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How to Observe Short Surface Cracks by Acoustic Microscopy

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ABSTRACT In the search for a technique for the observation of short fatigue cracks, scanning acoustic microscopy offers exceptional potential. The scanning acoustic microscope has now been developed to the stage where it may routinely be operated with a resolution better than a micron. It is generally used in reflection imaging of surfaces, and its unique advantage lies in the ability to show how acoustic waves interact with the elastic properties of the specimen. More specifically, factors that affect the propagation of Rayleigh waves may be observed with great sensitivity. This enables surface cracks to be detected and imaged even when they are only a few microns long and deep because, although they may be much less than a wavelength wide and therefore undetected by waves that are geometrically reflected from the surface, the Rayleigh waves excited within the surface can strike the cracks broadside and therefore be strongly scattered. This leads to greatly enhanced contrast from such cracks in acoustic micrographs, and gives exceptional sensitivity to short cracks at the earliest stages of their formation and growth. The theory of the contrast from cracks has been developed and experimentally verified, and this makes quantitative analysis and measurement possible. The acoustic microscope also reveals grain structure and second phases without any need for etching, so that the relationship between these and the development of cracks may be observed directly.

Introduction

Any study of short crack behaviour depends on sensitive detection and observation of the crack. At present the usual method of measuring short cracks is by a replication technique, which involves taking several plastic replicas at intervals during a test. The replicas are then examined in reverse order, starting with the last, in which the crack should be largest and followed by working backwards through the series. Despite the well-known difficulties of the method, and its relative labour intensiveness, some fundamental results have been obtained using the replica technique (**1**)(**2**).

The detection of short cracks in a carbon steel demonstrates clearly the limitation of the replication technique. In this case the first sign of fatigue damage capable of imprinting the replica is the formation of multiple persistent slip bands (psbs) which form and extend across a ferrite grain (**3**). A small proportion of these psbs contain cracks which initially grow along the psb plane. Within this stage of growth the cracks are indistinguishable from the slip bands until, at a much later stage, the crack begins to propagate into the

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grain. This concealed period of crack growth represents an important part of the lifetime, e.g., between 0.5–0.7 of the total lifetime of a specimen. Much information and understanding of short crack growth could be gained if these small cracks were to be observed and measured with some degree of certainty.

The requirements for examining cracks at the earliest stages of fatigue life are that it must be possible to see cracks that may be only a few microns in length and less than a micron wide. It must be possible to observe them non-destructively, so that afterwards the test may continue and the progress of the same crack followed. It is also desirable to be able to relate the position and development of the crack to the surrounding microstructure.

Scanning acoustic microscopy offers the unique possibility of meeting these requirements directly, without any need for replicas. The principle of scanning acoustic microscopy is becoming increasingly well known (**4**)(**5**). It has not proved possible to make an acoustic imaging system that will give an image of all points on an extended object simultaneously, but it is possible to make an acoustic lens that has excellent focussing properties on its axis. This is achieved by grinding a small spherical cavity in the centre of one face of a disk of sapphire, and growing a zinc oxide transducer on the opposite face. A drop of water is placed between the spherical surface and the specimen, so that acoustic waves generated by the transducer propagate through the sapphire, are refracted at the lens surface, and come to a focus in the water. Because of the very high refractive index involved, geometrical aberrations are negligible, and the size of the focussed spot is limited solely by diffraction. Acoustic microscopes can be operated readily at frequencies up to 2 GHz. The velocity of sound in water is 1.5 μm ns^{-1}, so that for a lens of large numerical aperture the resolution is comparable with that available using light microscopy. Scanning acoustic microscopes are usually operated in reflection for high resolution work, and for this purpose the transducer is excited with a short pulse at the required frequency. When the resulting acoustic pulse is reflected by the specimen it returns again through the same lens and in turn excites an electrical signal on the transducer. The strength of this signal is measured, and this gives a value for the acoustic reflection from that point on the specimen surface. In order to build up an image, the lens is moved in a raster over the surface, and the signal from each point is fed to a corresponding address in a digital framestore that enables the complete image to be displayed on a television monitor. If the specimen has significant variations in surface height, then the image may simply represent the topography of the specimen. Therefore for most metallographic purposes the surface is polished (but not etched), to a smoothness and flatness better than a wavelength, and much more interesting contrast can then be obtained that is unique to acoustic microscopy.

Contrast

The advantages of using acoustic waves for microscopy come from the unique ways in which they can propagate in solids. One such advantage lies in their

ability to penetrate materials that are opaque; it is this ability that is exploited in conventional ultrasonic non-destructive testing. In high resolution scanning acoustic microscopy another advantage is exploited, namely the distinctive origin of the contrast in the interaction of the acoustic waves with the elastic properties of the specimen. In the majority of materials this is dominated by the excitation of surface (or Rayleigh) waves in the specimen. These are waves that contain components of both longitudinal and transverse elastic waves that decay exponentially away from the surface. They can be strongly excited by the acoustic waves arriving from the lens in an acoustic microscope and, by varying the defocus (i.e., the distance, z, between the focal plane of the lens and the surface of the specimen), the contrast in the scanning acoustic microscope can be made very sensitive to factors that affect their propagation (**5**). Such factors may change due to material composition (for example, if the lens is scanning over a second phase) or perturbation of the surface wave velocity by a surface layer, or attenuation. Grain structure, too, can affect the contrast, because the propagation of surface waves on elastically anisotropic materials depends on their crystallographic orientation, and this varies from one grain to another. Grain structure is therefore revealed without any need for etching. Particularly strong contrast can be obtained from surface boundaries and cracks, because the Rayleigh waves can be strongly scattered by these. It is important to realise that this can happen even when the cracks are very thin. This means that even when such cracks are much too fine to be imaged by waves that are simply geometrically reflected from the surface, because they are much narrower than the resolution spot size (whether it be acoustic or optical), they can nevertheless give strong contrast because of the way that they scatter the Rayleigh waves that are generated in the surface and then strike them from the side.

Images

A comparison of optical and acoustic images of fatigue cracks is presented in Fig. 1. The specimen was a plain bearing with an Al–20%Si alloy that was being developed for increased fatigue resistance. The specimen had been subjected to a fatigue test and was being examined for incipient failure. The images shown are of a cross section through the bearing, with a steel substrate on the left and the alloy occupying the main area in the centre of the picture. The magnifications and the areas imaged are identical in the two pictures. It is quite difficult to find all the fatigue cracks in the optical picture, though perhaps with etching they could be revealed more clearly. But in the acoustic image, without the need for any special preparation beyond the initial polishing, it is rather easier to find the cracks. In this example an area of the specimen was chosen where the cracks could be found in the optical image, to faciliate comparison, but the scanning acoustic microscope also gives good contrast from the cracks in cases where they cannot be found at all optically (**6**).

Experience in imaging such cracks with the scanning acoustic microscope suggests that there are two important features of such images that must be

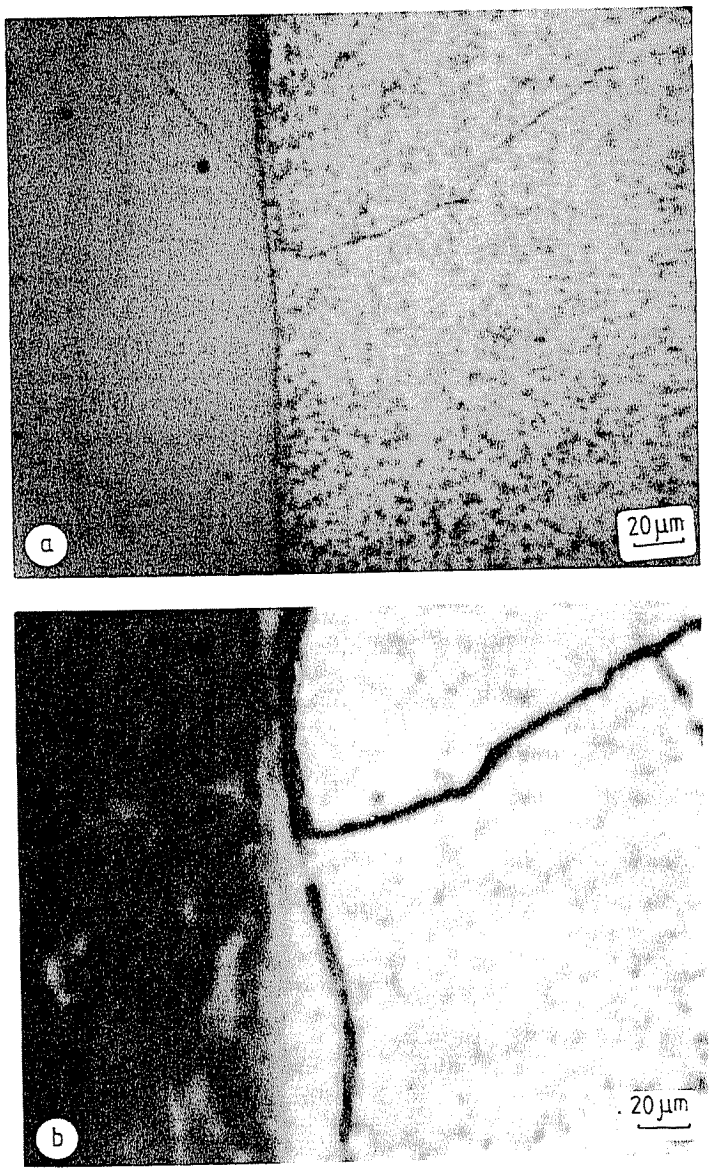

Fig 1 An Al–20%Si plain bearing which has been subjected to fatigue (The material on the left of the picture is a steel substrate): (a) optical micrograph; (b) acoustic micrograph (0.73 GHz)

understood. The first is that the width of the acoustic image of the crack may be much wider than the true width of the mouth of the crack in the specimen. This is apparent from the image of the fatigue crack in Fig. 1, and has been confirmed by SEM studies of cracks in TiN coatings, where cracks that gave strong contrast in the acoustic microscope at 0.73 GHz ($\lambda = 2$ μm) appeared in the SEM to be about 0.1 μm wide. The second is that the contrast that is seen depends sensitively on the amount of defocus employed; indeed, even relatively small changes in the defocus can lead to complete reversal of contrast. These effects have now been accounted for in terms of a theoretical model that has been developed for the images of cracks in the scanning acoustic microscope (**7**), and this has now been extensively verified experimentally (**8**). Although the theory is at present restricted to two-dimensions, it seems to give a good account of the phenomena that are found using a full spherical lens.

One of the tests of a good theory is that it should indicate how to obtain better results. Cracks are not the only features that give contrast in acoustic microscopy: contrast is also obtained from grain structure. If the elastic anisotropy is small, as for example with an aluminium alloy, then such contrast may be relatively weak. But for alloys such as stainless steel the grain contrast can be very strong. Two aspects of this must be distinguished. First there is the contrast between grain-and-grain, due to the differing surface wave propagation within a grain itself (**9**). This contrast is quite different from that due to a crack, because it is extended over an area, and will give different contrast either side of a boundary. Second there is the contrast due to a grain boundary (**6**). This has contributions both from the change in surface-wave impedance across the boundary, which leads to scattering, and from the change in velocity across the boundary, which leads to different Rayleigh angles. The contrast from a grain boundary can look very similar to contrast from a crack, and this can make it difficult to distinguish them. However, at a crack the scattering is in general much stronger than it is at a grain boundary, and the theory indicates that at grain boundaies the effect of scattering is in general much less than the effect of the change in Rayleigh angle. This in turn suggests that the contrast due to grain structure will be greatly reduced by imaging a specimen at positive defocus (i.e., with the specimen further from the lens than the focal plane) rather than in the more usual mode of negative defocus (i.e., closer than the focal plane) (**10**). When the microscope is used in this way the grain boundaries should disappear, and the cracks should be revealed by a pattern of interference fringes either side of them (**11**).

This problem and its solution are illustrated in Fig. 2. The specimen was a section through 316 stainless steel that had been subjected to fatigue loading. Figure 2(a) was taken at 0.37 GHz with $z = -20$ μm, i.e., the surface of the specimen moved five wavelengths towards the lens relative to focus. In this image the grain structure dominates the contrast, and it is not at all easy to find any cracks. Figure 2(b) was taken with $z = +32$ μm, and the picture looks very different. The grain contrast has almost completely disappeared, and there are

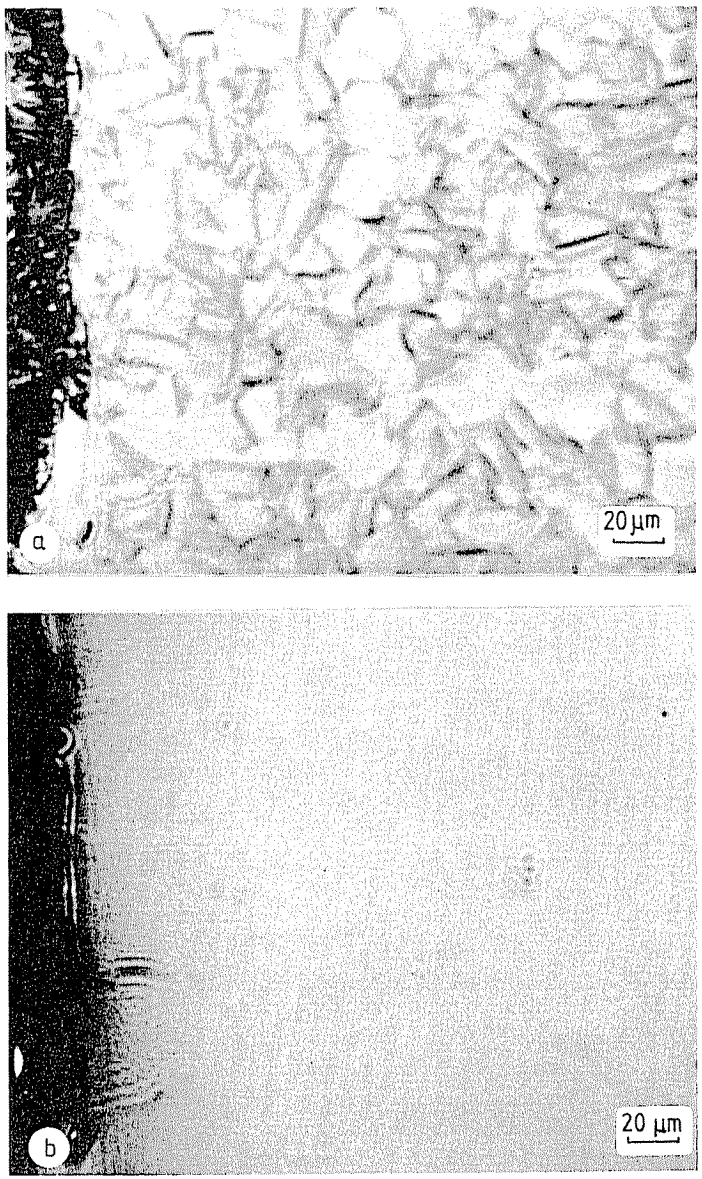

Fig 2 Fatigued 316 stainless steel, acoustic micrographs (0.37 GHz): (a) $z = -27$ μm; (b) $z = +32$ μm

three sets of fringes on the left, indicating three fatigue cracks that grew in from the original surface of the specimen before it was sectioned. Once they have been identified, these cracks can then be seen by looking back at Fig. 2(a), where they are present but camouflaged by the grain structure.

Discussion

Both Figs 1 and 2 present images of sections through specimens that contain fatigue cracks. However, it is equally possible to image the outside surface of a fatigue specimen. The preparation that is necessary is to polish, to ordinary metallographic standards, the area to be studied; this can be done before any fatigue cycling begins. There is no need for any etching because, as shown in Fig. 2a, grain contrast shows up well without it. By using a suitable scanning and fatigue cycling system it should be possible to study the formation and growth of short fatigue cracks in situ during the progress of a fatigue test. From the evidence presented here it will be possible to measure the length of cracks along the surface, and also their relationship to grain structure and second phases. It would also be desirable to be able to measure the depth of a crack into a specimen, without sectioning. That is a harder problem, and probably requires the development of swept frequency techniques to find the wavelength dependence of scattering by the crack.

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