Fatigue crack closure and its dependence on fracture features

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Fatigue crack closure has been directly observed in polymethyl methacrylate and the topography of the fracture surface features studied by interferometry. The mating fatigue striations were observed to meet ridge to groove. Thus the fatigue crack had advanced cycle by cycle deviating away from and back to the general fracture plane in an undulatory fashion. The offset distance was considerably greater than the permanent opening displacement of the crack tip, and crack advancement was essentially brittle in nature. A simple biharmonic loading programme has been used and the low frequency (mean stress change) also introduced its own longer wavelength undulations on the fracture surface. Observations on aluminium alloy indicate similar behaviour.

1. Introduction

It is generally accepted that the stress intensity factor range (ΔK) experienced by the tip of a growing fatigue crack will be limited, to some degree, by interference of the fracture faces during part of the load cycle. Because of this interference, crack opening is delayed during the rising stress phase of the cycle. The degree of interference that might be encountered would be expected to depend on the contour relationships between the two crack faces. In this respect there are the macroscopic features to be considered, and, on the microscopic scale, the fatigue striations themselves and other minor irregularities. As far as the fatigue striations are concerned, it has been variously reported by different authors that, on one hand, the grooves and ridges of these striations appear on the two surfaces as mirror images, i.e. the ridges meet ridges on closure and, on the other hand, that ridges meet grooves on closure.

The earlier observations were summarized by Jacoby [1]. It should be stated that they cover a wide variety of materials both metallic and polymer with consequent differences in plastic behaviour and it is probable that the degree of crack tip deformation is an important factor in determining the matching of striations. Views on this subject seem to have been somewhat influenced by a general preference for symmetric crack opening models even though the weight of experimental evidence suggests that fracture striations more commonly, in engineering materials, fit ridge to groove. There is no doubt that striation contours can be modified and distorted by crack closure itself and the whole matter is open to misinterpretation. This question, clearly, is not only related to the degree of interference that will be encountered on crack closure, but to the more fundamental issue of the crack extension mechanism itself, and whether brittle or ductile behaviour predominates.

In order to study crack closure and striation form it would clearly be an advantage to work with a material that is transparent so that *in situ* cracks can be examined through a stress cycle with direct viewing of the crack front. There have been a number of researches on the fatigue fracture characteristics of transparent polymers and it is generally accepted that these materials show a remarkable similarity to metals as regards fracture features. For this particular work polymethyl methacrylate (Perspex) was chosen. Cellulose acetate has also been examined to study particular aspects of variable amplitude fatigue behaviour but the results of that work will be reported elsewhere.

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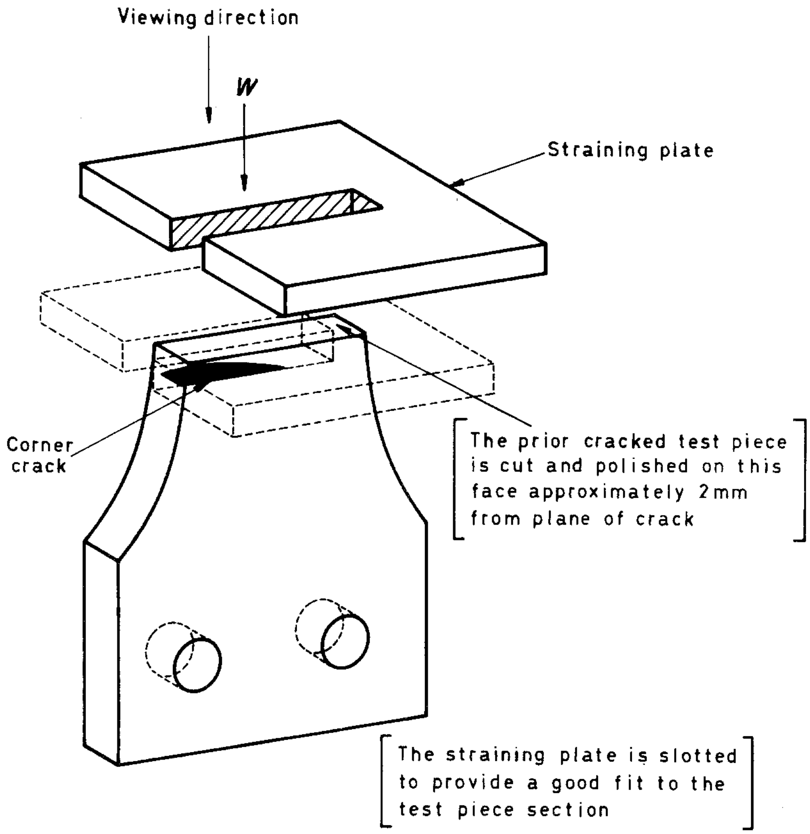


Figure 1 The preparation of a reverse plane bend fatigue specimen for observation of a crack subjected to cyclic load. The plate may be loaded by weights or a push rod.

2. Experimental details

In order to obtain a plan view of embedded cracks, test pieces, in which fatigue cracks had been grown, were cut and polished as shown in Fig. 1. Perspex is highly transparent with a refractive index of 1.48 to 1.50. It can be polished to an acceptable optical standard to allow direct *in situ* observations of cracks. The interposition of a thickness of Perspex between the object and the microscope objective increases its working distance so that it is possible, by using a long working distance 4 mm objective, to view crack detail several millimetres below the specimen surface, at magnifications up to $\times$ 500.

The fatigue cracks were generated in reverse plane bending using either constant amplitude loading or a changing R ratio programme as shown in Fig. 2. The test was usually stopped at the longest possible crack, at which stage the crack growth rates could be as high as 30 μm per individual cycle at the highest R ratio in the programme. The striation pattern relating to the changing R ratio programme can be seen directly on an opened fracture surface, Fig. 3, and the crack growth data is plotted in Fig. 4. The details of this will be described later.

3. Fracture observations

As well as the *in situ* examination of cracks it was necessary to obtain quantitative topographical data for matching pairs of fracture surfaces. Normal incidence illumination with aluminium-

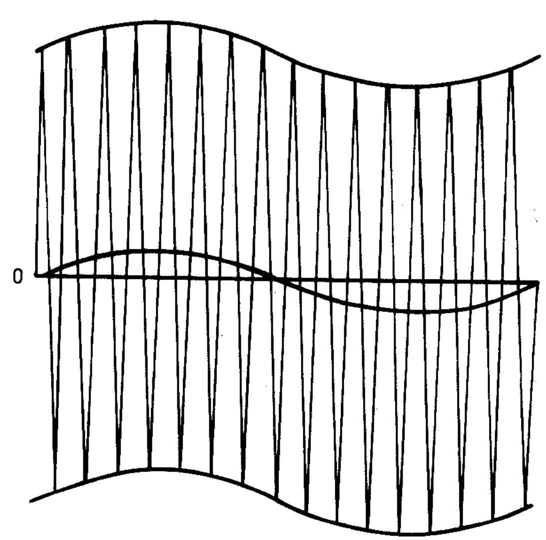
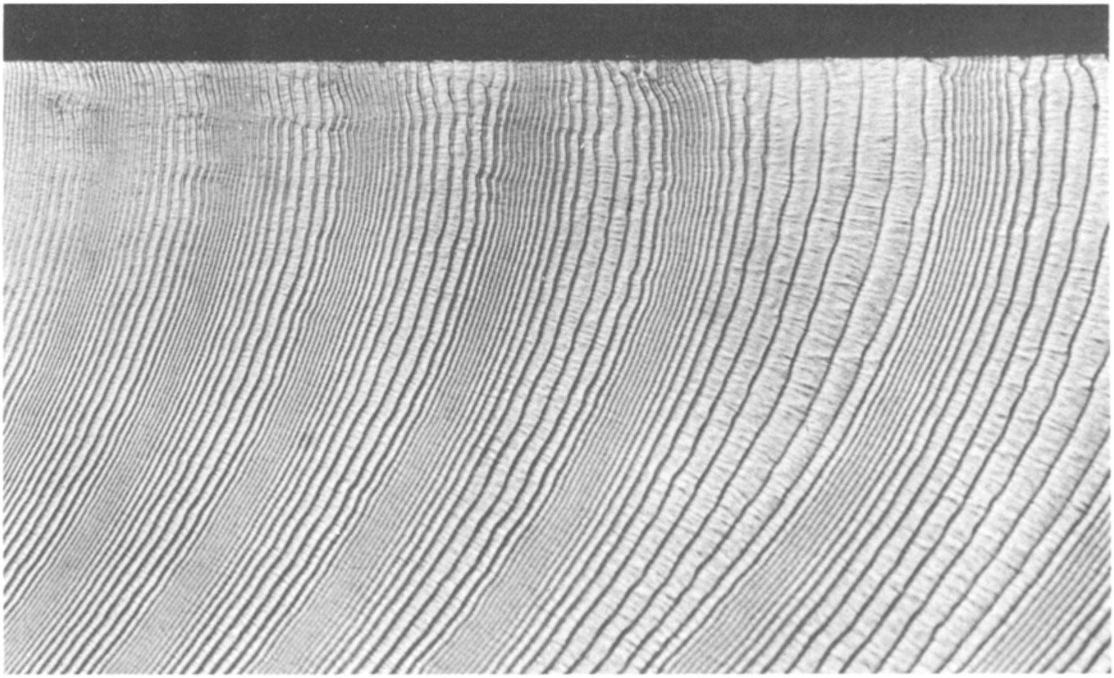


Figure 2 Fatigue loading programme. Frequency ratio 16 : 1. Amplitude ratio 7 : 1. R ratio change 0.75 to $-$1.33.



Frequency ratio 16:1
Load ratio 7:1

Actual frequency { 150 Hz / ~9.4 Hz }

Figure 3 Fatigue fracture–perspex, subjected to programme loading. Magnification × 211.2.

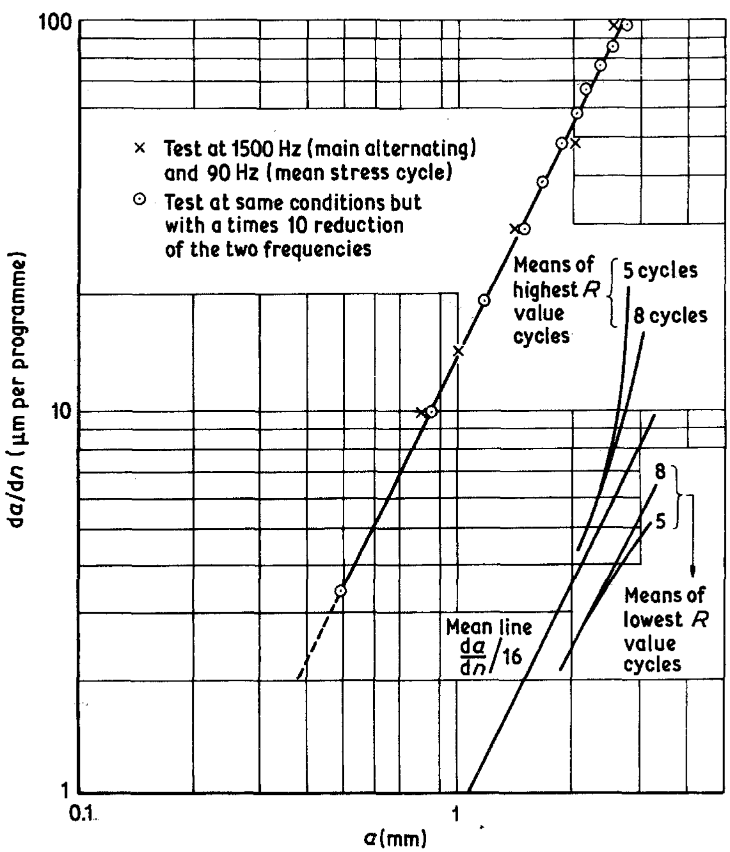


Figure 4 da/dn against crack depth a ($\Delta\sigma = 23.1$ MPa, $\Delta\sigma_m = 3.3$ MPa) for programme shown in Fig. 2.

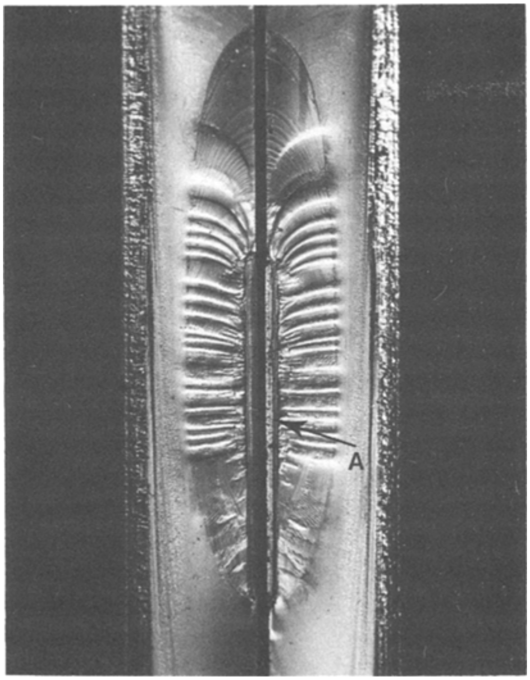


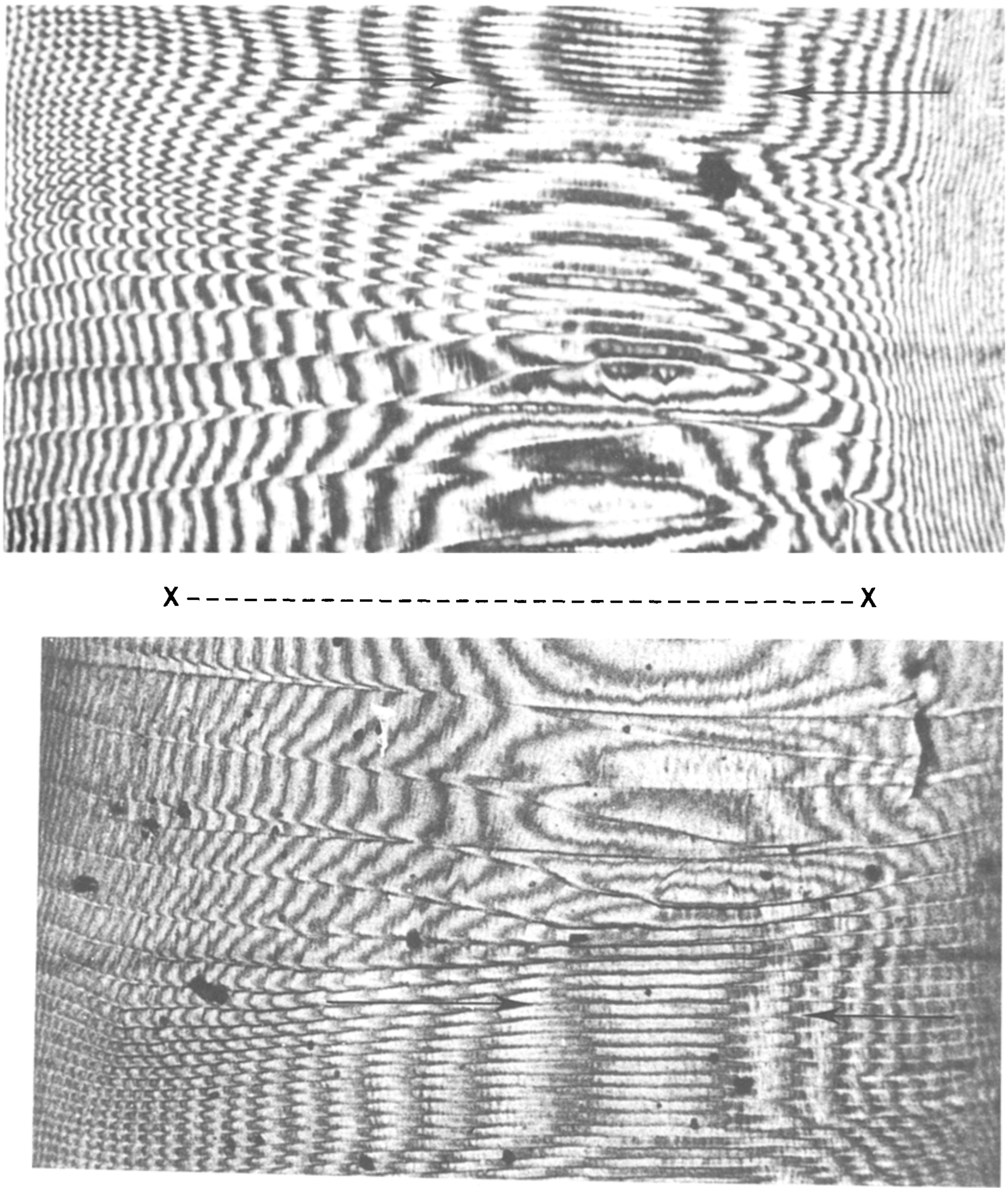
Figure 5 Matching fractures faces of Perspex fatigue specimen. Surfaces coated with aluminium and illuminated to indicate topographical relationships. Magnification × 5.5.

coated fractures gave the best contrast and provided an ideal reflective surface for interferometry. Before embarking on this microscopical examination low power macroscopic observations were made on the coarser undulations of a typical fracture surface. It was necessary to prove that these long range undulations fitted hill to valley in order to unequivocally interpret the fine detail interferometric evidence relating to the fracture striations themselves. Fig. 5 shows that, in fact, as was anticipated, the coarse undulations fit into one another; the hills or ridges of one fracture matching the valleys or grooves on the other. It is necessary, at this point, to explain how these undulations are formed. The fracture shown in Fig. 5 was produced by fatigue crack growth from a crack starter, arrow A, produced by scribing a groove across the flat face of the specimen. This coarse groove caused multiple crack origins and, no doubt, also introduced some residual stresses into the Perspex itself. It is known, and this has been described elsewhere, that offset cracks turn towards one another as they grow within the influence of one another [2]. The result is that the general fatigue crack path is divided to produce the plateaux that are frequently observed. Cracks that start from smaller more acute origins are generally flatter and attain greater perfection.

A Hilger and Watts surface micro-interferometer which uses a remotely situated highly reflective optical flat as the reference plane was used with mercury green illumination. Fig. 6. shows a pair of typical interferograms from two mating fracture surfaces.

The fringes observed on each fracture form contour lines to the topography that are referenced to the remote optical flat. There are experimental difficulties in precisely orienting each fracture, in turn, to the reference flat. This results in differences in the long range contour patterns of the two mating fracture which would otherwise have been mirror images. Nevertheless, this causes no problem to the interpretation as the contour relationships remain valid. If one examines the fringes where they cross striations it is clear that fringes on one slope of a longer range hill or valley are always displaced towards those on the opposite slope, as shown by the arrows in Fig. 6. It should be noted that, in the two interferograms, one of these undulations must be a hill and its mating region on the other fracture a valley, although which is which cannot be directly determined from the interferogram itself. Also represented in Fig. 6 is a region of inflection that will be discussed later. Fig. 7 illustrates in schematic form how these contours must relate to obtain the invariant fringe displacements observed.

The four schematic views (a), (b), (c) and (d) illustrate how two parallel fringes on convex and concave cylindrical surfaces would be displaced at ridges and grooves (representing striations) across those surfaces following paths of equal height, i.e. contour lines. Only the (b) and (c) combinations in Fig. 7 can exhibit fringes that shift towards one another i.e. a groove on a convex surface Fig. 7b and a ridge on a concave surface Fig. 7c. This combination of (b) and (c) can also fit together with respect to both the long range curvature and the ridges and grooves. The other combination that could have fitted in this respect, i.e. a and d, is invariably excluded. It is of interest to speculate on the physical causes for this. Firstly, consider the regions of inflection on fracture surfaces where concave and convex segments join. It is clear that, from the foregoing discussion, a striation must change from a ridge to a groove or a groove to a ridge as it passes the point of inflection, and that



Arrows indicate direction of fringe displacement

Figure 6 Interferograms of matching fracture faces, axis of symmetry or "fold" line, x---x.

the mating surface features must also respond similarly to maintain the conditions of (b) and (c) in Fig. 7. This change is illustrated in Figs. 8 and 9. From Fig. 8 it can be seen that at the inflection zone where the surface groove or ridge practically disappears the crack front has suddenly bowed forward indicating that the absence of a tilt in the crack has increased the effective stress intensity factor. Another characteristic of this zone is that the textural detail of the fracture surface is accentuated. It should be mentioned that the frontal curvature of the crack shown in Fig. 8 gives a

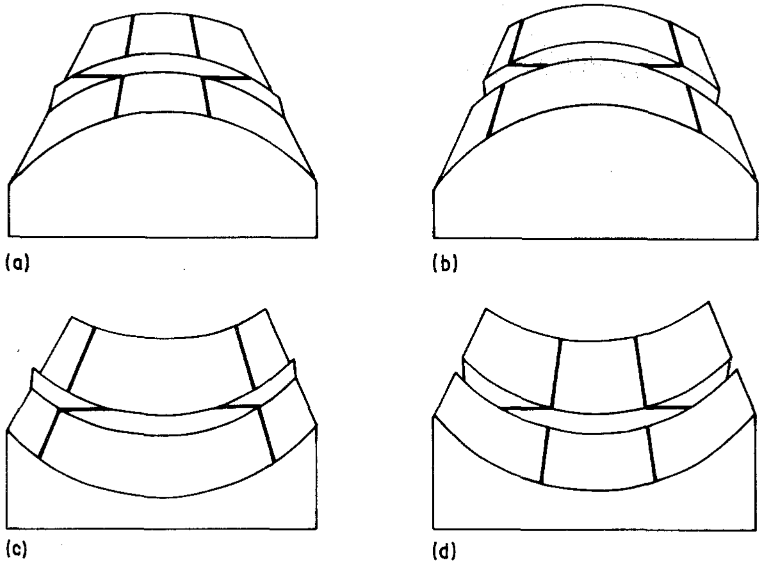


Figure 7 Three-dimensional views showing contour or fringe displacements for ridges and grooves on convex and concave cylindrical surfaces.

somewhat erroneous impression of the position of the inflection zone which in fact is tilted approximately 7° with respect to the plane of the illustration.

Considering now the detailed form of the striations themselves, the displacement between the top of the hill or ridge and the bottom of the valley was about 1 fringe, i.e. half of the wavelength of the light used (mercury green), ~ 546/2 nm. It is of interest to note that this vertical displacement was virtually constant irrespective of the striation width (the crack growth rate). The shapes of the striations are illustrated in Fig. 10.

4. *In situ* crack observations

Although the topography of the mating fracture faces can be measured individually by interferometry, each against a reference plane, the direct viewing of an *in situ* crack can give a better indication of any minor differences between the matching faces by observing differences in the air gap between the faces. Such mismatch or "out of register", if it should exist, will affect crack closure conditions.

The preparation of the test pieces used for this purpose has already been described, and a particular specimen which has provided a number of

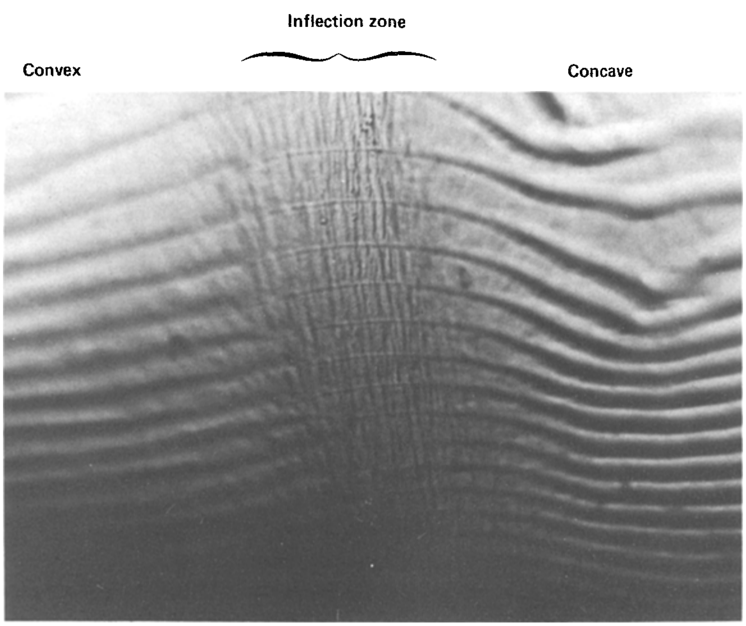


Figure 8 Grooves changing to ridges on crossing inflection zone. Magnification × 620.

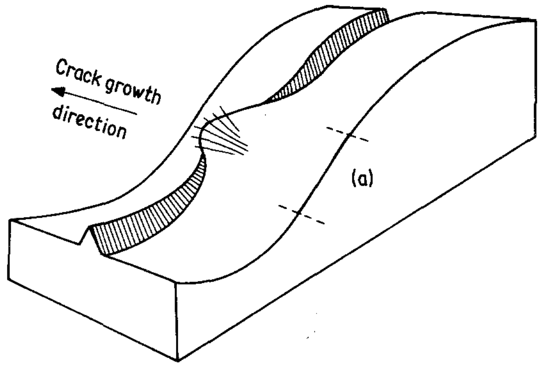


Figure 9 Schematic illustration of striation ridge to groove transition at region of surface curvature inflection. Inflection region (a) (see also Fig. 6).

observations, had been subjected to the fatigue programme shown in Fig. 1 using the 1500/90 Hz combination, and the stress levels $\Delta\sigma = 23.1$ MPa and $\Delta\sigma_{mean} = 3.3$ MPa. It should be pointed out that the striations produced by this programme were, in form, similar to those produced at constant amplitude.

The topographical contrast (for the *in situ* crack) results from interference of the light reflections from the top and bottom crack surfaces. An air gap (the crack) will change its wedge angle with crack opening displacement, and these local changes cause fringe shifts, i.e. colour differences. On a crude scale the fringes are parallel to the crack front and move into the front as the crack is opened. The number of fringes entering the front are a measure of the crack tip opening displacement, and the fringe spacing across the fracture can be used to calculate the air wedge angle. In practice the best miscroscopical resolution is obtained with the thinnest possible crack ligament, but this has been found to be generally too compliant to achieve a K_I high enough to cause an observable individual stage II fatigue crack extension. Thus a plastic hinge forms if a critical bending stress is exceeded. Thicker ligaments can be tolerated, but for the present work where optimum resolution was required to study striation form the thin ligament was preferred, even though it limited the K_I that could be applied.

For the present purpose some simple description of the formation of interference colour fringes is required. It has been stated that interference of the reflected rays from the two fracture surfaces occurs and in this instance we have a material with a refractive index $= \sim 1.5$ with the air gap having an RI = 1.0. For normal incidence reflection the intensity of the reflected light is a maximum at places for which $2h = n\lambda$, where h is the air gap thickness, λ is the wavelength of the reflected light, and $n = 1/2, 3/2, 5/2 \ldots$. Using white light illumination, as one moves through 2nd, 3rd and 4th order, colour mixing diminishes the purity of the fringe colours, although they could still be discerned as separate fringes and counted to about the 8th order. For the present purpose we are only interested in the 1st and 2nd orders, i.e. the fringes

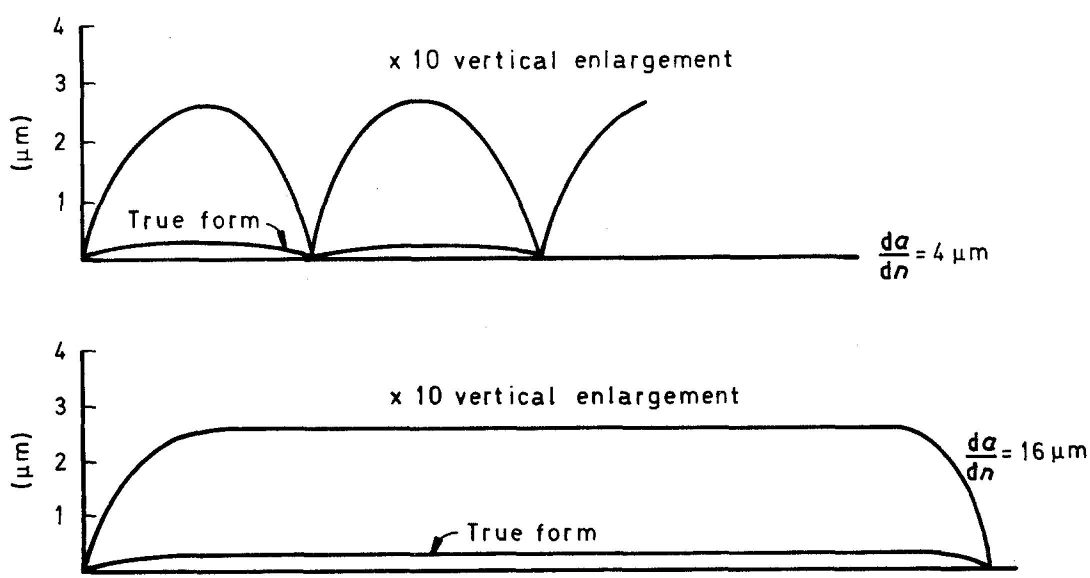


Figure 10 The relative forms of fatigue striations at 4 and 16 μm per cycle.

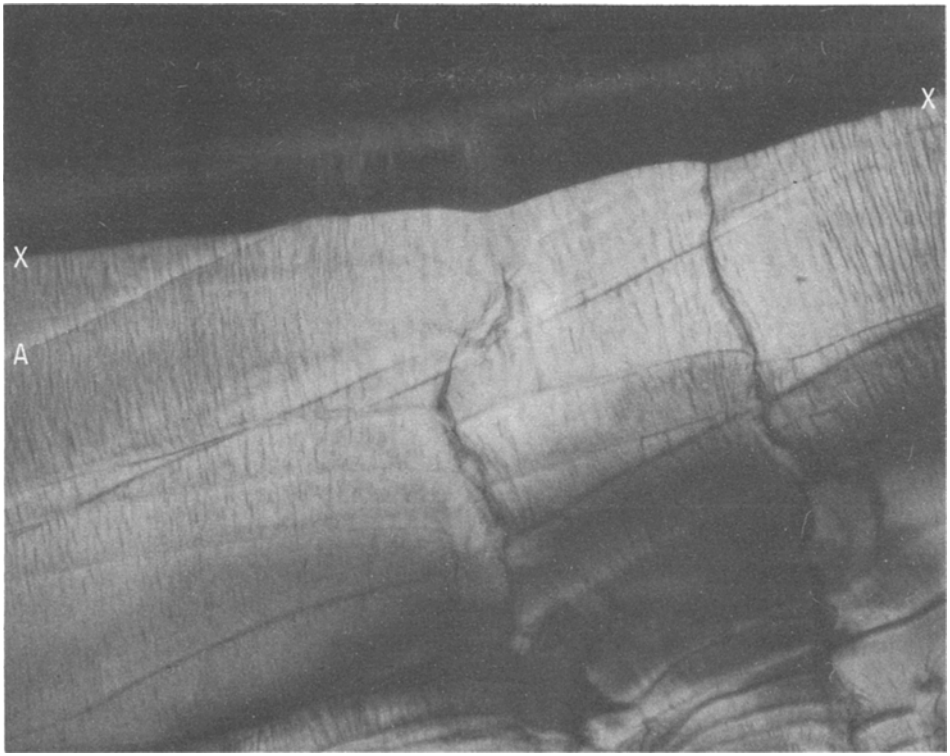


Figure 11 Crack near tip with small opening load. Magnification × 550.

nearest to the crack tip. When the two reflecting faces make contact, i.e. $h \rightarrow 0$, total interference occurs and no light is reflected. (This corresponds to the black spot observed at the centre of Newton's rings produced with a convex lens/optical flat combination.) With a very small air gap we observe firstly reflected white light and as the gap is increased a straw colour appears at an air film thickness of ~ 150 nm.

If one now examines the crack near the tip, firstly with a small opening load, one can see that it is reflective, i.e. it is open to the tip or front, XX in Fig. 11, and the 1st order colours appear at about 0.1 mm from the tip. Fig. 12 shows the same field of view but with a closure load on the crack. The areas of contact now appear dark, i.e. there is no light reflection, although some light reflects where gaps exist at the various topographical features. These very small gaps are associated with striation ridges and grooves, the "cliff" edges radiating in the direction of crack growth, some anomalous lines lying at an angle to the crack front, and indicated at A in Fig. 11, and to a slight degree the textural detail of the fracture itself. The crack could be cycled through the load range and this pattern of closure repeated. A slight increase in the closure load caused a progressive increase in the closure area working back from the crack tip, but the load requirement to continue this increase soon became excessive. Different cracked test pieces appeared to have different degrees of permanent closure when at rest, but such variations might have resulted from the release of internal stress when the specimen was sectioned for observation. The previously mentioned anomalous lines are thought to be spurious crack front striations that develop on the "opening" part of the cycle after welding has occurred on closure.

In the areas of contact (dark) the features previously mentioned appeared in contrasting light, i.e. the gap was such as to enter the straw coloured fringe. This must represent a gap < 150 nm, and probably considerably less than 150 nm. Figs. 13 and 14 show an area of the fracture somewhat further away from the crack tip than that of Figs. 11 and 12. The crack opening is different for the two illustrations, for Fig. 13 being reduced so that the 1st order colours are visible (relating to Fig. 11) and Fig. 14 shows the crack opened somewhat so that the blue fringe has moved from the bottom right hand side of Fig. 13 to the top left

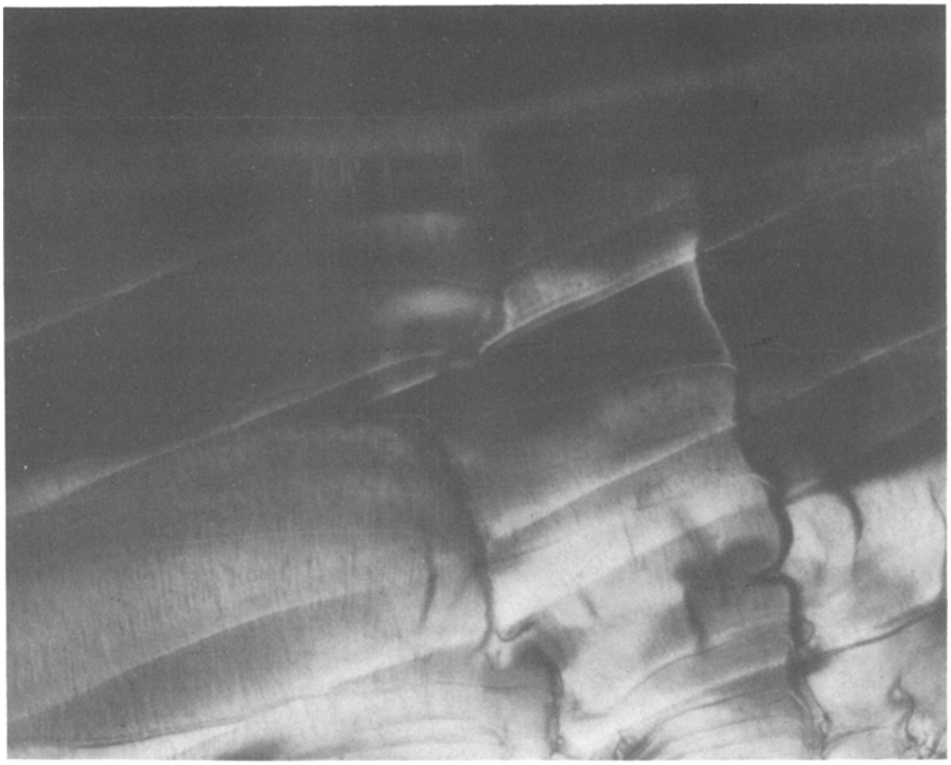


Figure 12 Same view as Fig. 11 but with a closure load on crack. Magnification × 550.

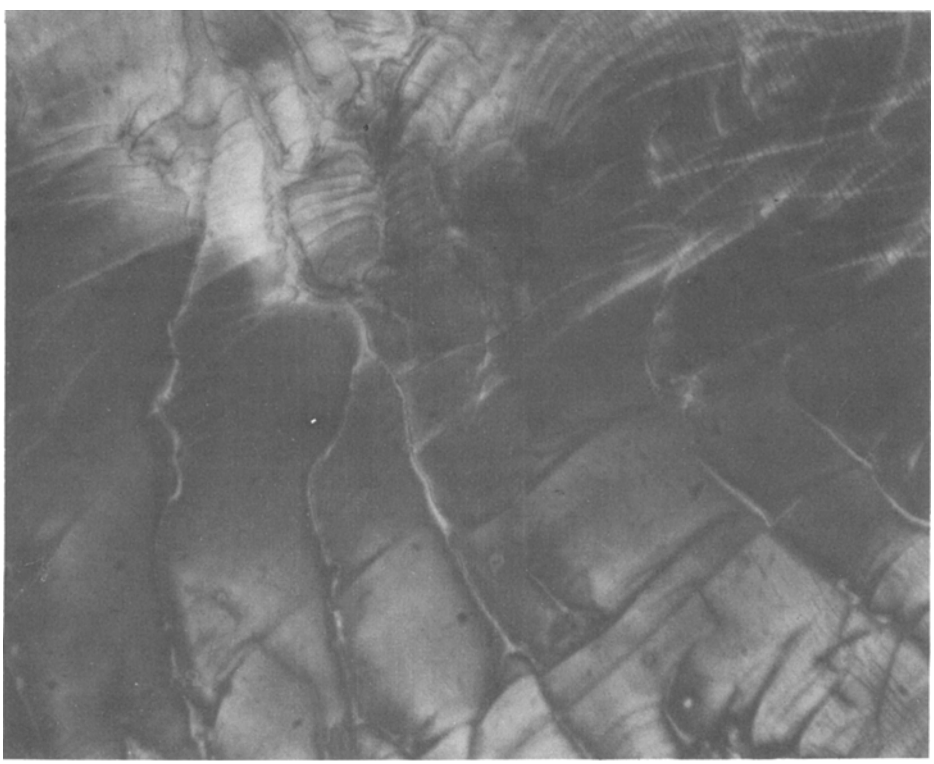


Figure 13 Showing an area of fracture further away from crack tip than in Figs. 11 and 12 and reduced so that 1st order colours are visible. Magnification × 550.

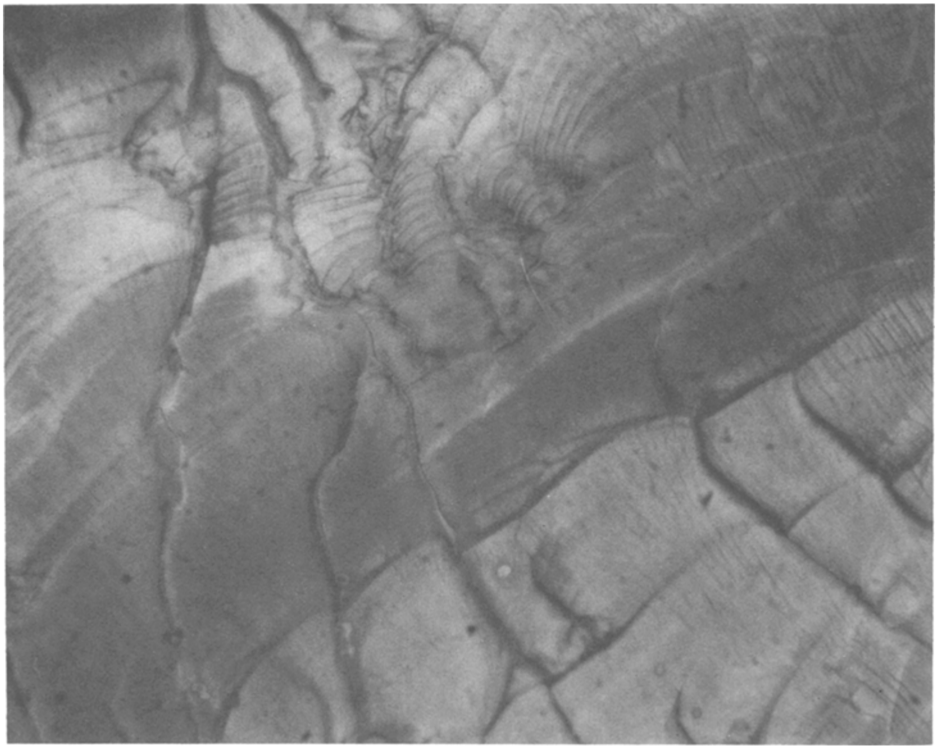


Figure 14 As Fig. 13 but with crack opened somewhat so that the blue fringe is shown. Magnification × 550.

hand side of Fig. 14. In this field of view the fracture striations are well defined and brought into colour contrast. It was seen from inspection of the two illustrations that there were colour shifts across the striation contours, e.g. violet/magenta to yellow/brown. These represent ~ 50 nm differences in air gap.

Referring back to Figs. 11 and 13 a diffuse zone ahead of the crack tip can be observed which is about 30 μm deep and which seems to be brought into contrast by some optical refraction effect. Within this zone "arrow-like" features with colour fringes are also observable. These features appear to correspond to the textural markings exposed on the fracture itself and might represent incipient delamination. The fringes observed within these arrow-like markings seemed permanent, inasmuch as even the application of high crack opening loads caused no movement. Similar features were observed lying just below the fracture face in some areas suggesting that they are not all exploited by the extending crack.

5. Discussion

It thus appears that, although the striations match ridge into groove there are residual differences which are shown in Fig. 15. This could be explained if there was an increasing–decreasing permanent COD arising from some degree of plasticity so that a permanent strain of varying amount was imparted by the crack tip through the stress cycle. Most of the published models for fatigue crack extension are based on this latter premise.

There are, clearly, only two possible causes for the appearance of fracture surface features or perturbations of any sort. Firstly, the growing crack can wander from the general crack plane. This could happen in the elastic sense, i.e. as a purely brittle crack. Secondly, a changing but not necessarily symmetrically disposed plastic zone could give the crack a changing crack tip opening displacement. Clearly crack tip deflection and CTOD could be involved together.

In the present instance the interferometric measurements clearly show that crack tip deflection provides most of the surface displacement although there is a minor contribution, about 20% from what must be irrecoverable deformation.

It is now necessary to consider the two components in more detail. As has been described a convex fracture surface exhibits a striation ridge and a concave surface a groove. Fig. 15a represents

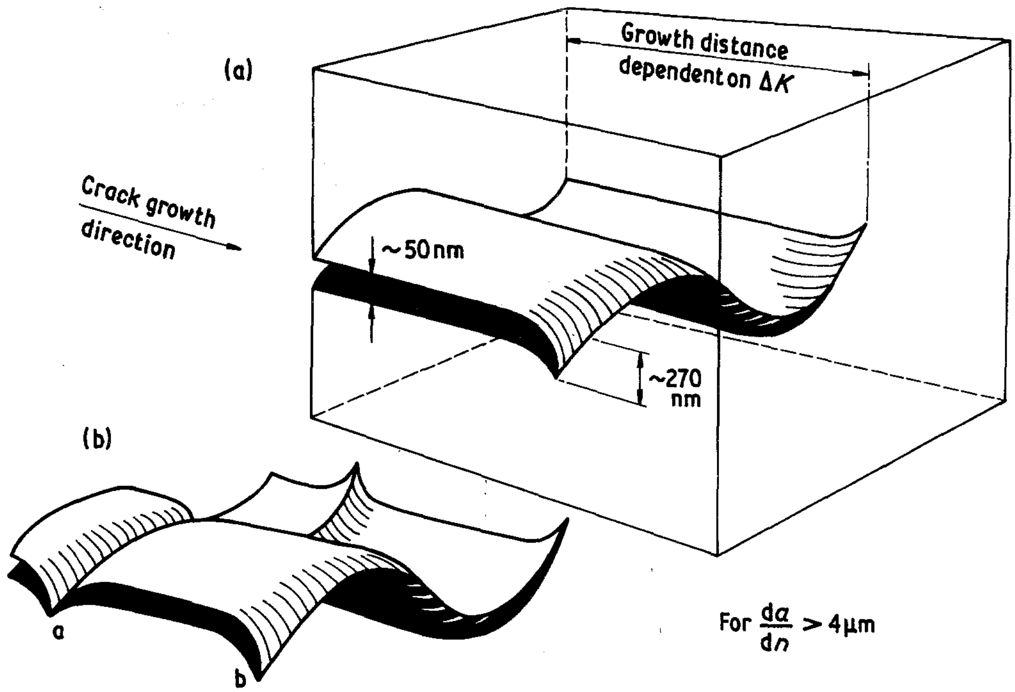


Figure 15 Schematic form of striations with dimensions (a) and repeat striation form (b).

only part of the striation and as the grooves and ridges appear to be cusps the crack must suddenly climb back to the general fracture plane, as shown in Fig. 15b. No attempt has been made to relate this sequence to the stress cycle, but from considerations of earlier work on ascending–descending load programmes, it is though that the cusp point represents the position of the crack at the beginning of the cycle and as the stress is increased to a point at which crack extension starts the crack climbs and turns to lie in the general fracture plane (at high stress most of the fracture during the crack extension is flat). As the stress is reduced to zero the crack now turns away from the general fracture plane.

It can be seen from inspection of mating striations that, between points a and b in Fig. 15b, one fracture face is longer than the other (as measured in the crack growth direction). The striation form, at least in a particular growth rate range, can be considered as circular, and the two different curvatures give ~ 18% difference in the lengths. This differential strain accumulating during the crack growth cycle would cause the crack tip to deflect in the manner observed. Such differential strains would not arise if there was a fully symmetrical state of stress and fracture plane. However, the crack develops long range curvature which upsets this symmetry. It can be seen from Fig. 5 that this long range curvature had hardly diminished at all with extension of the fatigue crack although it quickly disappears in the fast fracture stage. This suggests that the curvature is maintained by the grooves and ridges, i.e. the deviations of the crack tip, and that these in turn depend on the asymmetry derived from the curvature. It has already been shown that where the long range curvature reduces to zero (zone of inflection) the crack tip deviations are practically removed. Through the range of crack extension rates observed, where interferometric measurements could be made, the crack tip deviation from the general plane remained virtually constant. However, if one considers Fig. 10 it would seem that the deviations must get smaller as the striation spacing (crack growth rate) reduces below 4 μm and they are never likely to be large in proportion to the crack extension dimension. Furthermore, at the highest crack growth rates the deviation becomes insignificantly small compared with the planar crack extension.

Up to this point the discussion has been limited to the form of individual striations from single load actions, albeit within the variable R value programme that has been described. If one now considers the whole programme "striation" or

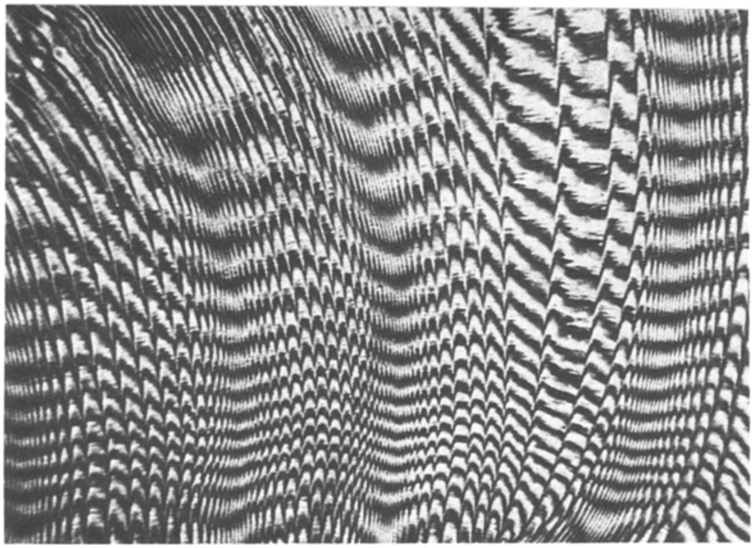


Figure 16 Interferogram showing the long range undulations of the fatigue fracture surface that relate to the lower frequency change in R ratio (refer to Figs. 2 and 3). Magnification × 174.

band in relation to the long range curvature it is seen that it behaves in precisely the same way as the individual loading striations i.e. the cyclic mean stress is imposing deflections of the crack path but now on a larger scale; that of the programme band as has been described elsewhere [3, 4]. At low growth rates when this band is typically of a width where the individual load striations are best resolved, $\sim 4\,\mu$m, it is impossible to distinguish the two types of striation, and only in a crack growth rate range where the individual contributing striations can be resolved can the programme bands be identified. This point has been recognised for some time by those analysing complex load fatigue failures for the purpose of crack life assessment. However, it is now possible to quantify the features that are resolved microscopically, and it can be seen from Fig. 16 that the programme induced crack deviation is of about the same order as that produced by the individual loads, i.e. ~ 270 nm and, furthermore it obeys the same deflection direction relationship. Using the interference fringes from *in situ* cracks the programme band itself shows some slight gaping, as did the individual load striations.

The programme band cycle relates to $\Delta\sigma_m = 3.3$ MPa, i.e. 1/7th of the main $\Delta\sigma$. Referring to Fig. 2 it will be seen that when the mean stress is rising during the programme the 1st four imposed cycles have a larger upward ramp than downward ramp and conversely when the mean stress is reducing the upward ramp is smaller than the downward ramp. It is suggested that it is this bias that produces the programme undulation. Although this mean load change seems small it clearly raises and lowers K_{max} through a significant range with respect to crack growth, as is evident from the considerable differences in crack growth rate between $\sigma_{m(max)}$ and $\sigma_{m(min)}$ that are shown in Fig. 3. This change in da/dn is in fact itself variable and clearly dependent on crack depth, changing from 2.5 : 1 to 6 : 1 with the increase in crack depth over the field of view represented in Figs. 3 and 4. The increasing contribution from R ratio at higher ΔK levels to crack growth rate has been well recognized in metals, where the explanation has been based on an increasing contribution of tensile rupture to the crack extension distance. Although this has always been envisaged as the contribution from discrete crack jumps with an entirely different fracture mode, in the present instance there is no question of crack jumping in the sense that it is observed in metals, i.e. on the sudden extension of small sectors of the crack front under a completely different mode of failure, the crack advance in this case being coherent stable fatigue crack growth that does not differ essentially from that observed at the lower ΔK values. The mean growth rates for groups of cycles are indicated in Fig. 4 together with the mean line, i.e. $da/dN_{(programme)}/d_{(frequency\ ratio)}$, in this case 16. Again, the increasing crack contribution from the high ratio cycles is evident.

The crack growth does, however, differ in one aspect and that is that the crack front at the higher growth rate in the programme becomes more

Figure 17 Programme striations in aluminium alloy 2240-T3. Magnification × 1260.

irregular. However, where fatigue cracks in Perspex are growing at very high rates, approaching the critical failure condition, the fronts are observed to be smooth, and do not contain these irregularities.

Earlier work on aluminium alloys showed that a sequence of constant amplitude loads ascending an increasing mean stress ramp were particularly damaging, producing ~3 times the growth rate expected for those conditions of ΔK and R ratio [4]. In the case in question the ramp followed a period of constant amplitude fatigue at a lower R ratio. In the present work the mean load has been changed sinusoidally and an inspection of Fig. 3 shows virtual symmetry between the "up ramp" and "down ramp" crack growth rates with only, perhaps, the slightest tendency for an increase in growth rate on the "up ramp".

As was stated in the introduction, past work has shown the remarkable similarity between the fatigue fracture features of polymers and metals. The present work has extended the comparison further and shown that striations produced by the individual loads and those coarser markings produced by the sinusoidal programme both result, in the main, from crack tip deviations from the general fracture plane. This had been found for aluminium alloys as well, and Fig. 17 shows a fatigue fracture surface in the commercial aluminium alloy 2024-T3 where, when subjected to the load programme used for the Perspex revealed very similar striations, with the growth rate changing with mean stress in the same manner as for the polymer. Similarly an aluminium alloy containing 6% Zn and 3% Mg in the fully precipitation hardened condition was subjected to this same biharmonic fatigue loading programme. It exhibited the programme markings both on the transgranular areas of fatigue fracture, Fig. 18, and also on the intergranular fatigue facets, Fig. 19. This demonstrates that fatigue crack fronts, even in metals, extend in a steady manner not only on the transgranular paths but also the intergranular ones. When constant amplitude fatigue loads were used no individual striations could be resolved at these low crack growth rates and the intergranular facets, particularly, were featureless. The brittle featureless appearance of low crack growth rate facets has

Figure 18 Transgranular fatigue fracture facets exhibiting programme markings, 1 mm from origin. Magnification × 560.

Figure 19 Intergrangular fatigue fracture facets exhibiting programme markings, 1 mm from origin. X 580.

led to suggestions that, at low stress intensity factors fatigue crack growth was an erratic process where some tensile fracture was contributing to the general crack extension. This belief has been coupled with the idea that some period of damage accumulation with no crack extension preceded the tensile jump, and has also been used to explain the strong σ_{max} dependence of crack growth rate at near threshold conditions. It is now clear that, even for short cracks, the one to one relationship of striations to fatigue load holds, and this is so for both trans and intergranular modes of crack extension. It was shown, earlier, that increasing σ_{max} (the consequence of increasing the R ratio) in Perspex increased the brittle component of the striation, but it did so in a coherent manner along the crack front. It is now clear that this happens also in aluminium alloys, and the conclusion must be that the brittle component is, in fact, the tensile fracture contribution, and therefore controlled by σ_{max}, but in neither case is there any tensile fracture jump that is dissociated from a striation. This is not to say that, on a microscopic scale, the crack extension is constant around the crack front. On the contrary, particularly in metals, there are considerable differences in growth on the various elements that have been described as plateaux. In some places crack growth may be temporarily impeded, but the "catching-up" process is still by fatigue crack growth. The only form of erratic crack growth that has been observed is the "so-called" crack jumping which relates to the K_{IC} of the material and has a crack front geometry aspect, as has been described elsewhere [5].

6. Further discussion and conclusions

The similarity between the fatigue fracture features of polymers and metals and alloys has been accepted for some years and because of this similarity common ground has been sought to explain the phenomenon of the striations that are observed on both classes of material. As with metals the contribution of crack tip plasticity has been emphasized. The present work, and that done earlier on an aluminium alloy, begins to indicate that the features we see in both cases stem from the extension of a very sharp crack tip and the topography is developed, in the main, from the deviation and wandering of the tip rather than by plastic displacement. there is, without doubt, the development of a plastic zone at the crack tip, but even in metals the sharp crack penetrates this in a brittle manner and because of the destruction of lattice perfection, that crack tip behaves as though in a continuum and thereby responds only to the direction of the local tensile stress. Thus crack growth is controlled, overall, by the elastic strain, but the degree of plastic strain at the tip controls the CTOD and the size of the continuum zone through which it penetrates. The resulting degree of acuity on the plastically deformed tip must affect the level of the elastic stress at the tip itself.

It would seem likely that in those reported cases where striations mirror one another on the mating fracture surfaces the crack tip plastic deformation has been so extensive as to override and mask the crack tip deflection. Nevertheless the deflection is likely to be there and to be associated with the brittle crack extension component.

7. Conclusion

1. Crack topography and *in situ* determinations of CTOD can be established by interferometric methods.

2. Direct observation of crack tip closure reveals the degree of fracture register and the distribution of the closure regions.

3. Fatigue crack fronts extend with periodic deviation from the general fracture plane to produce the commonly observed striation.

4. Over a wide range of crack growth rates the maximum deviation from the general plane remained constant, ~ 270 nm.

5. The direction of the deviation or deflection of the crack front is not random, but bears a strict relationship to the long range curvature of the fatigue fracture surface, always deflecting into the convex fracture region and out of the mating concave fracture region thus indicating the importance of the elastic stress in determining growth behaviour.

6. One consequence of Conlusion 5 is that striations appear as ridges on concave surfaces and grooves on convex surfaces.

7. The measured permanent CTOD was about 20% of the deflection distance of the crack tip from the general fracture plane.

8. The strong similarity in the appearance of fatigue fracture features in polymers and metals results from the fact that in stage II metals crack through crack tip plastic zones that present such a highly disturbed lattice that the crack behaves as in a continuum. At very small plastic zone sizes the presence of the surrounding undisturbed lattice may impose some crystallographic preference to the crack path.

9. No tensile fracture jumps divorced from fatigue striations have been observed, on the contrary, striations relate in a 1 to 1 fashion with the load applied, even in the short crack regime.

10. The dependence of fatigue crack growth rate on σ_{max} appears to be related to its effect on the brittle crack extension component of the striation.

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