An Electron Microscope Investigation of Fatigue Deformation in Copper

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The initial fatigue deformation in copper has been shown to be characterised by the presence of deformation bands of high dislocation density, frequently found in conjunction with linear arrays of a dark spot defect. Also noted at this stage was the presence of heavily jogged dislocations. The final fatigue structure consisted of patches of very high dislocation density, occasionally aligned in a specific direction, resolvable as either round or elongated dislocation loops.

1. Introduction

Previous electron microscope studies on fatigued structures have shown the deformation to be characterised by the presence of alternate regions of high and low dislocation density. The arrangement varies with the metal under examination; for, whereas, with aluminium, substructure formation is clearly observed [1], in copper it is only partially achieved.

The two methods commonly used for the investigation of fatigue damage involve thinning bulk specimens or using thin sheet samples cemented to a substrate. The former is the most realistic approach but also the most laborious. The latter is a very convenient method, and is particularly useful if it can be shown that the deformation is substantially the same as found in bulk specimens.

The deformation produced by reversed strain cycling of copper in thick specimen form has been identified in an investigation by Segall [2]. He found the dislocations to be arranged into patches of high density, in a relatively dislocation-free matrix, and that these patches, when examined under a higher magnification, were resolvable into either round or elongated dislocation loops. Segall was not able to establish any connexion between the fairly linear deformation bands seen on the surface using an optical microscope and the deformation seen in the electron microscope. Laufer and Roberts [3], however, using a preferential polishing technique on bulk copper single crystals, have shown a distinctive dislocation structure to be associated with these surface deformation markings.

The second approach has not been attempted with copper, but recently Wei and Baker [4] have shown, using high-purity iron, that deformation bands consistent with those seen on the surface did occur in the interior of a fatigued sample, and that associated with these bands were linear arrays of dislocation loops.

The present work has attempted to show the relevance of the observations on thinned copper specimens to the results found in bulk specimens.

2. Experimental Details

Specimens were prepared from electrolytic copper sheet, 0.5 mm thick, by cold-rolling down to 0.15 mm, followed by annealing at 800° C for 3 h under an argon atmosphere. The specimens were cemented to a standard, copper fatigue specimen and tested in a Weidemann-Baldwin fatigue machine. The maximum bending stress was limited to 10×10^3 to 12×10^3 lb/in.^{2} (1 lb/in.^{2} = 7×10^{-2} kg/cm^2), which it was known would give a life *circa* 10^7 cycles, and the test was generally interrupted prior to failure. The sheet specimens were detached by immersion in a bath of toluene and subsequently thinned electrolytically. The foils were examined in a Siemens Elmiskop 1 microscope at 100 kV.

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3. Results

Preliminary observations of foils which had not been strain-cycled showed the dislocation density to be low, and the individual dislocations to exist as a random array of tangles.

The first test was run at a maximum bending stress of 10^4 lb/in.^{2} for 5×10^5 cycles. Examination showed the formation of fairly linear bands of light deformation, easily resolvable at a magnification of 20 000. Fig. 1 is an example of this phenomenon and shows the dislocations to be long and joggy in nature. Fig. 2 is another example which shows the linearity of the band more clearly. One can also see, in this micrograph, a feature known as a dark spot defect. Here the distribution of these dark spots appears to be quite random, but in other regions they could be seen to be arranged on a plane intersecting the major deformation band, as shown in fig. 3. Occasionally, these dark spots could be seen to be interspersed with dislocation loops.

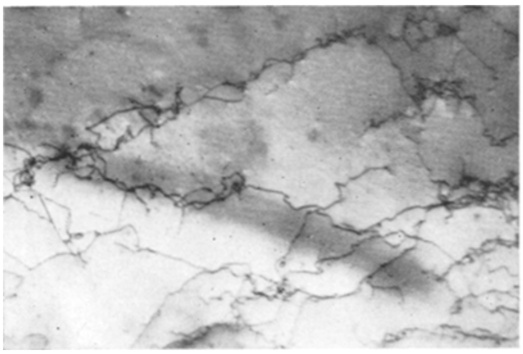

Figure 1 Low dislocation-density band – copper (s_{max} = 10^4 lb/in.^{2}, i.e. 7×10^2 kg/cm^2; $N = 5 \times 10^5$). (×17 500)

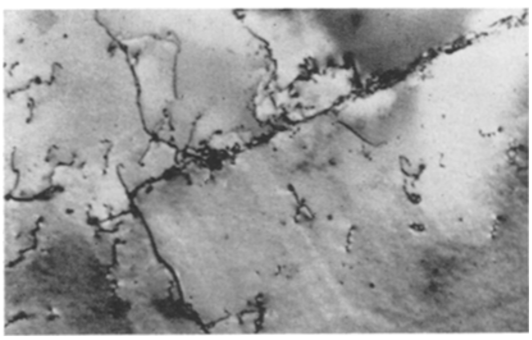

Figure 2 Linear deformation band – copper (s_{max} = 10^4 lb/in.^{2}; $N = 5 \times 10^5$). (×17 500)

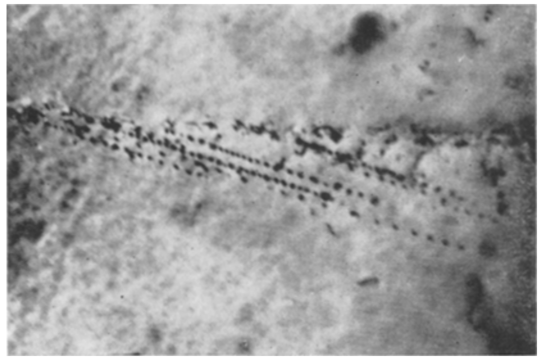

Figure 3 Linear arrays of a dark spot defect associated with a deformation band – copper ($s_{max} = 10^4$ lb/in.^{2}; $N = 5 \times 10^5$). (×17 500)

A further phenomenon detected, possibly associated with this dark spot defect, was the presence of short dislocations which appeared to be held strongly at one point. This feature is shown in fig. 4; and it is quite possible that they are dislocations pinned by sessile jogs of the nature discussed by Segall.

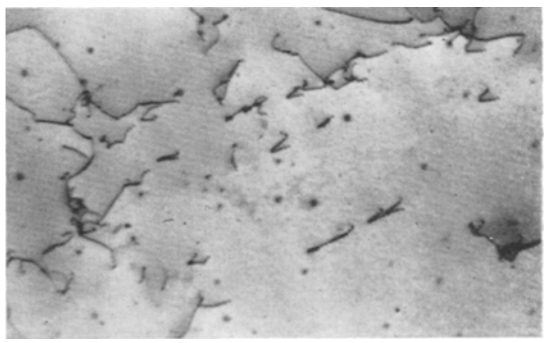

Figure 4 Heavily jogged dislocations – copper (s_{max} = 11.5×10^3 lb/in.^{2}; $N = 2.5 \times 10^6$). (×17 500)

A test conducted at 11.5×10^3 lb/in.^{2} for 2.5×10^6 cycles showed a marked change in the character of the deformation. Here, it was found that isolated patches of high dislocation density existed, similar to those found by Segall in bulk copper specimens, and also regions containing elongated dislocation loops (see figs. 5 and 6). The linearity seen earlier is absent in these micrographs, and the dislocations were generally shorter and more dispersed.

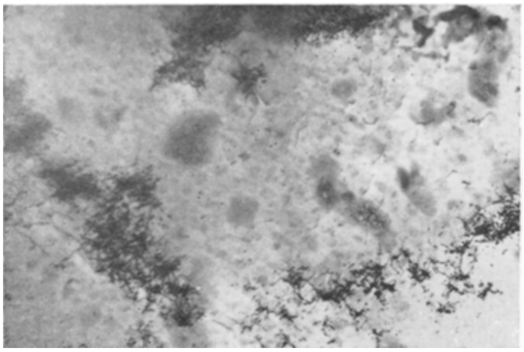

Figure 5 Patches of high dislocation density forming a partial sub-structure – copper (s_{max} = 11.5 × 10^3 lb/in.^{2}; N = 2.5 × 10^6). (×17 500)

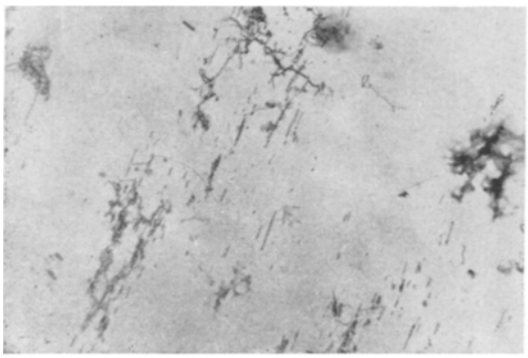

Figure 6 Elongated dislocation-loop structure – copper (s_{max} = 11.5 × 10^3 lb/in.^{2}; N = 2.5 × 10^6). (×17 500)

4. Discussion

The evidence presented here indicates that several forms of deformation are produced during a fatigue test. Plastic-strain amplitude, number of cycles, and proximity to the surface are all factors controlling the type of structure produced.

In a small plastic-strain amplitude test, conducted for only a fraction of the expected life, deformation is characterised by the presence of linear, light deformation bands containing long dislocations. Frequently, linear arrays of dark spots, occasionally resolvable as dislocation loops, are associated with these bands. At higher strain amplitudes and longer lives, deformation is seen to consist of patches of high dislocation density containing round or elongated dislocation loops. This latter observation is important, for the deformation seen here is very similar to that recorded for bulk specimens of copper after a fatigue test, and indicates that the results obtained from thin sheet samples are realistic.

The observation, in copper, of rows of dark spots has an interesting parallel with the results found in iron by Wei and Baker. They found regular arrays of dislocation loops to occur near the surface, whilst the more irregular form of deformation occurred only in the centre of sections.

One possible explanation for this variation can be deduced from optical microscope work, where it has been noticed that the initial crack or intrusion is in a specific slip band, but that later crack growth can be in an irregular fashion. It is conceivable that the linear deformation bands, regular arrays of dislocation loops, and dark spot defects precede the intrusion formation, whilst the heavier deformation, generally remote from the surface, is produced at the slip band zone crack-tip, where one would expect a much higher stress to exist owing to the stress concentration produced by the initial crack. This stress concentration could be the cause for the eventual movement of the jogged dislocations resulting in the dislocation-loop formation observed.

5. Conclusions

(*a*) Early fatigue deformation in copper appears to be characterised by the formation of linear deformation bands consisting of long dislocations.

(*b*) Dark spot defects, in regular linear arrays, are frequently found in association with the initial deformation band.

(*c*) Heavily jogged dislocations have been detected early in a test and could be the cause of the later form of deformation observed.

(*d*) Deformation after continued cycling was seen to consist of patches of high dislocation density, resolvable as round or elongated dislocation loops.

(*e*) The consistency, between the deformation observed here and in bulk copper samples, indicated that the thin sheet samples yield realistic results.

References

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