Available online at www.sciencedirect.com
ScienceDirect
Scripta Materialia 56 (2007) 987–990
Scripta MATERIALIA
www.actamat-journals.com

Grain refinement and crack prevention in constrained groove pressing of two-phase Cu–Zn alloys

Kaiping Peng,[a] Lifeng Su,[a] Leon L. Shaw[b,*] and K.-W. Qian[a]

[a]College of Materials Science and Engineering, Fuzhou University, Fuzhou, Fujian, China
[b]Institute of Materials Science, University of Connecticut, Storrs, CT, USA

Received 26 October 2006; revised 19 January 2007; accepted 29 January 2007
Available online 2 March 2007

The applicability of constrained groove pressing for grain refinement and improvements in mechanical properties of two-phase Cu–Zn alloys is demonstrated. It is shown that the grain size and volume fraction of the β′ phase in the Cu–Zn alloy should be kept small through proper heat treatment, and a die design with a wider groove can reduce stresses at the most severely loaded region of the workpiece, all of which allow higher numbers of pressings to attain better grain refinement and improved properties.

Keywords: Severe plastic deformation; Copper alloys; Grain refining; Crack prevention

Severe plastic deformation (SPD) is one of the most effective methods for producing nanocrystalline (nc) (grain size < 100 nm) or ultrafine-grained (100 nm < grain size < 1000 nm) materials [1]. The most commonly used SPD processes are equal channel angular pressing [1–9], high-pressure torsion [2,3], accumulative roll bonding (ARB) [10,11], repetitive corrugation and straightening (RCS) [12–14], constrained groove pressing (CGP) [15–19] and constrained groove rolling (CGR) [19]. The last four methods were developed for producing plate-shaped materials. However, ARB has strict requirements for the surface condition of the rolled plates and the atmosphere during the roll-bonding process [10,11]. In contrast, RCS, CGP and CGR impart large plastic deformation to the sheet material with little or no change in the cross-sectional area. As a result, there is no requirement for bonding between sheets in the consecutive pressing, rolling or corrugating steps, and the processes can be performed in the ambient environment [12–19].

The effectiveness of RCS, CGP and CGR processes in reducing the grain size from tens of micrometers to submicrometers has been demonstrated in several materials. However, nearly all of the materials investigated so far are single-phase materials, such as commercially pure Al [15,16,18,19] and commercially pure Cu [12–14,17]. These single-phase materials are very ductile and thus suitable for multi-pass rolling, pressing or corrugating to attain the desired ultrafine grains. However, whether RCS, CGP and CGR can be applied to multi-phase alloys, which are typically less ductile than pure elemental materials, remains to be investigated.

In this study we have investigated the applicability of constrained groove pressing for grain refinement and improved properties in two-phase Cu–Zn alloys. In particular, attention is paid to the factors that influence cracking of Cu–Zn sheets during CGP and the approaches that can alleviate cracking so that multiple pressing can be performed to attain grain refinement and improvements in mechanical properties.

Two commercial Cu–Zn alloys, Cu–40Zn and Cu–38Zn, were investigated in this study. The chemical composition of Cu–40Zn was 59.8% Cu, <0.15% Fe, <0.05% Pb, <0.01% Sb, <0.005% Bi, <0.01% P and Zn balance (in wt.%), whereas the composition of Cu–38Zn was 61.76% Cu, <0.10% Fe, <0.03% Pb, <0.005% Sb, <0.002% Bi, <0.01% P and Zn balance. The as-received Cu–Zn sheets were cut into $60 \times 50 \times 2$ mm plates, and were subsequently annealed at different temperatures to obtain the desired grain sizes and volume fraction of the second phase before the CGP process. The annealing was conducted in a resistance-heating furnace under the ambient atmosphere with the temperature ranging from 450 to 600 °C. To prevent oxidation, all the samples were embedded in Al_2O_3 powder during

* Corresponding author. Tel.: +1 860 486 2592; fax: +1 860 486 4745; e-mail: leon.shaw@uconn.edu

1359-6462/$ - see front matter
doi:10.1016/j.scriptamat.2007.01.043

annealing. The setup for the groove pressing of the annealed samples was similar to that described by Shin et al. [15]. As shown in Figure 1, the groove angle of the die, θ, was 45°, and the width of the groove and its height were both equal to t, which was a variable evaluated in this study. After the first groove pressing, the sample was flattened via a set of flat dies. In this study, one groove pressing plus one flattening was called one pressing cycle. The sample was turned over 180° and shifted by a distance of t (the width of the groove) after the first pressing cycle. This allowed the undeformed region to be deformed in the second pressing cycle. After the second pressing cycle the sample had an accumulated and homogeneous effective strain of 1.16 throughout the sample because one groove pressing resulted in an effective strain of 0.58 in the deformed region (Fig. 1c) and the subsequent flattening led to an additional 0.58 effective strain. Two pressing cycles allowed every portion of the sample to attain an effective strain of 1.16. The pressing and flattening were conducted using a CMT-5305 Instron machine with a crosshead speed of 12 mm min^{-1}.

The microstructures of samples before and after groove pressing were examined using an optical microscope (XJL-03) and a scanning electron microscope (Philips XL30). The Vickers hardness of samples before and after groove pressing was determined under 1 kgf (9.8 N) load with a 15 s holding time. To examine the uniformity of deformation, the first location for the hardness measurement was 5 mm away from one end of the sample and the subsequent location was 5 mm apart from the previous location along the x-direction (Fig. 1a). At each location, five measurements were taken along the z-direction, and the hardness value reported for each x-location was the average value of the five measurements along the z-direction. Some groove pressed samples were machined to dog-bone-shaped specimens (with dimensions of $20 \times 10 \times 2$ mm) for tensile tests. This was performed using a CMT-

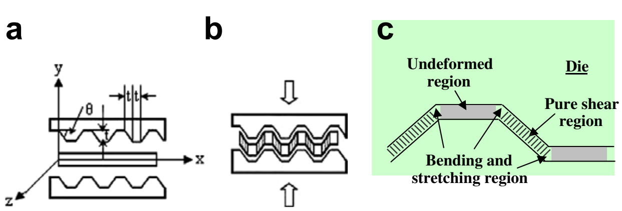

Figure 1. Schematic of groove pressing: (a) showing the die and workpiece before groove pressing, (b) during groove pressing, and (c) showing regions of different deformation modes in the workpiece. The shear strain and effective strain in the pure shear region are 1.0 and 0.58 per pressing, respectively.

Figure 2. A cracked Cu–38Zn sheet after two pressing cycles. Note that cracking occurs at the corner of the groove pressing tooth.

5305 Instron machine with a constant strain rate of 8.3×10^{-4} s^{-1}.

Figure 2 shows a fractured Cu–38Zn specimen after two pressing cycles. Note that the crack always initiates at the corner of the tooth where the material is subjected to the most severe loading condition (see Fig. 1c). Tables 1 and 2 summarize the cracking behavior of Cu–40Zn and Cu–38Zn specimens after 550 and 460 °C annealing, respectively. As expected, the data in Tables 1 and 2 reveal that the composition of the Cu–Zn alloy has a substantial influence on the cracking propensity of the alloy during CGP processing. For example, 550 °C-annealed Cu–40Zn exhibits cracking at three pressing cycles, whereas 460 °C-annealed Cu–38Zn has no cracks until five pressing cycles. The observed effect of the composition can be traced back to the difference in microstructure between Cu–40Zn and Cu–38Zn. As indicated by the Cu–Zn phase diagram [20], both Cu–40Zn and Cu–38Zn at the annealed condition contain two phases, α and β', at room temperature, but Cu–40Zn has more β' (an ordered intermetallic). The image analysis confirms this trend, showing that the 550 °C-annealed Cu–40Zn possesses 10.6 vol.% β', while the 460 °C-annealed Cu–38Zn contains 7.6 vol.% β'. Since the β' phase has lower ductility than the α phase [21], Cu–40Zn with more β' exhibits a higher tendency for cracking than Cu–38Zn.

The effects of the annealing temperature on the cracking propensity of Cu–38Zn specimens are shown in Table 3. The Cu–Zn binary phase diagram indicates that the Zn solubility of the α phase is largest at 454 °C and the order–disorder transition of the β phase takes place at around 460 °C [20]. Thus, to avoid the formation of the ordered phase β' during holding in the annealing treatment, the annealing temperature was chosen within the range 460–600 °C. It can be seen from Table 3 that the low temperature annealing (<540 °C) imparts

Table 1. Cracking behavior of Cu–40Zn during CGP

Sample ID	First pressing cycle	Second pressing cycle	Third pressing cycle	Fourth pressing cycle	Fifth pressing cycle
40-1	No cracks	No cracks	Fractured	–	–
40-2	No cracks	No cracks	No cracks	Cracked	Fractured
40-3	No cracks	No cracks	Fractured	–	–