ft/°F @ 77°F).

Melting Point 660 ± 1°C
(1220 ± 1.8°F)

Electrical Conductivity/Resistivity 4.8 ohm m
(15.8 ohms/circ.mil/ft @ 68°F)

2. ALLOY 5083 - H321

Ultimate Tensile Strength 304 MN/m^2
(44000 lb/in^2)

Yield Strength 2.14 MN/m^2
(31000 lb/in^2)

Modulus of Elasticity 68900 MN/m^2
(10×10^6 lb/in^2)

Poissons Ratio 0.33