JOURNAL OF MATERIALS SCIENCE 17 (1982) 1413–1419

Measurement of fatigue-induced surface plasticity

W. L. MORRIS, R. V. INMAN, M. R. JAMES
Rockwell International Science Center, Thousand Oaks, CA 91360, USA

A method is presented for measuring at a surface the localized plastic strains induced by fatigue within individual grains. The technique uses mica flakes distributed on a sample surface as reference gauges, relative to which strains in the surface can accurately be determined. An application of the method to the study of fatigue induced microplasticity in an Al 2219-T851 alloy is discussed. On an unfatigued specimen, subjected to applied stresses less than the yield strength, deformation is elastic over gauge lengths comparable with the grain size. After fully-reversed cyclic loading at a peak tensile stress of 75% of the yield strength for 20×10^3 cycles, the larger grains in the alloy exhibit a residual tensile strain after a tensile loading cycle. Neighbouring smaller grains are driven into elastic compression to accommodate this tensile plastic deformation. Peak localized tensile plastic strains may exceed 0.5% at the surface. This technique will be useful in evaluating models of fatigue crack initiation and surface damage accumulation.

1. Introduction

For fatigue at stress amplitudes substantially less than the alloy yield strength, plastic slip near the specimen surface is blocked by the grain boundaries [1, 2]. Crack initiation is attributable to a progressive increase in localized microplasticity within individual grains [3, 4]. Models of this process are commonly divided into two sequential parts. First, the peak tensile plastic strain produced within an individual grain, on each loading cycle, is predicted with an appropriate model of mobile dislocation development. Next, an initiation criterion is employed to relate the probability of crack formation to the type, geometry and mechanical properties of the site of weakness within the grain and to the peak plastic strain of the matrix material within the grain.

Such models can, in principle, be validated by comparing predicted and measured rates of crack initiation. If disposable model parameters limit the sensitivity of such evaluations, the model describing microplasticity can instead be tested by directly measuring the amount of fatigue-induced plastic strain within individual grains. In this paper, we describe a technique to make such measurements which has several advantages over other methods used to obtain similar or related data.

In essence, we use a small ($\sim 20\,\mu m$) flake of mica located within a grain of interest as a reference gauge and measure strains in the surface relative to this gauge in a scanning electron microscope (SEM). This method is more accurate for measuring small plastic strains than selected-area backscatter electron channelling [5] or stereo-imaging [6], which are best suited for the measurement of plastic strains larger than 0.5%. The method also avoids the interperative problem encountered with channelling, where one must calibrate the measurement using uniaxially strained specimens. The sensitivity with which deformation at the surface can be measured with a reference gauge appears to be comparable to that obtained by Pangborn *et al.* [7] with their use of X-ray double-crystal diffractometry, but the reference gauge data are obtained directly in terms of local strain and are therefore simpler to relate to current initiation models. The reference gauge method permits crack initiation models to be evaluated by measuring peak strains in preselected

0022–2461/82/051413–07$03.34/0

grains containing potential initiation sites of interest.

The capabilities and limitations of the technique are described. Results are presented for an Al 2219-T851 alloy for which progressive fatigue at stress amplitudes below the yield strength produces increasing plastic strain at the surface, with preference for development of the largest plastic strain in the larger grains. Elastic strains in the smaller grains at the surface are shown to be driven into compression during unloading to accommodate these changes.

2. The strain measurement technique

The strain measurement technique, illustrated in Fig. 1, uses as a reference gauge a flat particle of mica lying on the specimen surface within a grain. We measure the distance, L, between points A and B (in Fig. 1) on the substrate for zero externally-applied stress and then, in the microscope, apply the tensile load cycle to the surface, returning to zero applied stress. The new distance, L', between A and B is then determined and the residual cyclic strain, ϵ, parallel to the principal stress axis is defined as

$$\epsilon = \Delta L/L = (L'-L)/L. \quad (1)$$

The measurement thus determines the width of the stress–strain hysteresis loop at zero external load. If ϵ is non-zero, local yielding has taken place, although not necessarily within the grain of measurement. ϵ is the sum of the local plastic strain and the internal elastic strain necessary to accommodate yielding in surrounding grains.

The mica flake provides a reference which substantially increases the accuracy of the measurement of ΔL. High-resolution SEM micrographs are obtained which show both the substrate and the mica edge (Fig. 2). Such micrographs taken before and after loading at each point A and B are then observed with a stereosccopic viewer. Small relative displacement in position between the mica and substrate in the before and after loading pairs causes the edge of the mica to appear to lie at a different depth than the substrate. Displacement of the substrate relative to the mica can accurately be determined with a floating point device such as in common use in aerial mapping (Fig. 3). The apparent height of the arrow above the substrate is a function of the true distance between the arrows under the viewer. The observer adjusts the traveling arrow so that it first appears to lie at the same depth as the substrate, and then at the same depth as the mica, and the linear displacement of the traveling arrow is recorded using a micrometer. ΔL is the sum of the linear displacements at points A and B (see Fig. 1). The human eye uses the entire image to make apparent height decisions and the resulting sensitivity in measurement of displacement can be substantially better than that obtained from direct measurements off the micrographs. With good micrographs the statistical scatter from repeated measurements in displacement obtained with our equipment is ± 0.005 cm. Using micro-

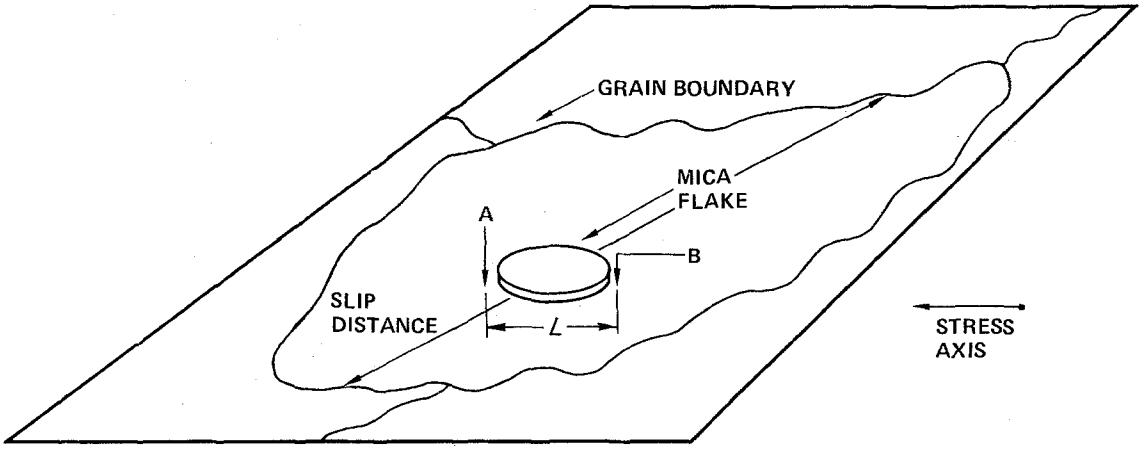

Figure 1 The reference gauge technique. The mica flake lies within a grain and is not bonded to the substrate. Strain over the gauge-length, L is determined by measuring the locations of points A and B, before and after loading, relative to the mica. The maximum slip distance, (plotted in Fig. 5) is the larger of the two grain widths through the mica flake, measured at a 45° angle to the principal stress axis.

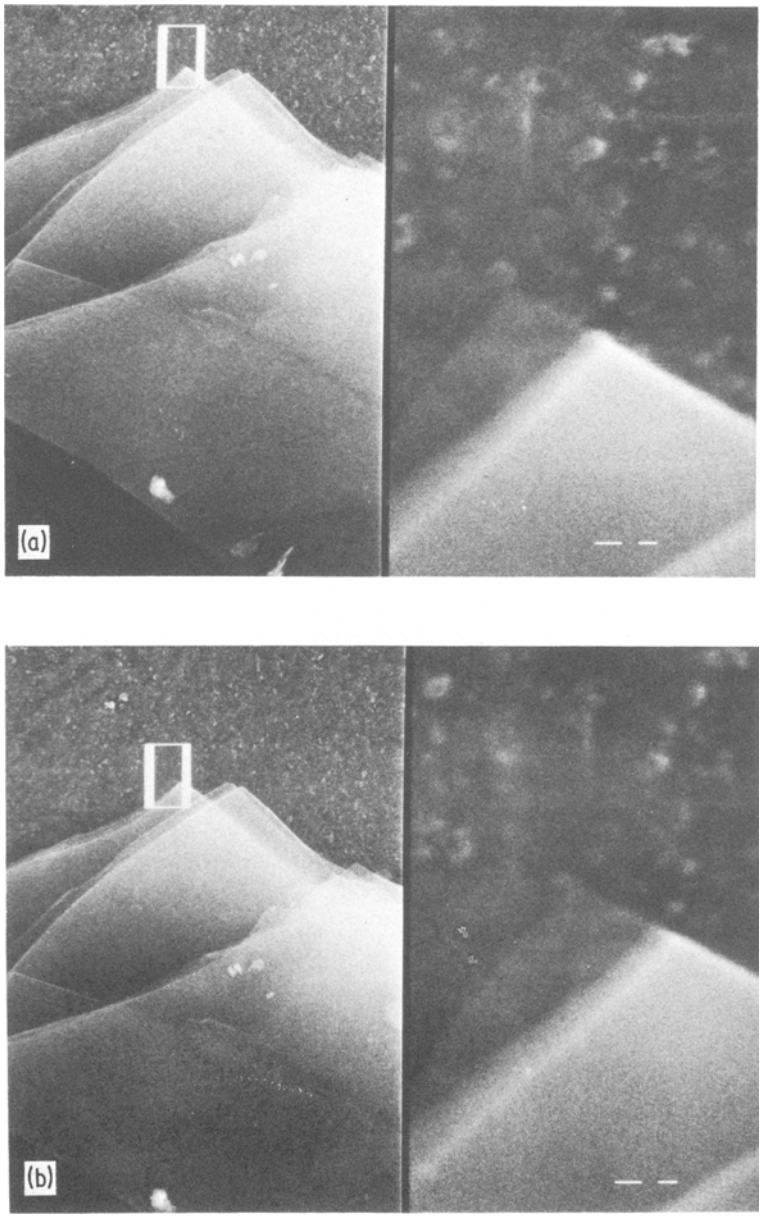

Figure 2 Typical micrographs of an area near the edge of a mica flake: (a) before loading and (b) after loading. Dual magnification is used to facilitate relocation of the measurement point after loading, with the low magnification half at × 2650 and the high magnification half at × 26500. The mica edge is to the left in all views. The substrate in (b) is 58.0 nm further to the right of the mica than in (a). The shift is much easier to see when the pair of micrographs are viewed stereoscopically.

graphs taken at a magnification of 35×10^3, ΔL can be measured to ± 2 nm. The resulting sensitivity in strain is, of course, a function of the gauge length, L. Strains of (0.010 ± 0.005)% can be measured within individual grains with optimum microscope resolution.

There are several tricks to make this technique work well. Mica flakes in a size range of 15 to 60 μm can be prepared using a rotating-blade glass cutter to crush mica in a mortar. The best flakes are very thin and flat so that they maintain close contact with the substrate, and thus both the mica edge and the substrate can be brought into simultaneous focus in the SEM. An added advantage of thin, flat mica flakes is that they are less likely to tilt relative to the substrate as a result of the loading. Such a movement would introduce error into the strain measurement. In our experience, tilting occurs for about one particle out of 20 and is easily recognized, since different points on the mica edge appear to lie at different heights. There is no accurate way to correct for tilting and data from such particles are not used. It is not necessary to coat the mica

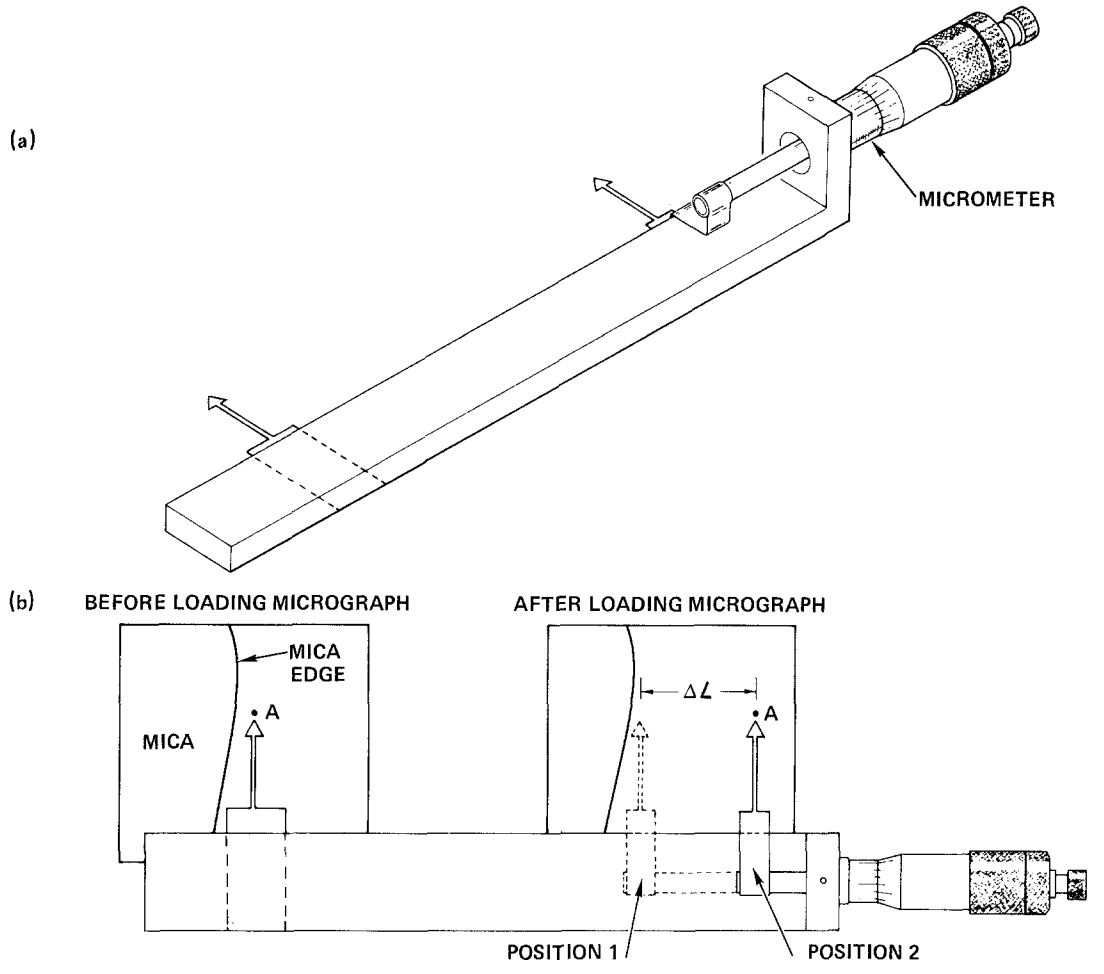

Figure 3 A floating point device as pictured in (a) is used to measure displacement of the substrate relative to the mica. The pointer on the left is fixed while that on the right moves laterally by turning the micrometer.The observer places the instrument over the two micrographs (before and after loading at the same position, either A or B) and using a stereoscopic viewer, adjusts the traveling pointer so that it first appears to lie at the height of the substrate. This is illustrated in (b) as Position 2 (Point A on the substrate has moved during the loading cycle). The traveling pointer is then adjusted so that it appears to lie at the same height as the mica (Position 1). The linear displacement read on the micrometer is ΔL at Point A. Accuracy in the measurement of ΔL is substantially improved by stereoscopic viewing.

particles to prevent charging in the SEM, but stigmation of the electron beam in the vicinity of a particle measurement site is advisable.

3. Experimental approach

Tapered cantilever flexural fatigue specimens were prepared from rolled plate stock of Al 2219-T851, with the specimen surface in the rolling plane and with the principal stress axis parallel to the rolling direction. The mean grain-size in the rolling direction was 80 μm and the mean grain-size in the long transverse direction was 60 μm. The alloy yield strength was 360 MPa. The specimens were machined with progressively decreasing cutting depths to minimize residual surface stresses. They were mechanically polished ending with 0.05 μm Al_2O_3 powder and chemically-etched to reveal the grain boundaries. Residual stress measurements using X-ray diffraction indicated all samples were within ± 20 MPa of being stress-free.

The specimens were fatigued in dry air in flexure, using stroke control and fully-reversed loading ($R = -1$), and were then lightly dusted with mica flakes. Flakes within grains of interest were located by optical microscopy (× 250). These were only chosen for use as a reference if they appeared to lie flat on the substrate, with

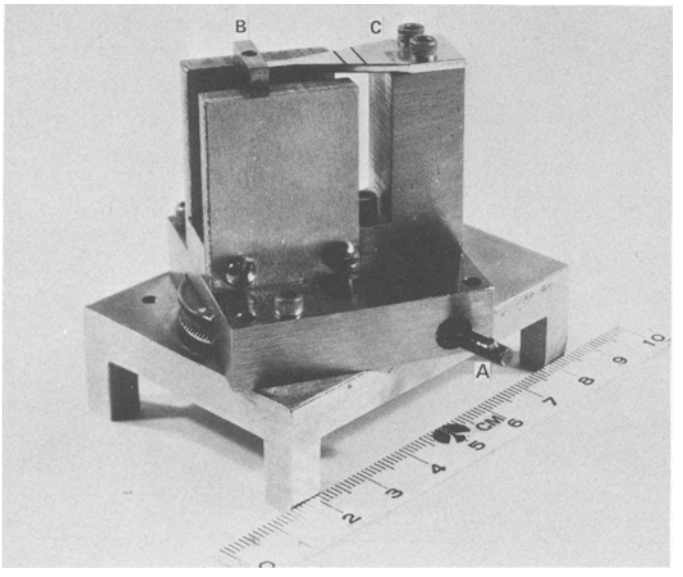

Figure 4 Jig used to load a flexural fatigue specimen in the SEM. A reversing drill is connected through a rotary drive-coupling into the microscope to the shaft (A) which moves the load bar (B) up or down along guide shafts via a worm gear. Surface stress on the specimen (C) is calibrated to the deflection of (B), which is monitored by counting drill revolutions (typically 450 turns to yield). Data are taken only from grains within the region defined by the parallel lines.

at least 15 μm of gauge length parallel to the stress axis within a grain. A map of the location of each was made using an X–Y stage on the optical microscope which was then transferred to another map compatible with the X–Y stage of the SEM. This faciliated the rapid location of the chosen measurement sites in the SEM. The grain size at a measurement site was determined from the optical micrographs.

Flexural loading through the tensile half-loading cycle was performed in the SEM using the jig shown in Fig. 4. A reversing drill connected to a rotary drive-coupling into the SEM was used to operate the jig. Measurements were made at zero load to avoid tilting of the surface which could introduce error. To obtain the proper hysteresis loop, unloading in air after fatigue was completed through the compressive half-cycle.

4. Results and discussion

Measured values of residual cyclic strain, ϵ, are given in Fig. 5 for Al 2219-T851 alloy, plotted as a function of the maximum slip distance to the grain boundaries measured through the centre of the measurement site. As illustrated in Fig. 1, the maximum slip distance within the grain is measured at a 45° angle to the principal stress axis. Data are presented for two cases.

The open circles show data for a specimen cycled through a single half-loading cycle with a peak surface stress of σ_{max} = 270 MPa (0.75 σ_{yield}). The residual strains for all grain sizes are indistinguishable from zero, indicating that the material is purely elastic for the first tensile loading cycle. We have found that, at least initially, values of ϵ in the larger grains progressively increase with fatigue. Tens of thousands of cycles are required to produce maximum values of ϵ in the largest grains in the alloy at $\sigma_{max} = 270$ MPa.

Data after 20×10^3 cycles of fatigue in dry air are given by the solid circles in Fig. 5. These clearly show a preference for ϵ to be largest in the larger grains, consistent with models proposed by Chang *et al.* [8] and Tanaka and Mura [4], describing fatigue crack initiation. The strains are quite large and must require that substantial redistribution of the local stresses within the neighbouring grains occur in order to accommodate the fatigue-induced microplasticity. For instance, small grains in which ϵ is negative are found to lie at the boundaries of large grains in which ϵ is positive. Apparently, a large grain yields in tension and, on unloading, imposes as elastic compression on itself and neighbouring grains. Undoubtably, the true tensile plastic strain in the larger grains was larger than the measured ϵ value.

The expected error in the measurement of ϵ is small compared to the observed scatter, which can be attributed to such factors as the variation of the crystallographic orientation of the grain, the depth of the sub-surface grain boundary, and the location of the measurement site within the grain. If we allow for a possible 0.2 % compressive elastic

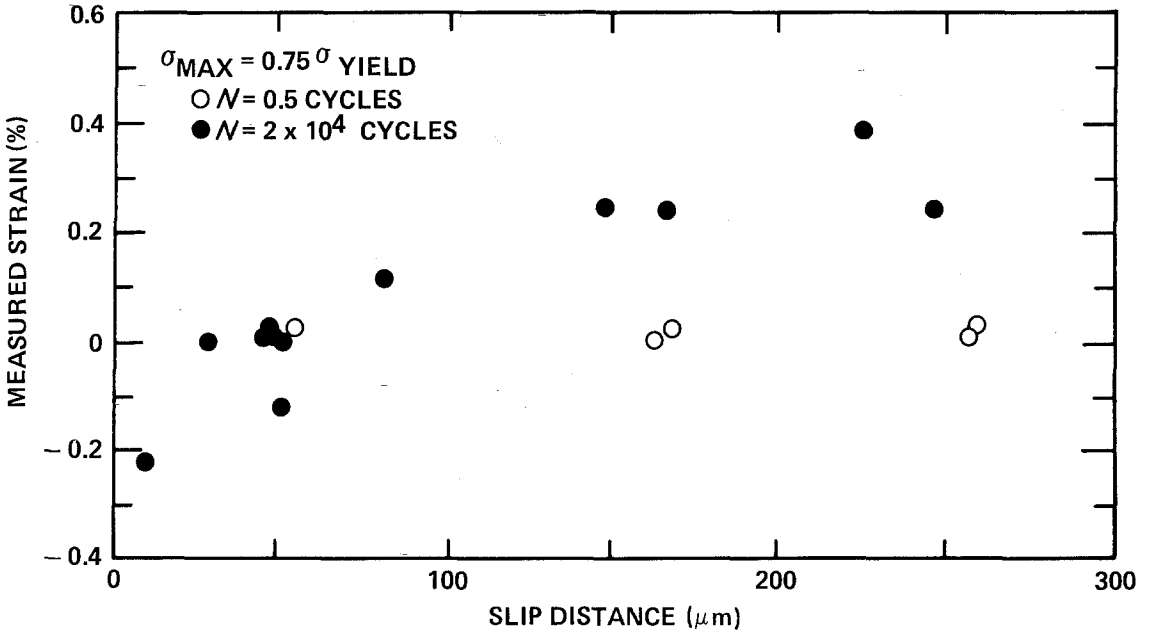

Figure 5 Measured residual cyclic strain is plotted against the maximum slip distance through the measurement site for two periods of fatigue.

strain reacting on the large grains, it appears likely that the peak localized tensile plastic strain in the surface may exceed 0.5% after 20×10^3 cycles. Thus, it is not suprising that surface constituent particles in Al 2219-T851 alloy fracture in the larger grains in substantial numbers after such fatigue [3, 9].

We believe these changes are localized near the surface. No opening of the stress–strain hysteresis loop was observed in axial fatigue of smooth bar specimens of Al 2219-T851 cycled at σ_{max} = 270 MPa, verifying that bulk plastic deformation did not take place. The measurement of residual surface strains thus provides a unique opportunity to study fatigue-induced changes in surface ductility, and a comprehensive evaluation of these processes in aluminium and its relationship to crack initiation is in progress.

The possibility of applying the reference gauge technique to measure local modulus and the local flow stress is also apparent. These measurements require determination of strain under load which, on flexural loading samples, causes the surface to tilt. As a result, the measured values of strain will be scattered about the true strain due to a change in perspective of the mica relative to the substrate, as mentioned previously. If the particle is of a nearly uniform thickness, this error will be small. A more direct way to eliminate the perspective problem would be to use an axial loading stage.

5. Summary

An experimental technique has been described which enables measurement of the local residual strain within individual surface grains. Thin, flat mica flakes have been used as reference gauges, and strains in the surface induced during a tensile loading cycle have been determined by comparison with the mica. For loading at a peak stress less than the yield strength, strains in an Al 2219-T851 alloy were found to be elastic for the first tensile cycle. After fatigue, the large grains exhibit a net residual tensile strain, for a half-tensile-loading-cycle, which is composed of tensile plastic and compressive elastic components. The simplicity and accuracy of this technique make it ideal for future studies regarding the process of localized deformation and crack initiation.

Acknowledgements

The experimental measurement technique was developed using Rockwell International Internal Research and Development funds. The residual microplastic strain measurements were made as a part of a programme to model the effect of humidity on surface ductility, supported by the Office of Naval Research under contract No. N00014-79-C-0334.

References

1. W. L. MORRIS, M. R. JAMES and O. BUCK, *Met. Trans.* **12A** (1981) 57.
2. S. TAIRA, K. TANAKA and Y. NAKAI, *Mech. Res. Comm.* **5** (1978) 375.
3. W. L. MORRIS and M. R. JAMES, *Met. Trans.* **11A** (1980) 850.
4. K. TANAKA and T. MURA, *Met. Trans.* **13A** (1982) 177.
5. D. L. DAVIDSON and J. LANKFORD, *Trans. ASME J. Eng. Mater. Tech.* **98H** (1976) 24.
6. D. R. WILLIAMS, D. L. DAVIDSON and J. LANKFORD, *Expt. Mech.* **20** (1980) 134.
7. R. N. PANGBORN, S. WEISSMAN and I. R. KRAMER, *Met. Trans.* **12A** (1981) 109.
8. R. CHANG, W. L. MORRIS and O. BUCK, *Scripta Met.* **13** (1979) 191.
9. M. R. JAMES and W. L. MORRIS, unpublished work.

Received 21 September
and accepted 9 October 1981