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Shear bands evolution in ultrafine-grained aluminium under cyclic loading

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The microstructural response and deformation mechanisms under cyclic and monotonic loading were investigated in a commercially pure Al subjected to grain refinement by cryorolling. A fatigue dependent shear banding and grain coarsening was detected and it was shown that pre-existing shear bands induced by cryorolling play a vital role in this regard. A rapid initial cyclic softening dominated by activation of pre-existing shear bands is replaced by a more gradual cyclic softening dominated by grain coarsening within these shear bands.

Keywords: Ultrafine-grained microstructure; Low-cycle fatigue; Shear bands; Microstructural instabilities

Ultrafine-grained (UFG) materials are attractive materials due to their high strength/weight ratio. Despite their potential, there are some uncertainties in regard to their deformation response which have slowed their commercial application. Generally, high dislocation densities stored in the microstructure of UFG materials reduces their microstructural capacity to accommodate applied strain, leading to low ductility and poor low-cycle fatigue properties [1–6].

Accordingly, shear banding and dynamic recovery mediated grain coarsening have been reported to be the main operating mechanisms in UFG materials in response to cyclic loading [7–10]. Considering that UFG materials are mostly manufactured through mechanical work, understanding the role of pre-existing defects introduced by the grain refinement practice will be instrumental in developing a global model in regard to their deformation behaviour. Wu and co-workers [11] studied the microstructural damage evolution in UFG copper produced by equal channel angular pressing (ECAP) and observed recrystallization and grain coarsening aligned in the direction of the pre-existing shear bands. Therefore, they proposed that the pre-existing shear bands produced in the final ECAP pass can play an important role in the microstructural response to cyclic loading. Kwan and Wang [12] observed the same behaviour in UFG copper produced by accumulative roll bonding (ARB), and showed that reactivation of pre-existing shear bands leads to grain coarsening in these regions during low-cycle fatigue (LCF). In contrast, Höppel and co-workers [13] observed intersecting shear bands in UFG Cu produced by ECAP, and suggested that shear banding due to fatigue is not, in fact, induced by the activation of a pre-existing shear band developed in the last pass of ECAP; rather, an interaction of cyclically induced grain coarsening and grain rotation triggers localization of deformation, which leads to further grain coarsening and eventually the spread of shear bands. It is therefore unclear which of these mechanisms is responsible for cyclic softening during LCF of UFG materials.

Our previous work on cryorolled Al (presented in Ref. [10]) showed extensive shear banding accompanied by grain coarsening. The present authors have also shown that shear banding can play an important role in the LCF behaviour such that the higher density of shear bands in cryorolled UFG Al leads to higher fatigue ductility [14]. The purpose of the present paper is to further investigate in more detail the evolution of microstructural damage and shear band formation in UFG pure Al in response to different loading conditions. Of

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Table 1. Chemical composition of investigated materials (all in wt.%).

	Cu	Mg	Mn	Si	Fe	Ni	Zn	Al
CP Al	0.001	0.0026	0.0021	0.22	0.081	0.0048	0.0067	99.6

particular interest is the difference in microstructural development during monotonic and cyclic loading, which it is hoped will give great insight into the fatigue behaviour of these new materials.

A commercial-purity (CP) Al ingot with the chemical composition given in Table 1 was used in this study. The ingot was cut into blocks of dimensions 10 × 42 × 50 mm, then homogenized at 530 °C for 1 h before cryorolling. The total 80% reduction was achieved in 20 passes at liquid nitrogen temperature. Following cryorolling, the samples were subjected to annealing at 275 °C for 15 min.

The microstructural characterization was conducted using Leo 1530 and Supra 55 VP scanning electron microscopes. The fatigue test was performed under the fully reversed total strain amplitude control condition using a frequency of 0.5 Hz, a triangular waveform and $\Delta\varepsilon_t/2 = 0.0044$. More details on the experimental procedure are provided elsewhere [10].

The representative microstructure of the cryorolled (CR) Al is shown in Figure 1a. As can be seen in the figure, the initial microstructure contains a high density of shear bands, with an average spacing of about 22 µm and an estimated grain/subgrain size of about 700 nm. The misorientation profile obtained over the distance marked in Figure 1a shows a large orientation gradient in the shear band area (Fig. 1b).

The monotonic deformation response of CR Al in Figure 2 clearly shows the absence of work hardening, along with limited uniform and total elongation. The main characteristic of the microstructure in the necked area after tensile deformation shown in Figure 2b is the presence of elongated grains.

The stress amplitude vs. the number of cycles at $\Delta\varepsilon_t/2 = 0.0044$ in a non-logarithmic scale for cryorolled Al in Figure 3 shows that noticeable cyclic softening occurred. Generally, pre-worked UFG/nanocrystalline (NC) metals such as those subjected to severe plastic deformation are highly prone to cyclic softening under the LCF test condition; this has been attributed to microstructural instabilities [2–7]. Our previous work has shown shear banding and grain coarsening to be the main microstructural instabilities in CR Al that lead to cyclic softening [10]. As shown in Figure 3, a two-stage cyclic softening rate was detected for the cryorolled Al. A rapid sharp drop in the stress amplitude occurs during the first ~50–100 cycles. Following this drop, a substantial reduction in the cyclic softening rate occurs for the remainder of the fatigue life. The sudden change in the cycling softening rate could be indicative of a change in the deformation mechanism under cyclic loading. Our surface relief observations revealed shear band activity after as few as 10 cycles. Therefore, it is possible that a sudden activation of shear bands due to cyclic loading accounts for the rapid drop in the stress amplitude at the beginning of the LCF test. To clarify this, surface relief observation was performed to quantify the change in the shear band density relative to the number of cycles. For this purpose, the cyclic fatigue test was interrupted

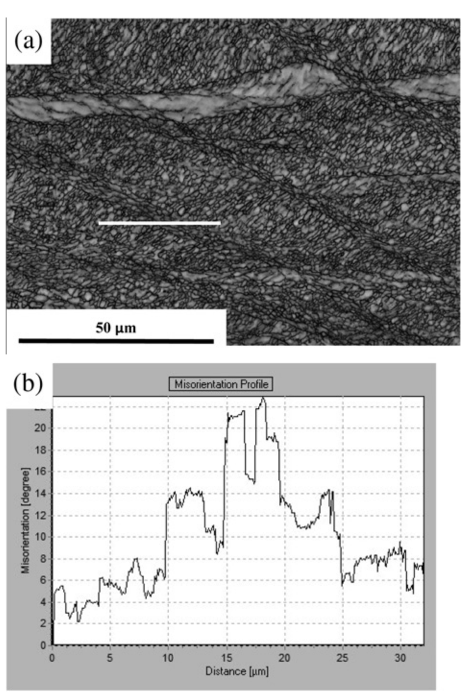

Figure 1. (a) Starting microstructure of CR Al. (b) Misorientation profile over the distance marked by the white line.

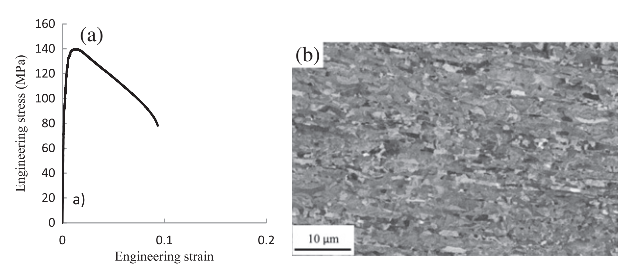

Figure 2. (a) Monotonic stress–strain curve for CR Al. (b) Angular selective backscatter image of necked area after tensile deformation.

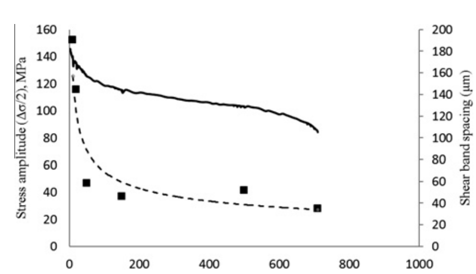

Figure 3. Evolution of stress amplitude and shear band spacing (dashed line is trendline) vs. number of cycles at $\Delta\varepsilon_t/2 = 0.0044$. The shear band spacing was measured on the surface using optical microscopy.