Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 25(2015) 2571−2580
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Segmentation of copper alloys processed by equal-channel angular pressing

Omid NEJADSEYFI[1], Ali SHOKUHFAR[1], Vahid MOODI[2]

1. Advanced Materials and Nanotechnology Research Lab, Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran;
2. Young Researchers and Elites Club, Birjand Branch, Islamic Azad University, Birjand, Iran

Received 11 October 2014; accepted 10 February 2015

Abstract: This research provides experimental evidence for localized shear, billet cracking, and segmentation during the processing of various copper alloys. The results demonstrate that although many parameters affect the shear localization, there is a direct relation between segmentation and alloy strength (hardness) that is related to the alloying elements and constitutive phases. For instance, alpha brass is successfully processed by ECAP at room temperature, but alpha/beta brasses fail even at a temperature of 350 °C. Finite element simulation of cracking and segmentation was performed using DEFORM^{TM} to investigate the influence of different parameters on segmentation. The results confirm that friction and processing speed have narrow effects on attaining a perfect billet. However, employing back pressure could be reliably used to diminish shear localization, billet cracking, segmentation, and damage. Moreover, diminishing the flow localization using back pressure leads to uniform material flow and the billet homogeneity increases by 36.1%, when back pressure increases from 0 to 600 MPa.

Key words: back pressure; brass; bronze; damage; flow localization; stress−strain behavior; tensile strength; ductility

1 Introduction

The grain size of a polycrystalline metal is directly affecting its mechanical properties. At low temperatures, the strength is related to the grain size through the Hall−Petch relationship, which is of the form:

$$\sigma_y=\sigma_0+k_y d^{-1/2} \tag{1}$$

where σ_y is the yield stress, σ_0 is the friction stress, d is the average grain size, and k_y is a constant value of yielding. This equation demonstrates that reducing the grain size is beneficial for increasing the strength of the material. In addition, reducing the grain size enhances the superplastic formability of materials [1,2].

Grain refinement through the application of thermo-mechanical treatment leads to the grain sizes in the order of a few microns. However, these procedures cannot refine the grains up to the submicrometer (0.1 to 1.0 μm) or nanometer (<100 nm) range. To achieve ultra-fine grain size, it is necessary to use alternative techniques, in which materials are subjected to severe plastic deformation (SPD) without incurring any significant change in the overall dimensions of the work-piece. Processing of alloys and metals through the SPD methods is attractive because it introduces significant grain refinement in bulk solids. Among various SPD techniques, equal-channel angular pressing (ECAP) has attracted much attention than other SPD methods in the last decade. Easy configuration, low cost, and the ability to produce relatively large samples of bulk ultrafine-grained and nanostructured materials are the most important advantages of this process [3]. In ECAP, a sample in the form of a rod or bar is pressed repetitively through a die to impose high strain to the work-piece. Some materials, specifically those having hexagonal close-packed crystal structure, are difficult to process by ECAP due to the limited number of slip systems. Such materials are prone for shear localization, segmentation and multiple cracking when they are pressed at room temperature [4]. These problems may be limited or even avoided by increasing the processing temperature and/or changing the channel angle within the die [5]. However, increasing the pressing temperature leads to larger grain sizes.

As the aim of the ECAP process is grain refinement together with the producing materials without defects, cracks, and segments, several procedures have been

Corresponding author: Vahid MOODI; Tel: +98-21-8406-3224/+98-937-806-6059; Fax: +98-21-8867-7274; E-mail: vahidmoodi@yahoo.com
DOI: 10.1016/S1003-6326(15)63877-8

adopted to avoid the development of shear bands and deformation inhomogeneity during the process. These procedures include using ECAP dies having angles larger than 90°, performing the process with low speed, increasing the processing temperature, using preliminary deformation step, and incorporating back pressure into the pressing operation. This research was conducted to reveal the damage evolution during processing various grades of copper alloys, and to provide experimental evidence for the occurrence of cracks, segmentation and shear localization in ECAP. However, considering cost, time, and availability of experimental procedures leads to concentrate on the numerical methods to assess the influence of different parameters in the ECAP process. In addition, less attention has been made on using finite element analysis (FEA) to predict damage, and segmentation in the literature. Among available reports, FIGUEIREDO et al [6] used FEA to evaluate the evolution of damage in an aluminum-based alloy. The analysis demonstrated that the cracks might be formed in the interiors of materials with strain hardening behavior (annealed sample) and the propagation of those cracks led to billet segmentation. Conversely, in near perfect plastic behavior (the samples processed by ECAP), there might be superficial cracking on the upper surfaces of the billets. However, those cracks were reasonably stable. They studied the effect of strain-rate sensitivity and die angle on the segmentation using numerical simulations and concluded that billet cracking and segmentation might be reduced in difficult-to-work alloys by increasing the strain-rate sensitivity and/or by increasing the channel angle within the die [7]. Generally, most of the studies dealing with ECAP, and specifically those related to flow localization in ECAP, concentrate on the materials such as titanium and magnesium. Therefore, in order to expand the current knowledge in this field, the effects of different processing parameters on the flow localization of Cu-based alloys were dealt using finite element analysis (FEA) and experimental tests.

2 Experimental

In this work, the ECAP process was conducted on five commercial Cu-based alloys as specified in Table 1. Free machining brass (also known as architectural bronze), and forging brass are categorized in alpha/beta alloys with more than 37% zinc. However, forging brass, containing less than 37% zinc is classified as alpha brass. Phosphor bronze, or tin bronze, is an alloy containing copper, tin, and phosphorous. Tin remains in the alpha copper solid solution and the phosphorus forms copper phosphide phase. When the content of tin is above 10%, as shown in the copper−tin phase diagram, a second phase is formed, which is brittle. Furthermore, gear bronze has a strong bronze matrix (alpha phase) with a fine dispersion of the hard delta phase, which improves the strength of the alloy.

Table 1 Specifications of processed materials by ECAP

Alloy No.	Name	UNS number	Nominal composition	Vickers microhardness
A	Free machining brass	C38500	Cu−39%Zn−3%Pb	147
B	Gear bronze	C92900	Cu−10%Sn−3.5%Ni−2.5%Pb	128
C	Forging brass	C37700	Cu−39%Zn−2%Pb	105
D	Phosphor bronze	C51000	Cu−10%Sn−0.25%P	93
E	Cartridge brass	C26000	Cu−30%Zn	86

To conduct ECAP on the above-mentioned materials, all samples were cut and machined to be 10 mm in diameter and 40 mm in length. Prior to ECAP, annealing heat-treatment was performed for all samples by keeping the billets at 500 °C for 3 h and then letting them to cool down to room temperature.

The ECAP process was performed at room temperature through a single pass with a pressing speed of 10 mm/s. In the case of sample failure, the temperature was increased up to 350 °C to repeat the process. A closed die made of H13 steel with a cross-channel angle (Φ) of 90° between the vertical and horizontal channels and an outer corner angle (Ψ) of 20° was used. A heater was incorporated within the die to control the temperature. In addition, graphite powder was used as lubricant during ECAP process.

The Vickers microhardness values were measured using Shimadzu Type M microhardness tester with a load of 0.49 N for a dwell time of 10 s. Furthermore, the tensile tests were performed on the specimens, prepared from longitudinal direction of the samples, with 5 mm in gage diameter, and 25 mm in gage length employing an initial strain rate of 0.01 s^{-1}.

Optical microscopy and scanning electron microscopy were used to observe the microstructure of the annealed and processed billet. For this purpose, the billets were cold-mounted in epoxy and surface preparation was conducted by grinding the samples using 100, 240, 400, 600, 1200, 2000, and 3000 grit SiC papers and then by employing alumina polishing powder. Then, the billets were chemically etched in a solution of $FeCl_3$, HCl, and C_2H_5OH (3 g, 10 mL, and 90 mL, respectively) at room temperature for 15 s.