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# CRYSTALLOGRAPHIC FATIGUE CRACK GROWTH IN Al-4%Cu AGED TO CONTAIN GP ZONES

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## INTRODUCTION

There have been various reports in the literature of cleavage or cleavage-like fatigue crack growth in a range of aluminium alloys [1,2]. Very recently such behaviour has been noted in Al-4%Cu under a variety of conditions of heat treatment [3-5]. It has been found that in the presence of varying amounts of $\theta''$, $\theta'$ and $\theta$ particles, crystallographic crack growth occurs along (100) planes [2]. However in material aged to contain GP1 zones, where this type of failure has been observed the planes of propagation have been identified, at least for monocrystals, as (111) [4] or (111) and (112) [5]. This present study was initiated on polycrystalline Al-4%Cu in various stages of ageing to investigate the conditions under which such faceting occurs.

## EXPERIMENTAL PROCEDURE

Single edge notch, pin-loaded specimens were cut from 3 mm thick sheet of composition Al-4.2 wt%Cu (Si <0.01%, others <0.001% each) obtained from Alcan International Ltd. They were homogenized at 540°C for three days which gave a grain size in the range 0.1-1 mm. Different batches were then:

1) Slow cooled in the furnace to give the overaged structure of large $\theta$ particles (5-10$\mu$, with an approximate spacing of 50$\mu$).
2) Quenched then aged at 190°C for 20 hrs to give the peak aged structure with predominantly $\theta''$ and $\theta'$ particles.
3) Quenched then aged at 130°C for 18 hrs to give a fully developed GP1 structure.
4) Tested as quenched - these were termed "solid solution" specimens but room temperature ageing would have given them a GP1 structure, although less well developed than in the specimens aged at 130°C.

In general, specimens were notched to a depth of 2 mm, a larger 5 mm notch being used for some GP1 specimens. Fatigue loading was carried out on a Schenck Fatigue Testing Machine under air in a tension-zero mode at 30 Hz. The fracture surfaces were studied in a scanning electron microscope, and facet orientation was determined by a back reflection Laue x-ray diffraction method. The facets were aligned visually perpendicular to the x-ray direction, large facets being chosen to minimize the error involved. A series of repeated observations on the same facet (with the facet realigned between each observation) yielded a consistent orientation for the facet plane, with a standard deviation of 2.3°.

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## RESULTS

On a macroscopic level the fracture surfaces near the notch were generally perpendicular to the applied load (characteristic of plane strain) tilting over to give 45° slant cracking in the later stages of growth (characteristic of plane stress). In peak hardened and overaged specimens, fatigue failure was largely intergranular with extensive dimpling. No facets were found on the fracture surfaces. However, all but the most highly loaded GP1 specimens exhibited large, regular facets. Diagram 1 shows the S-N curves for these specimens. It is seen that facet formation is associated with low loads and long life, i.e. slow crack propagation. Under these conditions the naturally aged specimens fared rather better than those aged at 130°C indicating that a finer distribution of zones inhibits this type of fatigue crack growth. The effect of the notch becomes less important at lower loads.

The crystallographic nature of the facets is shown clearly in the SEM fractographs (Figures 1-3). The facets began to appear soon after crack initiation, close to the notch, and seemed to have no consistent angular relationship to the direction of applied stress; some facets deviated from the normal fracture path by up to 80°, i.e. were almost parallel to the loading direction. The proportion of total fracture area taken up by facets varied inversely with load, being as high as 80% for the lowest loads. In each specimen, the faceted region gave way eventually to a region of ductile striations (Figure 4). Here the fracture surface became perpendicular to the applied stress. Near the region of final yield, cracking was intergranular and was accompanied by heavy deformation on the lateral sides of the specimen.

The wealth of large, clean facets allowed a reasonably large sample of orientation measurements to be made by the back reflection Laue technique. The results are shown in Diagram 2. The maximum permissible experimental error can be taken as four times the measured standard deviation, i.e. 9.2°. Facets with orientations within the range of deviation from the (111) pole can be assumed to be (111) planes; facets falling outside this range are clearly not (111) planes. On this basis, some two-thirds of the facets studied were found to be of (111) orientation. Of the remainder, one facet was close to (100), one close to (112) and two were close to (123). The rest were of more complex orientation. Laue patterns from facets formed at an early stage of cracking were composed generally of undistorted spots, while facets from later stages of cracking tended to display asterism, implying a build-up of plastic deformation as cracking proceeded. Such deformation was clearly seen in the SEM on these later facets.

## DISCUSSION

Robinson and Beevers [6] have suggested that grain orientation control of crack propagation ceases when the zone of plasticity at the crack tip becomes of the order of the grain size. In the present specimens, the facets are a clear example of grain orientation control which gives way, as plastic deformation at the crack tip increases, to a region of ductile striations where no individual grains can be distinguished. The peak aged specimens showed a similar effect; early parts of the fracture surface had a 'furrowed' structure which changed direction sharply from grain to grain, before cracking became intergranular.

Bouchet, De Fouquet and Aguillon [5] have attributed the largely intergranular failure of material containing $\theta''$ to a weakening of the grain boundaries by a heavy concentration of large $\theta''$ particles. Such localized precipitation and its associated precipitate-free zones would explain the dimpled appearance of the intergranular regions in the present study. The presence of dimples or cusps, which were seen in both the peak-aged and overaged specimens, indicates ductile yielding around large second phase particles. In the overaged specimens the larger precipitates could be seen in the bottom of the dimples in the SEM. Further study is envisaged of underaged material containing $\theta''$ and $\theta'$, to see if the transgranular (100) faceting reported by Garrett and Knott [3] can be obtained in the presence of stronger grain boundaries.

The extremely regular, parallel surface markings on the facets (Figures 1 and 2) appear to be fatigue striations formed with a minimum of plastic deformation. A crack progressing at right angles to the applied load would open up in a Mode I fashion (normal tensile opening). However few of the facets lie in this normal plane so varying amounts of shear would be introduced. For example the facets shown in Figure 1 are inclined at about 70° to the tensile axis so the parallel striations indicate a predominantly Mode II (sliding) type of propagation. Mode III (tearing) shear would result in curved striations such as those shown on one of the facets in Figure 2.

The preferred plane of crack propagation appears to be (111) although clearly other planes are possible under certain conditions. A striking example is shown in Figure 1 where the crack front moving along nearly coplanar (111) planes in neighbouring grains (A and C) found it easier to move along a conveniently oriented (100) plane in the sandwiched grain (B) than to deviate from its propagating plane onto another (111). This suggests that the surface energy difference between the two types of plane is fairly small, as it appears to be in the case of pure aluminium (see discussions in references [3] and [5]). The spacing of the finest striations on these facets is about $1\mu$ corresponding to a cracking velocity of $1\mu$/cycle. This is beyond the limit of environmental influence ($0.1\mu$/cycle) as determined by Garrett and Knott [3]. Since the (100) facets reported by them also persisted beyond this crack velocity, the choice of propagation plane cannot be attributed to alteration of the surface energies by diffusing atmospheric molecules. Thus, Garrett and Knott's observation of a different preferred plane may have resulted from the different microstructures present in their specimens.

## ACKNOWLEDGEMENTS

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Figure 1  Scanning Electron Micrograph of GP1 Zone Specimen, Showing Coplanar Facets (60x)

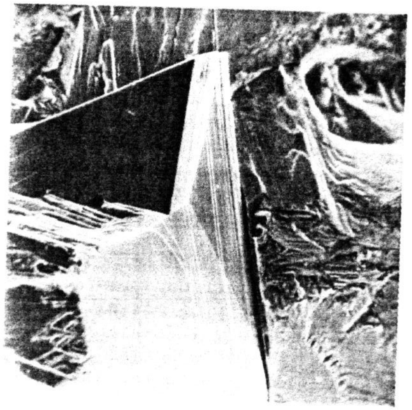

Figure 2  Scanning Electron Micrograph of GP1 Zone Specimen, Showing Faceted Feature on the Fracture Surface (130x)

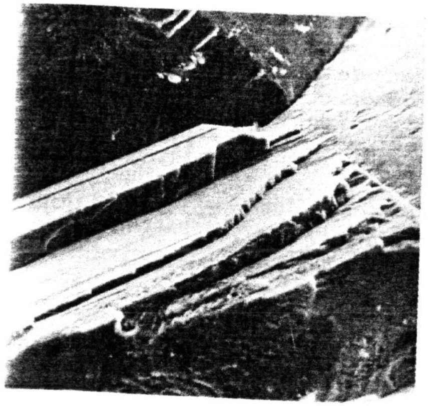

Figure 3  Scanning Electron Micrograph of GP1 Zone Specimen, Showing Parallel Facets Separated by Steps (250x)

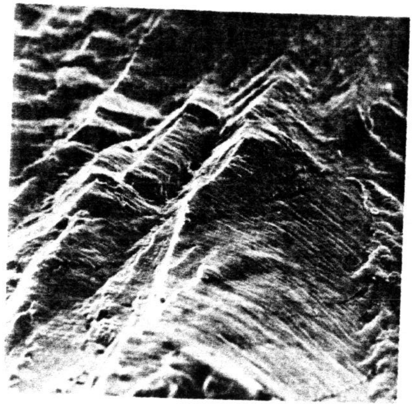

Figure 4  Scanning Electron Micrograph of GP1 Zone Specimen, Showing Typical Ductile Striations During Later Stages of Cracking (135x)

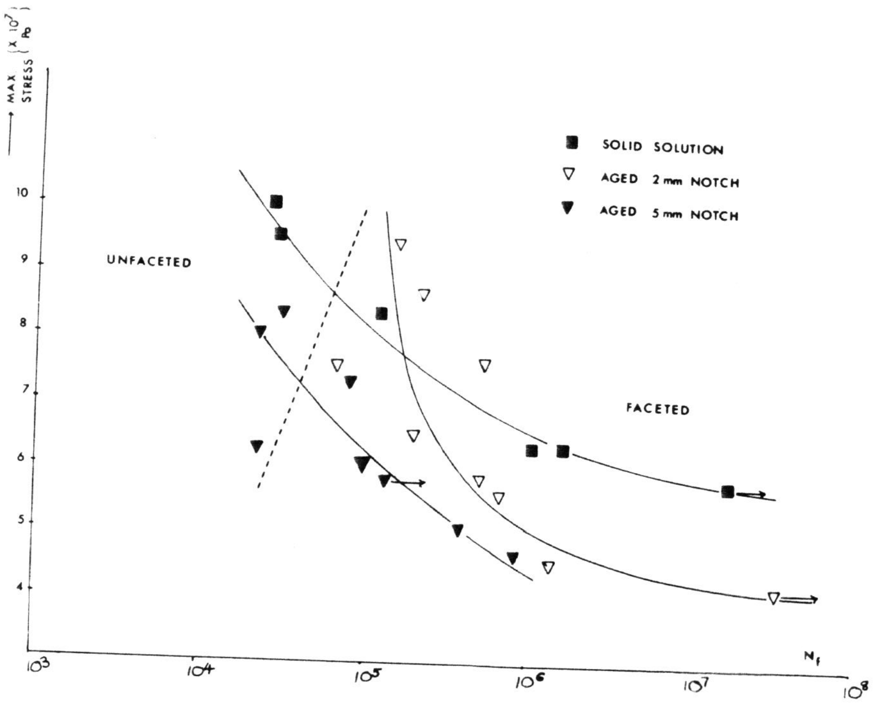

Diagram 1  S-N Curves for GP1 Zone Specimens

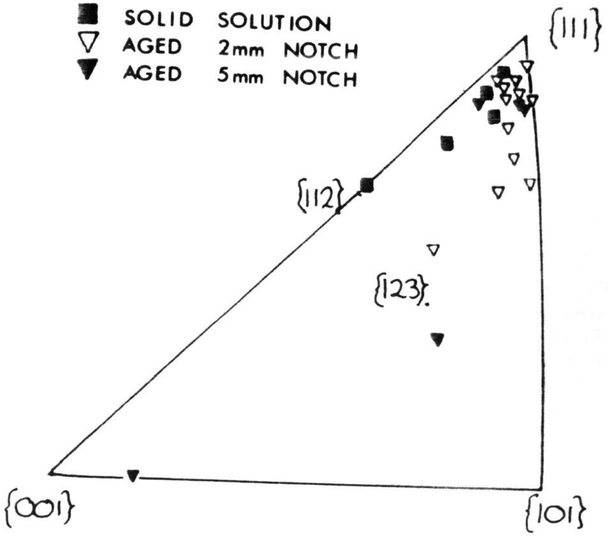

Diagram 2  Orientations of Facets