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CYCLIC PLASTIC BEHAVIOUR OF UFG COPPER UNDER CONTROLLED STRESS AND STRAIN LOADING

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Resume

The influence of stress- and strain-controlled loading on microstructure and cyclic plastic behaviour of ultrafine-grained copper prepared by equal channel angular pressing was examined. The stability of microstructure is a characteristic feature for stress-controlled test whereas grain coarsening and development of bimodal structure was observed after plastic strain-controlled tests. An attempt to explain the observed behaviour was made.

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1. Introduction

Ultrafine-grained (UFG) materials prepared by equal channel angular pressing (ECAP) exhibit in comparison with the conventional grain (CG) size materials improved tensile properties [1–3]. It can be supposed that also fatigue properties of UFG materials are better. But this simple hypothesis cannot be generalized for all types of fatigue loading. It is obvious from recent studies that fatigue life of UFG structure depends on loading regime [4, 5]. Whereas in the case of a stress-controlled loading the fatigue life is generally higher, in the case of strain-controlled loading the fatigue life could be even lower in comparison with CG materials. Fatigue behaviour of UFG materials is further dependent on parameters of the applied method of severe plastic deformation and on the details of this process, which can substantially influence the resulting microstructure. This is why further research focussed on the understanding of the reaction of UFG microstructure on different types of fatigue loading is necessary before the UFG materials can be successfully and safely applied in cyclically loaded engineering applications.

2. Material and experiments

UFG Cu of commercial purity of 99.9 % processed by ECAP technique was used in this study. The number of passes by the B_C route was equal to 8, (Fig. 1). The route B_C means that after each pass through the die the billet is rotated around its longitudinal axis about 90°.

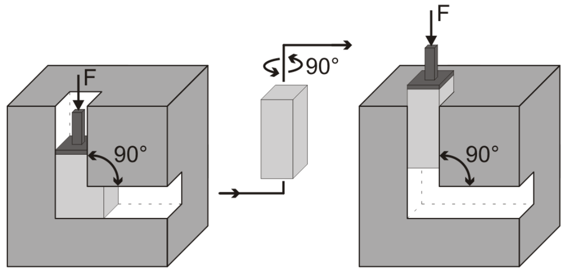


Fig. 1. Scheme of B_C route of ECAP method

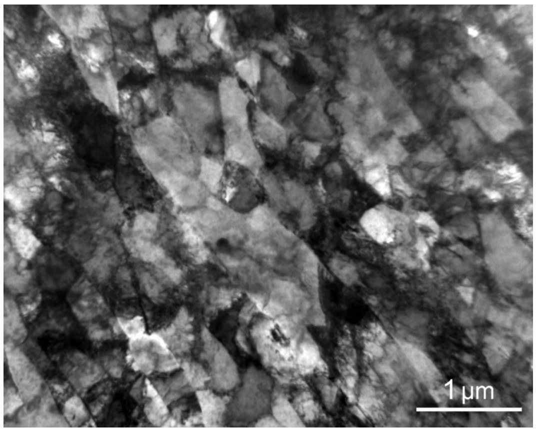
The fatigue tests under stress-controlled loading were performed on a servo-hydraulic testing machine Shimadzu EHF-F1 on cylindrical specimens. Fatigue tests under plastic strain-controlled loading were carried out on a servo-hydraulic testing machine MTS 810. In both cases the cyclic plastic response was measured by a clip-gauge extensometer located on the gauge length of the specimen.

Microstructure of material after fatigue loading was investigated by means of transmission electron microscopy (TEM) in CM12 TEM/STEM Philips electron microscope and electron backscattered diffraction (EBSD) in scanning electron microscope Philips XL30 with EBSD detector.

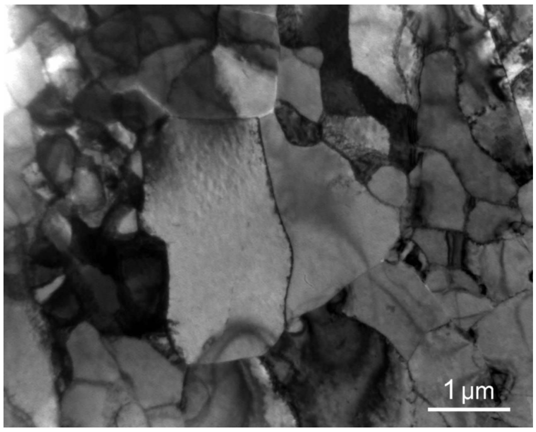
3. Results

Dislocation microstructures of UFG Cu after fatigue loading under stress control with the stress amplitude $\sigma_a = 340$ MPa (Fig. 2a) and under plastic strain-control with the plastic strain amplitude $\varepsilon_{ap} = 0.1\%$ (Fig. 2b) observed by means of TEM were compared. The cyclic stress-strain response for both tests is shown in Fig. 3 by the curves denoted as (1). Stress amplitude of 340 MPa used for the stress-controlled loading was chosen to be equal to the value of the maximum stress amplitude attained in the strain-controlled loading at the beginning of the test. Microstructure after the stress-controlled loading, Fig. 2a, remains unchanged, when compared to the structure before fatigue. Small elongated grains can be seen in Fig. 2a, whereas microstructure after strain-controlled fatigue loading changed substantially. It can be characterized as an equiaxial and bimodal grain structure, Fig. 2b. The same conclusion can be drawn from Fig. 4, which shows the microstructure examined by means of EBSD analysis.

The cyclic plastic response determined in stress-controlled test can be seen in Fig. 3a. The softening curves determined for strain-controlled fatigue loading are shown in Fig. 3b. It is obvious from both figures that the cyclic softening is a characteristic behaviour irrespective of the type of fatigue loading.



a)

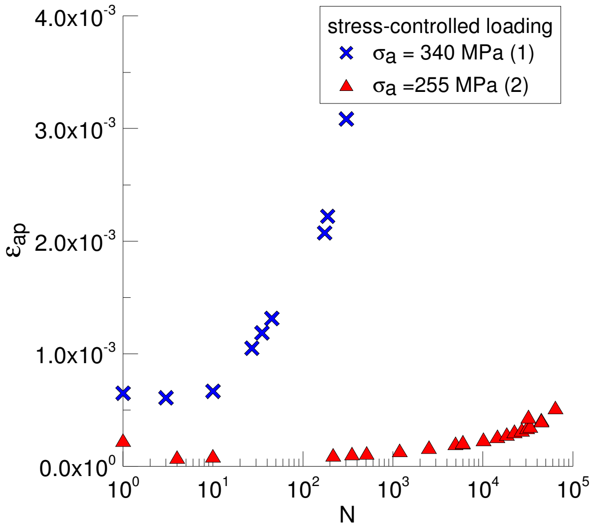


b)

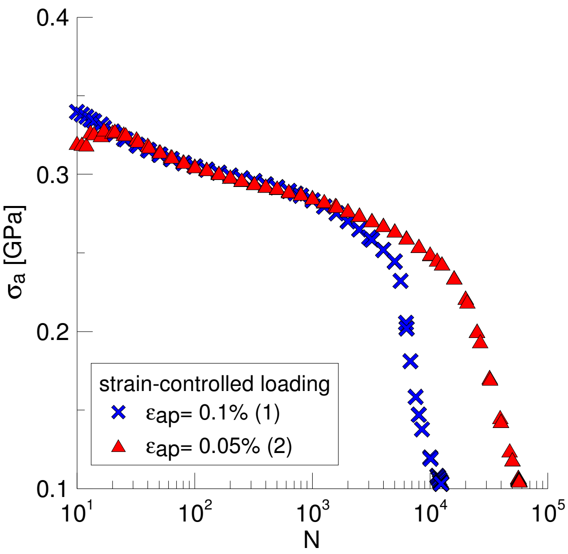
Fig. 2. TEM micrographs of UFG Cu after fatigue loading under a) controlled stress, b) controlled strain

From the comparison of the corresponding curves in Fig. 3 it can be concluded, that the lifetime under strain-controlled loading is shorter than that under stress control.

The curves presented in Fig. 3, enable to evaluate roughly the cumulative plastic strain applied during the fatigue loading. The determined values for particular tests exhibit a scatter, however, there is no substantial difference in the stress and strain controlled tests as regards the attained cumulative plastic strain amplitude.



a)

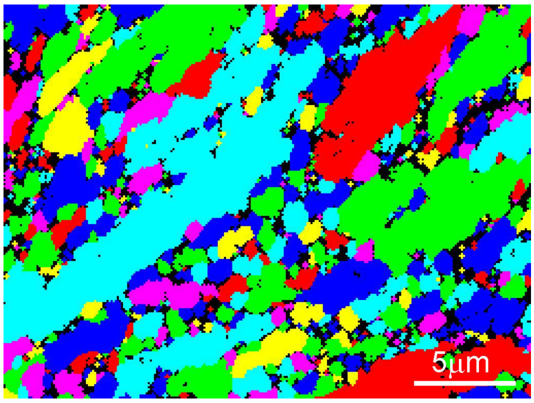


b)

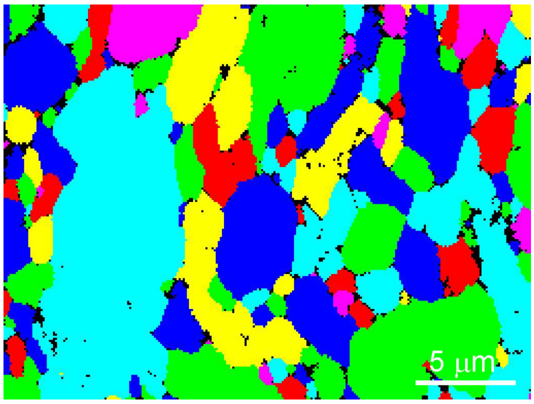
Fig. 3. Cyclic deformation response: a) stress-controlled and b) strain-controlled fatigue loading

4. Discussion

Influence of fatigue loading on UFG microstructure, its stability and related mechanical behaviour has been recently discussed in literature. There is a non-uniform opinion what causes the differences in the reported behaviour and stability of UFG structures cycled under stress- and strain-control. Lower fatigue life of UFG materials characteristic for strain-controlled loading is often explained by the development of bimodal structure. It was also suggested that purity of material could play a role; high purity UFG copper seems to be more sensitive to the grain coarsening and to the related deterioration of fatigue properties. Related results and opinions to this effect, which can be found in literature, are not consistent and some of them are even contradictory.



a)



b)

Fig. 4. Microstructure of UFG Cu after fatigue loading as observed by EBSD: a) stress-controlled test, b) strain-controlled test
(full colour version available online)

The observation of the grain growth and the appearance of bimodal structure after fatigue loading under strain-control (Fig. 2b) are in agreement with the results presented in [6–8]. However, there are differences in the results described in literature in the case of the stress-controlled loading. Höppel et al. [7] observed changes of microstructure of UFG Cu, whereas other authors did not observe any substantial changes of the grain size [9], which is in agreement with results of this study.

Cyclic softening in stress-controlled tests and in strain-controlled fatigue loading shown in Fig. 3 agrees with the cyclic plastic response described by other authors. For strain-controlled loading all authors observed this tendency [6–8]. In the case of stress-controlled loading the cyclic softening was observed with the exception of the smallest stress amplitudes in very high-cycle region [7, 10].

The cyclic stress-strain behaviour experimentally determined in this work indicates, that the difference in the final microstructure after fatigue under different modes of loading cannot be simply explained by the level of the stress amplitudes. The microstructure corresponding to the both curves denoted as (1) in Fig. 3 is different, though the maximum stress amplitudes are similar. Actually, the stress amplitude in the strain-controlled test decreases from the initial value and in the course of the test is lower than that in the stress-controlled test. Also the value of the cumulative plastic strain amplitude corresponding to the both tests does not seem to be the decisive factor. The cumulative cyclic strains corresponding to the both types of tests are in one scatter band of data. The only difference between the two test modes, which can result in the different microstructure, seems to be the stress-strain response at the very beginning of the tests. There is relatively low plastic strain amplitude at the outset of the stress-controlled test when compared to the strain-controlled test. It can be supposed that just the cycling with low strain amplitude at the beginning of a stress-controlled test can prevent the substantial changes of microstructure due to subsequent loading with increasing plastic strain amplitude. The influence of small amplitudes on the initial microstructure after ECAP can result in its stabilization, whereas large initial plastic strain amplitudes can result in its quick degradation and subsequent local coarsening. However, this idea is based on a small number of tests; further experimental study is necessary to support this opinion.

5. Conclusions

1) Microstructure of UFG Cu examined in this work was found to be unstable after plastic strain-controlled fatigue loading. Grain coarsening and development of bimodal structure was observed. Stress-controlled fatigue loading with the stress amplitude corresponding to the maximum of that reached in the strain-controlled test does not result in any change of the microstructure.
2) In both loading regimes, i.e. for strain-controlled tests and stress-controlled tests the cyclic softening was observed.
3) It is assumed that the observed differences in microstructure after stress and strain control fatigue test can be related to the different cyclic plastic stress-strain response at the beginning of the tests.

Acknowledgements

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