NON-FERROUS METALS IN MARINE ENGINEERING

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The wide range of metals included in the non-ferrous group have many and varied inherent qualities which render them of major industrial importance. It must be admitted that single outstanding features rarely constitute sufficient grounds for the selection of a metal for service, but suitable alloying, in conjunction with fabrication and heat-treatment, has largely provided a solution by enhancing overall qualities. In consequence, these alloys serve a most vital role in ensuring efficient operation and adequate service life of machinery and structures, although the proportion employed in relation to other materials may be relatively small.

Such is the case in marine engineering, where recent improvements and developments have increased the number and types of alloys in service, in addition to widening their general field of application.

Corrosion

In the first place, the corrosive nature of marine environments constitutes one of the most arduous service conditions metals are required to withstand in their many applications. At the beginning of the century the corrosion problems associated with marine condensers were recognized to be dezincification, impingement attack, pitting, and galvanic action. The benefits conferred by additions of up to 0·05 per cent arsenic in minimizing dezincification of α-brasses and aluminium brasses are now well established. Since the ($\alpha + \beta$) 60 : 40 brass does not respond to such additions, the use of this alloy has been confined to components of working sections which have sufficient thickness to tolerate reasonable amounts of dezincification.

Impingement attack or corrosion erosion was observed to result in rapid deterioration of the alloys then employed. The high local liquid velocities, associated with air bubbles in excess of a critical size, produced a scouring action capable of removing protective scales and deposits, thereby accelerating corrosion. Increase of temperature and any form of local obstruction, which increased liquid velocities, enhanced this effect. Since copper undergoes erosion due to liquid velocity alone, it has now been confined to less arduous services in water systems. The arsenic-bearing 70 : 30 brass is still employed for condensers in which liquid velocities do not exceed 7 ft/sec and provides suitable service life in these applications. Where higher velocities are associated with aeration, 70 : 30 cupro-nickel tubes, with iron contents of 0·4–1·0 per cent and manganese 0·5–1·5 per cent, are widely employed or, alternatively, 76 : 22 : 2 aluminium brass inhibited with arsenic is used.

In view of the benefits obtained from small additions of iron and manganese to 70 : 30 cupro-nickel, the influence of iron on alloys of lower nickel content was investigated. Marked improvements of both impingement-resistance and attack experienced under stagnant conditions were obtained from iron additions of 1–2 per cent to alloys containing 5–10 per cent nickel. Alloys of this type with 5 per cent nickel and 1·05–1·35 per cent iron have prospects of being widely employed for condenser and other purposes. The 10 per cent nickel, 2 per cent iron alloy is, however, preferred in the United States.

Tin-bearing copper alloys with tin contents below 8 per cent have so far proved inferior to these alloys, although when the content is of the order of 12 per cent, good resistance to erosion has been observed. Coatings of zinc, tin, nickel, or chromium have been applied to the surface of non-ferrous tubes, but have not been considered worthy of continued use. Duplex tubing, in which different alloys are utilized for bore and external surfaces, have frequently been considered for specific purposes. In America this form of tube is again receiving consideration, combinations of copper, various brasses, aluminium bronze, or cupro-nickel being supplied with aluminium, Monel, nickel, or steel external contact metals. Chemical and refrigeration plant represent the greatest application of these forms of tubing, but as yet few data are available on the service experience obtained.

Particular problems are those involving severe pitting of these alloys due to marine growths. Bio-fouling tends to be more severe on alloys having enhanced corrosion-resistance. In addition to causing pitting by its own action, the growth tends to trap decaying debris, thereby increasing the attack on the metal surface. Adequate water velocities and careful maintenance assist in reducing these forms of deterioration.

The use of dissimilar metals, whether in contact or in different parts of a continuous system in contact with sea water, inevitably leads to cathodic corrosion. The relative value of the electrode potential for each metal or alloy, immersed in sea water, indicates the liability of marine corrosion occurring in the more anodic metal, when two or more are involved. As a preliminary precaution, therefore, metals and alloys of widely differing potentials should be avoided in these instances, although severe restrictions may thus be imposed on the range of suitable materials available.

Steel-to-aluminium alloy jointing is becoming increasingly frequent with the extension of the usage of aluminium alloys to structural and machinery applications. Local contact at faying surfaces of structures is usually avoided by interposing galvanized strip or non-metallic packing, bolting with surface-protected steel bolts and by the application of zinc chromate paint. In some instances unprotected local steel-to-aluminium contact has resulted in rapid corrosion of the aluminium. In machinery applications, when the necessity arises, zinc coating of the steel is usually adopted as the most feasible method of protection. However, when extruded aluminium alloy hollow sections were employed for cooling grids with brine circulations in refrigeration plant, avoidance of corrosion at steel-bodied shut-off valve connections was not achieved, and these grids have been dispensed with.

Steel riveting of aluminium structures exposed to marine atmospheres is, therefore, undesirable, although in other respects it offers a suitable jointing method.

Copper and nickel alloys are avoided in contact with aluminium and its alloys, and the effects of copper to steel contacts are minimized by zinc coating the steel surfaces or by the employment of protection blocks which corrode sacrificially. Zinc is widely used in this connection, the high-purity form being considered the most effective. However, owing to the ineffective bonding of zinc to steel and to the semi-impervious layer of corrosion product formed on the zinc surface after short-time operation, doubt has been cast on the value of this metal as a protector for marine purposes. Despite the possible validity of these criticisms, however, zinc is still extensively used and must be of some merit. Addition of $\frac{1}{2}$ per cent lithium to the zinc has been suggested as a means of obtaining a less insulating corrosion product, but no record has so far been observed of this alloy finding use in service.

Iron or steel affords protection to copper alloys and is not only beneficial in reducing the corrosion due to electrolytic action, but it also enhances the corrosion-resistance of aluminium brass. Nickel-base alloys, being more noble, are generally confined to applications with stainless steels or to components where the sections are such that some degree of corrosion may be tolerated.

Protective coatings or blocks of more anodic characteristics therefore form the most common method of limiting these forms of corrosion. In recent years the economic and practical value of cathodic protection of buried pipelines and structures has offered an alternative means of minimizing corrosion. High-purity magnesium anodes have proved most effective and, in conjunction with suitable impressed potentials and current densities, have been extended in use to protect marine pipelines, structures, and the submerged surfaces of ships laid up in reserve. Only limited experience has been obtained with sea-going vessels, as many as 106 magnesium anodes being located on the bilge keel. Whilst such refinements might prove effective in extending docking periods for operational warships, the benefits afforded to merchantmen are doubtful, as these vessels are docked at frequent intervals for many purposes.

A most serious corrosion problem exists in oil-tankers, which carry alternately oil cargo and sea-water ballast in the same tanks. Flat surfaces, and other regions which do not drain efficiently, undergo rapid corrosion. The combined influence of the oil and the sea water promotes this extreme deterioration, the high oxygen contents of the oils being mainly responsible, although the sulphur content has also been suggested as an additional contributory factor. Steaming out of the tanks aggravates these conditions by loosening adhering scale and increasing the chlorine ion concentration at the higher temperatures involved. Although cathodic protection, involving the use of an active magnesium or other type of anode, has been applied in limited instances, controversy exists as to the economic and practical advantages obtained.

Aluminium alloys are claimed to have a high resistance to corrosion under these conditions, and might offer alternative means of reducing deterioration either as spray coatings, linings, or complete tank units. So far these alloys have not been tried, but future development may involve their use.

The deposition of minute quantities of one metal from solution on to another of more anodic characteristics in water-carrying systems in whose construction dissimilar metals have been used, has been observed to accelerate corrosion failure. Copper transmitted in this form to galvanized steel or aluminium components was the metal mainly concerned, but this example demonstrates the further need of careful material selection for the conditions appertaining.

The high rate of corrosion of metals which can be associated with electrolytic action presented marine engineers with major problems over 100 years ago. For example, the severity of corrosion of iron screw-shafts running in sea-water-lubricated brass bushes and in the vicinity of copper sheathing, led to the fitting of brass sleeves or liners to the shaft as a means of protection. At the present time, limitations on the selection of the wide range of metals and alloys available to the engineer are imposed by similar problems. Solutions offered by surface coatings, wastage blocks, or impressed cathodic protection cannot always be employed, or are not entirely efficient. An effective solution appears to be far from obvious, and the engineer can only hope that the metallurgist, in his researches, may develop more efficient methods of passivation.

Cavitation Erosion

One of the most severe forms of metallic-surface deterioration is associated with damage sustained by cavitation erosion. Under the suction conditions of dynamic fluid flow, the surfaces of propellers, impellers, and similar hydraulic machinery components may suffer this form of erosion. The collapse of cavities formed on these surfaces is considered to release quantities of energy in the form of localized forces, similar in nature to water hammer. The magnitude of these forces may be sufficient to bend propeller blades, but their confined character more commonly induces highly localized stresses in the metal, producing surface rupture and severe distortion of the crystal structure. Damaged surfaces tend to increase local turbulence, enhancing cavitation tendencies and extending the depth and area of the eroded zone. The mechanism of failure is not fully understood, and controversy exists as to the part played by corrosion.

Marine propellers experience this form of damage to varying extents, depending on the design, the conditions of operation, and the material of which they are made. Cast iron and cast steel are prone to have local regions of porosity which are easily eroded and give rise to a deeply pitted form of attack. Bronzes, which are of a more resistant nature, exhibit eroded regions having the appearance of areas that have been subjected to intense local sand-blasting. Despite their more resistant nature, however, bronze propellers have been known to decrease in weight during service by as much as 10 per cent, attributable to overall corrosion and erosion losses. Such losses not only impair the propeller's efficiency, but also reduce its inertia. In consequence, the one-node mode of torsional vibration of the machinery dynamic system will be raised, and critical vibrations may be placed out of barred speed ranges or brought in close proximity to service or operational speeds.

Improved propeller designs based on extensive hydrodynamic studies are expected to reduce cavitation conditions, but the higher powers transmitted and the turbulent flow imparted by the stern of the ship will limit the benefits likely to be obtained. The application of alloys having the maximum resistance to this form of cavitation erosion has therefore been considered. In order that the relative merits of the available alloys might be ascertained, experimental techniques simulating extreme cavitation conditions on the surfaces of suitable specimens have been adopted. Erosion-resistances were based on weight losses in standard exposure times and, whilst some degree of variation of results is inevitable, good guidance is given to the relative resistance of the alloys involved. A reasonable assessment of the erosion-resistance of an alloy is given by the product of the surface Brinell hardness number and the corrosion-fatigue resistance expressed in tons sq in for 50 million cycles of reverse bending. The more highly resistant alloys have values in excess of 800, and in descending order of merit they include austenitic stainless steels, aluminium bronzes, with or without nickel additions, low-nickel stainless steels, silicon Monel, Monel metal, high-tensile bronze, and Turbadium bronze. Below 800, the normal manganese bronzes, silicon bronzes, phosphor bronzes, gun-metals, cast irons, and aluminium alloys are placed. This does not imply that the manganese bronzes which have given such good service have poor resistance, but they are used purely as a basis of comparison.

Cast iron, which is still widely used as a propeller material, should have its surface skin intact, as this increases its resistance to erosion, as do additions of copper, nickel, and chromium. Soft alloy 'stopper' metals employed to plug local casting defects are of negligible value.

Nickel deposits, applied to the surfaces of cast-iron propellers of trawlers, have provided increased corrosion- and erosion-resistance in service. The severe corrosion, which occurred at fractured sections, and the high cost of the deposit caused this practice to be abandoned, however. Similar deposits applied to bronze propellers have also proved uneconomical. Spray coatings of zinc, lead, and aluminium have been applied to cast-iron propellers in service. Of these metals, pure aluminium was found to be the most reliable, although respraying of exposed areas became necessary at intervals.

Erosion losses were found to increase with increase of sea-water temperature, up to 50°C, used in laboratory tests, and this feature must be taken into account when comparing the merits of the metals in service. Of the alloys tested showing cavitation-erosion characteristics superior to those generally used, the stainless steels and aluminium bronzes appear the most suitable for manufacture and service purposes. Since uniformity of cast structure is advantageous in providing homogeneous properties throughout the propeller mass, the grain refinement obtained from iron and manganese additions to 9–12 per cent aluminium bronzes should be beneficial.

Experiments clearly indicated that aluminium, nickel, or both, as additions to copper or copper–zinc-base metal, resulted in alloys having low cavitation-erosion-loss characteristics. The latest materials used for large marine propellers are copper-aluminium alloys with nickel and iron additions, resembling that specified in B.S. 1400 A.B.2, and the more recent copper alloy with high aluminium and manganese content. Castings having maximum weights of 25 and 35 tons have been made in these alloys, respectively, and even larger castings are under consideration.

Impellers of pumps are invariably of gun-metal, manganese bronze, aluminium bronze, Monel metal, or stainless steel. Cast surfaces can frequently be retained, thereby offering superior resistance to corrosion and erosion. The last three materials quoted are usually employed where the conditions are most severe in respect of temperature, stress, and erosion.

The exceedingly low erosion-resistance of aluminium alloys cannot be neglected if these materials are to be used for hull construction and for small-sized propeller castings. The service experience under conditions of erosion has not yet been sufficient to establish the resistance of these alloys, but, should the experimental evidence be borne out, alternative materials may have to be used for hull sections that experience cavitation.

Sprayed metal deposits applied for the protection or reclamation of surfaces experiencing cavitation erosion have been found to be of only temporary value, both experimentally and in service. The porosity associated with these deposits is probably responsible, and sound fusion welds represent the best method of repair and surfacing.

Fatigue

Alternating stresses, arising from the excitation of natural modes of vibration of machinery and component mass-elastic dynamic systems, have resulted in many service failures. Mathematical analysis in conjunction with dynamic stress measurements, obtained during operation of machinery installations, has led to a reduction in failures of this type, either by the avoidance of critical vibrations in the vicinity of operating speeds, or by limiting vibration stresses to values below the fatigue strength of the materials employed.

Alloys having enhanced fatigue strength are advantageous where these conditions are involved, in that they permit higher stress levels to be tolerated. In addition, where the actual magnitudes of the stresses are indeterminable, higher-strength alloys can extend service life by increasing the number of cycles to rupture, and may even provide a complete solution.

Whilst cold working is readily employed for improving the mechanical properties of non-ferrous alloys, the availability of many alloys capable of acquiring enhanced strength by heat treatment, has offered marked advantages. In many instances, precipitation-hardening or quenching to obtain structures of the acicular martensitic type, has had such a marked influence as to render non-ferrous alloys competitive with ferrous materials in many applications.

The low corrosion-fatigue strength of plain carbon and many low-alloy steels, confirmed by reverse-bending salt-spray tests of 50–100 million cycles' duration, at less than 4,000 lb/sq in has been responsible for machinery failures. Copper- and nickel-base alloys, in particular, offer excellent corrosion-fatigue characteristics, and manganese, aluminium, and phosphor bronzes, Monel metal, and K Monel metal have all been used in preference to these steels for many shafting applications, including screwshafts of limited size. In addition, these alloys are frequently preferred to the chromium stainless steels because of the tendency of this material to pitting, especially in the presence of graphite grease.

Corrosion-fatigue strengths of many alloys have been determined experimentally for cycles of stress in excess of 50 million, and they provide the engineer with useful design data.

At elevated temperatures the influence of mean stress in relation to fatigue is of marked importance, owing to the deformation due to creep. At a given elevated temperature, the limitations imposed by fatigue strength and creep strength form individual extremities.

The magnitude of vibratory stresses, occurring when natural frequencies of components are excited by external influences, is dependent on the degree of damping available. Whilst the significance of the damping capacity of material has not yet been fully assessed, in instances where accurate determinations have been made, low values have been recorded for many metals and alloys. Internal damping cannot, therefore, be relied on to limit alternating stresses to values below the fatigue strength. This does not necessarily imply that the inherent damping properties of metals are insignificant, for, in similar application, a metal of superior damping characteristics might give longer service life.

Use of Metals at Elevated Temperatures

The advent of the gas turbine focused attention on the requirements of alloys for service at elevated temperatures. As operating temperatures even higher than those at present employed would be desirable, the search for superior materials continues. In this country, with the exception of the well-established Nimonic series of alloys, ferritic and austenitic steels have so far proved most suitable for these purposes. Both heat- and creep-resisting steels contain high total contents of nickel, chromium, cobalt, molybdenum, titanium, niobium, tungsten, and manganese, thus demonstrating the importance of non-ferrous metals in these applications. Indeed, the total content of these metals frequently exceeds 45 per cent, and for heat-resisting purposes the higher the temperature, the greater the amount of non-ferrous metals present.

To a large extent, gas-turbine alloys have been based on three primary metals, typical being nickel–chromium–iron and nickel–cobalt–iron alloys and, more recently considered in Canada, nickel–aluminium–molybdenum alloys. Stiffening against creep depends in these alloys on the precipitation of constituents, provided in some instances by small additions of other elements. With the possible limits of these types of alloy being approached, materials based on higher melting point metals have been receiving greater attention. Chromium, titanium, and molybdenum are the metals mainly involved and, although the purer forms of these metals are not themselves suitable for high-temperature application, alloys may be developed with more favourable characteristics.

The search for high-temperature materials has tended to mask the desirability of determining the operational limits of many familiar alloys used at less-elevated temperatures. Information provided by short-time tests is undesirable, as doubts remain as to the degree of stability of structure and as to the reliability of stress assessment based on these findings, when applied to components of installations constructed for long-duration service.

Copper-base alloys used in steam plant applications have received little attention in long-term investigational work, and suitable pressure–temperature design criteria are based on very limited experimental data. Tests of not less than 10,000 hours' duration are essential on many of these alloys, and the failure of copper alloys in gas-turbine heat exchangers also demonstrates the lack of knowledge of their scaling qualities in many atmospheres.

Metal to metal contact is not uncommon at elevated temperatures, and galling has frequently been encountered at steam valve faces and guides. All steels are susceptible to this form of surface rupture, and the use of Stellite surface deposits has proved the most feasible method of overcoming these difficulties. Silicon Monel metal has good anti-seizing properties at these temperatures, but low ductility and high hardness of the cast 3·75 per cent silicon alloys can lead to thermal cracking with temperature gradients.

Surface deposits of Stellite are widely used for I.C. engine exhaust valve faces to extend the service life at the high temperatures encountered. Oxyacetylene flame-welded deposits of 80 : 20 nickel-chromium alloy are being increasingly employed for the repair of Diesel engine valves and provide high resistance to corrosion and cracking.

For steam turbine blading the ferrous alloys have almost completely replaced non-ferrous alloys in new construction. Stainless iron and nickel-chromium ferritic and austenitic steels are the most commonly employed, replacing existing copper and nickel-copper alloys. Non-ferrous materials are widely used for gland purposes, and the most suitable alloys for the various operating temperatures have been quoted as being : brass up to 850°F, S Monel (3·5 per cent silicon) below 1,300°F, and Nimonic 75 for higher temperatures.

Although the engineer can usually make suitable allowance for the expansion of metals with temperature, the use of dissimilar metals presents many complex problems. The joint application of aluminium and steel to ship construction has been receiving attention, mainly from the point of view of achieving a suitable design to minimize induced stresses.

Temperature gradients, involving thermal conductivity in addition to expansion, are of a more serious nature. Distortion and thermal-fatigue failures are becoming more common with increased operating temperatures. Data provided by metallurgists on mechanical and physical properties of alloys and their variation with temperature have been useful in design, but the factors controlling thermal shock and fatigue failure require greater attention if these are to be avoided in service.

For piston heads of I.C. engines, cast iron has given excellent service and is still preferred by many engineers. Its replacement in heavy-oil engines by forged steel was mainly based on increased soundness and pressure-tightness, although the use of centri-spun 13 per cent chromium cast steel is based partly on its superior heat-resisting properties. Whilst 20 per cent chromium steel is considered superior, as yet this material has not been tried. Aluminium deposits on cast-iron heads have been applied to reduce the heat-absorption characteristics, but opinion differs as to the value of such measures. For heavy slow-speed engines, light-alloy piston heads have not been used, as the saving in reciprocating masses is insufficient to warrant them.

High speed engines, however, employ cast aluminium-alloy pistons to a great extent, as the reduction in reciprocating masses is of great value. Well-established 'Y' alloy and R.R. alloys are used, and reliability has been sufficiently good to merit their continued service.

Applications of Light Alloys

The advantages of light-weight construction, employing aluminium alloys of suitably high specific strength and good corrosion-resistance, are not so marked in shipbuilding as in other transport industries. In addition, the extensive experience obtained in steel construction and the equipment of yards to handle steel fabrication have militated against the use of light alloys when the latter are not readily adaptable to similar processes. The extension of light alloys to ship construction has, therefore, been based more on long-term policy, and extension of their application is increasing with design and practical experience.

Scantlings of aluminium structures have been based on somewhat greater values than those given by the strength ratios of the equivalent in steel. Weight-saving, therefore, amounts to approximately 50 per cent of a normal steel structure. The advantages for the present use of light-weight construction have been summed up :

(*a*) A reduction in topside weight which increases the stability of the vessel, offering advantages not only in new construction, but in reconversion work.

(*b*) Greatly increased corrosion-resistance of aluminium alloys, particularly against the detrimental effects of petroleum and its products.

(*c*) Greater flexibility in the design of vessels operating in conditions which impose limitations on draft, beam, and length.

(*d*) Reduction in contamination of cargo and ease of cleansing refrigeration and other holds.

(*e*) For naval vessels, the non-magnetic characteristics and weight-saving are important, the latter permitting increased armour and armament.

(*f*) Greater flexibility in hull design, permitting increased speed with the same machinery power or less power for equivalent speeds.

Of these items the first has been the most important in merchant ship construction, finding application mainly in passenger vessels. Topside weight-saving has been effected by manufacturing masts, superstructures, funnels, davits, lifeboats, and accommodation fittings in aluminium alloys. The S.S. *United States* has incorporated in its construction a total of some 2,000 tons of these alloys, and a total weight-saving of 15–20 per cent of the original displacement is claimed as a result of the direct and indirect influence of these materials. With the exception of this ship, such extensive quantities of light alloys are not encountered in the many other merchant ships of composite construction. For these ships the quantities used range up to 250 tons.

For structural purposes aluminium alloys with up to 5½ per cent magnesium are considered most suitable. With this maximum magnesium content and small additions of manganese and chromium, the tendency for precipitation of the β phase has been obviated, and so has the stress-corrosion associated with the presence of this phase. Aluminium–4 per cent magnesium alloys (N.P. 5/6) are used for plate manufacture, as they are more suitable for hot working than those of higher magnesium content. The mechanical properties are generally good and meet the maximum stress requirements of 17 tons/sq in with comparative ease. Further, their good welding characteristics render alloys of this composition superior to those of the heat-treatable type of alloy. Details of the light alloys used in ship construction are given in TABLE I.

Alloy N6 (5 per cent magnesium) is used for rivets, as well as H10 (1·0 per cent magnesium, 1 per cent silicon), the latter having superior extrusion qualities to the former alloy and being, therefore, more favoured. However, it is usually employed in the heat-treated (WP) condition, as is the corresponding American alloy 61S-T4. These alloys do not work-harden to the same extent as N6, but age-harden to give higher proof stresses. Age-hardening of rivets after quenching is a drawback in shipyard practice, but it was overcome during construction of the S.S. *United States* by adopting the aircraft industry's practice of refrigerated storage. A temperature of $-10°F$ was employed, the rivets being wrapped in aluminium foil or other insulating material to assist in delaying precipitation-hardening between the time of removal from storage and the actual time of driving.

TABLE I.—*Aluminium Alloys Used in Ship Construction*

(a) *Percentage Compositions (Nominal)*

	Cu	Mg	Si	Fe	Mn	Cr	Zn	Al
N5/6	..	3·9	..	..	0·8	..	..	Rest
N6	..	5	..	..	0·5	..	..	,,
H10	..	0·7	1·0	..	0·4	..	..	,,
61S-T (U.S.A.) ..	0·25	1·0	0·6	..	..	0·25	..	,,
Lloyd's requirements * ..	0·1	5·5	0·60	0·75	1·0	0·5	0·1	,,
Lloyd's requirements † ..	0·1	1·5	1·30	0·60	1·0	0·5	0·03	,,

(b) *Mechanical Properties (Minima)*
(Typical values are given in parentheses)

Alloy	Size or Condition	0·1 per cent Proof Stress, tons/in²	U.T.S., tons/in²	Elongation, per cent	
				On 2 in	On 8 in
N5/6	$\frac{3}{16}$-$\frac{1}{4}$ in	8 (15·5)	17 (20·5)	12 (13·8)	(10·1)
	$\frac{1}{4}$ $\frac{1}{2}$ in	8 (12·0)	17 (19·5)	12 (22·3)	(15·4)
NE6	Up to 2 in	8 (8·5)	16 (17·0)	15 (25)	..
	Over 2 in	7 (8)	16 (17·0)	18 (25)	..
HE10	W	7 (10·0)	12 (15·5)	18 (25)	..
	WP	15 (18·0)	18 (20·0)	10 (13)	..
61S-T6	Plate	15·6 (17·4)	18·7 (20·0)	10 (15)	..
	Bar	15·6 (17·4)	16·9 (20·0)	10 (15)	..
Lloyd's requirements	All	8	17	..	10

* Non-heat-treated   † Heat-treated

Rivets are driven both hot and cold, pneumatic methods being used for N6 rivets of the order of $\frac{1}{2}$ in dia (cold) and $\frac{3}{4}$ in dia (hot). The heating of aluminium alloy rivets requires greater attention than is usual in steel rivet practice. Light alloy rivets are worked in a temperature range of 400°–500°C, higher temperatures being most undesirable.

The high-strength, heat-treated Duralumin and aluminium–magnesium–zinc types of alloy are not employed in marine construction owing to their inferior corrosion-resistance. In the clad condition these alloys are not economic propositions, although they have been employed in some German naval vessels.

Many small craft have been constructed entirely of light alloys, using normal and stressed-skin techniques. They provide means of gaining general experience of fabrication methods, as illustrated by the recent manufacture of a 72-ft yacht of light alloy welded construction. For the aluminium alloys to be extensively used in ship construction, efficient welding techniques must be developed. The self-adjusting inert-arc method, as used in the fabrication of this yacht, at present provides the most suitable method of fusion welding. However, as yet, this method is severely limited for general shipyard use by the degree of penetration obtained, the need to maintain a clean and corrosion-free filler wire, and the difficulties of maintaining an inert atmosphere during open air welding. The high degree of reliability attained in the fusion welding of steels has, therefore, placed aluminium alloys at present in a less favourable position.

Ease of handling gives the light alloys great advantages for hatch covers, crankcase doors, and similar applications. In the engine room, however, apart from these uses and piston castings, light alloys are not extensively employed, as the savings in weight are not sufficiently vital. Where these alloys are employed for crankcase, sump, and cylinder castings, the engines concerned are generally used for other land purposes where these features are advantageous. Some engine builders have even considered offering cast iron as an alternative for marine purposes. In consequence, the cast aluminium alloys containing silicon and magnesium find only limited scope in the machinery of merchant ships.

The ultimate tensile strength of aluminium alloys used in ship construction is still relatively low, 20 tons/sq in being an almost limiting value for normal plates and sections. It must, therefore, be appreciated that the development of alloys having superior strength while retaining the other desirable properties of existing alloys, remains an important consideration.

Use of Titanium

The remarkable resistance of titanium, in the high-purity form or with small alloy additions, to severe attack by both hot and cold sea water has aroused the interest of the marine engineer. Although this metal has not so far been used for marine purposes, the mechanical properties and corrosion-resistance are of such a high order as to render it very suitable for many applications in this industry. The problems associated with its production and fabrication, in addition to its exceedingly high cost, impose severe limitations on the engineering importance of the metal. In addition, the elevated-temperature properties are disappointing, and until greatly improved alloys are developed, little competition will be offered to existing high-temperature materials.

The resources of this metal are sufficiently great and readily accessible to warrant its consideration for the requirements of engineering industries.

Bearing Metals

The maintenance of film-lubrication conditions between metal surfaces in relative movement constitutes the ideal requirements of service. Non-ferrous metals which exhibit a low friction coefficient and a high resistance to local seizure, in relationship to journal materials, perform a most important function in this connection.

Whilst these qualities are of major importance, the bearing metal must also have adequate mechanical strength at the operating temperatures to withstand the applied bearing loads, and sufficient ductility to tolerate normal amounts of malalignment. In addition, the rate of wear undergone by shaft and bearing surfaces must be exceedingly low and the corrosion-resistance must be of a high order. A great deal is, therefore, required of a bearing metal, and it is not surprising that no ideal alloy exists and actual selection for particular service represents a compromise or an ingenious combination.

Methods of assessing the relative merits of bearing metals with any degree of reliability have not yet been established, and controversy as to the controlling qualities still exists. The maximum loading per unit area forms a major feature in relation to both the strength of the metal and the degree of wear which may be tolerated. The product of this load and the surface velocity, often quoted as a criterion, leaves much to be desired, as variation within this product of either factor may be too wide.

In practice, two main types of plain bearings are used, thin- and thick-shelled. For heavy engineering purposes, where heavy loads, low speeds, and flexibility occur, thick-shelled bearings are employed. Moreover, in I.C. engine practice, when line boring is preferred, thick-shell practice is obviously involved. The shell thicknesses vary from 8–12 mm at a journal diameter of 600 mm to 2–4 mm for small diameter shafts. Although thinner shells may appear to be more favourable for the larger bearing diameters, this has not been confirmed in practice, and war-time economy measures involving reduced shell thicknesses proved unsuccessful.

Marine engines in many instances have shafting of normalized plain-carbon steel with Brinell hardness values between 121 and 173, the lower hardness being more commonly used. White-metal bearings, therefore, are employed of the high-tin Babbitt types, containing 80–93 per cent tin. The large surface areas which may be involved in bonding these bearing metals to copper alloys, cast iron, or cast steel present difficulties in obtaining entirely effective union over the whole surface. In the absence of suitable methods for proving the bond —other than hammer testing—keying of the metal is still widely employed as an added precaution, although it offers little improvement against fatigue failure.

Higher speed engines, with increased bearing loads, high oil temperatures, shaft journals of heat-treated steel with a Brinell hardness of 300 and line-bored bearings employ thick-shelled lead-bronze, usually tin-backed to steel. The refinement of using top and bottom half-shells of different metals (i.e. white metal on the lightly loaded side and lead-bronze on the highly loaded side) is no longer widely employed. Such refinement was based more on considerations of economy than on bearing theory, and hence the change to all-lead-bronze bearings and the disappearance of this technique.

In practice, failures of thick-shelled bearings are divided evenly between (*a*) wiping and running of the metals, and (*b*) cracking or breaking up of the surface. A high percentage of failures of type (*a*) were due to oil starvation arising from neglect. Cracking of bearing metals by fatigue is exceedingly common, and may be associated with high oil temperature or simply with the inability of the metal to resist the loading conditions.

These failures are invariably associated with the bearing halves supporting the high loads in reciprocating machinery. Bottom halves of main and crosshead bearings and top halves of bottom-end bearings, therefore, are most susceptible to cracking, although bottom halves of bottom ends also suffer a fair proportion of failures in practice.

Alternative bearing metals having increased strength while retaining the other qualities of the high-tin Babbitt metals have not yet been produced, and engineers must, therefore, contend with the failures as best they can. Whether the aluminium–20 per cent tin alloys or the 30 : 30 : 40 copper–silver–lead alloy, exhibiting higher fatigue properties, will prove superior to either of those described in thick-shell applications has yet to be demonstrated.

More lightly loaded bearings for line shafting and similar purposes utilize lead-base Babbitt metals. These give excellent service, especially in view of the flexibility of marine shafting installations and the variation in alignment with loading conditions of the ship.

The realization that greatly increased fatigue strength is a feature of very thin layers of bearing metals has led to the development of thin-shell bearing practice. These bearings are not extensively employed in marine engineering, but are found in some high-speed main and auxiliary engines. Shafts hardened by surface methods are most commonly used with bearings of this type. White metals and lead-bronze layers cast-bonded to steel shells are both favoured, although the latter find greatest usage, with or without lead and indium coatings. The excellent anti-friction properties of lead and indium reduce engine frictional losses, and extended use of these metals in bearing applications is expected.

Top-end bearings are made of white metal, lead-bronze or, more commonly, phosphor-bronze bushes, depending on the type of engine, pin hardness, lubrication, and temperature. Bearing metals of similar type are used in pumps, in addition to other bronzes, whilst for under water service an alloy of zinc 30, tin 68, and copper 2 per cent is frequently preferred.

Stern tube and rudder bearings are salt water lubricated, being of lignum vitæ and gun-metal mating materials. The stern tube bearing supporting the tailshaft and propeller is of vital importance, as the ship must be docked for examination or repair to be carried out. Wear of the lignum vitæ must be kept to a minimum, and as gun-metal has provided a suitable contact metal in this respect, alternatives have not been greatly considered.

Gun-metals within the range 88 : 10 : 2 to 87 : 8 : 5 or leaded gun-metals of the 85 : 5 : 5 type are generally employed in the static or centrispun cast forms for these cylindrical liners. Where facilities are inadequate for casting in the entirety, sections may be cast and joined after shrinkage on to the shaft, by fusion-jointing methods. On completion of machining, the liner may be tested to 30 lb/sq in pressure to ensure soundness before shrinking on to the shaft. Contraction stresses in the longitudinal direction are reduced during shrinking by leaving a region of the bore at the liner centre with clearance and preferentially cooling this section first, after sliding on the shaft. Such regions are pumped up with red lead or similar compound, and the necessary holes, drilled for this purpose, are plugged.

Penetration of sea water between liner and steel shaft may promote corrosion-fatigue failure of the shaft and certainly electrolytic corrosion will occur.

Fusion Jointing and Deposition of Metals

The jointing, rectification, and repair of metals by fusion methods now form a major industrial process, and the adaptability of alloys to this type of union has become an almost essential feature. A wide range of methods have been developed for fusion jointing, including many having specific applications. Metallurgical soundness and physical properties equivalent to the parent metal provide the desired object of fusion-welding processes, although when high strength is not a primary feature, other forms of joint involving fused filler metal are available.

Low-strength joints, in which fusion of the parent metal is not attained, have wide application. Soft and hard soldering, brazing, and bronze welding represent the chief such methods. Soft soldering with tin–lead alloys, with or without antimony and silver additions, is applied where temperature and stress conditions are of a low order. Strength investigations on these forms of joint have indicated maximum values for a 50 : 50 tin–antimony alloy which solidifies over a wide range of temperature. The extensive use of soft soldering for iron, copper, zinc, lead, tin, nickel, and their alloys is sufficiently well known to require little comment.

Brazing, or hard soldering, involving deposits of copper–zinc alloys or copper–zinc–silver alloys (the familiar silver solders), provides alloys of superior strength capable of service at higher temperatures. Gas-torch, furnace, and pot-dipping processes, for jointing copper and its alloys, steels and stainless steels, nickel, silver, and tungsten carbide, form extensive assembly processes. The detrimental effects of a tensile stress, initiating cracking in steels during hard soldering, cannot be overlooked, and influences of the higher jointing temperature requirements must be considered in relationship to possible physical and structural changes in the parent steels. Monel metal is not appreciably impaired by brazing, slight reduction in strength only occurring.

The application of these methods to copper steam pipe flange attachment, providing many years of efficient service, and the jointing of steel shells to copper alloy tube-plates in heat exchanger practice, demonstrate their reliability. Bronze welding with filler rods having fusion points exceeding 920° C imposes limits on the parent metals, of which copper, copper–silicon alloys, cast iron, and steels are the most suitable. Although providing good joints, bronze welding is not widely employed, as methods involving fusion of the parent metal are frequently preferred.

In marine engineering the efficient welding of thick sections is essential, and many processes perfected for thin-gauge material have very restricted application. The degree of perfection attained in jointing steels by electric arc-welding processes has not been approached by any method applied to non-ferrous metals. Less extensive usage may be partly responsible for this fact, although greater complications of oxidization, melting points, thermal conductivity, and solidification characteristics have presented more formidable difficulties in these applications. In all instances, the degree of success obtained in fusion welding is greatly dependent on suitable preparation, fluxing, the development of efficient techniques, the operator's skill, and pre- and post-heating requirements. The quality of welds cannot be directly attributed to the unsuitability of a particular process without foundation on extensive experience. However, by elimination of some of the sources which could be responsible for error, simplification is achieved. Inert arc-welding processes, therefore, offer marked advantages when applied to many non-ferrous metals. The self-adjusting electrodes and argon atmosphere used in these processes have stimulated increased interest in this technique.

Despite the advances in welding processes, the practice of poured welding or ‘ burning on ’, first established in the foundry, is still used. Repairs to castings of copper alloys, aluminium alloys, and ferrous materials are most commonly encountered, and with careful procedure and suitable fluxing satisfactory repairs, with metal of similar analysis to the base casting, can be achieved.

Deposits of metals and alloys may be applied by fusion methods for reclamation and repair of worn and damaged surfaces or for corrosion-resisting purposes. Depending on the thickness required, either one of the methods referred to may be used or, alternatively, metal spraying may be adopted. The latter method offers advantages of simplicity, and any metal, except chromium, that can be produced in wire form may be deposited. However, since fusion of the parent metal is rarely achieved and the strength of the deposit is doubtful, reclaimed parts should possess scantlings sufficient to withstand the applied loads before rectification. The building up of bearing surfaces and worn shaft surfaces has been extensively undertaken by this process with good results.

Surface spraying of zinc or aluminium for corrosion-resisting purposes has been applied to steel, zinc being applied to the hulls of small ships and tank surfaces. The tendency for coatings to be porous requires that deposited metals should be anodic to the base metal, and fusion welding is preferable where severe erosion conditions prevail.

Electro-deposition of non-ferrous metal for reclamation, corrosion protection, and decorative purposes has become so well established as to require little comment. Nickel and chromium deposits have proved reliable for the reclamation of worn surfaces and in some cases have been preferred. Of the two metals, nickel has been most favoured, and for steel shafting continuous deposits in the form of bands obviate any possibility of the metal flaking off the surface.

Cadmium plating of steel in contact with aluminium has been proposed in constructions involving these two metals. The favourable electrode potential of cadmium could be utilized on the surfaces of steel bolts and similar items in contact with aluminium. Cadmium may, therefore, be used in this form to an increasing extent, engine builders in other industries having already proved its merits in reducing these dissimilar metal problems.

Non-ferrous metals are readily used in all these deposition processes, but fusion-welding methods have not yet attained the desired efficiency required for marine purposes, particularly in regard to aluminium alloys, some alloys with aluminium contents, and many high-temperature materials. The use of these materials is being influenced by this feature and can be increased only by the introduction and development of more efficient and reliable welding methods.

Fabrication Features

A high proportion of non-ferrous metals is used in the cast condition for marine engineering purposes, copper alloys being the principal materials concerned. A large number of these castings having weights less than 10 cwt are used for valve bodies and components, pump parts, bushes, brasses, and similar items, whilst stern tube parts, tailshaft liners, larger pump casings, impellers, and turbine nozzle castings more commonly weigh between ½ and 5 tons. Propeller castings are frequently of 30–40 tons weight in the cast condition, of which some 25–35 per cent may be removed in machining operations. These items comprise some of the largest castings made in non-ferrous alloys and demonstrate the castability of these alloys and the high degree of foundry control employed. Although castings of 50 tons weight represent the largest produced for marine purposes in manganese-bronzes, the size limitations are imposed by machining facilities and design requirements.

Propeller castings of high-tensile ($\alpha + \beta$) brasses or manganese bronzes are still extensively used, although aluminium bronzes are increasing in popularity as a result of their superior erosion qualities and increased strength, which permit greater flexibility in design. Although modified β-brasses of the high-tensile type offer excellent strength qualities, the liability of these alloys to intercrystalline cracking in sea water forms an undesirable feature. However, a limited number of propellers has been cast in alloys of this structure containing 2 per cent nickel and having tensile strengths of 35 tons/sq in. Nickel additions of this order to normal manganese bronzes increase the erosion-resistance, but tend to increase difficulties of repair and rectification. Turbadium bronze, an alloy of this type, has been employed fairly extensively, the propellers of the *Queen Mary* of some 32 tons finished weight being typical examples.

Few propellers complete their service life without some repairs being necessary to eroded areas or to make good damage sustained by striking submerged objects. Failures due to defective castings are comparatively infrequent, indicating the generally high quality obtained.

Improvements in foundry control, casting methods, and inspection techniques have enhanced the soundness and uniformity of properties of all castings. Although welding methods have provided simple means of reclaiming and repairing defective castings, it is essential that this fact should not be reflected in relaxation of control or of efforts to improve the casting procedure and so reduce the defects encountered.

The improvement in pressure tightness of bronze castings effected by lead additions has resulted in a preference for this form of alloy. Low pressure valve bodies and parts, sea connections, liners, and similar parts have, therefore, been cast in both these materials.

Manganese, nickel, and aluminium bronzes have been extensively employed for higher-pressure parts and more severe temperature conditions, although for steam chests steels are being more extensively used, as the upper operating limits of these non-ferrous alloys are being exceeded or have not been sufficiently well established to warrant their use.

Centrifugal casting methods are extensively employed where the form of the components is adaptable to the process. Both chill and sand moulds are used, the former for gear blanks and bushes, where the improved structures at the chilled surfaces are of importance ; sand moulds are employed for tailshaft liners and stainless-steel piston crowns.

The higher-strength alloys are taking precedence for cast machinery parts, the aluminium bronzes being the most popular. Difficulties due to the aluminium content do not appear to be unduly severe for casting or welding, provided that reasonable precautions are taken. Vulcan hydraulic coupling rotor and clutch parts have been cast in these alloys, the intricate oil passages being readily reproduced and the strength being adequate for rotational speeds in excess of 750 r.p.m.

Aluminium alloy castings are most commonly used for lower-strength parts where ease of handling is essential. Sand- and die-cast pistons of these alloys are widely used for the smaller oil engines, as in other industries. Die-casting and precision investment-casting of non-ferrous alloys have not been extensively used in marine engineering, although high machining costs have led to consideration of these methods for low-stressed turbine and other machinery parts, at present machined from wrought materials.

Wrought alloys are used for shafting purposes in extruded, rolled, and, less frequently, forged form. The convenience of rolled or extruded round bar is useful for shafting having loose steel couplings. In consequence, as a result of the generally available sections and economic considerations, shaft diameters in excess of 5 in are rarely used.

Aluminium alloys used in ship construction are not made in such convenient sizes and sections as steels, and a tendency to increase the sizes of plates, in particular, has been in progress to meet these demands. Cold working of plates and sections to obtain more favourable mechanical properties imposes limitations on welding, in that the weld and fusion zone will be inferior in strength to the remaining parent metal.

The use of the plasticity of non-ferrous metals is of value for jointing purposes. Metal gaskets are most commonly of lead, aluminium, tin, nickel, Monel metal, and copper. Selection of the metal depends on the pressure, temperature, type of joint, and possibility of galvanic action with the flange material.

Conclusions

Within the scope of this survey some of the merits and limitations of non-ferrous metals in marine engineering have been considered. Combating corrosion still provides the most important function of these metals, and although improved alloys have reduced the rate of deterioration against some forms of this attack, there is still plenty of scope for further developments.

For elevated-temperature applications, low-and high-alloy steels have replaced non-ferrous metals in steam plant and in steam turbine and gas turbine compressor components. The Nimonic alloys, however, are preferred by many manufacturers for gas turbine blading and similar stressed components.

Light alloys are still at an early stage of development for shipbuilding purposes. Their future progress is largely dependent on a reduction in cost for the equivalent steel structure, and this can be related to the necessities of improvements in both material and fabrication methods.

Whilst there is a trend for plain bearings of steam turbines to be of the steel-backed, thin-shell, white-metal types in place of the existing thick-shelled, bronze-backed types, similar trends are impossible in heavy-oil engines. Fatigue failures of the thick-shelled, white-metal bearings used in these engines are not infrequent, and bearing metals of improved strength and capable of use with plain carbon steel journals would be advantageous.

Many of the non-ferrous metals used have limitations of resources and production. In consequence it is undesirable that either the engineer or the metallurgist should restrict his views too greatly in considering alloys for particular service. With the large number of existing alloys and the prospect of further increases in the future, close co-operation between engineer and metallurgist is desirable in order that the most efficient and economical selections of material may be made.