Discussion

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Phil. Trans. R. Soc. Lond. A 1976 **282**, 123-130
doi: 10.1098/rsta.1976.0052

Discussion (Chairman: J. Fielding (*Hawker Siddeley Aviation Ltd*))

M. G. Gemmill (*Central Electricity Generating Board*)

The C.E.G.B. interest in gas turbines has developed steadily during the past decade from auxiliary service functions in large fossil-fuelled power stations to small power stations, entirely of gas turbine plant, whose principal purpose is to meet peak load demands. Here the ability of the gas turbine to be started up very rapidly is an important attribute.

The great majority of these gas turbine units have been derived from the use of established aero engines, such as the Avon and Olympus, as gas generators to drive a power turbine. These units are subject to planned maintenance after, at the most, 2000 h of operation when burning distillate fuel.

There have been instances of blade corrosion problems due to sulphidation attack and related high sodium levels in the fuel; the solution to this problem has been to control the fuel quality. Two prototype industrial gas turbines, each of *ca.* 55 MW output, are due to be commissioned at one of the Board's power stations in the near future. Here the aimed-for operational life before undertaking planned maintenance will be *ca.* 20000 h. This places greater emphasis on the need to appreciate any time-dependent process affecting engineering performance. From a materials standpoint these are corrosion resistance, thermal and high strain fatigue and creep-rupture.

Specific problems under study in blade materials are the consequences of corrosion-resistant coatings upon the mechanical properties and the limits of acceptability of defects. The latter involves crack growth monitoring under conditions of creep, high strain and high cycle fatigue.

As the future emphasis should be directed towards gaining a better understanding of material behaviour in the projected engineering situations the physical metallurgist has to think beyond the metals themselves and consider, for example, the interactions that occur between metals and coatings.

Mr H. E. Gresham (*Rolls Royce* (1971) *Ltd*)

Another important use of the gas turbine is as a gas pumping engine where modified Avon engines have run without any maintenance for over 30000 h and are now approaching 40000 h. This is a state of reliability far exceeding any other high duty mechanical contrivance and shows the effect of environment and starting and stopping on the life of an engine. In an ideal environment design factors come into play and give the right answers, but as soon as we start putting salt in the fuel we get trouble with the hot parts of our engine and we have such effects as thermal fatigue, stress corrosion, corrosion fatigue; so the story goes on.

It is necessary to design the material for the application so that an Admiralty turbine operating in the sea is of a different material from one used in the air, where the cleaner environment enables higher stressed materials to be used.

A. D. Hall (*Westland Helicopters Ltd*)

When considering factors that inhibit the achievement of maximum material properties, I do not think that we can forget fretting which is often an overriding phenomenon. Now it may be that this has no place in a conference of physical metallurgy but I would be most interested to hear other people's views.

There are materials problems that seem to be peculiar to helicopters. On a conventional helicopter, the main rotor blades are attached to the hub through hinges which allow freedom in the flapping, lag and pitch sense. On the Lynx helicopter, partly to reduce maintenance and partly to improve control power, we have substituted the flat and lag hinges by elements in bending. Here the requirements are high fatigue strength with low stiffness, coupled with the inevitable requirements of low weight, low notch sensitivity and good fracture toughness properties. Our solution to this problem was the 'workhorse' titanium alloy, Ti 6A1 4V, in the annealed condition. We found, however, that the effect of high mean stready stress on fatigue strength was more critical than we had first predicted and we had to design our way out of this problem with the penalty of higher rotor control power than was strictly necessary. Another area of interest is the main rotor blades. The current generation of helicopters has, on the whole, blades made of hollow aluminium alloy extrusions. On the Lynx, however, the 'matched stiffness' concept has led to a blade requiring appreciable stiffness taper in flap and lag. Our solution has been to fabricate the blade in stainless steel sheet section bonded together. Requirements here were formability, good fatigue characteristics and integrity and high erosion resistance.

We have still a long way to go with the full adoption of fail-safe characteristics for the rotor and transmission systems of helicopters. This requirement, together with the need to produce complex shapes for blades and hub, is leading us to look at other means of construction. Here the ability to tailor stiffness to design concepts, the 'fail-slow' and easy formability characteristics make reinforced plastics, both glass and/or carbon future contenders in this field.

Finally a word on gear box casings where high rigidity, stability and stiffness and, of course, low weight are needed. We have used thick magnesium alloy castings but one of the problems here is to provide satisfactory corrosion protection. I believe that we are overdue for new thinking in this area.

H. Tyrer (*British Aircraft Corporation*)

The commonness of problems between the 'lightweights' and the 'heavyweights' has already emphasized the necessity of discussion between metallurgists and engineers in each particular activity. I think it is now obvious that the metallurgists and engineers from the different activities should get together. Referring to the significance in heavy engineering of tensile strength, I would like to suggest that a proof stress plus total energy to fracture might be a more valid approach to what is being sought. I would like to ask James, considering that the fatigue resistance of light alloys has not improved in the last 20 or 30 years, what can be done by direct design to improve the general fatigue resistance of structures? I would also like to ask Imrie why maraging steels have been pushed to one side. Considering that they are readily weldable, the increase in design efficiency so obtained could probably offset the slightly lower mechanical properties.

D. James (*British Aircraft Corporation*)

Hall (this discussion) made a reference to the problem of fretting, suggesting that this conference was the wrong place in which to discuss it as it was not a materials characteristic. I suggest that it is and that it should be dealt with by metallurgists and materials engineers. It is essentially a surface stress problem which should respond to surface treatment developments.

My company has been very conscious of the problem of surface fretting as a cause of fatigue in pseudo-static joints in airframes for many years and we have made extensive use of interference fit pins or bolts as a means of overcoming the problem. This solution does not lend itself to the type of problem Hall probably has in mind. Hence the suggestion that surface treatment developments should be explored.

Tyrer (this discussion) asked if we can improve conditions by recognizing the limitations of the material and adapt our design to get the maximum out of it. This, of course, we do in various ways. The use of interference fits in joints, which has just been mentioned, is one example. Another is the attention paid to providing a standard of corrosion protection adequate to deal with the anticipated environment.

One speaker this morning was critical of the use of the ultimate tensile stress as a measure of material quality on the grounds that what was really being demonstrated in the tensile test was an instability. To me this is an academic controversy. What better method can be found for demonstrating the point at which such instability occurs than the simple tensile test?

I. L. G. Baillie (*British Aircraft Corporation*)

Although James (1.4) and Imrie (1.5) both recorded a lack of progress for aluminium alloys I would express some optimism that the peripheral behaviour problems of fracture mechanics, stress corrosion, etc. are now being brought under control. In this event, aluminium may be similar to the balanced set of properties which Irvine reports for 300 M.

Considering the future balance of properties I would ask whether Mr James envisages going through a learning curve phase of increasing working stresses with materials at present strength levels, or whether he sees a direct improvement of static properties as being of immediate importance. As a corollary to this, I would ask whether James considers that absolute freedom from exfoliation and stress corrosion troubles is essential. This can be associated with attempting to seek more representative methods of checking corrosion performance.

I would also refer to the future development of acceptable aluminium alloys. Imrie, in figure 1 of his paper, shows 2 % per year increase in strength for steels from 1940 to 1970, and I wonder what rate of improvement of *working* stresses should be regarded as a target. For example, for successive generations for aircraft of a given type (e.g. subsonic medium range airliner, supersonic fighter, etc.), hopefully say each 5 years, this 2 % per year rate would give 10 % improvement for each new aircraft. Would James regard this as a reasonable target for future development work?

Finally, I would refer to Imrie's paper. He shows that, from 1970, the u.t.s. of *all* undercarriage materials has remained constant and he seems to be generally satisfied with this state of affairs. I find this rather surprising, for users of materials normally make very different noises even in the presence of material suppliers and developers.

Does Imrie imply that there are other considerations which prevent further developments? For example

(*a*) is undercarriage stiffness now an overriding constraint on higher working stresses.

(*b*) are thicknesses now so reduced that they cannot be further reduced without introducing unacceptable handling problems?

(*c*) is the chance of success so low that it is not justifiable to use the increasily limited development funds to search for them?

G. W. Meetham (*Rolls Royce* (1971) *Ltd*)

I would like to comment on the compromise situations in materials selection for gas turbine engines, with particular reference to the paper by Glenny & Hopkins (1.6). Unfortunately there is a broad inverse relationship between the strength and corrosion resistance of the superalloys used for the highest temperature components in the engine. As a family cobalt alloys are more corrosion resistant in contaminated environments than nickel alloys, but as Nicholson (3.8) points out in his paper, the problem of finding an adequate strengthening precipitate for the former remains unsolved. Without wishing to minimize the corrosion problems experienced by industrial engines it must be pointed out that aero gas turbines in, for example, helicopter applications experience at least equally severe environments. These problems may well have common solutions.

High strength and low density tend to be incompatible characteristics in superalloys. The latest alloys contain high density elements such as Mo, W and Ta, with beneficial effects on strength but adverse effects on alloy density. Finally, in considering the conference title there is an example of a very practical contribution that I should like to highlight. This concerns the design of cooled turbine rotor blades. The designer needs to know the total temperature distribution in his blade designs. Conventional temperature measuring techniques such as thermal paints and thermocouples provide valuable but incomplete information. It is much more informative to section such turbine blades and carry out a detailed examination, using optical and electron microscopy, of the microstructure.

L. P. Pook (*National Engineering Laboratory*)

Basic design is done before a fracture analysis. To do a fracture analysis we must first decide whether we are dealing with a cracked or an uncracked situation. James (1.4) deals with aluminium airframe structures in which cracks occur early during life – therefore a cracked situation. By contrast Imrie (1.5) deals with high strength undercarriage materials and attempts to delay crack initiation as long as possible – essentially an uncracked situation. The resistance to crack growth (by any mechanism) is perhaps the best definition of the rather elusive concept of toughness.

In a cracked situation the fracture mechanism becomes important, and life is largely dependent on fatigue crack growth. Unfortunately physical metallurgy can do very little about fatigue crack growth rates, whereas it has been able to help in the uncracked situation. Confusion over the significance of the values obtained in various mechanical tests, for example what value of K_{Ic} should be specified, arises when considering which tests are to be done. Some tests appear in material specifications simply to ensure that the material is of consistant quality, i.e. they are quality control tests, whereas others are used to provide numbers which are used in design, i.e. they are design information tests. The aircraft industry does not seem to believe its own calculations and proceeds to expensive service simulation tests.

I conclude with two points referring to James's paper. First, creep damage can only offset fatigue behaviour when pores develop, i.e. when tertiary creep is reached. The possible detrimental effect is likely to be swamped by larger cracks already present in the structure. Secondly, increasing efficiency of aircraft structures offers prospects of improvement in fatigue crack growth resistance as this is more dependent on the Young modulus than strength.

R. Wedge (*Rolls Royce* (1971) *Ltd*)

Several speakers have referred to the safety of structures. In the aircraft engine field we are concerned with the integrity of the rotating parts. The energy we have to contain, when a crack propagates through a turbine disk through to its final burst, is equivalent to arresting a motor car of 1 tonne travelling at 100 km/h. It is obvious that the aircraft manufacturers are not able to contain those missiles, so we must address ourselves to the crack propagation and fracture toughness behaviour and considerable effort is put in on the physical metallurgy side. Full scale testing is demanded – a very expensive and time consuming activity.

R. G. Baker (*National Physical Laboratory*)

Is full advantage taken of the improved weldability of maraging steels as compared with 300 M for undercarriages? Perhaps some of the problems of making large forgings can be avoided by joining sub-components. Could this in principle offset the greater cost of maraging steels? Do we need to heat them as much if we can join them more easily?

I would like to question the use of the Charpy or Izod test either as a definitive or quality assurance test for high strength materials. Little of the Charpy/Izod energy is really concerned with a relevant measure of fracture toughness. Should we perhaps think of pre-cracked Charpy specimens or do we need more sophisticated tests even for quality assurance?

H. K. Farmery (*Ministry of Defence* (*Procurement Executive*))

In the aircraft industry environment-assisted-failure of aircraft materials is generally referred to cases which occur under static loading conditions such as stress-corrosion or hydrogen embrittlement or under zero load such as exfoliation attack. It is rare to refer to corrosion fatigue which is appropriate to the dynamic loading conditions prevailing in aircraft, and it is even rarer to see test specimens or structures being fatigue tested in an environment more aggressive than that of the shop floor – hardly typical of service conditions. Yet there is ample evidence stretching back from the work of Gough & Sopwith on simple S/N curves at the N.P.L. to the fracture mechanics approach on pre-cracked specimens of today to suggest that for many high strength materials of aircraft interest, corrosive environments as innocuous as plain water can have an appreciable effect in reducing fatigue resistance – especially at low stress concentrations.

Do Imrie and James rate corrosion fatigue a real hazard to designers in the growth of sub-critical cracks which must be taken into account when assessing the relative merits of materials for aircraft structures?

M. J. May (*British Steel Corporation*)

It is important to remember that, in utilizing a criterion such as the impact value in a Charpy or Izod test as a basis for material selection, the total energy involved in fracture is made up of two parts. One relates to the initiation of a crack from a specific notch configuration while the other relates to the propagation of the crack through the specimen. Considering the Charpy impact properties for a typical ultra high strength steel tempered over a range of temperatures there are several tempering conditions that could be used to achieve an acceptable level of Charpy energy to fracture, however, if one were to conduct identical tests on specimens containing a crack rather than a machined notch the energy to fracture would be markedly reduced, the magnitude of the reduction being dependent on the tempering temperature (as can be seen in figure 1). In the highest strength condition (T = 200–300 °C) only 2 J of a total fracture energy of 20 J is associated with crack propagation the other 18 J being associated with initiation from the machined notch. Unfortunately, in the real situation cracks and discontinuities can be such as to eliminate or markedly reduce the large energy requirement for initiation. I think this reinforces the point made previously by Baker (this discussion).

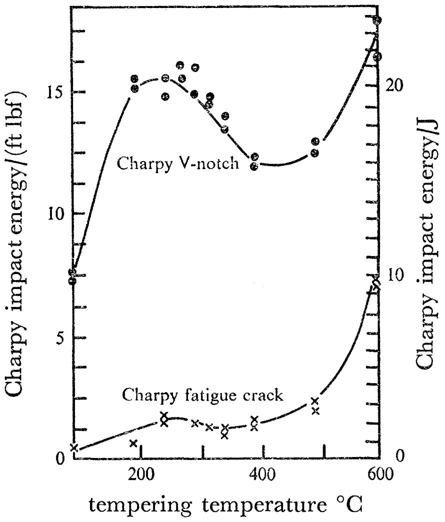

Figure 1. Longitudinal fracture properties of the high silicon Ni-Cr-Mo-V steel (cast FZ 0115).

Nevertheless, such tests can be used and will continue to be used for quality assurance but have considerable shortcomings in relation to material selection for design requirements.

I would agree with Imrie (1.5) that of the ultra-high-strength low alloy steels the 300 M grade has one of the highest combinations of strength and toughness at the 1650 N/mm^2 proof strength level (2000 N/mm^2 tensile strength). However, in terms of fracture resistance considerable benefit is gained by reducing the strength level to 1450–1500 N/mm^2 in terms of the initial crack size for fracture at a given stress level. Perhaps even greater importance is the marked increase in resistance to stress corrosion cracking that can be obtained in the lower strength condition.

It is argued by the undercarriage designer that any reduction in strength level imposes an additional weight penalty and if adopted would still result in critical crack sizes that are borderline from a non-destructive inspection point of view. These are, of course, valid points and emphasize the need to adopt the attention to detail and quality control outlined in Imrie's paper. It is perhaps salutory to reflect, followng the theme suggested by Kelly (centenary lecture), that when a scientific analysis raises doubts on material selection the requirements and needs of trade necessitate the development of an appropriate art. Such I believe is the situation which has been developed successfully over the years by the undercarriage designer and manufacturer.

D. James (*British Aircraft Corporation*)

In reply to Baillie (this discussion) I would remind him of some discussion I had with him some 15 years ago over a proposal to use a stainless steel FV 520 in the welded and precipitation hardened condition at high stress levels on an aircraft landing gear. He warned me of the hazards of stress corrosion in such a condition on the basis of the published data. I suggested that in looking at the published data in the context of the proposed application, we should look very carefully at the comparative environments of the proposed application and that relevant to the published data. In practice, the application has been completely satisfactory over a long period of commercial airline operation.

Baillie raised a question as to the benefits to be obtained from higher strengths in new materials. Strength levels should not be considered in isolation. In many cases modulus of elasticity as affecting the stiffness of a structure is of equal, if not greater, importance.

Pook (this discussion) raised some doubts about the feasibility of getting improvements in modulus of elasticity. I am assured by my metallurgical friends that these improvements are possible. One particular experimental alloy with which we had some experience a number of years ago, was the lithium bearing alloy X2020 produced by Alcoa. Its higher strength and modulus of elasticity compared with the aluminium-zinc-magnesium alloys was unfortunately associated with very poor manipulative qualities, which made fabrication difficult. I understand that refinements of composition have been developed which made this basic type of alloy a reasonable prospect for the future.

It was suggested in discussion that airframes are designed for cracked conditions and perhaps landing gears for uncracked conditions. We do not design the airframe to have cracks but we do accept that accidental damage does occur and we have to take account of these possibilities as well as those of fatigue crack development in our use of materials. It was also suggested that there should be no need to carry out full scale testing in view of the very detailed and elaborate design calculations carried out. I would like to think that this is a correct assumption and I try to press it in the interests of economy but it is very difficult to persuade the airworthiness authorities of the validity of the case.

In reply to Farmery (this discussion), I agree we do not do very much testing which is positively identified with corrosion fatigue. It would be extremely difficult to draw meaningful quantitative conclusions from such tests in view of the uncertainties of the relationship between test time histories and real time histories under these conditions. However, much full scale fatigue testing is done under corrosive conditions, e.g. long term pressure cabin tests in water tanks.

W. M. IMRIE (*Dowty Rotol Ltd*)

Pook (this discussion) indicated the difficulty of quantifying fracture-toughness as a design criterion. While agreeing I would in fact give consideration to the K_{Ic} of a potential material, but only as a preliminary screening evaluation. Improved toughness could be significant from the standpoint of greater reliability and is a desirable factor in raising the confidence level in the mind of the user.

Farmery (this discussion) asked about corrosion fatigue. Dr Forsyth (2.3) explained that crack growth rate is dependent upon the test frequency. I do not think that the published laboratory data are very relevant to undercarriage design, where the accent is on avoiding the onset of corrosion and of crack-initiation.

Tyrer (this discussion) thought that energy-to-fracture was an important criterion in design. I support this view and refer to figure 3 of my paper (1.5), which illustrates how the introduction of vacuum-remelted steel, with its resultant improved transverse ductility, leads to an increase in energy-to-failure.

Tyrer also asked why we had chosen 300 M in preference to other low alloy steels and additionally, would not maraging steel be a superior material? With regard to 300 M, the choice was made because of the vast data available from American sources, particularly in large sections. Additionally, our own work has indicated that it is certainly as good as, if not better than, all other comparable materials. Even so I believe that, for example, a Ni-Co-Mo-V alloy could be developed in the U.K. to perform satisfactorily but it is unlikely that the funds would be available on which the necessary confidence level could be acquired.

With regard to maraging steel, I would say we are very satisfied with its technical performance on the Harrier undercarriage, but that the easier manufacturing route was insufficient to offset the higher cost of the alloy in heavy sections, when compared with 300 M. Other factors militating against its use are:

(*a*) the capital tied-up in purchasing economic batches of forgings which have to be stored for many months awaiting machining,

(*b*) the financial loss which occurs if, for example a machinist makes a false cut in a large component,

(*c*) the lack of consistency in transverse ductility in large forgings, and

(*d*) the high degree of temperature control required by the forger in order to avoid thermal embrittlement.

I would also point out that the application of both 300 M and maraging steel in undercarriages is dealt with in detail in the references at the end of my paper.

Baker (this discussion) referred to the advantages of the weldability of maraging steel but we have shown that 300 M is capable of being solid-phase welded with almost 100 % parent-metal properties at the weld.

May referred (this discussion) to work at B.S.C. which has shown that some of the materials possessed a much higher degree of toughness than 300 M, although the strengths were lower. Although it has been generally accepted for a very long time that lower strengths are normally associated with higher toughness in the case of undercarriages such increases cannot be accomplished at the expense of strength.