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Hardening and Strain Localization in Single and Polycrystalline Materials Under Cyclic and Monotonic Deformation

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Executive Summary

The subject program on substructure evolution initially focused on strain localization produced by fatigue cycling and especially how such localization affects the cyclic response of polycrystalline pure metal. The results of this work have been reported previously and published at length. The list of publications attached covers the body of this work. The latter stages of the program have dealt with strain localization in the heavy monotonic deformation of alloys, which eventually produces forms of localized deformation that include coarse slip bands (CSB's), which are aligned to slip planes, and macroscopic shear bands (MSB's), which are not aligned to slip planes. These forms of strain localization are important in that they limit the usable ductility of the material in forming processes.

In order to improve the understanding of strain localization in monotonic deformation, channel die compression tests were performed on single crystals of an Al-4.0wt% Cu alloy which were aged so as to engender either θ'' or θ' precipitates. Selection of crystal orientations provided conditions of either geometric hardening or geometric softening to the active slip systems in order to evaluate the effect of geometric softening on strain localization. Geometric softening of the active slip systems significantly enhanced shear band formation over that observed for geometric hardening. Electron Backscatter measurements showed that macroscopic shear bands accommodate the large strains observed within them through geometric softening. Additionally, conditions of geometric softening produced a significant decrease in flow stress associated with the formation of macroscopic shear bands that has not previously been reported in channel die compression tests.

The critical shear stress for coarse slip band formation was shown to be constant for specimens containing either θ'' or θ' precipitates, but the values for each of these morphologies differed. TEM observations of coarse slip bands confirmed that the change in critical shear stress corresponded to a change in the mechanism of formation of coarse slip bands between materials containing θ'' and θ' precipitates. This is consistent with the change in workhardening behavior of the materials.

The value of critical shear stress for θ'' agreed with previously published values for aluminum copper alloys with solid solutions, GP zones, and θ'' precipitates. Correlations between the critical shear stress for coarse slip band formation and the

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critical shear stress at which strain localization occurs in fatigue in these microstructures, along with similarities between the temperature dependence of these values supports the idea that the mechanism of coarse slip band formation is similar to the mechanism by which strain localization occurs in fatigue.

Research Objective

An extensive review of the literature showed that there existed significant questions about the mechanisms of shear band formation during heavy nonotonic deformation. Such bands will form in alloys containing both shearable precipitates (such as θ'' in aged Al-Cu alloy) and "non-shearable" precipitates, e.g. θ' in Al-Cu alloy. In particular, there was conflicting evidence as to the role of shearing of precipitates, cross slip mechanisms for strain softening, and geometric softening in shear band formation.

Sheared precipitates are observed in macroscopic shear bands (MSB's) of specimens containing θ' precipitates, but not in the surrounding matrix. The primary arguments against a precipitate shearing or softening mechanism are: 1) that shear bands are observed in materials that do not contain shearable precipitates, and 2) that coarse slip bands (CSB's) have been shown to form on the conjugate slip plane while that slip system had deformed significantly less than the primary system. Another proposal, for strain softening through a dislocation mechanism, also could not be ruled out. The lack of a temperature dependence to the critical resolved shear stress for the formation of CSB's suggests that a cross slip mechanism may occur. Lastly, there is extensive evidence which shows that the material within CSB's and MSB's geometrically softens as a result of lattice rotations observed within these bands. Clearly, further investigation was needed to define the critical mechanisms(s) involved.

Additional questions have arisen from these investigations as to whether MSB's and CSB's are micromechanically similar or different. Macroscopic evidence suggests that they are different, but microscopic evidence is unclear on this point. The fact that MSB's are observed to form at clusters of CSB's in tensile tests of specimens containing θ'' suggests a relationship between these two forms of bands. However, no data exists in compression on this material to verify this behavior.

The questions raised above demonstrated the need for further investigation, and provided the basis for the objectives of the latter part of the investigation listed below.

- 1) To investigate the proposed mechanisms of shear band formation of both CSB's and MSB's through channel die compression tests of Al-4.0 wt% Cu with θ'' and θ' precipitates and high purity Al.

- 2) To investigate the role of CSBs in the formation of MSBs through observations in channel die compressions tests.

Experimental Approach

Al – 4% Cu alloy in poly- and mono-crystalline form, as well as pure aluminum, was produced in specimen configurations suitable for channel die compression testing, because the slip geometry is conveniently defined by this method of deformation and it gives rise to strong localized slip, such as CSB's and MSB's. The alloy was aged to produce structures containing either precipitates θ'' or θ' precipitates. Standard methods were used for producing and characterizing the alloy crystals and polycrystals.

Two different crystal orientations were used in the experiments: $[\bar{1}23]$ and $[\bar{1}49]$ as the compression axes. The $[\bar{1}23]$ orientation was chosen to provide a large difference between the Schmid factors of the primary and secondary slip systems. The $[\bar{1}49]$ orientation was chosen to maximize the Schmid factor on the primary system, and the primary Burgers vector was arranged to be parallel to one face of the crystal contained in the channel die. This sample geometry allowed unambiguous interpretation of a plane strain crystallographic deformation. The crystals deformed to varying degrees so as to produce various microstructures including CSB's and MSB's were analysed by various methods. A novel experiment (based on the Cottrell Method) was devised to measure the friction and back stress components of the flow stress in order to obtain direct evidence of whether or not strain softening occurred in MSB's. In addition, a series of techniques were used to record and evaluate the deformation of the specimens, including optical microscopy, SEM, TEM and EBS. Microscopy techniques provided qualitative information into the homogeneity of deformation on both macro and micro scales, while EBS measurements recorded changes in crystal orientation.

Findings and Conclusions

Based upon the results obtained from the techniques employed and the interpretation of these results reported in the Ph.D. thesis of C. Warner the following conclusions can be made:

- 1) A range of crystal orientations can be selected which will provide active slip systems which geometrically soften under testing conditions of plane strain compression. This is accomplished by orienting the primary slip system's Burgers vector in the transverse direction of the channel die, orienting it with the biaxial stress state.

- 2) An orientation that provided geometric softening will accentuate inhomogeneous slip and provide a strong condition for producing localized deformation, in the form of CSBs and MSBs. Local inhomogeneities in deformation lead to lattice rotations which increase the resolved shear stress on the active slip system. This effectively softens the material leading to greater strain in that region.
- 3) Macroscopic Shear Bands localize deformation through geometric softening. MSBs will form in material which is either geometrically hardening or geometrically softening. However, conditions of geometric softening produce MSBs which are associated with a considerable decrease in flow stress.
- 4) In material which is geometrically softening, MSBs appear either through deviations from a propagating CSB, or through intersections of CSBs.
- 5) CSBs appear to result from a work hardening breakdown. In channel die compression, specimens which are geometrically hardening exhibit a relatively homogeneous distribution of CSBs. In specimens which are geometrically softening, this leads to a few inhomogeneously distributed CSBs which carry greater strain.
- 6) The mechanism of CSB formation is by a breakdown in work hardening mechanisms, but this varies between different microstructures, and leads to a different critical shear stress in microstructures containing θ'' versus θ' .
- 7) The critical resolved shear stress for CSB formation is constant among microstructures containing solid solutions, GP zones, and θ'' precipitates. The similarity of the temperature dependence of this critical shear stress to the plateau stress in fatigue, implies that a similar mechanism might be involved with the formation of PSBs and CSBs in these materials, namely non cubic slip on $\langle 110 \rangle \{100\}$ systems. This is further supported through the similarity between the plateau stress for Al 4.0 wt% Cu with θ'' , 95 MPa, and the critical shear stress for CSB formation, ~ 100 MPa. Lastly this is supported by the similarity between the observations in TEM of PSBs at high strains in this material and the CSBs observed here.
- 8) The formation of CSBs in material containing θ' precipitates appears to occur through a process of shearing of precipitates, as evidenced by the shearing of precipitates along a (111) slip plane in a sample without MSBs.

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