MODERN FRACTURE CONTROL PLANS

IS THE NAVY MISSING THE BOAT OR TURNING A BLIND EYE?

BY

B. F. JONES, B.SC., PH.D.,
T. R. H. M. BROWN, B.SC.,
AND
G. ROSE, B.SC., PH.D., C.ENG., M.I.M.
(Metallurgy and Ceramics Division, Materials Department, A.M.T.E., Holton Heath)

Introduction

In any historical treatment of the origins and development of what has become known as the fracture mechanics approach to fracture control, a reference will be found to the Liberty ships of World War II. Of approximately five thousand merchant ships built during that war, over one thousand had developed cracks of considerable size by 1946. Between 1942 and 1952 more than two hundred ships had sustained fractures classified as serious, and at least nine T-2 tankers and seven Liberty ships had broken completely in two as a result of brittle fractures. There are, of course, numerous examples of fracture problems in other fields of engineering. However, with such a clear demonstration of the fact that cracks can and do occur in practice in the marine environment it is ironic that the Royal Navy (and indeed many other navies) seems so reluctant to accept at the design stage the fact that they must learn to live with cracks. Whilst the philosophy of living with cracks has been developed through the medium of fracture mechanics over the past two decades, naval designers both within and outside the Royal Navy have to a large extent remained aloof from the field. That is not to say that at various stages its potential has not been recognized and indeed various groups of scientists within the Establishments have wrestled with the subject for most of that period. However, now that the scientists have progressed to the point where they think they can provide solutions to some of the current naval problems they are unable to find designers and engineers closer to the practical end of the scale who can take their ideas on board and provide sensible assessments of their value, leading to modification and improvement.

The reason for this situation is not too difficult to understand. The Navy has generally engineered with traditional, well-understood materials; been under less pressure to save weight than some branches of engineering (e.g. aerospace); and had fewer safety problems than others (e.g. nuclear). In the absence of a pressing weight problem, there has been a tendency to design components with large safety margins (a policy compatible with requirements for shock resistance) reducing the necessity to define operating stresses with great accuracy. With the notable exception of the submarine, the knowledge that a serious failure in a ship is less likely to produce the catastrophic result of a similar failure in an aircraft (and anyway there is always the lifeboat, or the lifejacket, or the ability to swim) reduces the urgency of the development of fracture control plans. And now as the requirements begin to change, as submarines become of ever increasing relative importance and consideration of economy and weight saving encourage the use of new, less familiar materials, we are also faced with a manpower shortage. When the pressures of current problems become large for a diminishing number of engineers and scientists, the introduction of new ideas and approaches becomes increasingly difficult.

The importance of this problem cannot be underestimated, because to provide any real benefit the fracture control plan must become an integral part of the design process. The nature of the subject is such as to demand a multi-disciplinary approach with operations analysts, engineers, mathematicians, and metallurgists trading their operational and design requirements, stress analyses, numerical manipulation, and materials properties to provide the most economic, efficient, and safe optimization possible (FIG. 1). This process will require an investment of highly qualified personnel, with the full benefit of their endeavours recognizable only in the long term.

Fracture mechanics, because it is concerned with the definition of limiting conditions has, quite wrongly, acquired pessimistic connotations arising, in part, from its widespread application to the retrospective analysis of failed components. It can, in fact, make a very positive contribution in extending our design capability by providing the only method we have of assessing whether we can live with cracks. It is the purpose of this article to encourage the development of these ideas through from the laboratory into the area of design. In order to do this only the barest reference will be made to the details of the science of fracture mechanics which can be found in any one of a number of references, but illustration is given of practical examples of how the approach might be applied to provide positive solutions to some current naval problems.

FIG. 1—TRADING EXPERTISE

Fracture Mechanics

The subject of fracture mechanics is concerned with cracks and provides a means of assessing whether they will get larger. Thus the application of fracture mechanics starts with the tacit assumption that cracks exist in components or fabricated structures. If it can sensibly be argued that cracks or crack-like defects do not exist and will never exist during life, then the subject of fracture mechanics as discussed here cannot be applied. However, experience tells us that all too frequently cracks do occur in real life. For example, in welded components or structures it is extremely difficult to be sure that no cracks or crack-like defects exist especially where long weld runs exist in complicated geometrical arrangements. Even when components can be certified free of cracks as a result of careful control in manufacture and detailed non-destructive inspection, it is not easy to ensure that defects will not be introduced during handling or service by mechanical or environmental damage. In addition cracks can initiate in previously undefected materials due to fatigue or stress corrosion. Thus it is clear that many design problems fall into the category where they can be treated by a fracture mechanics approach.

However, it is important to recognize that the detailed application of fracture mechanics is potentially expensive and time consuming, especially if it demands the provision of design data in a form not readily available and thus require large experimental programmes or complex stress analyses. Before embarking upon the fracture mechanics approach, it is advisable to ensure that such a detailed assessment is appropriate. The most significant factor in this regard is a decision on the likely consequences of failure of the component in terms of safety, cost, and operational implications and whether these considerations warrant a fracture mechanics approach.

Once it has been decided to embark upon the fracture mechanics route, it is essential to commence with an accurate and detailed definition of the function of the component and the service conditions to which it will be subjected (i.e. loads/time/temperature/environment). Such considerations will allow judgements to be made on the relevance of existing design data and a definition of the requirement for additional design data. In parallel with this process, it is necessary to decide upon the desired failure mode or fracture control plan as this may also influence the sort of data required for design. For example, in the case of a critical pressure vessel it may be highly desirable to ensure that if a crack were to grow undetected the vessel would leak and so make the crack obvious before it reached a size when it would run catastrophically (the 'fail-safe' or 'leak-before-break' criterion). In other cases one might rely on an assessment that failure will not occur within a stated life (the 'safe life' criterion). Intimately involved in the approach for all control plans are considerations of non-destructive testing (NDT) or proof-test requirement for the component. The fracture mechanics approach may in some cases dictate the NDT sensitivity required or, as more often seems to be the case, the design may be limited by the sensitivity of the NDT available under the particular conditions of fabrication and service for the component.

An appreciation of the fracture mechanics approach must begin with a notional understanding of the terms 'stress intensity' and 'fracture toughness'. Stress intensity (K) is a term used to describe the stress state at a crack tip and is a function of the applied stress and loading mode, the size and shape of the crack, and the degree of constraint (or amount of plasticity) present at the crack tip (FIG. 2). (There are two other main terms similar to 'K' which will be encountered in the field of fracture mechanics. These are the path independent contour integral (J) and the crack tip opening displacement (COD or CTOD). However, for simplicity, no further reference will be made to these terms other than to note that they are generally compatible with the concepts described in

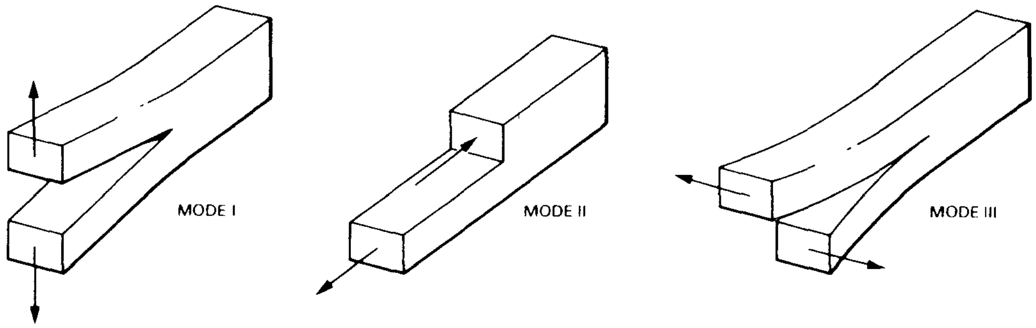

FIG. 2—THE THREE BASIC MODES OF LOADING A CRACKED BODY

relation to K.) Depending on geometric details of the crack and the body in which the crack lies, there are a variety of mathematical expressions to describe the stress intensity for a particular applied stress. It is generally considered that the opening mode of loading (mode I) is most critical and this aspect has received greatest attention. For a given crack in a given body, as the stress is progressively increased, the stress intensity at the crack tip also increases. Under certain circumstances the crack will become unstable and propagate rapidly before the net section is overloaded. Of course, one of the reasons that metals are such useful engineering materials is that they are 'forgiving' and we use their plasticity to redistribute stresses at critical design features. Thus, if we ever reach a situation in practice where the crack runs before there is appreciable local plastic flow, we have lost a very useful way of 'shaking down' stresses in redundant structures. The critical stress intensity (K_c) at which the crack runs (before net section yield) is related to the toughness of the material and to how far the crack tip can deform locally. In thick sections, the amount of plasticity is small and the critical stress intensity is a minimum (K_{IC} for mode I loading) and relatively independent of geometrical considerations. In thinner sections, the proximity of the free surface allows more local plastic flow and consequently K_c is higher, i.e. it is dependent on geometrical considerations. However, the fracture mechanics tool remains useful in spite of this in two main ways. Firstly, although it is obviously sensible to avoid designs in which K_{IC} would be truly relevant, it is often useful to apply the value for material toughness which is known to be the minimum under circumstances where it is desirable to use conservative designs. Secondly, it is possible to determine experimental values for toughness using specimens which reproduce a similar degree of plasticity to that envisaged in practice (generally by matching section thicknesses) and although these values do not represent an absolute material property they can be useful in design.

An additional development of the fracture mechanics approach has been the derivation of mathematical expressions which can describe with reasonable accuracy the relationship between stress intensity and the rate of 'slow' crack growth by processes such as fatigue or stress corrosion. It is well known that fatigue contributes to a large number of service failures, so it is useful to have a means of predicting the proportion of the life of a component that will be required for a crack to grow from some initial size (e.g. the limit of NDT) to a larger critical size.

Armed with this appreciation of the scope of the fracture mechanics approach, its application to a number of specific problems is outlined below.

Titanium for use in High Integrity Seawater System Components

The potential advantages and some of the problems in using titanium in seawater systems have been discussed previously in the *J.N.E.* (Vol. 26, No. 1, p.

111) where it was explained that from a range of potentially useful alloys availability reduced the options to commercial purity (CP) titanium and the higher strength alloy Ti-6Al-4V (6–4). It was further indicated that consideration of the stress corrosion susceptibility of 6–4 encouraged the view that CP titanium possessed greater potential.

A problem with the use of a new material in a critical application is the absence of experience with that material. For example, copper-based alloys have been used in sea-water systems over a number of years and the problems of design with such materials have, to a certain extent, been learned by trial and error. No such experience exists with titanium. Although there can never be a substitute for hard experience, the use of fracture mechanics can minimize this disadvantage.

Two examples are given below of the application of fracture mechanics to titanium components. The first describes the design of a titanium header where the fracture mechanics approach helps to provide the technical confidence to use the 'new' material and highlights the implications of shock requirements. The second describes an analysis of the failure of a condenser tube in a test rig where fracture mechanics helps to demonstrate that a simplifying modification of the tube design can provide a satisfactory component.

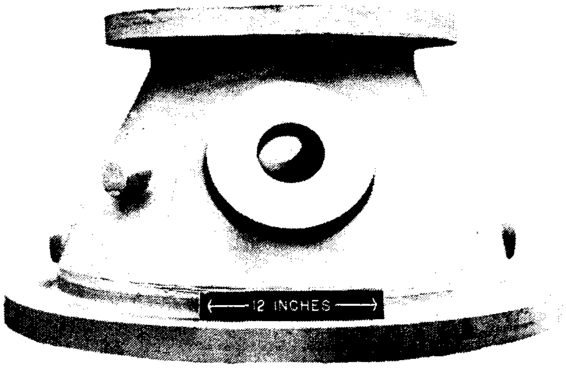

FIG. 3—TYPICAL CONDENSER HEADER

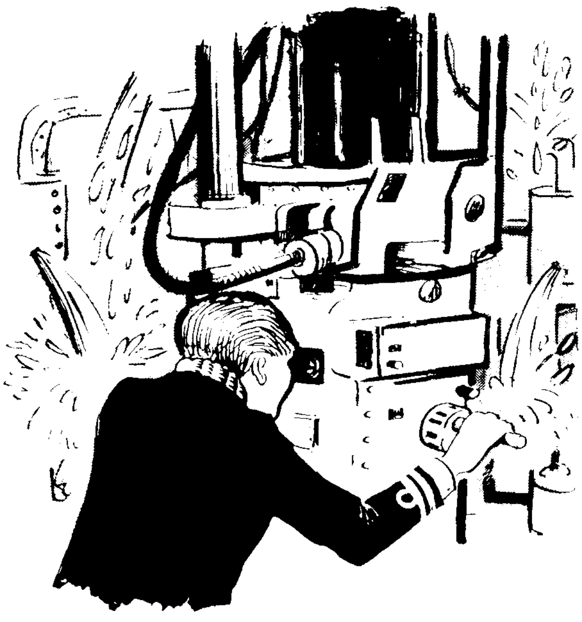

FIG. 4—'LEAK-BEFORE-BREAK' GIVING AN EARLY INDICATION OF IMPENDING CATASTROPHIC FAILURE

Titanium Header

The header is a large component shaped like a truncated cone with flanges at each end (FIG. 3). Its total length is of the order 0·5–1 m and its diameter increases from about 0·5 m at the narrow end to about 1 m at the large end. It behaves as an internally pressurized vessel containing sea-water and, in the case of a submarine, the internal pressure corresponding to the diving depth of the submarine. Catastrophic failure of this component could result in flooding and loss of the submarine, and thus its integrity is of the highest concern. For this reason it is desirable to avoid catastrophic failure at all costs, and a leak-before-break failure mode giving an early indication of an impending failure would be a great advantage (FIG. 4). Normal operating conditions result in cyclic changes in internal pressure relating to the changes of depth of the submarine. There is an additional requirement for the header and sea-water system to survive shock loads arising from enemy attack.

As previously discussed in the *J.N.E.*, preliminary information on cast 6–4 revealed very low ductility which caused some concern in relation to shock requirements. Together with fears in relation to stress corrosion of 6–4, a wrought and welded fabrication in CP titanium became the favoured option. In the absence of experience on the design side with a fracture mechanics approach, it was recommended at an early stage that the component should be designed by conventional methods and the resulting structure checked using a fracture mechanics route. Determination of the relevant properties of the material and also the development and characterization of welding methods proceeded in parallel with the design exercise.

Whilst the conventional mechanical properties of CP titanium were much as anticipated and satisfactory methods of welding established, the toughness properties were largely disappointing. Because of the complexities and the limited extent of our current knowledge of this relatively new material, it is judged that an extremely low value of toughness must be used in the assessment. The value selected incorporates allowance for the surprising observation that even the relatively weak CP material selected for study revealed a susceptibility to slow crack growth under certain conditions. This low toughness indicated that use of the material at high stresses would mean a particularly small critical crack size—approaching the limit of NDT, and thus including little allowance for fatigue. This requires caution in the case of a welded component where residual stresses can approach the yield stress of the material unless stress relief is applied. Provided that stress relief was effectively achieved, the use of a 'typical' design stress of $\frac{1}{2}-\frac{2}{3}$ yield stress provides much more acceptable critical crack sizes such that sensible designs could be undertaken commensurate with a high degree of confidence in NDT. But, at typical header wall thicknesses, it could not be assumed that there was a high probability of a leak-before-break failure mode. Under these circumstances CP titanium might be viewed as inferior to current materials.

However, comparison of this information with the details now available from a conventional design changes the balance of this judgement. It transpires that the allowance for shock loading so dominates the design of this component that normal operating stresses are very much lower than the $\frac{1}{2}-\frac{2}{3}$ yield stress typical of so many normal engineering designs. The peak stresses experienced in normal operation would be of the order of only $\frac{1}{5}$ yield stress and under these conditions the probability of leak-before-break is greatly enhanced, and CP titanium would appear a much more favourable material.

It is interesting to note that the entry of shock requirements into the design process has such a significant effect on the normal operating stress. The shock requirement and shock design approach does not specifically incorporate any consideration of cracks in a structure. Although this aspect obviously requires some consideration in the future, no basis exists at present for deviation from the current shock design philosophy. However, the implications of the application of a shock philosophy on materials selection are considerable, and can be illustrated as follows. The use of conventional operating stresses of $\frac{1}{2}-\frac{2}{3}$ yield stress means that crack growth due to stress corrosion or fatigue can be quite large during the life of the vessel or the interval between inspections. Thus the size of the crack which would cause concern is much smaller than the critical crack size to cause failure since we must allow for significant crack growth. If the prospective loads due to shock are very much higher than the normal operating loads, the position is quite different. The shock loads are of short duration and very rarely applied, and so produce negligible crack growth. The normal operating stresses are now very low ($\frac{1}{5}$ yield stress for CP titanium headers), and so cause little crack growth. The result is that one no longer has to worry about cracks growing and may be able to use stronger materials even if they are more sensitive to cracks. For example, a disadvantage of selecting higher strength steels for conventional applications is that they tend to be susceptible to stress corrosion crack growth and thus the useful proportion of their strength is limited. However, in a design which allows for shock in the manner described above the likelihood of normal operating conditions being below the stress corrosion threshold is much higher and the use of the higher strength is more feasible.

This sort of argument also applies to titanium, of course, and can be extended by a further unusual factor in that no significant economic premium would be paid for using the high strength 6–4 alloy rather than CP titanium. Under these circumstances the 6–4 alloy might be employed at similar stresses to those for CP titanium without fear of stress corrosion and possibly with enhanced shock resistance. The opportunities for optimizing the use of the 6–4 alloy and achieving an overall more efficient design are obvious and warrant further development. But it must be noted that such an approach requires careful consideration of residual and other internal stresses which must either be removed or accounted for in the design.

Thus application of the fracture mechanics approach to the design of the titanium header has the following benefits because it:

(*a*) demonstrates the high probability of a leak-before-break failure mode;

(*b*) indicates the direction for future improvements in design;

(*c*) provides a means of handling problems such as stress corrosion cracking and eliminates the necessity for blanket avoidance of materials susceptible to stress corrosion cracking.

Titanium Condenser Tube

Much of the incentive for a titanium sea-water system derived from consideration of the heat transfer properties of titanium condenser tubes. It was believed at an early stage that advanced-geometry convoluted tubes (approximately 15 mm diameter, 1 mm wall thickness) which are produced by 'roping' plain tubes might be used and several batches were obtained for test purposes. Due to problems with NDT, it has since been decided that plain tubes would be preferred, but a recent failure of an advanced-geometry condenser tube on a cyclic test rig (FIG. 5) raised questions that could only be answered by the application of fracture mechanics.

The problem arises because the probability exists that minute cracks could be present in the manufactured tubes as fabricated. Recent developments in manufacture and NDT will limit the depth of defects to about 0·1 mm, but the presence of defects of this size must be considered in design. In the case of the advanced-geometry tube which failed under test in less than the required number of cycles, it was thought that an initial defect of the order of 0·1 to 0·3 mm deep had led to the failure and there was some concern that even the plain tubes would not prove satisfactory.

A fracture mechanics analysis based on fatigue crack growth rates suggested that the tube should not have failed even with a 0·3 mm deep initial defect.

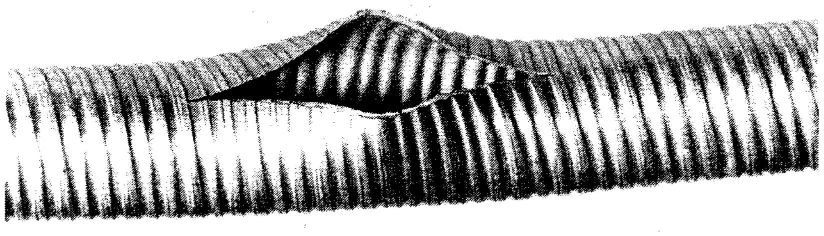

FIG. 5—FAILED TITANIUM ADVANCED-GEOMETRY CONDENSER TUBE

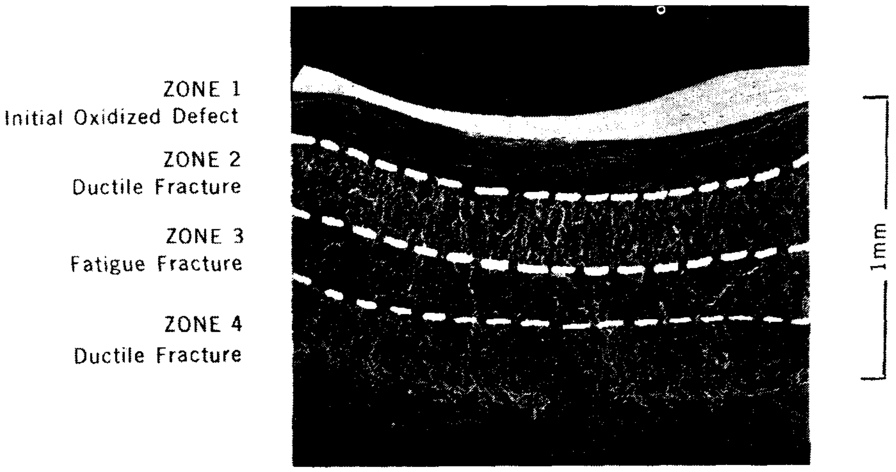

FIG. 6—CROSS SECTION OF THE FRACTURE SURFACE FROM FAILED TITANIUM CONDENSER TUBE

The analysis indicated that the tube should ultimately burst at the maximum operating pressure by net section yielding and rupture when the crack was about 80 per cent through the wall, and observation of the failed tube by optical and scanning electron microscopy suggested this was the case. However, growth of the crack from 0·3 to 0·8 mm by fatigue was not predicted by the fatigue analysis. More detailed examination of the fracture surface from the tube revealed that instead of the anticipated three zones (i.e. initial crack 0·3 mm deep, fatigue zone from 0·3 to 0·8, and plastic overload failure zone from 0·8 to 1·0 mm), four zones were evident (FIG. 6). The initial oxidized 0·3 mm defect was followed by a zone 0·2 to 0·3 mm deep which exhibited ductile features not normally associated with fatigue. The next zone of about the same depth (0·2 to 0·3 mm) exhibited a cleavage-like fracture appearance typical of fatigue fracture surfaces in titanium. The final collapse zone showed extensive ductile dimpling and tearing. Fatigue crack growth of 0·2 to 0·3 mm from about 0·5 to 0·8 mm, rather than∿0·5 mm from 0·3 to 0·8 mm, is predictable by fracture mechanics. The conclusion is that rather than a 0·3 mm initial defect, before testing the tube contained a 0·5 mm deep crack. This probably arose by the further extension of the original shallow defect as a result of the roping operation which produces the convolutions on the tube. This suggestion is supported by the fact that no further heat treatment is applied after roping, thus explaining the presence of a non-oxidised ductile crack. Since no NDT was applied after the roping operation (and indeed this would be difficult and is part of the reason for preferring plain tubes), the presence of such a crack is quite feasible. In retrospect, it is perhaps not surprising that the roping operation which produces considerable deformation of the tube would cause some extension of a pre-existing sharp defect.

However, the importance of this failure is that the observed fatigue crack growth and fracture characteristics provide confidence in the fracture mechanics approach to both the fatigue and final failure of the tube. This enables us to provide an assurance that in the case of an inspectable plain tube, if it can be guaranteed that no initial defect greater than 0·2 mm deep exists then, under the envisaged operating conditions fatigue crack growth will not be a problem. Thus, although it seems that the complete elimination of small defects in the condenser tubes is not feasible, the use of fracture mechanics helps to demonstrate that plain titanium condenser tubes can still be employed safely, and provides the means of defining the NDT requirement.

Memory Alloy Couplings

Memory alloy couplings are an ingenious invention which utilizes the shape-memory effect of a nickel titanium alloy to provide a convenient means of joining pipes. The coupling is mechanically expanded after cooling to liquid nitrogen temperature, slipped over a liner and the pipes to be joined, and a leak-tight joint is obtained as the alloy contracts to its original size on warming to room temperature (FIG. 7). The coupling was originally envisaged for application in positions where access for welding or brazing was inadequate. However, because of their success, there is the suggestion that they have been more widely applied in recent years, particularly as highly skilled welders have increasingly been attracted to more lucrative North Sea operations.

One major disadvantage of this concept is that the couplings operate at very high stresses (close to their yield stress), a factor which is likely to make them susceptible to cracks. Recently there have been a few coupling failures although without serious consequences; circumstances where a failure could have catastrophic results can, however, be envisaged. Thus, it was essential to analyse the failures and suggest solutions to the problem to avoid the immediate withdrawal of all critical couplings and the concomitant financial and operational penalties.

Analysis of the failed couplings suggested that the problem had commenced by the formation of corrosion pits in regions where paint films were either non-existent or had broken down. This appeared to have been followed by the development of stress corrosion cracks which grew to a critical size when the coupling failed. Laboratory tests indicated that fairly concentrated acidic solutions containing chloride ions were necessary for the pitting and stress corrosion processes, and subsequent consideration of the possible environments in the proximity of the failed couplings showed that such service conditions were possible under some circumstances.

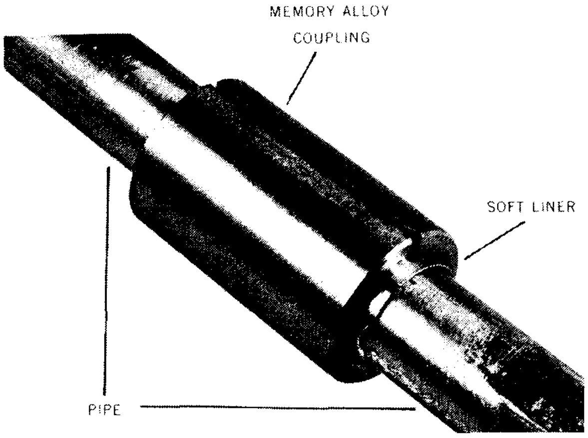

FIG. 7—MEMORY ALLOY COUPLING (SPLIT LONGITUDINALLY) SHOWING LINER AND PIPES

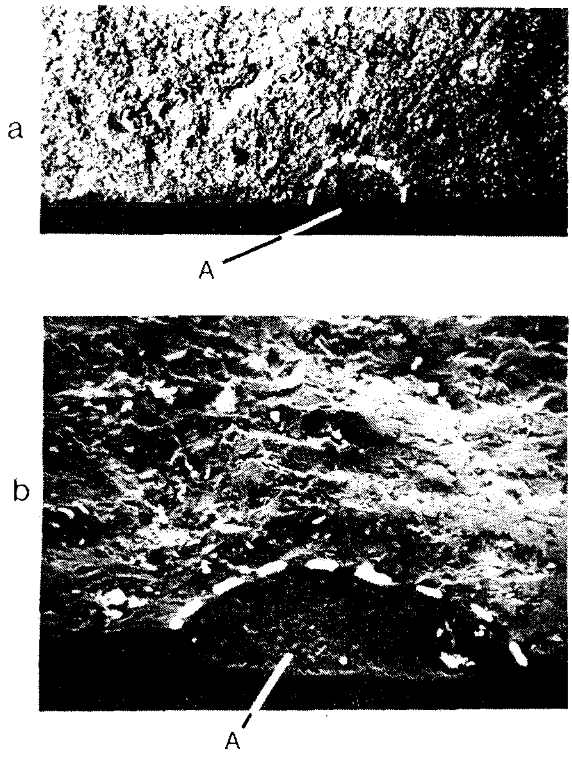

FIG. 8—FRACTURE SURFACE OF MEMORY ALLOY COUPLING—(a) SHOWING EXTENT OF STRESS CORROSION CRACK EMANATING FROM CORROSION PIT AT A, AND (b) CORROSION PIT SHOWN AT HIGHER MAGNIFICATION

In the failed couplings the stress corrosion cracks appeared to emanate from relatively shallow (0·3 mm) pits when, even at yield stress loading, the stress intensity was very low (FIG. 8). However, laboratory stress-corrosion tests on precracked specimens have demonstrated that the thresholds for stress corrosion crack growth could well be at the predicted low stress intensities. Good agreement was also obtained between the predicted and observed critical crack depth for final failure.

Fracture mechanics has been used in this instance to identify the environments which could cause stress corrosion cracking and to define the sensitivity of the material to very small corrosion pits, indicating the necessity for improved protection of those couplings which are likely to be exposed to the dangerous environments and whose failure might have critical consequences. Although some checks on fatigue crack growth properties are recommended, there appears to be no inherent problem with the coupling material provided adequate protection from aggressive environments can be achieved. Several promising methods for doing this are now under investigation.

Submarine Tailshaft Cracking

The discovery of a large crack in a submarine propeller tailshaft when it was removed from the submarine at refit has caused some concern. This is because of the possible serious consequences of complete fracture of the tailshaft compounded by the fact that the crack had developed unnoticed. The application of fracture mechanics has helped to identify the nature of the problem, and suggests how the design and maintenance of the component can be modified to minimize future problems.

The tailshaft in question was a hollow shaft of diameter about 17 inches with a wall thickness of a few inches, varying somewhat from point to point on the shaft. The crack which caused some concern had penetrated the wall of the shaft and extended in length to over half the circumference (FIGS. 9 and 10). Although no cracks of this size had been discovered previously, problems of pitting and cracking in shafts have been familiar over many years. The root of the problem centres on the electrochemical reactions which occur when sea-water contacts dissimilar metals (in this case the steel shaft and a gunmetal liner) giving rise to the rapid formation

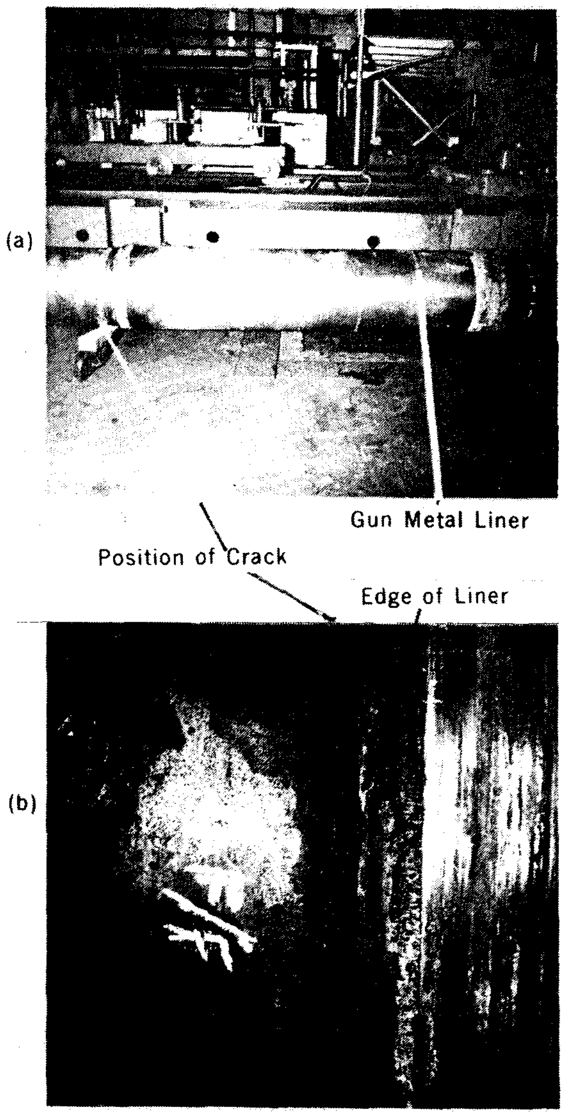

FIG. 9—CRACKED TAILSHAFT—(a) SHOWING LOCATION AND (b) SHOWING DETAIL

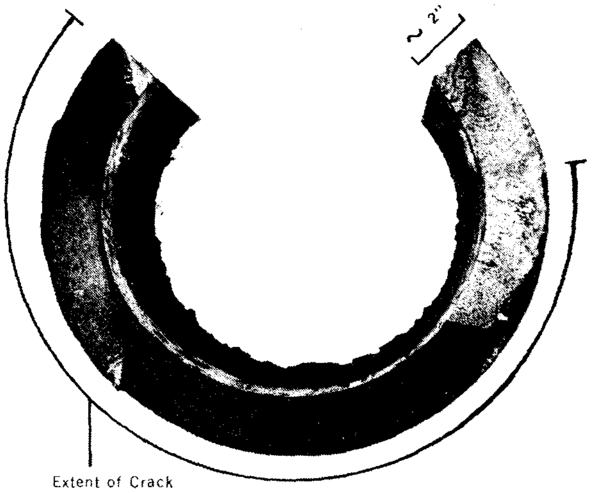

FIG. 10—BROKEN SECTION OF TAILSHAFT SHOWING EXTENT OF CRACKING

and growth of corrosion pits. Despite the fact that this problem has long been recognized, and attempts are made to keep such junctions dry, no completely satisfactory protection technique has been found and corrosion pitting at such junctions is frequent. Such is the extent of this problem that procedures have been developed for either temporary *in situ* treatment of shallow corrosion pits to blend out the defects by grinding and hence reduce their effect as stress raisers, or the more permanent reclamation of the shafts by machining out larger defects and building up the shaft to its original size by weld repair. The maximum size of defect which can be treated by grinding only, without recourse to weld repair, has been specified.

Fortunately, in the instance of the cracked shaft, a clear record of a grinding repair had been retained to provide an accurate picture of the 'starting' condition of the shaft. This information showed that the blending operation had been continued to the very limit of the allowed depth at which point there were suspicions that minute cracks might have remained (FIG. 11). The proximity of the gunmetal liner had also complicated the blending operation, limiting access and resulting in a groove rather sharper than would normally be expected.

This information allowed the analysis of the failure in fracture mechanics terms using stresses and cycles supplied by D.G.S. and estimates of fatigue crack growth rates which have gradually been improved and updated by laboratory testing. This assessment indicated that cracks of a depth similar to the 'allowable' grinding repair (which could be envisaged either by a poorly ground repair as in the present case or by subsequent rapid corrosion pitting at the root of a ground repair) were at a stage where fairly rapid growth by fatigue could commence. The development of the observed crack by fatigue agreed well with the fatigue calculation, giving confidence in the assessment. Estimation of the critical crack size for the shaft indicated that the final crack was close to being critical.

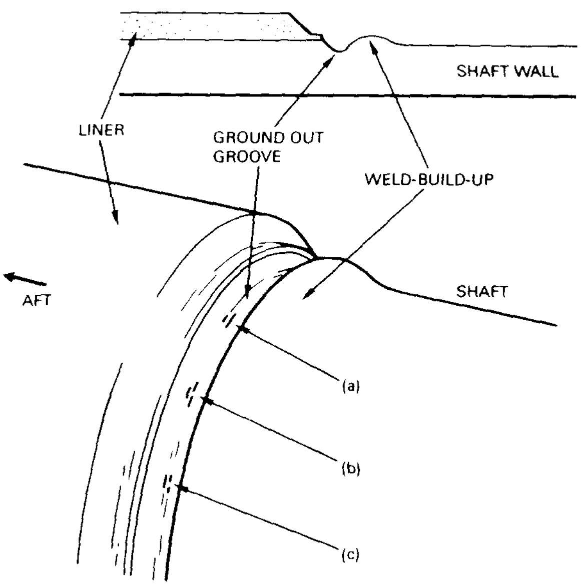

FIG. 11—ORIGINAL CONDITION OF TAILSHAFT
Maximum depth of groove = 6·5 mm
(a) Sub-surface defect; single, isolated, very small
(b) Surface breaking defect; 1 inch long
(c) Surface breaking defect; 2 inches long
All three defects of no measurable depth

Although this work is not yet complete, it has pinpointed current shortcomings and is defining options for changes in design and/or operational philosophy for future shafts. As a result of fears following the discovery of the large crack, a particularly cautious response ensued requiring the careful monitoring of all pits. Attempts are currently in hand to use a fracture mechanics approach to define more closely the 'criticality' of pits and which will, hopefully, allow sensible scheduling of repairs in relation to operational requirements.

High-pressure Air Bottles

High pressure air bottles in submarines are subjected to cyclic loads by internal pressurization and corrosion by internal contamination with salt water. Fears that corrosion could result in unacceptable wall thinning or the development of fatigue/corrosion-fatigue cracks has led to the policy of periodic proof testing every 4–6 years. Because of accessibility problems and fears of a catastrophic burst of a bottle during proof testing, the bottles are removed from the submarine—an expensive and time-consuming process that requires penetrating the pressure hull. Considerable incentive exists either to provide a safe means of proof testing *in situ* or to extend the period between proof tests, or both. One of the solutions which has been suggested is the use of an 'Acoustic' proof test which uses the non-destructive inspection technique of acoustic monitoring to provide an early indication of the existence of cracks, so that if necessary the pressure could be reduced in a proof test prior to catastrophic bursting.

This problem is amenable to analysis by fracture mechanics. Comparison of experimental burst test pressures with a fracture mechanics assessment shows good agreement (FIG. 12). Analysis of the implications of proof testing at the pressures currently employed suggest that they are of limited value in revalidating the bottles for further extended use, and that the pressures necessary to provide such assurance are probably impracticable. However, analysis of fatigue crack growth using rather tentative growth rate data suggests that very large initial defects would be necessary to cause problems. Even incorporating the strict requirement that only a leak-before-break failure mode could be tolerated, relatively large initial defects, several centimetres long and several millimetres deep, would have to go undetected to produce failure in twice the current operational period between proof tests. Given the simple geometry of the bottles and the absence of welds, it appears likely that detailed NDT before installation could give good assurances for safe operation of the bottles throughout an entire projected life of twenty-five years without recourse to proof testing.

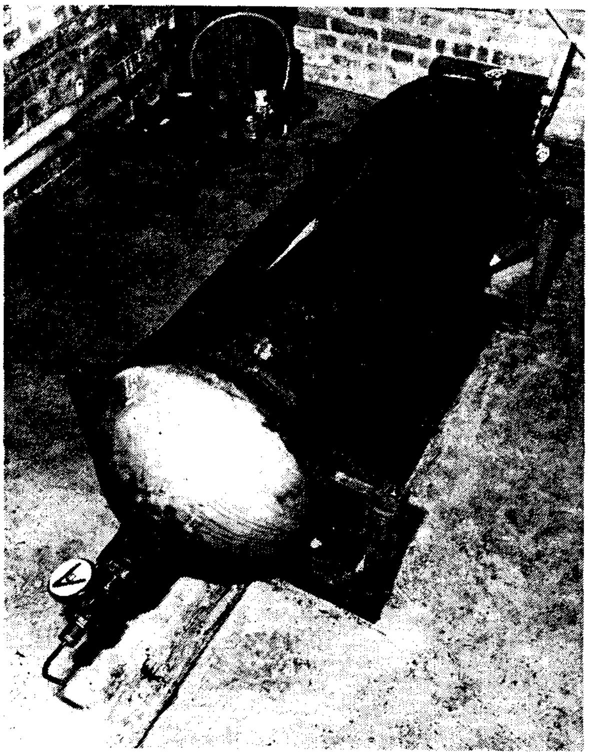

FIG. 12—HIGH-PRESSURE AIR BOTTLE BURST UNDER TEST AT AMTE(HH)

Thus the application of fracture mechanics in this case suggests that the lives of the air bottles could be safely extended, thus avoiding expensive and time-consuming revalidation. Whilst such conclusions require confirmation by further studies of the fatigue and fracture properties of the air bottles, the preliminary indications are so encouraging and the potential savings such as to encourage further development of this approach.

Conclusions

The examples described in this article give a clear indication of the potential value of the application of fracture mechanics to naval problems. The failures described amply illustrate the fact that cracks do exist and grow in real structures and this in itself provides good support for the argument that the possible existence of cracks should be recognized and accounted for at the design stage. The failure analyses described are invaluable in that they provide real examples against which to test the predictions of the fracture mechanics approach and, as indicated, the procedures stand up well to such critical examination. Where there have been failures it has been relatively easy to demonstrate the value of fracture mechanics to the engineer, and some appreciation and enthusiasm has been evident. However, use of the approach in failure analysis represents only a small part of the potential of fracture mechanics. As discussed in the 'Introduction' its true value will be realized only when it becomes an integral part of the design process, and in order for this to happen the design engineer must become familiar with the subject and learn how to use it.

The view from the Research Establishment has limited horizons but, even without the knowledge and experience of the design engineer, it has become clear from the nature of the problems and questions he raises that the potential of the approach is considerable. It promises the possibility of the use of new materials (including the surprising indication that naval rather than conventional applications might allow the use of more exotic metals and alloys) and the more efficient use of existing materials leading to improvements in safety, economy, and operational capability. However, unless positive steps are taken to create the multidisciplinary environment for the full development of these ideas, there is a great danger that the Royal Navy will both figuratively and literally 'miss the boat'.

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