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Micro-structural evolution subjected to combined tension–torsion deformation for pure copper

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ABSTRACT

A finite element simulation and experiment were conducted to investigate the characteristics of combined tension–torsion (CCT) deformation. According to the simulation results, a very obvious strain gradient distribution develops on the cross-sections of specimens. The equivalent strains obtained by simulation and the incremental theory of plasticity are in good agreement. The experimental results indicate that the micro-structural evolution on the cross-section and longitudinal section act similarly; grains at the edge suffer a higher degree of refinement compared to those in the center, which is consistent with the simulated results. The micro-voids proliferate and grow as the torsion turns increase, but the volume of the voids decreases, and voids tends to aggregate when a critical torsion strain is reached. The EBSD investigation indicates that grains in the processed specimens are mainly small-angle grain boundaries, and the misorientations concentrate between 2° and 10°.

1. Introduction

Because a reduction in grain size increases the strength and toughness of the material at ambient temperature, good formability and super-plastic ductility can also be achieved. Bulk ultrafine-grained (UFG) materials developed via severe plastic deformation (SPD) methods have attracted widespread interests [1–4]. Severe deformations, such as those produced by cold rolling or drawing, can significantly refine the microstructure at ambient temperature. Conventional SPD methods, including equal channel angular press (ECAP) [5,6], high-pressure torsion (HPT) [7–9] and twist extrusion (TE) [10,11], have proved effective for producing UFG materials. Nevertheless, HPT suffers from shortcomings; it fails to produce sufficient material that can be used both for mechanical testing and for practical applications. ECAP deformation, although capable of producing a large volume of materials, usually requires the compacting and canning of particles, but full density may not be achieved after one or even multiple passes [12]. To overcome these problems, various special SPD methods, such as the torsion-equal channel angular pressing (T-ECAP) process that uses cross loading, were proposed [13]. Wang et al. [14] proposed a novel SPD method entitled combined tension–torsion (CTT) deformation for grain refinement.

The microstructure and texture evolution plays a critical role in mechanical properties. Conversely, large numbers of grain boundaries contribute significantly to the microstructure evolution, which leads to unique properties of UFG materials compared to coarse-grained ones. Valiev et al. [15] determined that a UFG Al alloys produced by HPT exhibits a very high tensile strength. However, when subjected to less severe deformation, the cellular microstructures formed with low angle grain boundaries. Moreover, the nanostructures formed from SPD are UFG structures of a granular type containing mainly high-angle grain boundaries. Ito and Horita [16] reported that the improvement in the mechanical properties is caused by the accumulation of dislocations and formation of sub-grain boundaries. According to the work by Beyerlein and Tóth [17], SPD processes substantially changed the texture depending on the strain levels. The deformation texture affects many aspects of material behavior, such as the strength, work hardening, formability and grain refinement. A proper micro-structural study helps us to develop a better understanding of structural properties. In this regard, more research on the microstructure and texture evolution of specimens processed using continuous hybrid process needs to be conducted in detail to investigate the change in the mechanical properties.

In the present study, ABAQUS 6.11 was used to simulate the CTT deformation. The degree of plastic deformation is expressed in terms of the percentage equivalent strain. Optical microscopy (OM) was used to characterize the longitudinal and cross-sectional microstructure, while scanning electron microscopy (SEM) was used to study the micro-voids produced during plastic deformation. An

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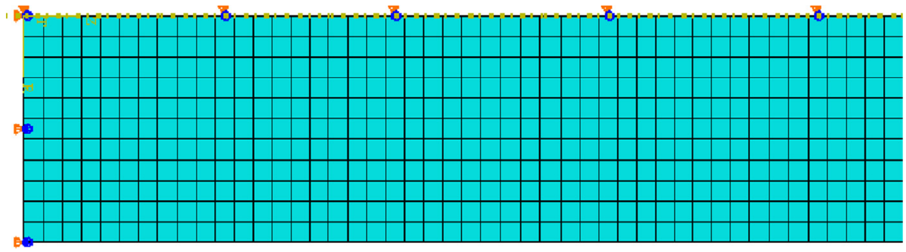

Fig. 1. Finite element model of the bar.

electron backscattering diffraction (EBSD) test was conducted to analyze the angle between the grain boundaries.

2. Simulation and experimental procedure

The CTT simulation for commercial pure copper was carried out using ABAQUS v6.11. Considering the asymmetry of the sample geometry and loading conditions, the simplified model for the simulated test is shown in Fig. 1; the left end is a fixed end, while the upper end is the symmetry axis of the longitudinal section. The tensile and torsion were applied at the right end of the specimen. The detailed parameters for the simulation process are listed in Table 1.

The initial 100-mm long cylindrical commercial pure copper billets, whose nominal chemical compositions are shown in Table 2, were calibrated with a 50-mm gage length and a 5-mm gage diameter for the CTT experiment. The specimens were preconditioned by annealing at 650 °C for 2 h, followed by furnace cooling to room temperature. First, the specimens were pre-stretched at a strain of 0, 0.059, 0.119, 0.178, 0.238 and 0.297 and strain rate of 0.34 mm min^{-1} in electronic tensile testing machine, WDS-10, followed by the subsequent torsion test at room temperature with torsion turns of 0, 4, 6, 8, 10 and 12 at a torsion rate of 0.25 turns min^{-1} in the torsion testing machine XC-10. All experimental specimens were marked by P_mT_n, where P and T represent the pre-stretched experiment and subsequent torsion experiment, respectively; m and n represent the pre-stretched strain and torsion turns, respectively. For example, P_2T_{10} represented the CTT-ed deformation due to a pre-stretched strain of 0.059 and 10 torsion turns, and P_2T_n represents the CTT-ed deformation for a pre-stretched strain of 0.059 and various torsion turns. The processed specimens were again wire-cut symmetrically into vertical and horizontal segments. The segments were subjected to coarse grinding and fine grinding with a waterproof abrasive followed by mechanical polishing with diamond powder. For the OM test, the samples were etched with a solution containing $FeCl_3$, HCl and H_2O (at a ratio of 1:3:20) for 10 s. The EBSD test was conducted on the SEM machine, b-Tescan, allocated with a HKL Channel5 EBSD. Twenty kilovolts of accelerated voltage with a sample tilt of 70° and acquisition frequency of 5.32 Hz were used as the experimental parameters in SEM. The target location was determined by the prepositional back-scattered probe, and the step length was 0.5 mm.

Table 1
Detail parameters for CTT stimulation.

Diameter	5.0 mm	
Length	50 mm	
Young's modulus	125,000 MPa	
Poisson's ratio	0.35	
Plastic parameters [18]	349.201	0.000000
	357.484	0.111429
	366.689	0.143204
	371.266	0.181374
	377.695	0.216349
	384.116	0.258752
	391.460	0.301149
	397.890	0.335064
	405.241	0.372156
	411.670	0.407132
	418.098	0.443168
	425.448	0.481321
	432.801	0.516291
	439.235	0.547022
	445.661	0.584120
	455.790	0.616952
	465.919	0.648723
	479.734	0.691081
	500.000	0.800000
	520.000	0.900000
	530.000	1.000000
	540.000	1.100000
Instance type	Dependent (mesh on part)	
Procedure type	Static, General	
Nlgeom	on	
Increment type	Automatic	
Element type [19]	CGAX4	
Element number	500 × 11	
Approximate global size	0.1 mm	

Table 2
Chemical composition of pure copper T2 (wt%).

Bi	*Sb*	*As*	*Fe*	*Pb*	*S*	*Others*	*Cu*
0.001	0.002	0.002	0.005	0.005	0.005	0.08	99.90

3. Results and discussion

3.1. Equivalent strain distribution and grain refinement

The simulated equivalent strain (ES) distribution results of P_1T_n and P_4T_n are shown in Fig. 2. The ES distribution on the cross-section was clearly non-uniform during the torsion process. The ES was higher at the edge but lower in the center; a strain gradient distribution was evident on the specimen cross-section, which has been confirmed as significant for strengthening and grain refinement [20]. According to the incremental theory of plasticity based on Levy–Mises theory [21], the ES in CTT-ed deformation can be calculated with the following formula:

$$\varepsilon=\varepsilon_1+\varepsilon_2=\ln(l/l_0)+2\pi nr/(\sqrt{3}l) \quad (1)$$

where ε_1 and ε_2 represent the ES produced by the uniaxial tensile deformation and torsion deformation, respectively; l_0, l, n and r are the initial billet length, pre-stretched billet length, torsion turns and pre-stretched billet diameter, respectively.

Fig. 3 shows the curves of the ES (ε_{max}) versus the pre-stretched strain (ε_{pre}) calculated using the simulation and Eq. (1). The maximum ES obtained from the simulation agreed well