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The Selection of Materials for Ship Structures [and Discussion]

Stuart Cannon, Brian Ralph, D. W. Chalmers and G. Victory

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The selection of materials for ship structures

By Stuart Cannon[1] and Brian Ralph[2]

Departments of [1]Mechanical Engineering and [2]Materials Technology, Brunel, The University of West London, Uxbridge, Middlesex UB8 3PH, U.K.

An overview of the procedures to be adopted in selecting materials for use in ship structures is given. In general, materials are selected on a cost basis to meet a 'basket' of mechanical properties such as stiffness, strength and fracture toughness. Such a selection procedure may well not give sufficient importance to the dynamic loading of the structure (fatigue), the special problems associated with the joining (welding) process and the influences of the conjoint effects of corrosion. At this stage, these effects are given scant attention, although it is clear that they need to be incorporated into the design process. Methods by which these influences may be incorporated into a design data base are reviewed based on an analysis of ships which have failed and experiments designed to simulate the total environment in which a ship operates.

1. Introduction

Often the loss or failure of ships is attributed to failures of the materials from which they are built or to the methods by which these materials have been fabricated during construction. A notable set of examples of this would be the brittle fracture of a number of the Liberty ships during and immediately after World War II (Biggs 1960). There are many more recent examples as for instance in the case of M.V. *Kurdistan* which broke in two in March 1979.

For what comes later it is perhaps worthwhile reviewing some of the factors behind this particular example (Corlett *et al.* 1988). The *Kurdistan* was carrying bunker oil which was maintained at +60 °C in rough seas where the temperature at the time of the incident was −1 °C. Further, the ship had just been extricated from a field of pack ice. Detailed investigations established that the fracture initiation occurred at a defect in a repair weld in the bilge keel ground bar and that this repair weld exhibited poor fracture toughness. Once initiated, this crack was able to propagate through the bilge keel and into the hull through the fillet welds attaching the bar to the hull so that the hull cracked in two.

In some cases where ships are totally lost, studies of sister ships may yield vital clues as to the possible mode of failure. Should one ship fail then there is a distinct possibility that similar ships may fail in an analogous manner. This form of comparative analysis is central to the thinking of the aerospace industry.

One aspect of materials selection is clearly to learn by mistake. Here, where relevant parts of failed ship structures can be examined, a 'forensic' examination is of real value in helping to establish cause/effect and in suggesting better materials selection procedures. The causes of failure may be established by microscopical/microchemical investigations of fracture surfaces (Ralph 1990) and often this is a relatively straightforward process only requiring a comparison to be made with

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micrographs from the failure region with those in published atlases (Engel & Klingele 1981).

2. Basis of materials selection

The selection of materials has developed to the point of being an established science (Charles & Crane 1989). The procedure involved in the selection process obviously involves cost factors (Ogle *et al*. 1982) which include both the price of the base material and how expensive it proves to be to form into the required shape. In general, the ease of forming and joining are central to the process of selecting materials. Above all, it is the basket of properties available from any one material which governs its choice for a particular application. The ability to specify the conditions that an artefact will meet in service, perhaps including any artificial 'overloading' that it may meet, is crucial in establishing the properties which are most important in the selection procedure. In many cases the key properties will be mechanical (e.g. stiffness to avoid buckling, strength to resist tensile loads and, perhaps, above all fracture toughness to resist brittle failure). However, depending on the service environment many other physical properties may be crucial (as in the choice of glass fibre reinforced plastic as the hull material for minesweepers to reduce the magnetic footprint (Chalmers 1988)). It is all too easy for many engineers to ignore chemical properties (relevant to corrosion and degradation). Thus although chemical engineers might be expected to specify corrosion-resistant materials for chemical plant, naval architects, offshore engineers and mechanical engineers might be expected to concern themselves with the mechanical properties of materials first and then try to protect against corrosion of the structure using cathodic protection (such as 'bolt on' sacrificial anodes). Perhaps the above stresses the importance of education in relevant materials topics to naval architects, etc. (Brown & Tupper 1988; Ralph & Bodsworth 1990).

The development of materials selection procedures was initially driven by the aerospace industry for both the airframe and the engine (Betteridge 1974; Peel & Evans 1983). Clearly the economic viability of air travel and its safety have much to do with the development of materials which have ever-improved specific properties (that is the property per unit weight).

3. Materials selection for ship structures

Amongst smaller craft aimed at the leisure market there is considerable sophistication in the choice of materials for their construction. Thus materials used in windsurfers and in racing dinghies and yachts owe much to the materials developed for the aerospace industry. In these smaller craft it is common to find relatively sophisticated composite materials (incorporating Kevlar, glass and carbon fibres in polyester and epoxy matrices) being used as the main construction materials for hulls, together with stiffening by girder foams created from a number of polymers (figure 1). In other cases, high strength aluminium alloys, often again originally developed for the aerospace industry, may be used for the construction of the hull as well as the spars.

For larger ships, the construction of the main structure is dominated by the use of steel and for reasons of cost, ease of fabrication, etc. this is likely to remain the case for the conceivable future. For people who are not materials specialists there are a bewildering array of steel grades available. However, for the shipbuilding industry,

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Figure 1. An example of the use of advanced materials in building small boats. In this case the total mass of the hull and paddle is under 5 kg. (Courtesy Dr Niels Hansen of the Risø National Laboratory, Denmark.)

Table 1. *Properties and composition of shipbuilding steels*

grade...	A	D	E
C (%)	0.23 max.	0.21 max.	0.18 max.
Mn (%)	2.5 × C min.	0.7–1.4	0.7–1.5
Si (%)	0.5 max.	0.1–0.5	0.1–0.5
S (%)	0.05 max.	0.04 max.	0.04 max.
P (%)	0.05 max.	0.04 max.	0.04 max.
A (%)	—	0.015 min	0.015 min.
minimum yield stress/MPa	230	235	235
UTS MPa	400–490	400–490	400–490
minimum elongation (%)	22	22	22
Charpy *J*	—	47 at 0 °C	27 at −40 °C

the seven major classification societies agreed in 1957 to unify their requirements for shipbuilding steels so that only five basic steels were approved (Boyd & Bushell 1962). Today these five grades still exist but only three (A, D and E in table 1) are in common usage in the British shipbuilding industry (Taylor 1985).

The classification given in table 1 is based partly on chemical composition and partly on a limited selection of mechanical properties. The minimum yield stress, ultimate tensile stress and minimum elongation to failure all give values measured under simple tensile loading and thus ignore the 'influences' of any oscillating stresses. Likewise the Charpy impact energy is measured in an impact test and, where given, is a parameter which has something to do with toughness. Here a material is accepted/rejected based on the energy consumed in creating the fracture at a specific test temperature. It is perhaps surprising that modern fracture toughness parameters (such as K_{1C}) are not quoted since these give a much better indication of the size of critical defect which will give rise to catastrophic brittle failure (Knott 1973).

As well as ignoring many crucial properties, a classification such as that given in table 1 also omits the key relationships between properties and microstructure and it is this understanding which has led to so many developments of materials in the aerospace industry.

Plain carbon steels, of the type classified in table 1, are essentially iron carbon alloys. An understanding of the range of microstructures, and hence properties

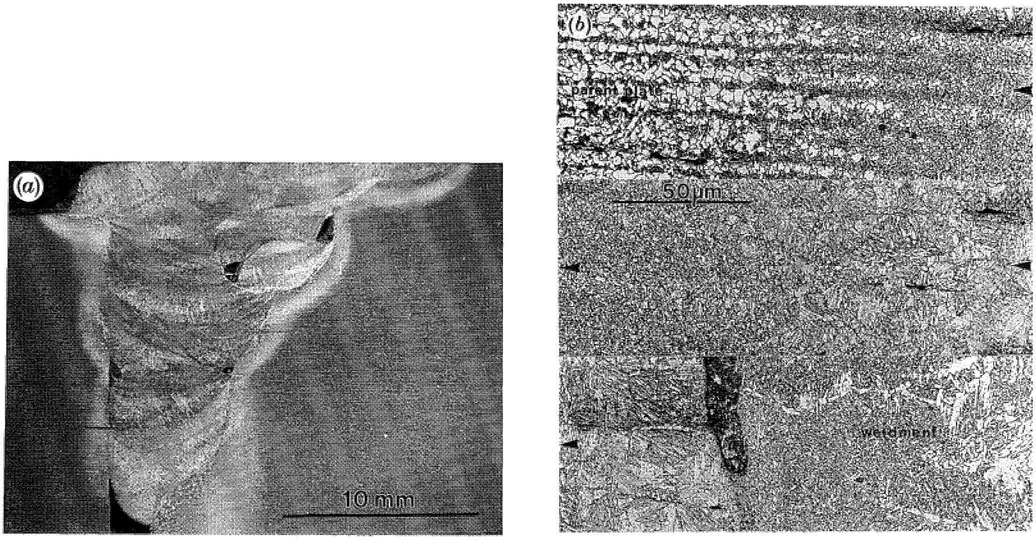

Figure 2. A light micrograph through a typical weld showing a considerable disruption in the microstructure in the heat-affected zone. This butt weld has been made by multipass manual metal arc welding in BS4360 50c plate steel. The low magnification image (*a*) reveals a number of defects in this weld arising from lack of penetration, lack of fusion, cavities and slag inclusions. The higher magnification images (*b*) reveal the disturbance to the microstructure which occurs in the heat-affected zone. The three parts of this figure (*b*) track across the heat-affected zone marked on (*a*) from the weldment to the parent plate, as shown.

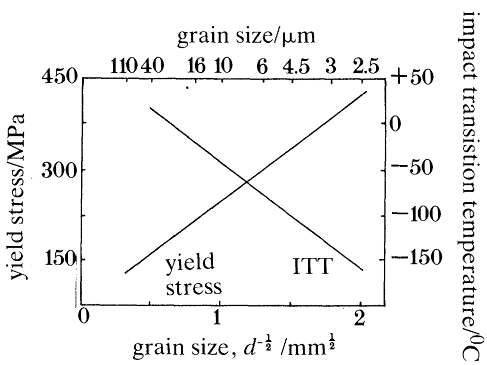

Figure 3. This figure shows how the yield stress and ductile-to-brittle transition temperature vary with grain size. Thus a reduction in grain size leads to an increase in both strength and toughness. (After Pickering 1978.)

available, may be appreciated in simple terms from the iron–carbon phase diagram. In general, the microstructures achieved depend on carbon (or truly carbon-equivalent) content and cooling rate. Thus if a ship grade steel is cooled relatively slowly from the γ-austenite range, the resulting microstructure will consist of crystallites of relatively pure iron (α-ferrite) interspersed with regions of an eutectoid mixture (termed pearlite) of α-ferrite and an intermetallic compound (Fe_3C–cementite) (as in the parent plate detail in figure 2). By subtle changes in alloy chemistry and thermomechanical processing the percentages, sizes and distributions of ferrite and pearlite can be adjusted. Since ferrite is relatively soft and ductile, while pearlite is relatively strong and brittle, even for a steel of fixed composition a wide range of mechanical properties may be generated. Of absolutely key importance here is to control the grain (crystallite) size of the microstructure. Figure 3 illustrates this point in giving plots of the variation in yield strength and ductile-to-brittle impact transition temperature with grain size. The ductile-to-brittle transition temperature is another, very relevant, toughness parameter and plots of this type establish the very important concept that the only way to simultaneously increase the strength and toughness of a material is to reduce its grain size. It is customary to refer to this process as grain refinement and a wide range of steels have been developed on this principle (particularly for the offshore construction industry) referred to either as microalloyed steels (Gray & Stuart 1987) (because trace additions of elements such as titanium and niobium are made) or as high strength low alloy (HSLA) steels (Honeycombe 1981). The benefits which accrue from grain refinement are usually expressed in the form of a Hall–Petch equation (Hansen & Ralph 1982):

$$\sigma_y = \sigma_i + k_y d^{-\frac{1}{2}}, \tag{1}$$

where, in this form, σ_y is the yield or flow stress, σ_i is referred to as the friction stress and is a measure of the difficulty of propagating slip (plastic flow) through the base material, d is the grain size and k_y is a measure of the ease of propagating slip across grain boundaries. Similar equations may be written for the ultimate tensile stress and for the fracture stress.

Not all the possible phase changes, and hence microstructures developed, appear on a simple phase diagram, since this only gives an impression of thermodynamic equilibrium. In the case of steels, in particular, there exists a range of other phases and phase mixtures which can be generated by increasing the cooling rate applied from the austenite range. Under very rapid cooling conditions (quenching) a hard, brittle phase is generated (termed martensite) because insufficient time is left to partition the carbon which is therefore retained in supersaturated solid solution. Extremely fine-scale, complex microstructures are associated with ferrous martensites which may be subsequently heat-treated (tempered) to generate different (often desirable in the case of cutting tools) properties. In general, the phases present in tempered martensites are ferrite and cementite but the scale and distribution differs from that in conventionally cooled samples of the same steel. By alternative cooling schedules it is possible to generate bainitic microstructures, which again consist of ferrite and cementite in yet different distributions which offer a different combination of relevant mechanical properties.

The relevance of the discussion, albeit brief, above of heat treatment/microstructure/properties to the fabrication of ship structures is particularly profound, when the influence of welding technology and particularly the heat-affected zone are considered in §5.

4. Property requirements for the construction materials of ships

Attempting to define the conditions that a ship structure will meet in service is clearly a major province of a naval architect. On the basis of his or her predictions, the basis and order of importance of the properties of materials will have to be set.

Among the factors which need to be considered are (1) stresses; (2) strain rates; (3) temperature; (4) chemical environment; (5) conjoint effects. These are considered in varying amounts of detail in the following subsections.

4.1. *Stresses*

It has been customary in the ship design process to consider the major tensile and compressive forces acting on the ship structure which is in turn considered as a hull girder structure. Compressive forces (due to hogging and sagging) must be resisted by 'designing' in sufficient stiffness to resist Euler buckling; the principles of which are well understood within the framework of conventional mechanical engineering (Ueda *et al.* 1983). In a similar manner, presuming the distribution of normal tensile loads may be calculated, a combination of cross-sectional area and yield stress will give a means of resisting permanent deformation. Further, since metallic materials (e.g. steels) will usually undergo some permanent plastic deformation prior to failure (at the ultimate tensile stress) there is a safety margin potentially built in to the structure.

However, such an approach is not without its pitfalls and in modern materials technology terms we normally build in an additional parameter, fracture toughness. Here the starting point is to consider firstly an ideally brittle material (linear elastic fracture mechanics) where a pre-existing defect, of physical dimensions, $2c$, propagates under a stress, σ_P, in a brittle manner when

$$\sigma_P = \sqrt{(2E\gamma/\pi c)} \quad \text{and} \quad K = \sigma_P \sqrt{(\pi c)}, \tag{2}$$

where γ is the free energy of the surface, E is Young's elastic modulus and K is a fracture toughness parameter.

Above all, measurements of fundamental fracture mechanics parameters permit a critical crack length (or defect size) to be predicted which gives a formal basis for design and quality control in the design process. Such a procedure has been developed by the pressure vessel industry and has resulted in formal codes of practice (BSI PD 6493, 1980).

In the discussion above, a dead loading condition has been assumed and the influence of oscillating stresses has been ignored. Although some authors have suggested that fatigue failure of ships is unlikely (Wecks 1953) this appears to ignore the influence of hull movement in a seaway and the patterns of cargo loading and unloading to which a ship is exposed during its lifetime. Essentially it presumes a static rather than a dynamic existence for a ship which seems unrealistic (Price 1989). Further, the dynamic pattern of stresses on a hull are essentially multiaxial and it has been established that fatigue failure is enhanced (by a factor up to 10) under such conditions (Pei *et al.* 1989).

Fatigue crack initiation occurs only at surfaces and the whole process of fatigue crack initiation and propagation is particularly sensitive to stress concentrations and residual stresses. It is now common to look at the fatigue process within the remit of fracture mechanics. This approach has the advantage of helping in the prediction of fatigue failures. Modified versions of equation (2) may be used for this purpose:

$$\Delta K = K_{max} - K_{min} = \Delta\sigma \sqrt{(\pi a)}, \tag{3}$$

where $\Delta\sigma$ represents the range of stress from maximum to minimum, the Ks refer to the fracture toughness parameters, termed stress intensity, ΔK is hence the range in stress intensity value and a is the defect size. From such an approach it is possible to calculate the crack growth rate $\Delta a/\Delta n$ (where n is the number of cycles) and determine the point at which the crack size, a, exceeds a critical size, c, and thus where the failure mode will move to brittle behaviour (Mughrabi 1989).

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4.2. *Strain rates*

Deformation processes in all materials are to some extent dependent on strain rate. Of the metallic materials, steel has a crystal structure (body centred cubic) which tends to put it in the moderately sensitive to strain rate classification. The crucial factor here is to remember that high strain rates tend to discourage plastic deformation in steels leading to a higher likelihood of brittle failure.

4.3. *Temperature*

For steels deformation processes are temperature dependent with the ductile-brittle transition temperature defining a transition range from low-temperature, brittle behaviour to high-temperature ductility. However, this transition temperature is also sensitive to the strain rate (see §4.2) and to stress concentrations. It is for this reason that tests of the Charpy type help in ranking a toughness parameter for materials (Rolfe & Barsom 1977).

4.4. *Chemical environment*

For a ship two related forms of corrosion must be considered: (*a*) that due to galvanic effects between dissimilar metals and alloys in contact; (*b*) that due to differential aeration in one alloy.

The first case is clearly the more severe locally and rules as to what materials should be used for skin fittings, etc. on steel hulls have grown up. These suggest that such fittings should be made from a more noble material, which in the absence of some corrosion protection (such as sacrificial anodes) will concentrate the corrosion to the steel plating nearby.

The second type of corrosion (*b*) is perhaps not so obvious and an understanding of this, and many other forms of degradation, comes from the pioneering work of U. R. Evans and his team (Evans 1960) who was originally inspired to do this work from a concern he developed into the rusting of ships in World War I. This study established that this form of corrosion was controlled by the local dissolved oxygen concentration in sea water; with the anodic (dissolving) areas being those where this concentration is lowest.

One further aspect of corrosion requires some mention here and that is the influence of variations in the microstructure. The point to be made here can be exemplified by pointing out that the microstructure in figure 2 has been revealed by etching, which is a corrosion process. Thus a combination of local chemistry and variations in the microstructure modifies the local distribution of anodes and cathodes and this can lead to particular problems in weld areas (Kwan 1990).

4.5. *Conjoint effects*

These have been alluded to before but may now be treated rather more systematically. Combinations of high stresses, especially near stress concentrations, low temperatures and high strain rates will favour brittle fracture (Sumpter 1986). Further, the basis of linear elastic fracture mechanics requires an atomically sharp crack and this is produced where an oscillating component of the stress pattern initiates and propagates a fatigue crack. For instance in fracture mechanics testing, it is common to machine pieces with a notch in them to produce a stress concentration (the geometry is not unlike that used in test of the Charpy type). Before fracture mechanics testing, these samples are then precracked using a fatigue

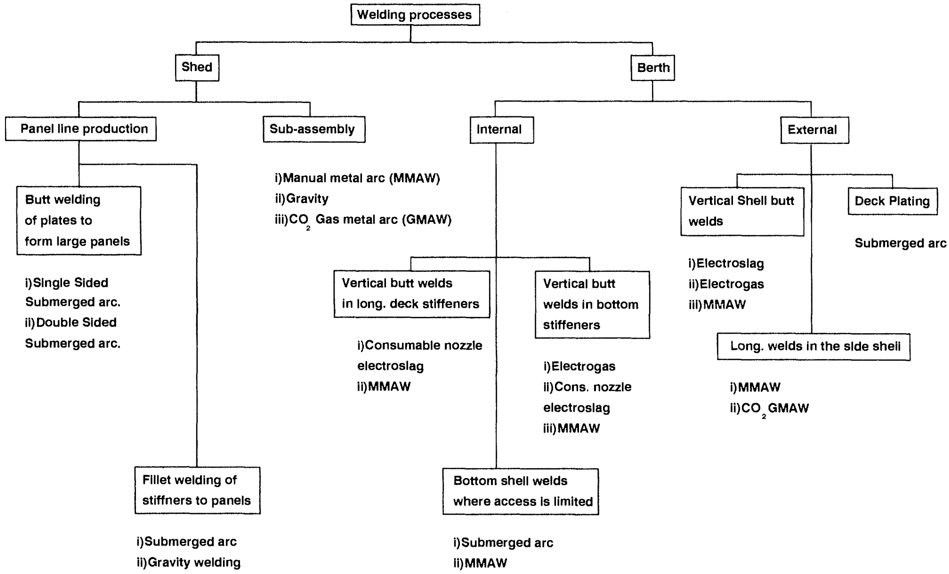

Figure 4. A schematic diagram illustrating the main forms of welding used in the construction of a ship.

machine to produce an atomically sharp crack. Essentially the notches are machined into the pieces purely to provide a stress concentration and to localize the region at which the fatigue crack is initiated.

The conjoint effects of stress and a corrosive environment also need amplification. In general, it is found that the crack tip is anodic (i.e. more readily corroded because it is in a higher free energy state due to local deformation, etc.) compared with the surrounding material. Thus the combination of a corrosive environment together with stresses (whether residual, thermally induced, or due to hull loading) is much more severe then either influence separately (Scully 1983). This is perhaps most simply exemplified by the case of the fatigue properties of conventional steels. If steels are subjected to fatigue tests in air (or better still in vacuum) they exhibit a fatigue limiting stress which is approximately half the ultimate tensile stress. This means that if the oscillating stress is below the fatigue limiting stress, fatigue failure does not occur. The behaviour in the presence of a corrosive medium (such as sea water) is different in that a fatigue limiting stress is not found and so a vanishingly small oscillating stress will eventually lead to a fatigue failure in sea water (Alawi *et al.* 1989). Thus a naval architect must develop an expertise in obtaining load histories, rather than extreme load cases. Every stress reversal, whatever the magnitude, is damaging with respect to fatigue.

5. Influence of joining technology

Welding has been the most commonly used joining technique in ship construction for several decades and weldment usually constitutes *ca.* 1% of the total mass of a ship. Earlier this century the production of mechanical joints by rivetting was the main method of construction. Rivetting had the advantage that failures tended to be confined to one or a few plates. Moreover, rivetting gives greater structural damping which gives lower amplitudes and frequencies of resonance, thereby leading to a safer structure in terms of fatigue (Johnson 1951). Welding the entire structure tends to mean once a crack is propagating in one plate or component that it can continue propagating through the entire structure. Hence there is some current interest in the possibility of using structural adhesives for shipbuilding (Hashim *et al.* 1989).

Welding has the advantages of versatility, flexibility and relative cheapness compared with other joining techniques. Many of the principal fusion welding techniques are used in the shipbuilding industry. The selection of a particular welding method depends largely upon the stage of construction (Phillip 1980) and figure 4 shows the principal techniques used in both the berth and the shed.

Not only are a large number of welding techniques adopted in the construction of a ship but the operating parameters of each of them will have a pronounced effect on the integrity of the resultant joint. It is for these reasons that welding and repair welding are forbidden in aerospace structures. Welding metallurgy is an extremely complex field and only recently have various agencies attempted to set up proper design codes.

It is not just the fusion (melted) zone, whether this involves filler material or not which is of importance. The entrapment of brittle phases such as oxide and toxic gases (e.g. hydrogen and nitrogen) can easily lead to defects. Further, the thermal history of the fusion and surrounding region will lead to thermally induced stresses which may produce a variety of types of tear defect at the time the weld is produced or during service. Again, these thermal stresses may well contribute to the growth of other forms of defect unless a stress-relief anneal is made.

In addition to the problems mentioned in the paragraph above are those concerned with microstructural modification in the region termed the heat-affected zone. The heat-affected zone extends from the fusion line between the weld metal and the parent line to the unaffected parent plate. The extent of the heat-affected zone and the amount of microstructural modification within each sub-zone varies with the type of welding process used and the operating conditions used (see figure 2).

To all these microstructural features have to be added those defects which arise from inadequate technique leaving portions of the weld incomplete. These may be at the surface or in one of the underlying weld passes and are obviously significant sites for stress concentration. Ship structures on average have 4.9 defects per metre of weld (Rogerson 1985).

Clearly non-destructive inspection/examination can help to detect some but by no means all of the defects which occur in welds. One possibility, now very actively researched, is to automate much of the welding process using seam-tracking robotics and to incorporate some non-destructive techniques to monitor weld penetration and perhaps other defects. As this idea progresses, it may well be possible to generate an 'expert system' which constantly monitors the welding parameters and optimizes the whole process (Fenn 1986). This will probably be aided by the design of ships which are unidirectionally stiffened (Hori *et al.* 1990). Such ships should also be associated with a reduced number of stress concentration sites and thus have fewer places where crack initiation may occur.

Although improving welding technique is central to ensuring the better integrity of ships, it must be remembered that there is a strong interaction between the weld and the parent material, as for instance exemplified by what happens in the heat-affected zone. Thus improvements in welding processes need to parallel more rigid specifications of the parent steels.

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6. Concluding remarks

When a materials specialist compares the use of materials in the shipbuilding and aerospace industries, he/she has the distinct impression that the shipbuilding industry has much to learn from colleagues who are aerospace engineers. There is clearly a need for more training of naval architects and others in the shipbuilding industry in the general area of materials science and technology. A significant body of research is needed which performs realistic environmental testing of combinations of plate and weld. Experiments in this area need a starting database which gives the likely service experience of stresses, etc., to be met during service life. The influence of both the stress state, in particular the dynamics of these, in combination with the corrosive environment needs specific attention (Ince 1990).

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Discussion

D. W. Chalmers (*HMS Saker, BFPO 2, U.K.*). This paper was presented in a provocative manner and implied that naval architects as a class are ignorant of material problems. In fact naval architects give a great deal of thought to material selection and, in view of the environment in which their ships have to function, would be foolish not to.

Higher strength in steel is not of much help to the ship structural designer on its own, as the critical failure modes are buckling, dependent mainly on stiffness, and fatigue, dependent on fabrication factors. The fabrication skill available to the shipbuilder is not of especially high quality, and higher strength steels as proposed in this paper are liable to need more skill in assembly thus increasing the cost. Low cost and not specifically low mass is the aim of the ship designer (unless he is designing a high-speed vehicle very sensitive to mass). There is little valid comparison with aerospace structures; funding is orders of magnitude less. A naval architect would be delighted to have four or five prototypes and be able to test them with thousands of channels of instrumentation, but who will pay?

A paper on selection marine materials is ridiculous without mention of light alloys and of composites, both used extensively to save mass where essential, and in the case of composites to save in maintenance and repair costs. There are moreover many other points that could be raised in discussing this paper, but there is little to be gained as the authors have clearly little understanding of their subject.

B. Ralph. We are glad that Dr Chalmers found the oral delivery of our paper provocative. Hopefully he will find the written version covers many of the points he raises in more depth. We are not suggesting a move to higher strength steel, rather that if such a move is contemplated other factors will need to be taken into account. We obviously appreciate the difference between the aerospace and ship industries. Notwithstanding this, we maintain our belief that more realistic testing taking into account conjoint effects would be of value. Our reasons for laying heavy emphasis on steel are clearly layed out in the text; although of course we appreciate, and mention, some of the developments in light alloys and composites.

G. Victory (*Surrey, U.K.*). Professor Ralph ignored fundamental differences between the operational conditions of the products which dictate that there shall be a different approach to the design, construction and inspection techniques. In effect he is trying to compare chalk and cheese!

1. Aircraft have to fly; so every ounce counts and more expensive materials can be justified if they save weight, while the small margins allowed in the design requires that supervision and inspection during construction are especially intensive and expensive. The much lower importance of dead weight in ships permits the use of cheaper, yet satisfactory, materials and obviously mild steel can be used as a basis on which to consider the benefits, or otherwise, of other materials. To date, only a higher tensile steel has proved worthy of consideration.

2. Building conditions and standards of labour in the marine industry require that a material which is more tolerant to less than ideal building sites and fairly minimal technical expertise workforce should have preference. Such a material is mild steel!

3. A ship can experience a moderately severe structural failure and survive. The same degree of failure in an aircraft in flight would mean certain death to all onboard, so better control and inspection during construction and in operation are essential.

If we are to look for reasons for the loss of ships, particularly bulk carriers, in the past few years, we must look elsewhere! The design of ships uses arbitrary maximum bending moments and shearing forces in still water, and an unknown allowance is made for vibration, wave and wind forces and impact with waves: 'slamming'. No allowances are made for faults in construction: weld faults, material imperfections or continuity of strength members. Nor are imperfections in the surveying procedure allowed for, especially surveys in service where the impossibility of surveying every area in a vast cargo tank the size of St Paul's Cathedral requires that extra material and a greater corrosion allowance should be provided.

Providing that these things are amended by Classification Societies by reducing the allowable bending moments and sheer forces and by adding to the corrosion allowance then there is no reason why casualties should not be substantially reduced!

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B. Ralph. We thank Mr Victory for his comments which he will find match many of the items discussed in the text of our paper. Although we would not wish to overstress a comparison of the aeronautical and ship industries, we still believe in looking at materials selection that some degree of comparison of practices is warranted. We share his views over the standards of fabrication and of design to meet service conditions.

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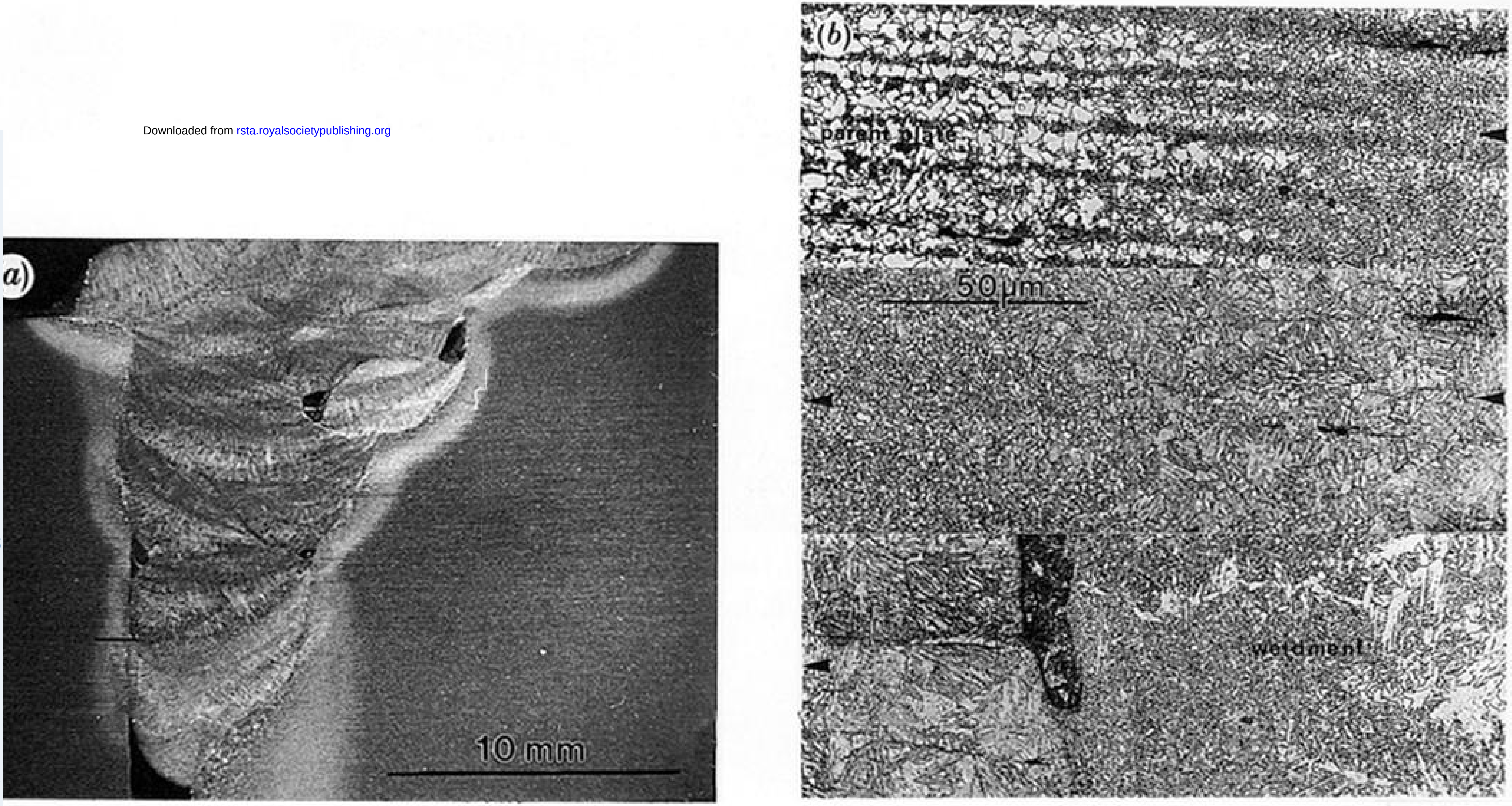
gure 1. An example of the use of advanced materials in building small boats. In this case the total ass of the hull and paddle is under 5 kg. (Courtesy Dr Niels Hansen of the Risø National aboratory, Denmark.)



igure 2. A light micrograph through a typical weld showing a considerable disruption in the icrostructure in the heat-affected zone. This butt weld has been made by multipass manual metal rc welding in BS4360 50c plate steel. The low magnification image (a) reveals a number of defects this weld arising from lack of penetration, lack of fusion, cavities and slag inclusions. The higher agnification images (b) reveal the disturbance to the microstructure which occurs in the heat-fected zone. The three parts of this figure (b) track across the heat-affected zone marked on (a) om the weldment to the parent plate, as shown.

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