OVERVIEW OF WORKSHOPS

R.F. Smith

A total of 332 papers was included in the Workshop Sessions, which took place on alternate evenings and afternoons during the first four days of the Conference. All the papers underwent a rigorous refereeing procedure. On receipt of a manuscript at Waterloo, copies were despatched to the appropriate member of the Editorial board, who would handle its review. He would, in turn, pass it to two referees for their opinion, on which he would base his recommendation to the Editor-in-Chief. The final decision on acceptance would then rest with him; and would be based on both the evaluation of the paper's technical merit and a weighing of factors such as the overall balance of the Conference and the origin of the paper. This process extended over the period from April 1976, when the first manuscript was received, to March 1977, when the last full manuscript was received and later accepted. Subsequent to this, several more papers were received in abstract form, and were accepted on this basis for presentation, where space in the programme permitted.

The workshop papers were classified into 7 parts:

	Part	No. of Papers
I	Physical Metallurgy	43
II	Voids, Cavities, Forming	44
III	Fatigue: Micromechanisms	40
IV	Fatigue: Mechanics	45
V	Analysis and Mechanics	67
VI	Applications	43
VII	Non-Metals	50

The exact scheduling of the Workshop Programme evolved from repeated iterations involving members of the Canadian Fracture Committee, the Local Arrangements Committee and the Editorial Board. Every attempt was made to classify papers correctly and to minimize clashes and overlaps. The task was in essence the organization of seven medium-sized conferences, in addition to the Plenary Conference!

The structure of the sessions was designed with the aim of producing active discussion and of developing continuity of themes. As all the papers were pre-published the authors were instructed to make only short (8 minute) presentations, stressing their major points and highlighting controversial and innovative areas. After the consecutive presentation of roughly five papers half the session time was devoted to discussion. This was led by a well briefed Workshop Foreman adopting the "rapporteur" approach. Integration of the sessions in each Part was fostered by Part Chairmen, who monitored the progress of their respective Parts through the week and attempted to develop and emphasise the connecting links between papers and in the discussion. This format was generally felt to be very successful and was instrumental in producing much meaningful debate. It was noticeable throughout the week that many of the lecture rooms held a capacity, or over capacity, audience : ample evidence that the transactions there had greater appeal than discussion in the foyer, which is frequently *not* the case. This stimulating *full house* atmosphere was particularly apparent in many of the sessions on Microstructures; Voids and Cavities; and Non-Metals.

No detailed record of discussion during the Workshop Sessions was taken. Instead the Part Chairmen were asked to compile what must necessarily be a rather subjective *Overview* of their sessions, and these follow below. These are not only useful now in directing attention to matters of greatest current concern, but will prove of considerable interest when set against any comparable documents which emerge from ICF5. It is indeed hoped that a similar approach to Workshop Sessions is adopted at ICF5 to develop further this *ICF style*.

I PHYSICAL METALLURGY

Introduction

The aim of this Part of the Conference was to examine the ways in which the various features of metallurgical microstructures affect the onset of fast fracture. The fracture modes considered were primarily those of transgranular and intergranular cleavage, together with some discussion of void-growth or fast shear mechanisms, which inevitably overlapped some of the content of Part II. Consideration of intergranular fracture encompassed embrittlement by trace impurity elements, by hydrogen and by liquid metals. 43 papers were presented, and points were raised in what was mostly very active discussion on virtually all of these. Thus it is not possible to do other than provide a general forward-looking summary of the events in these four vigorous sessions.

The main features of a microstructure that might be expected to be of importance in fracture processes are listed and discussed below.

Grain Size

Effects may arise, either because large grains can accommodate long dislocation arrays, which facilitate crack initiation or because (long) microcracks can propagate more easily in coarse-grained material. If "grain size" is then to be interpreted as the feature that provides a microstructural barrier to slip or to microcracks, it may turn out that the important parameter is the simple, as-annealed, grain diameter, the cell size in prestrained materials, or the martensitic lath or packet width in a quenched steel. Additionally, if any texture has been introduced into the materials during working, barriers between some pairs of grains may be weaker than usual, leading, for example, to cleavage facet diameters larger than the average grain diameter. In material containing a large volume fraction of hard matrix particles, it is not clear that grain size *per se* should be of great significance, unless the heat-treatment used to obtain the grain size has also produced grain-boundary embrittlement or hardening.

Second-Phase Particles

These may be divided into two sets : one composed of those which are deliberately produced to give matrix strength, such as carbides in steels or intermetallics in aluminium alloys : the other, comprising those present as non-metallic inclusions, such as sulphides, de-oxidation products, or coarse (> 0.5 μm diameter) intermetallics. Additionally, in steels, there may be particles, such as NbC, added in the first instance for grain refinement, which fit somewhat into both categories : larger particles pinning grain boundaries and acting rather more as inclusions; fine dispersions inducing matrix strengthening.

Dislocations interact strongly with the first set, producing high local stresses, such that, as the plastic strain is increased, the particle may shear, crack or cavitate. A particle which shears at low plastic strains induces planar slip, which gives sharp slip-bands, high stresses at the end of pile-ups, and easy penetration of protective surface films. Grain size might be expected to be of significance in such an alloy. Stronger particles may induce cross-slip and dislocation tangles/cell structures if the stacking fault energy of the matrix is not too low : the grain size should then be of less importance. Even in this second case, flow may localise to give intense shear bands at higher applied strains, perhaps because the particles crack or cavitate, by decohering from the matrix. In the former case, the strength of the particle itself is of importance : in the latter case, the strength of the particle/matrix interface is critical. Here, the segregation of impurities to the interface may strongly affect the work of decohesion. The strengths of carbides and carbide/matrix interfaces are of critical importance in the initiation of transgranular and intergranular cleavage fracture, and the cleavage fracture stress of the materials may often be related to carbide sizes, using Griffith-type arguments.

Large non-metallic inclusions are not expected to be strongly bonded to the matrix in a chemical sense, but tensile or compressive residual, "tessellated", stresses may exist near the particle, due to differential thermal contraction on cooling. Residual tension in the matrix may aid crack initiation (but the effect of the stress is very short-ranged) : residual tension in the particle may enhance particle fracture. As the size of the inclusion is reduced (fine-scale deoxidation products in weld-metals, 0.1 - 0.2 μm diameter intermetallics in aluminium alloys, fine sulphides in ESR steels), there may be evidence of particle/matrix bonding so that dislocation arrays are necessary to initiate voids : the more usual situation is, however, that in which voids are nucleated at very low plastic strains. Not only the volume fraction, but also the distribution of inclusions, may be important in controlling a material's ductility or toughness : for example, a redistribution of sulphide particles at austenite grain boundaries during "overheating", or fine-scale inter-dendritic MnS particles in a cast or incompletely worked steel, can give low toughnesses.

Dislocation Structures

Dislocations produced by transformation are usually associated with martensitic transformations. In low carbon steels, there is some evidence that yield strength is governed by lath width, but that cleavage resistance is controlled by packet diameter, although few pictures of microcracks arrested at packet boundaries have been shown. In higher carbon steels, plate martensite and retained austenite may also be present, but evidence that cleavage fracture remains trans-lath has been presented. Other possibilities are that the fracture runs along lath or packet boundaries, but these have not been proved unambiguously.

The effect of the distribution of dislocations produced by deformation is also of importance : planar slip being induced by low stacking-fault energy or easily-sheared particles (particularly in ordered alloys). Sharp slip-bands seem generally to be deleterious, (although they are associated with high cyclic hardening properties), but the conditions under which shear localisation can occur in a plastically deforming matrix, which has until then been deforming in a uniform manner, remain unexplained.

Further work also needs to be done to explain the effects of dislocation structures in controlled-rolled steels or thermo-mechanically treated aluminium alloys.

Trace Impurity Elements/Hydrogen

It is now fairly well understood that the segregation of certain impurity elements to grain boundaries (Bi in Cu; P, Sb, Sn, As, etc., in alloy steels) can in some way lower grain boundary cohesion, so that a crack may run at low stress along the boundary, and the toughness of the material is reduced. Often, hydrogen, supplied externally from a hydrogen atmosphere or an acidic corroding solution, seems to act in a similar fashion, giving intergranular fracture in an alloy with impure grain boundaries which would otherwise cleave in a transgranular manner. In many cases, interactions between impurity elements and major alloying elements can affect the details of segregation. It is conceivable that hydrogen may interact with matrix elements to form hydrides; however, there is no experimental support for this idea. The precise mechanism of embrittlement is as yet unclear, although a simple lowering of cohesive stress, by modification of the normal iron-iron interionic potential, seems preferable to any pinning mechanism.

Other Features

These include the degree of texture present in a material, which also affects the anisotropy of elastic constants and plastic flow. Additionally, the grains may have elongated and inclusions may be aligned preferentially in some directions. Segregation of alloying elements and carbides may also give rise to non-uniformity of properties in cast and wrought alloys.

Discussion

In the light of the many features of microstructure outlined above, it is hardly surprising that many of the workshop papers were not as clear-cut with respect to the operative micro-mechanisms as might have been hoped. The ensuing discussion often tended to concentrate on pointing out some of the other variables, which had not been taken fully into account : for example, that the heat-treatments used to produce variations in grain size in steel might, at the same time, produce differences in carbide sizes and distributions in dislocation sub-structures, and in the distribution of minor impurity elements. Appropriate plenary papers were assigned to particular sessions, but the authors of such papers were unfortunately not always present, so that the discussion could not always include comments on the models proposed in the plenaries. A glaring example of disagreement between workshop and plenary papers was shown in the very last

paper in the session on liquid metal embrittlement : figures presented in the workshop, and endorsed by most of the audience, were almost an order of magnitude different from those quoted in the appropriate plenary paper. Discussion in the final session, on embrittlement, was particularly interesting and constructive. Even here, as generally with previous sessions, the only overall conclusion to be drawn is that most microstructures are very complicated and that the details of the ways in which they fracture, under aggressive or non-aggressive environments, are idiosyncratic in the extreme.

J. F. Knott
C. J. McMahon, Jr.

II VOIDS, CAVITIES, FORMING

This part of the Conference was concerned with a variety of aspects of plasticity which occurred with concomitant void nucleation and growth including both low temperature and high temperature deformation modes. There was considerable discussion of the problem of void nucleation which emphasised the theoretical problems of void production at a variety of heterogeneities such as second phase particles, grain boundaries and sub-structural features. This is clearly an area in which more detailed criteria and mechanisms are needed. However, as a cautionary note, it should also be recognised that experimentally it is difficult clearly to rule out nucleation at second phase particles because this can occur at particles less than 10^{-2} μm in size. These can readily arise at very low overall impurity levels when, in addition, their spacing may be large.

In regard to the growth of holes some definitive experiments were reported which clearly related the displacement rate and cavity shape to the stress system around the growing void. The results are at variance with current theoretical models and it is clear that more precise constitutive relations are required for solids in which plasticity occurs without volume conservation. Further, it was clear from a number of papers that the criterion for strain localisation and its influence in prescribing the allowable strain to failure is of major theoretical and practical interest.

Clearly, these problems are important in forming operations. A number of important problems emerged during discussions including the need to relate R values, texture and the extent to which plane strain deformation is enforced on a microscopic scale. In addition, the majority of ductility models is related simply to the volume fracture of inclusions. However, in many forming operations, where fracture is initiated at the surface, the failure criteria may well reflect the distribution of inclusion spacing and be related to the minimum inclusion spacing. This may be of importance in such technological problems as the forming of plates which possess a sheared edge.

Turning to the question of the applicability of void nucleation and growth to high temperature deformation, it is apparent that both the theoretical models and experimental evidence are less clear cut. The evidence regarding cavitation during superplastic flow suggests that there is some disagreement regarding the occurrence of cavitation in all types of material at large plastic strains. This aspect is clearly important for defining the range of applicability of various constitutive equations for superplastic flow and the mechanisms of mass transport involved in achieving the overall strain.

In the field of high temperature deformation two salient features emerged from the discussion. First, it is clear that in many materials microstructural instabilities occur which have a profound effect both on the range of utilisation of constitutive equations and the definition of the mode of failure in terms of the operative stress and temperature required. Secondly, it is clear that more effort is required in formulating cumulative damage rules. For example, the ability to link microstructural models of damage, such as hole growth by diffusive flux or dislocation motion, to phenomena which involve path dependent deformation would be of immense value in predicting creep life under variable loading conditions.

Finally, it is germane to indicate that currently much effort is being expended on the production of fracture or failure maps for both low temperature and high temperature conditions. Although these concepts permit the rationalisation of a variety of existing data, it is of importance to extend their utilisation to path dependent phenomena and to recognise the limitations imposed on their use by microstructural changes and environmental effects.

In conclusion, it can be stated that the area of ductile failure and hole growth both at high and low temperatures is a fruitful one for future work based on the development of new constitutive equations and carefully controlled experimental studies. In particular, the areas of defining the total volume of material involved in hole growth, the criteria for strain localisation and the path dependence of cumulative damage models should provide fruitful areas for research in the next decade.

J. D. Embury
B. F. Dyson

III and IV FATIGUE : MICROMECHANISMS AND MECHANICS

The eighty-five papers contained in these two sessions attest to the current high level of interest in the fatigue process. Scheduling of these papers into the two parts had, of necessity, to be somewhat arbitrary, resulting in many delegates having to choose between two sessions of equally interesting sets of papers. However, almost all sessions in both parts were well attended and generated enthusiastic and often heated discussion.

Part III, under the theme of "micromechanisms", considered, in order : crack initiation mechanisms and their dependence on microstructure; the interaction of creep and fatigue at elevated temperatures; the effect of environment on fatigue; and finally the strain concentrating effect of discontinuities. Clearly this range of topics precludes giving, in a short review, more than a cursory view of the trend of the discussions. Characterizing the sessions in brief, it appears that the first three sessions had in common a pragmatic approach of detailed observations of the importance of individual microstructures in fatigue process rather than a preoccupation with general models. It seems reasonable at present to conclude that for some time practical advances in predicting the effects of creep-fatigue interactions will be aimed at particular temperature and deformation regimes of existing alloy systems. There is further evidence that for many applications the effect of environment must be included in determining creep-fatigue resistance.

Papers in the environmental session particularly exemplified a material by

material study of processes. Here again it appears that we have much to learn before generalized models can be put forward. In contrast to the first three sessions the last session on the effect of discontinuities on fatigue dealt with a topic which is reasonably well understood. Indeed, this session includes an interesting set of applications of notch analyses and gives a state of the art review of fatigue analysis techniques for notched components.

Part IV, in its first and last sessions, covered current observations and models of fatigue crack propagation. Discussion pointed out both the relatively good predictive abilities of current models and the still not completely resolved nature of crack closure and the threshold stress intensity. A particularly interesting observation relating to the former was reported by McEvily, who pointed out that recent observations indicated that the crack was, to a large degree, propped open by the surface layers in a plate, and that removal of these layers could strongly affect closure and related phenomena such as crack retardation. The consequent influence of specimen thickness on delay in variable amplitude loading appears to be a high priority problem. The two middle sessions dealt with a variety of special topics and applications. They, as a group, pointed out both that approaches outlined in the other two sessions could be applied to crack propagation and that the crack initiation phase, as noted in Part III, still requires special treatment. In addition, both papers and discussions considered features of metal deformation, biaxial straining, metallurgy and failure modes in non metallics so far neglected in simplified fatigue analyses. Each of these topics will no doubt receive further attention. The influence of metallurgical features on crack initiation and threshold stress intensity, as well as specimen thickness on crack closure, are, as yet, not satisfactorily resolved. However, it appears that at least the outline of a consistent approach to crack propagation has emerged. The approach at present relies strongly on empirical, but broadly based, observations. This suggests that, while advances in the mechanics of crack tip behavior and in metallurgical models will probably refine, amplify and explain present predictive methods, the approaches are essentially sound.

T. H. Topper
L. Coffin

V ANALYSIS AND MECHANICS

Part V of ICF4 itself comprised virtually a full conference. Sixty-four workshop papers were scheduled, and three were added at the last minute. The authors represented at least fifteen countries, and discussers and audience provided an even wider resource of interest, commentary, and evaluation. Papers were scheduled in six sessions (meeting in just four three-hour periods!) entitled Crack Growth, Dynamic Processes and Stress Intensity Factors, Fracture Analysis, J-Integral and COD, Non-Planar and 3-Dimensional, and Non-Linear. For the most part, papers were grouped well and thus stimulated a good deal of discussion.

It would oversimplify matters to lump nearly seventy papers into just a few categories, for of course each author or group of authors tends to work independently. The alternative of commenting here on each paper individually is repetitive, for the thrust of the work appears concisely in these Proceedings. It is more to the point, however, to make limited observations on certain *problems* which have or have not attracted the attention of the researchers at ICF4.

In broad terms, the community seems now less preoccupied with determining stress intensity factors by any of several methods; interest has shifted to what may be termed characterizing parameters, and to simulating crack growth processes. The previously dominant exercises of stress analysis (almost apparently for their own sake) are now to be found in efforts of greater scope, i.e. identifying and quantifying these characterizing parameters, including crack opening and energy related quantities. In this connection, it is to be noted that a main function of analysis and mechanics is to model an event or a process so that such parameters may be inferred, or perhaps a theory constructed. Observe, however, that, analysis by itself leads not to criteria - these require experimental confirmation.

What was heard at ICF4, therefore, was a variety of presentation whose objective appeared to be determination of the nature of one characterizing parameter or another, for a range of materials, geometries, and load configurations. Some papers focussed on mixed-mode excitation of a crack in an elastic medium, a particular issue of recent interest. The two key problems here, of course, are the stress modelling and the condition of criticality. Recent literature has been more concerned over the second, while the first - for compressive loading - remains not altogether resolved. Relatively little attention was given at ICF4 to finite element methods *per se*, although there is still viable activity to be found on this topic, and modelling of crack problems done in conjunction with numerical analyses was discussed but little. It was almost as though a consensus had been achieved to the effect that such questions are resolved and attention could pass to crack growth and characterizing parameters.

Accordingly, we were treated to discussions of J and other integrals, measures of crack opening, and other stress or energy based parameters. Without going over these papers one by one, we can make some observations. Owing to the fact that such work usually involves non-linear behaviour (i.e., plasticity and, sometimes, finite deformations), the requisite analyses typically proceed on the computer, employ finite elements as a solution tool, and are expensive. Some work, of course, is more analytical and relies on a simple model, e.g., the Dugdale zone. In all cases, however, it is prohibitive to investigate such aspects as the effect of modelling itself, numerics, variations in material representation and/or load configuration, and other implications of the assumptions which underlie a given study. Moreover, we know of no published work which gives a comparative evaluation of various analytical methods, computational or otherwise, which could serve to confirm that any one analysis is concerned. In a strict sense, therefore, these fundamental data cannot be regarded as wholly unique.

It follows that the behaviour of various characterising parameters may be peculiar to the data sets from which they were extracted. While we acknowledge that this difficulty may prove eventually to be negligible, the fact is that we do not presently know whether such is the case. Hence the characterising parameters, as described by different investigators, may be expected to relate only remotely to laboratory behaviour and, eventually to service performance. Moreover, the definitions of at least some of these parameters may be different when applied, first, to numerical results, and then to experimental observations.

We have then a rather loosely tied set of results. Crack opening, for

example, is defined differently in different (analytical) models ranging from a built-in blunting, to a separation at various positions along a crack's flanks - including an extrapolated position, to a stretch or strain at the crack's end; at the same time, experimental data relate to three-dimensional configurations of actual materials (ranging from polycarbonate to carbon steel). Contour integral quantities are well defined mathematically, have some appealing properties for certain idealisations of material behaviour, and are easily evaluated on the computer; at the same time, it is not they but their presumed analogues which exist experimentally. Crack growth in fact occurs, and it is modelled by approaches ranging from constant velocity behaviour in an elastic continuum to quasi-static node by node release of points in a finite element array, a technique requiring decision as to node spacing, conditions for release, simulation of material unloading and reloading.

Such are typical of problems attempted by the analysts reporting at ICF4 and such are the difficulties encountered in their work. We can applaud their efforts and dedication, and indeed do so. It should be recognised, however, that the final words have yet to be written on these problems, for the models and methods will be refined in the years ahead. In this connection, we note that analysts and mechanicists must increasingly turn to laboratory observations as a critical resource for the formulation of their work. Further, the laboratory will eventually become a proving ground so that results of the type presented in Part V of ICF4 will be both rigorously based in terms of mechanics and firmly corroborated, physically. Finally, the information we all seek ultimately to develop will provide bases for the design procedures which are needed to ensure new levels of integrity and reliability in critical structures.

J. L. Swedlow

VI APPLICATIONS

Attendance at the *Applications* sessions was generally quite good, and the discussions following the technical presentations always enthusiastic. The visual, aural and technical quality of these was universally excellent. The authors clearly laboured diligently in their preparation and all attending profited as a result. Authors whose first language is not English are especially congratulated for the fine presentations they made using a foreign language.

General observations gleaned from the technical presentations and discussions are as follows:

1. A number of investigators reported developing specimen configurations which closely resembled structural components. The resulting data were quite useful in predicting the behaviour of the actual components and have, at times, correlated quite well with data generated using standard fracture toughness specimens.

2. Other investigators reported developing specimen configurations designed to be more economical, or to have more complex stress states, than the standard fracture toughness specimens. The results presented indicate generally good correlation between test data generated using the standard configuration.

3. Several researchers developed stress intensity solutions for cracks in

various bodies, e.g. in stiffened panels, in holes, and in cracked lugs. These solutions will greatly aid analysts in predicting fatigue-crack propagation and fracture in structural components containing cracks.

4. The effects of various metallurgical parameters on fracture toughness were reviewed. These parameters, including hydrogen, oxygen and nickel contents, pore density and heat treatment all influence fracture toughness. The information on these parameters will be quite valuable to designers and fabricators as they select materials for structural use.

5. Several experimenters reported on the effects of temperature on fatigue crack propagation. Generally, fatigue-crack propagation is not affected by reductions in temperature as is fracture toughness, and the experiments reported helped to clarify the reasons for this.

6. Studies of both static and dynamic fracture toughness in metals were described. In some instances, unique light techniques were used to measure stress intensity factors during the tests. Correlations between the static and dynamic fracture toughness and the static and dynamic yield strength were reported. These techniques and correlations will prove quite helpful in predicting failure in rapidly-loaded structures.

7. Some researchers studied the effectiveness of various nondestructive test techniques. In some instances, acoustic emission techniques were very useful for detecting stress corrosion cracking. However, ultrasonic techniques can seriously underestimate flaw sizes (by factors of 4½ in some instances) in components. Such underestimations can lead to gross overestimations of the remaining life of the component. It is hoped that future *Applications* sections will deal with the reliability of nondestructive test techniques in greater detail. The reliability of any life prediction made using linear elastic fracture mechanics hinges critically on knowing the actual size of the initial flaw.

8. Virtually all authors added valuable test data to the technical literature. These data are invaluable to the analysts who must perform fracture mechanics analyses but who lack their own laboratory facilities.

In conclusion, *Applications* covered a wide range of interests. It provided the technical literature with many new and exciting concepts for future research, and provided the tools for solving some old problems. This section of ICF4 must be classified an unqualified success.

C. Michael Hudson

VII NON METALS

In this part, the fracture of a great diversity of materials was considered : ceramics, glasses, composite materials, polymers, biomaterials and concrete. Even metals appeared (in the form of prosthetic devices) under the guise of biomaterials. The workshop sessions were generally very well attended and the discussions vigorous, sometimes to the point of becoming heated. This led to many useful conclusions, which will be dealt with separately according to the type of material, in what follows.

Ceramics and Glasses

These two sessions will be considered together, since the topics discussed in each were closely allied, and fell into three general areas : 1. Factors affecting fracture toughness (also the topic of the Plenary paper), 2. Subcritical crack growth, and 3. Use of fracture mechanics data in engineering design. In the area of fracture toughness, the paper by Hubner sparked a lively discussion. His measurements on alumina demonstrated R-curve behaviour, in that the toughness increased as the crack extended. This mechanism was also discussed by Evans in his Plenary paper, and by Buresch in his workshop paper, and the subsequent debate over R-curve behaviour centred around the validity of the techniques used for fracture toughness measurement. The paper by Wiederhorn on the most reliable crack velocity -- stress intensity relation for subcritical crack growth in glass provoked some controversy. Wiederhorn felt that the data was best represented by relating crack velocity to a power function of stress intensity factor, although this did not have any theoretical basis. J.S. Williams pointed out that polymers also obey this type of relation, and that he had been able to derive the power law equation using the relationships for the time-dependent behaviour of yield stress and modulus which are established for many polymeric materials. (They show an inverse power law dependence on time.) Wiederhorn's response was that these power law dependencies were also empirical.

Composites

The Plenary paper on this subject showed that much progress has been made in understanding the factors that contribute to toughness in fibre reinforced composites. There are difficulties in applying fracture mechanics to these materials, however, and these are in large part due to the size of the "process zone" at the crack tip. They can therefore be avoided to some extent by testing samples with sufficiently large initial cracks, as is done with ductile metals. The workshop papers covered a wide diversity of composite types, including joints, laminated sheets, and planar composites with two components, as well as fibre reinforced materials. The scope for mathematical analysis was shown to be very great, but many participants felt that the paper on strength criteria was a solution in search of a problem.

Polymers

The Plenary paper on impact testing of polymers showed that, when suitably instrumented and interpreted, impact tests can give reliable data on the fracture properties of polymers. In contrast to this, the Plenary papers which attempted to relate the fracture of polymers to the behaviour of the individual polymer molecules indicated a complete divergence of opinion as to what was occurring. The evidence from recent experiments seemed to support Kausch rather than Peterlin. It was agreed that one of the most important phenomena occurring during the fracturing of polymers is crazing, i.e. the nucleation, growth, and coalescence of very large numbers of very small cracks. Annealing has a very great effect on crazing, and during the workshop sessions the importance of annealing craze-prone polymers before testing was stressed. The effect of environment on crazing can also be serious, and the silicone fluid used for applying pressure to polymers for multiaxial stressing was found to promote crazing. Crazing is also important in fatigue, where failure occurs by enhancement of craze growth and coalescence in polymers which craze.

Biomaterials

The micromechanical processes occurring during the fracture of bone are of great complexity, owing to the highly inhomogenous and anisotropic nature of this material. These generated food for thought when it was pointed out, in the Plenary paper, that in humans, well-used bones have very superior mechanical properties to those not much used. Prosthetic devices have to be mechanically compatible with the relevant part of the body, as well as unaffected by body fluids. The demands made on these devices are often extremely severe.

Concrete

Attempts to apply fracture mechanics to concrete aroused lively discussion, and participants questioned the validity of tests in which the artifically induced cracks were of the same order of magnitude as the dimensions of natural discontinuities in the material (e.g. interfaces and coarse aggregates). This problem is common to all composites. Concrete presents many problems of its own as well. There is the paradox of dry concrete, which is extensively cracked, being demonstrably stronger than wet concrete, which is uncracked. The active role of water in dimensional changes and strength reduction is nothing to do with lubrication.

Many other lively discussions, too numerous to detail here, took place during the generous time allotted for the purpose. It was noteworthy that the bringing together of fracture experts from several disciplines was a significant factor in promoting discussion, as often workers from different fields view a particular phenomenon in different ways.

M. R. Piggott