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High leaded tin bronze processing during multi-directional forging: Effect on microstructure and mechanical properties

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ABSTRACT

The high leaded tin bronze alloy has been studied during multidirectional forging (MDF) process with differing crystallite size (D) in the scale of 240–90 nm. The effect of MDF strain ($\varepsilon_{MDF}\sim$ 0.25, 0.50, 0.75) after 3, 6 and 9 passes respectively on the development of homogeneity and refinement in terms of dislocation density, twin spacing, twin lamellae thickness and their division have been studied using high-resolution transmission electron microscopy (HRTEM) and micro-hardness measurements using Vickers micro-hardness. X-ray diffraction peak broadening investigation has revealed that the crystallite size decreases down to 90 nm after 9 pass ($\varepsilon_{MDF}\sim$ 0.75). The tensile fracture surfaces have been studied using scanning electron microscope (SEM) of received (AR) and MDF specimens. The results of crystallite size and dislocation density on the strength of refined microstructure and nanostructure have been correlated with mechanical flow stress.

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1. Introduction

In last decade, the production of bulk nanostructured metals and alloys using severe plastic deformation (SPD) processes has been progressed rapidly with the aim of developing novel mechanical and functional properties in the materials [1]. SPD techniques like as multidirectional forging (MDF), equal channel angular pressing (ECAP), high pressure torsion (HPT), accumulative roll bonding (ARB) have been used to produce ultrafine grained material by applying very large plastic strain in various materials [2–4]. During 1990 MDF was introduced for the first time to fabricate ultrafine grained structure in bulk billets [5,6]. MDF is a repetition of free forging operation multiple times including setting and pulling operations with the changes of the axes of applied load [7].

Many researchers have been reported to study microstructure and mechanical behavior of copper and copper alloy after SPD [8–13]. Parimi et al. [8] reported SPD of copper and Al–Cu alloy by using multiple channel-die compression process. The nano size grain structured copper was achieved along with increased flow stress and hardness during compression. Kundu et al. [9] applied multiple compressions in a channel die at different temperature range on copper and result enhanced flow stress and strain rate sensitivity. Sarkar et al. [14] deformed interstitial free steel through ECAP to assess the microstructure by different XRD peak profile analysis using Williamson–Hall plot technique and the variance method as a function of strain (ε). The dislocation densities estimated from XRD were also correlated with experimental yield strength. Gubicza et al. [15] studied the microstructure of face centered cubic (FCC) metal and alloys processed through SPD methods and also correlate the yield strength with dislocation densities calculated using Taylor's equation. Thereby they reported the main strengthening mechanism for both metals and alloys were the interaction between dislocations. Ungar et al. [16] determined the particle size and dislocation structure in nanostructured copper by high resolution XRD profile analysis method using modified Williamson–Hall plot and modified Warren Aver Bach's plot and also reported that the twin boundaries found good agreement with TEM micrograph. Makhlouf et al. [17] studied the microstructure of Al alloy after ECAP using XRD and TEM. The high dislocation density along with improved mechanical behavior was obtained in the alloy.

The high leaded tin bronze (copper based alloy) was used in the present study finds application in automotive, agricultural, rail road, mining, off highway equipments [18]. The high leaded tin bronze has lower strength which makes this alloy to only use under moderate/light loading conditions and against unhardened shafts. The trouble with the target alloy was that it has not been specified to use under high loading or impacts applications. Since these alloy operated under moderate loads and high speeds only.

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But the situation for high loading and against hardened shafts was required the strength of the alloy to be improved. Therefore, the introduction of new mechanical properties in the alloy through MDF was aimed, along with its microstructural studies, so that the alloy functional conditions has been varied, such as used under high speeds, under high-load, and impact situations [19,20].

The production of bulk nanostructured metals and alloys (such as high leaded tin bronzes) has been carried out by using severe plastic deformation (SPD) with the aim of developing novel mechanical and functional properties. Generally, Cu-based alloys have been used in ancient times such as Romans and other civilizations to produce artistic and functional artifacts. Now days, we have been obtained more novel mechanical and functional properties, which as reported by many researcher from long time ago. The lowest grain size was detailed to be 400–600 nm for SPD processed pure Al [21], grain size between 100–450 nm for Cu alloy [22–24] also 70–110 nm for Cu–30 wt% Zn alloy [25]. In addition, post SPD recrystallization fabricates superior microstructure with ~4.5 μm grain size for Cu–5 wt% Al and for Cu–5 wt% Zn ~7.5 μm respectively [26]. Twinning is one of the key deformation methods for metals and alloys with small stacking fault energy (SFE), for silver (25 mJ/m^2), stainless steel (8–45 mJ/m^2), and α-brass (14 mJ/m^2) respectivley [27–29]. While, inclusion of Zn in Cu, 30% Zn alloy decreases the stacking fault energy (SFE) of pure Cu from 78 mJ/m^2 to 14 mJ/m^2 [27,29,30]. The dislocation density of Cu–0.7% Cr was $38 \pm 4 \times 10^{14}$ and hardness was 804 ± 38 Hv through severely deformed by HPT at room temperature (RT) and a rate of 1 rpm under a pressure of 4 GPa [31]. The hardness was 173.2 ± 4.3 Hv and yield strength was 640 ± 20 MPa at CR095 for Cu–30 wt% Zn [27].

The present investigation is aimed to study the microstructure and mechanical properties of high leaded tin bronze processed by MDF at room temperature. The characterization of MDFed microstructure has been carried out in terms of twin spacing (d_{twin}), crystallite size, twin lamellae thickness (λ) and their division at different level of MDF, to investigate the fundamental mechanism of microstructural modification. The result of strengthening due to twin spacing, dislocation density, and crystallite size on the mechanical flow stress of differently MDF specimens have been compared in this research work.

2. Experimental procedures

The material used in this study was high leaded tin bronze alloy (Cu–17 wt% Pb–6 wt% Sn–4.5 wt% Zn). Initially the alloy was cut into the measurement of 60 mm × 55 mm × 55 mm from square section and heat treated at 573 K (300° Celsius) for 1 hour using muffle furnace followed by water quenching. The process has been applied at room temperature and inside the MDF die [CAD model is shown in Fig. 1(a)] between top punch and bottom punch and pressed vertically downward number of times by changing the

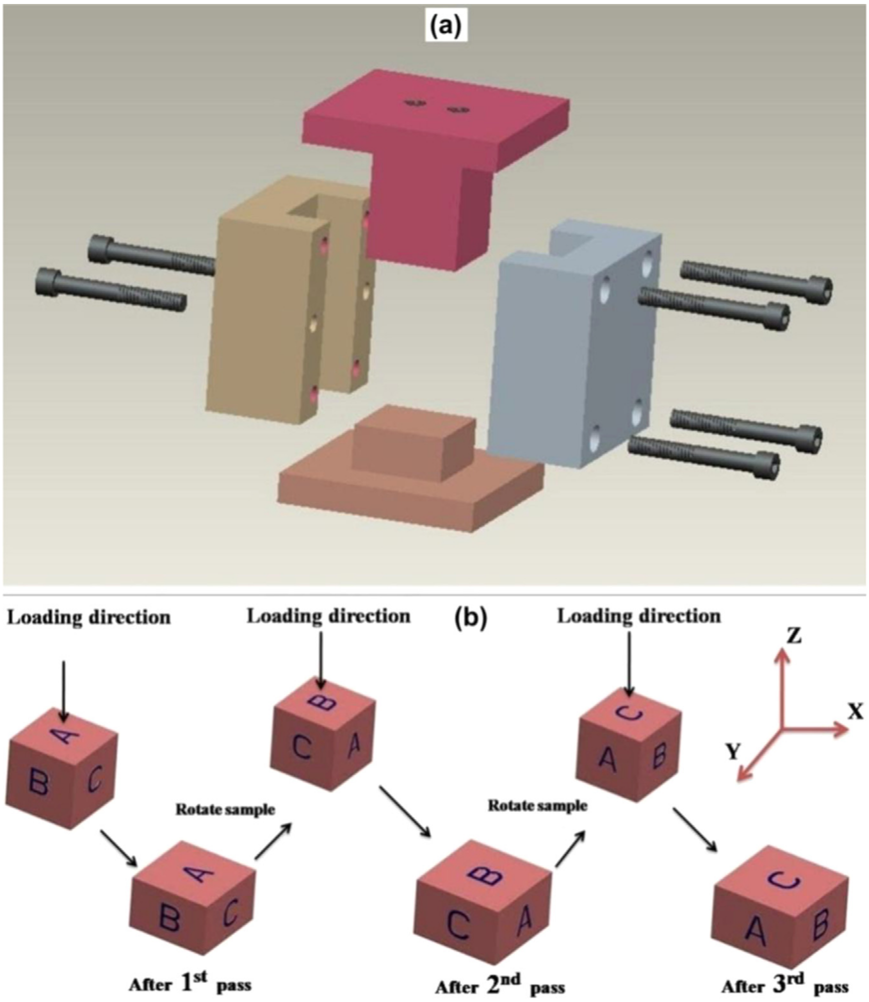

Fig. 1. Schematic showing (a) Computer aided design model of MDF die (Exploded View), Top punch, Bottom punch, and Left and Right die halves with Allen bolts. (b) Schematic of MDF processing of high leaded tin bronze for different passes.

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