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Acta Materialia 61 (2013) 5857–5868
Acta MATERIALIA
www.elsevier.com/locate/actamat

Improved fatigue properties of ultrafine-grained copper under cyclic torsion loading

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Received 16 March 2013; received in revised form 8 June 2013; accepted 16 June 2013
Available online 11 July 2013

Abstract

In this study, fatigue behaviors of pure copper with different grain sizes are investigated under cyclic tension–compression and torsion loadings. The fatigue responses of ultrafine-grained (UFG) Cu subjected to equal-channel angular pressing (ECAP) are compared and contrasted with those of coarse-grained (CG) and cold-rolled (CR) Cu. It is found from the *S–N* curves under the two different loading modes that, in the high-cycle fatigue (HCF) range, the fatigue strength of Cu does not exhibit strong dependence on the grain size under cyclic tension–compression loading, whereas the fatigue strength of UFG Cu is greatly improved over those of CG and CR Cu under cyclic torsion loading. Under cyclic tension–compression loading, the fatigue strength exponent decreases with the refinement of grain size; however, under cyclic torsion loading, with decreasing grain size, its fatigue strength exponent shows the opposite trend and goes up. To explain the phenomena above, the relations between the fatigue strength exponent and fatigue strength coefficient are discussed. Based on the two main stages of fatigue failure (crack initiation and propagation stages), the influences of grain size on fatigue strength exponent and fatigue strength in the HCF range under the two fatigue modes are comprehensively analyzed.

Keywords: Ultrafine-grained copper; Equal-channel angular pressing; Cyclic torsion loading; Fatigue strength; Fatigue crack

1. Introduction

Recently, ultrafine-grained (UFG) materials undergoing severe plastic deformation (SPD) techniques such as equal-channel angular pressing (ECAP), accumulative roll bonding, dynamic plastic deformation, high-pressure torsion have received much attention from researchers and have been actively studied [1–5]. Compared with the materials with conventional grain size ($\geqslant 10\ \mu m$), UFG materials present many attractive features, such as high strength, high hardness, improved resistance to wear and superior suitability for superplastic forming [1,2,4–11]. By adding alloying elements or introducing a high density of nanoscale twins in UFG materials, a good combination of strength and ductility can be obtained [12–14].

For prospective engineering applications of UFG materials, cyclic deformation and fatigue behavior are crucial. Recently, the related properties have been extensively studied, and several comprehensive reviews have covered this topic specifically [2,5,8,15]. The early work on fatigued UFG materials showed that, when the data were plotted on an *S–N* diagram, the low-cycle fatigue (LCF) strength was considerably improved by grain refinement [16]. Unfortunately, this improvement was generally found to decrease markedly in the high-cycle fatigue (HCF) range, which may be correlated with the microstructural instabilities of the strong hardened but less ductile UFG materials, as manifested in fatigue-induced grain coarsening (a phenomenon of some UFG materials in dynamic recrystallization at relatively low homologous temperatures) and massive shear banding [16–18]. In addition, when the purity of copper was reduced, grain coarsening was not found, and the fatigue strength could be improved [5], which

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http://dx.doi.org/10.1016/j.actamat.2013.06.032

means that the microstructural stability during cyclic deformation indeed plays an important role in the fatigue strength of materials.

Since the microstructural stability has a significant effect on the HCF fatigue strength, increasing the microstructural stability should be a good strategy for improving the fatigue strength of materials in the HCF range. For UFG Cu–Zn alloys, by increasing the content of Zn to restrict the dislocation cross-slip, the dynamic recrystallization and strain localization were effectively confined, and the fatigue strength in the HCF regime was successfully improved to a large extent [19]. In addition to this method, by applying surface mechanical attrition treatment (SMAT) to a 316L stainless steel, Roland et al. [20] obtained a microstructure with the grain size gradually increasing from the nanometer to sub-micrometer scale as the depth below the surface increased; meanwhile, a significant lifetime enhancement was observed in the region of LCF, and this became even more pronounced in the HCF region. They considered that the gradient of the microstructure can impede the dislocation movements, delay crack initiation and then visibly influence the fatigue performance.

Since the gradient of the microstructure can influence the fatigue performance in the SMAT materials, what about the effect of stress gradient on the fatigue behavior? Taking this question into consideration, torsion fatigue tests for solid cylinder specimen will be a deliberate choice, because a stress gradient exists in the cross sections of solid torsion components. In addition, there are many solid components in industries that are primarily under cyclic torsion loading conditions and, to date, most of the available fatigue properties of UFG materials are under axial loadings, and few cyclic torsion data can be found. Therefore, investigation of the torsion fatigue of UFG materials in solid specimens is necessary and meaningful in order to explore improvement in fatigue performance.

Among various SPD methods, ECAP has been recognized as a promising method for the fabrication of UFG materials in bulk form that are suitable for standard fatigue tests [1,21]. Hence, most of the fatigue studies performed so far have been made on UFG materials prepared by ECAP processing. Polycrystalline copper, relying on its simple microstructure, is often used as the model material to reveal fatigue damage mechanisms [22–25]. In the present study, stress-controlled tension–compression and torsion fatigue behaviors of coarse-grained (CG) Cu, cold-rolled (CR) Cu and ECAP Cu are compared, and the grain size and stress gradient dependences are explored.

2. Material and experiments

Pure Cu with three different states was used in this investigation: CG Cu, CR Cu and ECAP Cu. CR Cu, which was bought with commercial T2 brand 20 mm in diameter, were annealed at 800 °C for 2 h in an argon atmosphere to obtain CG Cu. Some of the CG Cu were processed by ECAP for four passes using route Bc (90° clockwise rotation around the billet axis between consecutive passes) at room temperature (RT) with a pressing rate of 20 mm min^{-1}. A die made of tool steel with an angle of 90° was chosen, resulting in an effective strain of ~1.15 per pass [26].

The experiments, including monotonic and cyclic tests, were conducted on solid cylinder specimens with a gauge size of 7 mm diameter × 10 mm using an Instron 8874 multiaxial fatigue-testing machine. For both monotonic tension and torsion tests, the strain rate was fixed at $5 \times 10^{-4}\ \text{s}^{-1}$. Stress-controlled torsion fatigue experiments were carried out under a sinusoidal load at RT in air, with stress ratio $R = -1$ and frequency $f = 15$ Hz. For tension–compression fatigue, the results in Ref. [19] were used for

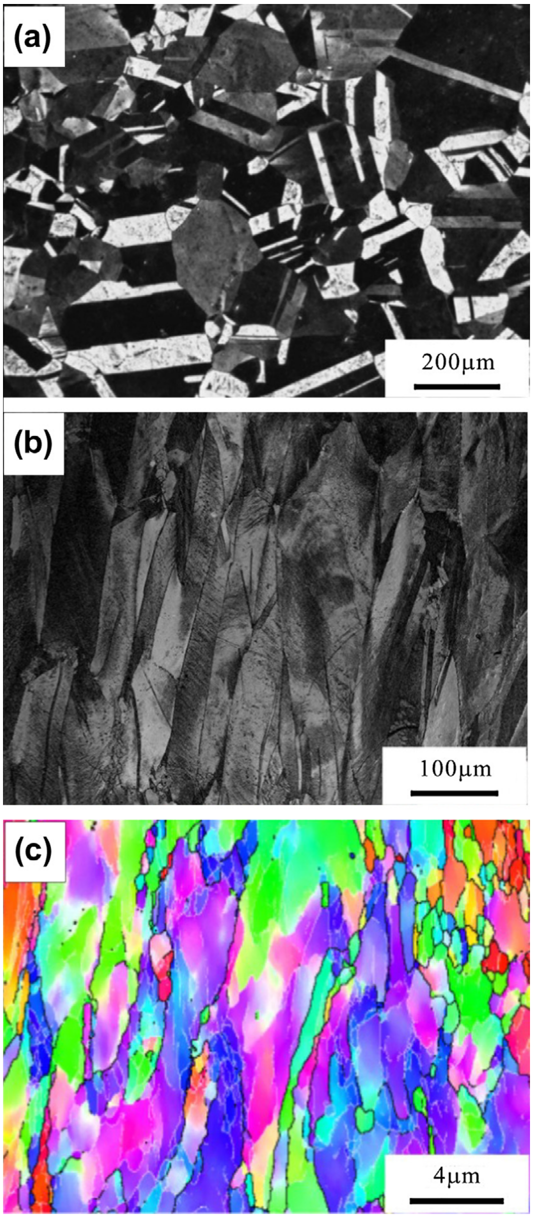

Fig. 1. Characteristics of typical initial microstructures of pure Cu: OM images of (a) CG Cu and (b) CR Cu; (c) EBSD image of UFG Cu.