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Effect of strain path on structure and mechanical behavior of ultra-fine grain Cu–Cr alloy produced by equal-channel angular pressing

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Abstract

The effect of strain path during severe plastic deformation via equal-channel angular pressing on grain refinement and structural features of a model Cu–Cr alloy is investigated in terms of grain shape, dimensions, preferred crystallographic orientation and distribution of grain boundaries with respect to the angle of misorientation. The mechanical behavior of differently processed specimens is assessed in both monotonic and cyclic tests aimed at clarification of the role played by different structural factors in the resultant mechanical properties. It is shown, that despite the considerable microstructural differences in the grain morphology and texture, the tensile and fatigue strength is only slightly affected by the processing routes chosen in the present study. However, the strain path and, therefore, the grain shape and texture have some effect on ductility and strain localization, which is particularly pronounced during cyclic loading.

Keywords: Copper alloys; Equal channel angular pressing; Mechanical properties; Fatigue; Structure; Texture

1. Introduction

Physical and mechanical properties of bulk ultrafine grained (UFG) materials (the grain size d is 100–1000 nm) have been the focus of numerous investigations during the last decade [1]. Equal-channel angular pressing (ECAP) [2,3] is a technique which allows the imposition of extremely large strains through intensive simple shear in bulk samples. During ECAP, significant grain refinement occurs together with dislocation hardening, resulting in the spectacular enhancement of the strength of a working material [1–4]. It has long been recognized that materials processing techniques involving severe plastic deformation (SPD) can produce very strong materials having a rather good ductility in comparison with those counterparts strain hardened via conventional processing schemes such as rolling, drawing, etc. [1].

The effect of strain path on structure formation during SPD has been investigated in many papers. The ECAP has been proven capable of creating a broad variety of structures differing by the grain (cell) size and shape, strength of crystallographic texture, fraction and distribution of high-angle grain boundaries (HAGBs). Iwahashi et al. [5] have argued that route Bc (90° rotation between successive pressings) is most efficient for formation of grain boundaries with high angles of misorientation during ECAP of pure Al. Contradictory conclusions have been drawn by Gholinia et al. [6] after high resolution electron back scattering pattern investigation in the Al–Mg alloy processed by four different routes. They concluded that route A (0° rotation) is most efficient while the route C (180° rotation) is least effective for development of HAGBs. The effect of strain path on the mechanical behavior, ductility and fracture

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has received only limited attention so far [7] and more experimental work is apparently needed to clarify this effect. To our knowledge, no investigations have been performed on the effect of strain path on fatigue of UFG materials to date. The latter issue is intriguing because the fatigue properties are often of primary importance for practical applications. Optimizing the cyclic resistance relies inevitably on understanding the relation between the fine-grain structure obtained during processing and the mechanisms of fatigue damage [8]. Simply speaking, it is unclear yet which structure is preferable for high- and/or low-cyclic fatigue performance.

In a recent investigation of Cu–Cr–Zr alloys produced by ECAP, particular attention has been paid to the role of the number of ECAP-passes and aging conditions on mechanical, thermal and electrical properties [9]. The objective of the present work is to explore the effect of strain path on the mechanical behavior of a model UFG Cu–Cr alloy and to clarify the role of microstructural features produced in the course of ECAP in tensile and cyclic properties. The Cu–Cr system was chosen for the present study for two reasons: (1) alloys are much more stable thermally and mechanically in comparison with pure metals, which allows us to get rid of any strain-induced structural instabilities such as grain coarsening during testing; (2) as a representative of face-centered cubic precipitation hardenable alloys, Cu–Cr can be readily produced by ECAP at room temperature.

2. Experimental

The Cu–0.36Cr (mass%) billets sized $14 \times 15 \times 175\ mm^3$ were solution treated at 1025 °C for 40 min and quenched in water before ECAP. Pressing through channels with sharp corners (intersecting at 90° square) was performed eight times with 0.4 mm/s velocity at room temperature via four different routes aimed at obtaining considerably different grain shapes and, possibly, crystallographic textures. The shear plane orientation after successive pressings via different routes involved in the present work is illustrated in Fig. 1. The processing schedules with monotonic (A) and alternating (CA and ACA) strain path were chosen. Considering a simplified geometry of plastic flow during ECAP [5,10,11], one can expect substantially different grain shapes (metallographic texture) and preferred crystallographic orientations (crystallographic texture) in the resultant structures after different strain paths. Route A commonly gives rise to a pancake-like grain structure significantly elongated in the transverse direction (TD) plane. After four pressings via route A one billet was 90° rotated once and then pressed four times again via route A (the sample is designated as A/B/A). After 90°

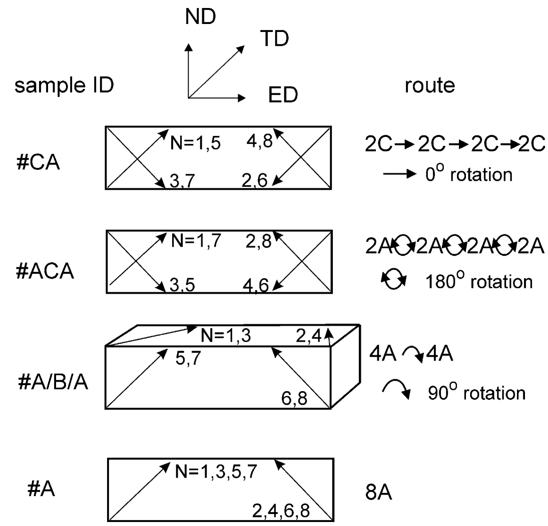

Fig. 1. Shear plane orientation and direction of shear (shown by arrows) in successive ECA-pressings, specimen labeling and mnemonic designations of routes involved in the present work.

rotation of the working billet the shear plane rotated as shown in Fig. 1 so that grain shape elongation is expected in two planes resulting in a fibrous-like structure. With routes CA and ACA, the initially equiaxed structure is supposed to be restored after each second or fourth path, respectively. With the present tool geometry, the effective shear strain imposed onto the billet per pass equals 2 so that the cumulative shear strain Γ for all processing schemes is 16. However, since routes CA and ACA imply reversibility of slip, the amount of shear strain $\Delta\Gamma$ accumulated during each "monotonic" pressing session without altering the strain path is different for all routes chosen for the present study as shown in Table 1. Hence, in the present work we shall explore the influence of $\Delta\Gamma$ on mechanical properties. To provide the uniformity of simple shear, the required boundary conditions [4,11,12] were fulfilled by minimizing the contact friction and ensuring a hydrostatic pressure in the deforming region.

Optimal aging conditions for ultimate strength were found after annealing at different temperatures for 1 h, Table 1. The peak aging conditions were determined from the Vickers microhardness measurements on the ED plane at the applied load of 200 g and the loading time of 15 s. The average values of at least five successive measurements are shown in Fig. 2 for the specimens #A and #CA. The samples processed via different routes attain their maximum hardness at slightly different temperatures because of different precipitation kinetics depending on pre-straining as has been convincingly demonstrated in previous investigations [13] on Cu–Cr alloys.

The samples for mechanical testing were shaped by spark erosion to have a nearly square cross-section of $2 \times 2\ mm^2$ and a gauge length of 10 and 3 mm for tensile and fatigue tests, respectively. The specimen axis was