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Experimental and theoretical analysis of microstructural evolution and deformation behaviors of CuW composites during equal channel angular pressing

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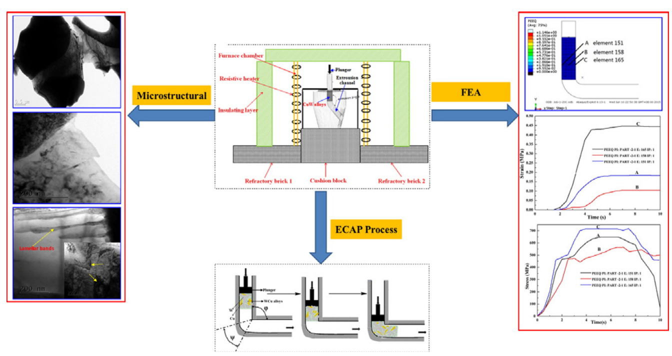
HIGHLIGHTS

- W grains were effectively refined after equal channel angular pressing (ECAP).
- ECAP process introduced lamellar bands with a high density of dislocations.
- Shear deformation is main refined grain mechanism of CuW composites during ECAP.
- Temperature and extrusion angle are two main factors during ECAP process.
- Finite element analysis can rapidly predict the experiment results.

GRAPHICAL ABSTRACT



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ABSTRACT

CuW composites were synthesized using an equal channel angular pressing (ECAP) technique. Microstructural evolution during sintering process was investigated using both optical microscopy and transmission electron microscopy (TEM), and their deformation mechanisms were studied using finite element analysis (FEA). Results showed severe plastic deformation of the CuW composites and effective refinement of W grains after the ECAP process. TEM observation revealed that the ECAP process resulted in lamellar bands with high densities dislocations inside the composites. Effects of extrusion temperature and extrusion angles on stress-strain relationship and sizes of deformation zones after the ECAP process were investigated both theoretically and experimentally. When the extrusion angle was 90°, a maximum equivalent stress of ~1001 MPa was obtained when the extrusion test was done at room temperature of 22 °C, and this value was lower than compression strength of the CuW composites (1105.43 MPa). The maximum equivalent strains were varied between 0.5 and 0.7. However, when the extrusion temperature was increased to 550 °C and further to 900 °C, the maximum equivalent stresses were decreased sharply, with readings of 311 MPa and 68 MPa, respectively. When the extrusion angle was increased to 135°, the maximum equivalent stresses were found to be 716.9 MPa, 208 MPa, and 32 MPa for the samples extruded at temperatures of 22 °C, 550 °C and 900 °C, respectively. Simultaneously, the maximum equivalent strains were decreased to 0.2–0.4. Furthermore, results showed that the maximum equivalent stress was located on the sample's external surface and the stress values were gradually decreased from the surface to the center of samples, and the magnitudes of plastic deformation zones at the surface were much larger than

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those at the central part of the sintered samples. FEA simulation results were in good agreements with experimentally measured ones.

1. Introduction

CuW composites have been widely used in the fields of electric contacts, plasma electrodes, large-scale integrated circuits in the lead frame, heat sinks for microwave tube, nozzle throat for rocket engine, and die-casting molds. They generally have good properties combining those of W phase (i.e., high strength and hardness, high melting point) with those of Cu phase (i.e., low strength, excellent plasticity, outstanding thermal and electrical conductivities) [1–2]. However, CuW composites have potential drawbacks such as poor toughness, which restricts their extensive uses in many stringent service conditions in industry [3–5]. This is mainly because W and Cu have no mutual solubility over the whole range of compositions in CuW composites at various temperatures, therefore, it is critical to search for new synthesis technologies to improve their mechanical properties such as toughness and thus expand their wide-range applications.

Equal channel angular pressing (ECAP), also called equal channel angular extrusion (ECAE), is one of the most efficient severe plastic deformation (SPD) processes which can provide micro- and nano-structures with ultra-fine grains. A unique aspect of the ECAP is that the billet is repeatedly pressed through the angular channel of the die, while a fixed cross-sectional shape of the billet is maintained. Therefore, there is no geometric restriction on the maximum strain that can be achieved to the billet, and it is possible to repeat the pressing for many cycles [6–7]. Recently, the ECAP was applied as a subsequent process for enhancing properties of W-based composites. For example, Gao reported that grain sizes of W were refined from 76.4 μm to 52.5 μm using the ECAP method, and the size and density of the internal pores were decreased accordingly [8]. Kecskes et al. found that W grain sizes (~40 μm) were effectively refined to a few micrometers after four passes of the ECAP at a temperature of 1000 °C [9]. Also, the ECAP was applied on the cast Al-SiC_p composites at room temperature in order to study the effect of ECAP passes on the SiC_p size and distribution [10]. Cu was subjected to ECAP under two different processing routes: B60 and B_C. As the cross sections of the samples were circular, a new route with a rotation angle of 60° in the same direction between consecutive passes was introduced [11].

Another common SPD method, high pressure torsion (HPT) process, has also been investigated by Sabirov et al. for W-based alloys, and effects of temperature on the sizes of deformation zone and refinement of grains were studied [12]. Results showed that the HPT process significantly reduced the grain sizes of W particles, and temperature during the HPT process had a significant effect on plastic deformation and microstructures of the W alloys.

With advances of computing and simulation technologies, computer aided engineering, such as finite element analysis (FEA) and process design method, has been widely applied in industry processes (such as forming of processes of metal and composites) in order to optimize the process parameters and reduce both the production time and process cost. Currently, various information can be readily obtained using the FEA, for examples, material deformation behavior, distribution of stress and strain, and elastic deformation of dies. Recently, ABAQUS, one of the most powerful FEA softwares, [13–14] has widely been used in designing and optimization of engineering structures and materials [15]. For example, Luo et al. simulated cold rolling processes of 6061 aluminum alloy rings using ABAQUS/Explicit codes and reported that plastic deformation of the rings was gradually expanded to the whole ring from the groove and an equivalent strain was decreased gradually from the edge to the center in the rolling process [16]. S. Goyal [17] reported that FEA of the shear punch testing is carried out to study the materials deformation up to yielding and the results are compared and validated with experimental data for four different materials (AISI type 1025 carbon steel, 2.25Cr-1Mo steel, Mod. 9Cr-1Mo steel and AISI 316 S). Zhao et al. investigated effects of the back-pressure on the plastic deformation of pure Cu during the ECAP using the ABAQUS [18]. ABAQUS has also been successfully applied to simulate plastic strain behaviors of pure Ti after different ECAP passes [19]. It was also applied to examine the complex material flow in a flat-die hot extrusion process and in an extrusion process for the dies with various numbers and locations of holes [20].

However, to the best of our knowledge, there is no any report on the study of the deformation behavior of CuW composites during the ECAP using both experimental investigation and FEA prediction/verifications. It is important to investigate the extrusion deformation process of CuW composites during the ECAP using FEA, because the FEA can help to optimize the process conditions for the ECAP method before the experimental work. Effects of extrusion temperatures and extrusion angles on stress-strain relationships and deformation behavior can be obtained from the FEA, which can provide new ideas or guidance and thus improve microstructures and distributions of stress and strain of the CuW composites system. In the present study, the above mentioned work will be carried out using the commercial FEA software ABAQUS, and the results will be verified with the experimental data.

2. Experimental procedures

2.1. ECAP process

The composites were fabricated by infiltrating the copper phase into W skeleton. A detailed preparation process was reported in our previous work [21]. The nominal weight fractions of W and Cu were 70 wt% and 30 wt%, respectively. For the ECAP sample preparation, the specimens were firstly machined into the form of a cylinder with a dimension of Φ 9.5 mm × 30 mm using a wire-cutting machine. The surfaces of samples were polished using a 240-grade abrasive sandpaper. The ECAP die consisted two split blocks of CrMoV alloy steel, which were held together to form a single internal channel of equal cross-sections with a V-shape configuration.

Channel of die with a diameter of Φ10 mm was used. As shown in Fig. 1(a), the ECAP process was conducted at different temperatures in air using a solid steel die with a channel angular of 135° and an extra angle of 45° at the outer arc of curvature. As presented in Fig. 1(b), all the samples firstly experienced one pass of ECAP. During this process, the samples were heated using an electric resistance heating furnace, and the temperature was controlled using a temperature controller. The extrusion temperature during the ECAP was measured using a high temperature infrared thermometer (Smart, AS892) and the accuracy in temperature was ±10 °C. In order to reduce the friction between the samples and inner wall of the die, all the samples and the inner walls of the channels were lubricated using a layer of graphite.

2.2. Finite element simulations of ECAP

Commercial FEA software, ABAQUS, was used to carry out the simulations with extrusion angles of 90° and 135° at different extrusion temperatures (e.g., 22 °C, 550 °C and 900 °C, respectively). All the simulations were performed with an extrusion speed of 3 mm/s and a process time of 10 s.