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Procedia Engineering 74 (2014) 2 – 5

Procedia Engineering

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XVII International Colloquium on Mechanical Fatigue of Metals (ICMFM17)

Initiation of fatigue cracks in ultrafine-grained materials in high-cycle fatigue region

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Abstract

Initiation of fatigue cracks in materials with conventional grain (CG) size was investigated very thoroughly in the past. There is an extensive knowledge on the localization of cyclic plasticity and early crack development; however, it cannot be straightforwardly applied to the ultrafine-grained (UFG) structures with the grain size below 1 μm, because the crack initiation mechanisms are related to dislocation structures, which cannot develop in UFG materials simply from the size reasons.

The paper brings results of an experimental investigation of the cyclic strain localization and crack initiation by means of focused ion beam technique (FIB). Two substantially different materials as regards the crystallographic structure, namely UFG Cu and magnesium alloy AZ91 processed by equal channel angular pressing (ECAP) were investigated and the observed characteristic features of crack initiation were discussed.

The observations bring evidence that in the high-cycle fatigue (HCF) region point defects generated by dislocation activity do play very important role in the fatigue crack initiation process in UFG Cu. Fatigue cracks initiate in slip bands which form in areas of near-by oriented grains and are characteristic by surface relief, consisting of extrusions and intrusions. Point defects and formation of cavities and voids along the active slip planes governs the HCF crack initiation. No grain coarsening and development of specific dislocation structure was observed in the regions of crack initiation in UFG Cu. The mechanism of the crack initiation in AZ91 alloy processed by ECAP was found to be similar to that known from CG alloy. The cracks initiate in cyclic slip bands which forms in individual grains due to their relatively large grain size. The initiated cracks propagate along the slip planes in a crystallographic way which corresponds to the quasicleavage mechanism often reported for CG Mg alloys.

Selection and peer-review under responsibility of the Politecnico di Milano, Dipartimento di Meccanica

Keywords: Fatigue of ultrafine-grained materials; localization of cyclic platicity; cyclic slip bands; fatigue crack initiation, point defects

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doi:10.1016/j.proeng.2014.06.213

1. Introduction

Fatigue strength of materials is determined by initiation and propagation of fatigue cracks. The initiation represents the dominant part of the fatigue life, particularly in homogeneous materials which are loaded in HCF region and which do not contain defects. The initiation of cracks takes place in areas of localized cyclic plasticity, which manifest themselves by formation of slip markings on material surface. That is why the mechanisms of localization of cyclic plasticity and fatigue crack initiation have been studied since the beginning of the investigation of fatigue damage one hundred years ago. Though very extensive and detailed knowledge of processes resulting in development of fatigue cracks is available today, some aspects of crack initiation mechanism are still not clear and are matter of discussion [1, 2]. The model of the development of the surface slip makings, consisting of extrusions and intrusions proposed by Essmann et al. [3] is based on the observation of ladder type dislocation structure of persistent slip bands (PSB) embedded in matrix structure. The model is based on formation of point defects in the walls due to the dislocation activity. Generation of point defects leads to expansion of the volume of persistent slip bands. Later on the model was extended and modified by Polák [4] and recently by Polák and Man [1] in the sense of more detailed conception of the generation and migration of vacancies resulting in the mass redistribution between PSB and matrix and development of stress fields in the neighborhood of the slip bands. The recent progress in the understanding of the mechanisms of the formation of surface slip markings and role of extrusions and intrusions in the crack initiation process is related to the new experimental methods, like atomic force microscopy and focused ion beam technique (FIB) enabling to visualize the details of the surface profile and subsurface structure.

The models of crack initiation were developed and experimentally verified almost completely at CG materials or on single crystals. The grain size is an important parameter in the theories of extrusion growth and intrusion development [1, 5] and consequently for the fatigue lifetime. From this point of view a question arises, if the knowledge related to the fatigue crack initiation obtained at conventionally grained materials is useful also for materials with very small grain size. This question gains importance just because the ultrafine-grained materials attract the attention of researchers since the last two decades.

The aim of this paper is to present and discuss observation of cyclic slip markings and fatigue crack initiation in HCF region in Cu and AZ91magnesium alloy processed by ECAP.

2. Material and experiments

Cu of commercial purity was processed by ECAP by 8 passes by the route Bc. The resulting grain size (cell size) determined by transmission electron microcopy was 300 nm [6]. AZ91 magnesium alloy was processed by 6 passes by the same route, however due to the limited plasticity of the material the processing temperature was 573 K. The resulting microstructure was of bimodal type, consisting of fine and large grained areas [7] with the grain size of about 3 and 10 μm.

The HCF tests were performed under load control in load symmetrical cycle. The development of surface relief was examined by scanning electron microscopy. FIB technique was used to observe sections of surface relief with cyclic slip markings and to display the microstructure in the slip band vicinity.

3. Results and discussion

An example of cyclic slip localization in terms of slip markings on the surface of the UFG Cu specimen which failed after loading in very high cycle region (5×10^9 cycles) is shown in Fig. 1. The localization of the cyclic plasticity is very severe. It is concentrated in areas of grains with small disorientation (near by oriented regions) [6]. The areas are fully covered with extrusions and intrusions. The characteristic size of extrusions corresponds to the grain size of the UFG material, i.e. it is of about 300 nm. The rest of the specimen surface does not exhibit any signs of the cyclic slip activity though the very high number of applied loading cycles. It important to emphasize that the fraction of the surface covered with extrusions and intrusions is very small. This is obvious evidence that the cyclic plasticity in the HCF region takes place only in minor volume of material and thus it is highly localized.

Fig. 2 shows the FIB section perpendicular to the specimen surface. The FIB cut intersects the slip markings perpendicularly to their longer axis. Well developed extrusions rising up to 0.5 µm above the original surface can bee seen. Some of them are not accompanied by intrusions; see the case marked by the arrow in Fig. 2. This observation does not fit in fully with that by Man et al. on CG AISI 316 steel [8] and CG Cu [9] loaded in the low cycle fatigue region. They found that with increasing number of cycles the number of intrusions increases and finally all thick extrusions are accompanied by two parallel thin intrusions. The 3 µm broad serrated area denoted by A in Fig. 2 is characteristic by many short intrusions, which are also visible as depressions among extrusions in Fig. 1. The intrusions often do not penetrate deep into the material. However, Fig. 2 convincingly shows damage along the perpendicular slip planes inclined at the angle of about 45 degrees to the surface. This damage which penetrates deep below the surface is far from the possible stress concentration produced by surface roughness. The damage consists of elongated concatenated voids. Large isolated voids can be often found deep below the surface, see the objects indicated by white arrows in Fig. 2.

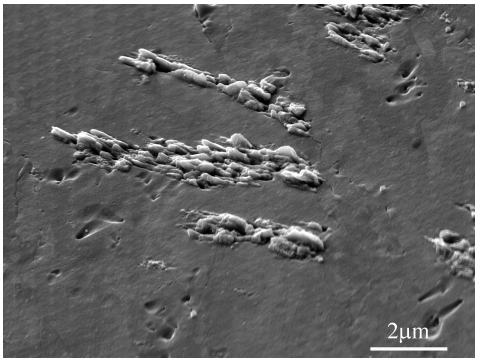

Fig.1. Surface slip markings on UFG Cu, gigacycle fatigue 5×10^9 cycles

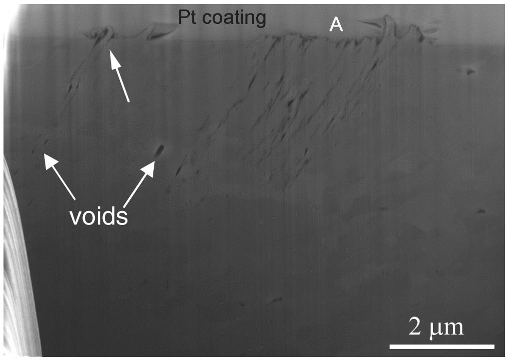

Fig. 2. Profile of slip markings on UFG Cu and subsurface damage, gigacycle fatigue

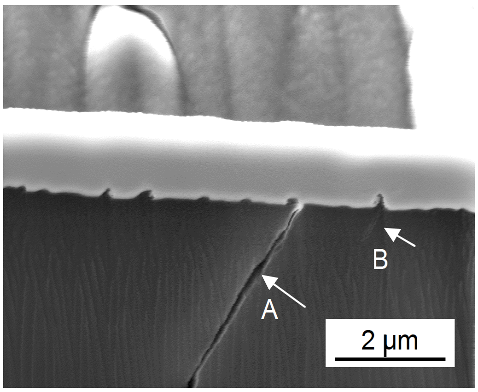

Fig.3. Profile of slip markings and fatigue cracks in UFG AZ91.

From Fig. 2 it can be further seen that the damage is not related to any dynamic grain coarsening. This is obviously in contradiction with the finding [10] that in UFG Cu fatigue damage occurs in the form of macroscopic shear banding and is accompanied by formation of bimodal structure consisting of locally coarsened grains in which the crack initiation can occur in the same way as in the CG material.

The observed formation of damage due to the cycling in the form of concatenated voids located along the slip planes in the regions of near by oriented grains is a witness for decisive role of point defects in the crack initiation process. The production of point defects in cyclically deformed metals has been documented experimentally by resistivity measurements some decades ago [4, 11]. In the UFG Cu which is characteristic by high ratio of grain boundaries it can be anticipated that the vacancies produced by dislocation activity within the suitably oriented grains located along the macroscopic slip planes can migrate and form clusters and concatenated elongated voids as can be seen in Fig. 2. This damage continuously develops during cycling and finally it represents the site from which the fatigue cracks start to grow. No specific dislocation structure in the slip bands seems to be necessary for formation of the observed cavitation damage. It is interesting, that quite similar observation to that presented in Fig. 2 was made by Weidner et al. [12] for CG Cu fatigued in very high cycle region far below the traditional PSB threshold, where the specific ladder like dislocation structures do not develop. They observed also serrated surface due to the fatigue and damage deep in the material, which was interpreted as stage I cracks. Similarly to our case, formation of isolated voids and cavities was observed.

Fig. 3 shows the FIB section of a surface of fatigued AZ91 processed by ECAP. Development of straight slip bands, very similar to those observed in CG Mg alloys is a characteristic feature of localization of cyclic plasticity. Well developed extrusions on the surface can be seen. The extrusions are in some cases accompanied by intrusions penetrating the material along the slip planes. An example of a short intrusion indicated as B can be seen in Fig. 3. The well developed and opened fatigue crack is marked as A. The fatigue crack initiation mechanism is very similar to that observed in coarse grained material and which is described as quasicleavage [14]; only the scaling is much lower. The slip bands develop within the individual grains in the large grained areas of the bimodal structure produced by ECAP, i.e. in the grains having the size of about 10 μm. This grain size substantially exceeds the grain size of UFG Cu. From the comparison of both the cases it is clear, that the crack initiation mechanisms can substantially differ in diverse materials processed by ECAP.

4. Conclusions

For fatigue crack initiation in UFG Cu loaded in the high cycle region the role of point defects generated by dislocation movement is crucial. Fatigue damage forms as concatenated rows of cavities and elongated voids along the active slip planes in areas of near-by oriented grains. No grain coarsening due to fatigue was observed. The initiation of cracks in magnesium AZ91 alloy processed by ECAP takes place in individual large grains of the bimodal structure and resembles the mechanism reported for conventionally grained alloy.

Acknowledgements

The Czech Science Foundation under the contract 108/10/2001 and Ministry of Education of the Czech Republic under the project CZ.1.07/2.3.00/30.0039 supported this work supported this work. The support is gratefully acknowledged.

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