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Effects of Deformation and Annealing Temperature on the Microstructures and Hardness of Cu-29Zn-0.6Bi Brass

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Abstract. The use of lead-free brass is growing due to the restriction of the lead content in many components. Bismuth replaces lead in the brass alloys and contributes to the machinability and pressure tightness characteristics. However, Bi is immiscible in copper and fills the inter-dendritic spaces during solidication that yields negative impacts on the mechanical properties. This research studied the effects of addition of 0.6 wt. % Bi on the characteristics of Cu-29Zn alloy during cold rolling and subsequent annealing process. The Cu-29Zn-0.6wt.%Bi alloy was produced by gravity casting in a metal mold with the dimension of 110x110x6 mm^3. The as-cast plate was homogenized at 800 ^{o}C for 2 hours and then cold rolled with the level of deformation of 20, 40 and 70 % in multiple passes. The samples with 70% deformation was annealed at 350, 400 and 450 ^{o}C for 15 minutes. Characterization of materials included Vickers hardness measurement and microstructural observation by using optical microscope and SEM. The results showed that addition of Bi reduced the grain size, formed discrete globules in the interdendritic areas and increased the hardness. The globules as dispersoid bismuth deformed and filled intergranular spaces during rolling and promoted the formation of cross slip mechanism at the 20% deformation. At the 40% deformation, the globules led to more closely spaced twin lamellae and increased the twinning density. The phenomena created an inhomogeneous deformation and promoted the formation of shear band. Annealing process dispersed the Bi globules into tight structures along the grain boundaries.The presence of dispersed bismuth increased the rate of recrystallization during annealing due to the increased in potential site for nucleation. In contrast, the dispersed bismuth acted as the pinning agent that inhibited the grain growth and developed smaller grain size which resulted in higher hardness.

Introduction

Cartridge brass contains zinc of ~ 27 to 30 % and is known to have the highest elongation among other brasses [1]. The highest elongation and low hardness result in a better formability [2]. However, the formability decreases with the addition of zinc content up to 37% due to the increase in hardness [3]. Addition of alloying elements such as Pb, Se, Bi, Mn and Co results in an increase in machinability and castability of brass [3].

Almost all cartridge brasses contains Pb in order to improve machinability and castability. However, the toxicity of Pb makes it obsolete [4]. Therefore Bi is widely used as a substitution for Pb, due to its similar function with that of Pb in increasing machinability and castability [5]. Both Bi and Pb are completely insoluble in brass and tend to segregate to the solid-liquid interface during solidification. They then form isolated particles inside the grain and along the grain boundaries [6, 7]. Addition of 0.1 wt.% Bi in Cu-30Zn resulted in good performance in cold rolling. In contrast, further addition of Bi to 1 wt.% make it extremely brittle and the samples were destroyed upon cold rolling [6].

Rolling is a process to reduce the thickness of a plate. This process results in a strain hardening and it drives to increase the hardness of brass [8,9]. Brass, which has FCC structure and low

Stacking Fault Energy (SFE), may have three deformation mechanisms: slip, twinning and shear band. Yan et. al [10] found that an Cu-32Zn alloy with 20% deformation showed the domination of slip mechanism. A few twinning was also observed in the microstructure as twin boundaries. Meanwhile, at the deformation level more than 40%, the shear band mechanism was dominant. On the other hand, Duggan et. al [11] described that Cu-30Zn with 60% deformation already showed shear band mechanism. The shear band mechanism would increase with the increase of grain size [12].

Annealing process has such interesting phenomena as recovery, recrystallization and grain growth. Lower ductility of brass resulted by strain hardening will be recovered during annealing [13]. High annealing temperature at the range of 400-600 ^{o}C will increase the stretchability of Cu-30Zn alloy [14]. In this work, the effects of cold rolling followed by annealing process on the hardness and microstructures of Cu-29Zn-0.6Bi (wt. %) alloy was investigated. The research was intended to understand the detail of deformation mechanism and the role of bismuth during rolling and annealing process.

Experimental Methods

The Cu-29Zn-0.6Bi (wt.%) alloy was manufactured by gravity casting process at the melting temperature of 1150 ^{o}C. The ingots of pure of Cu, Zn and Bi were used as feeding materials. The molten metal was poured into a 600 ^{o}C preheated metal mold with the dimension of 110x110x6 mm^3. The as-cast plate was homogenized at 800 ^{o}C for 2 hours in a muffle furnace. The nominal composition of the as-homogenized alloy is shown in Table 1. The plate was then cold rolled with the level of deformation of 20, 40 and 70 % in multiple passes [8]. The samples with 70% deformation were then annealed at 350, 400 and 450 ^{o}C for 15 minutes followed by water quenching. Microstructural observation was conducted by using optical microscope and Scanning Electron Microscope (SEM). Standard sample preparation included polishing with 0.5 μm alumina and etching with 10 % $FeCl_3$ in alcohol for 5-10 seconds. Hardness testing was performed by Vickers method with 300 g of load.

Table 1. Nominal composition of the as-homogenized alloy.

Zn	Bi	Pb	Mn	Fe	Si	Cr	Al	Co	Cu
29.05	0.625	0.005	0.005	0.005	0.005	0.005	0.005	0.031	70.18

Results and Discussion

Microstructures

Fig. 1 (a-d) illustrate the microstructures of Cu-32Zn [8], while (e-l) show those of Cu-29Zn-0.6Bi alloy before and after deformation at various levels. Fig. 1(a) and (e) show large and equiaxed grains resulted by homogenization process of Cu-32Zn and Cu-29Zn-0.6Bi alloys, respectively. From Fig. 1 (e) and (i), it is clear that Bi has tendency to reduce the grain size. Bismuth was segregated inside the grain and along the grain boundary with irregular and globular forms. At the 20% level of deformation (Fig. 1 (b,f,j)), the grains and Bi particles are more elongated with L/d ratio of ~ 1.74 and ~3.3, respectively. The Cu-32Zn alloy showed the formation of twinning with large twinning bands but in low density. While in the Cu-29Zn-0.6Bi alloy, cross slip is the dominant mechanism although twinning with closely spaced twin lamellae has also started to form. The Bi particles, both inside the grains and along the grain boundaries were also deformed as shown in Fig. 1 (j). This phenomenon indicates that the presence of Bi retard the formation of twinning. Twinning is the result of identical motions of atoms of a plurality of rows parallel to a twinning plane in the original lattice [7]. The identical motion of atoms is made difficult by the presence of Bi.

At the deformation level of 40% (Fig. 1 (c,g,k)), twinning becomes more dominant with the appearance of twin boundary in both alloys, although the Cu-29Zn-0.6Bi alloy has higher density and closer spacing of twin lamellae. The grains and Bi particles become more elongated than 20% deformed samples, with L/d ratio of ~4.3 and ~4.2.

At the deformation level of 70%, the mechanism extremely changes and is dominated by shear band. Exceedingly elongated grains were observed at this level (Fig. 1(d,h,l)). Bismuth particles on the grain boundary flattened together to form continuous phase, resulting in more heterogeneities in the microstructure. Both grains and Bi particles have the highest L/d ratio of ~15 and ~33, respectively.

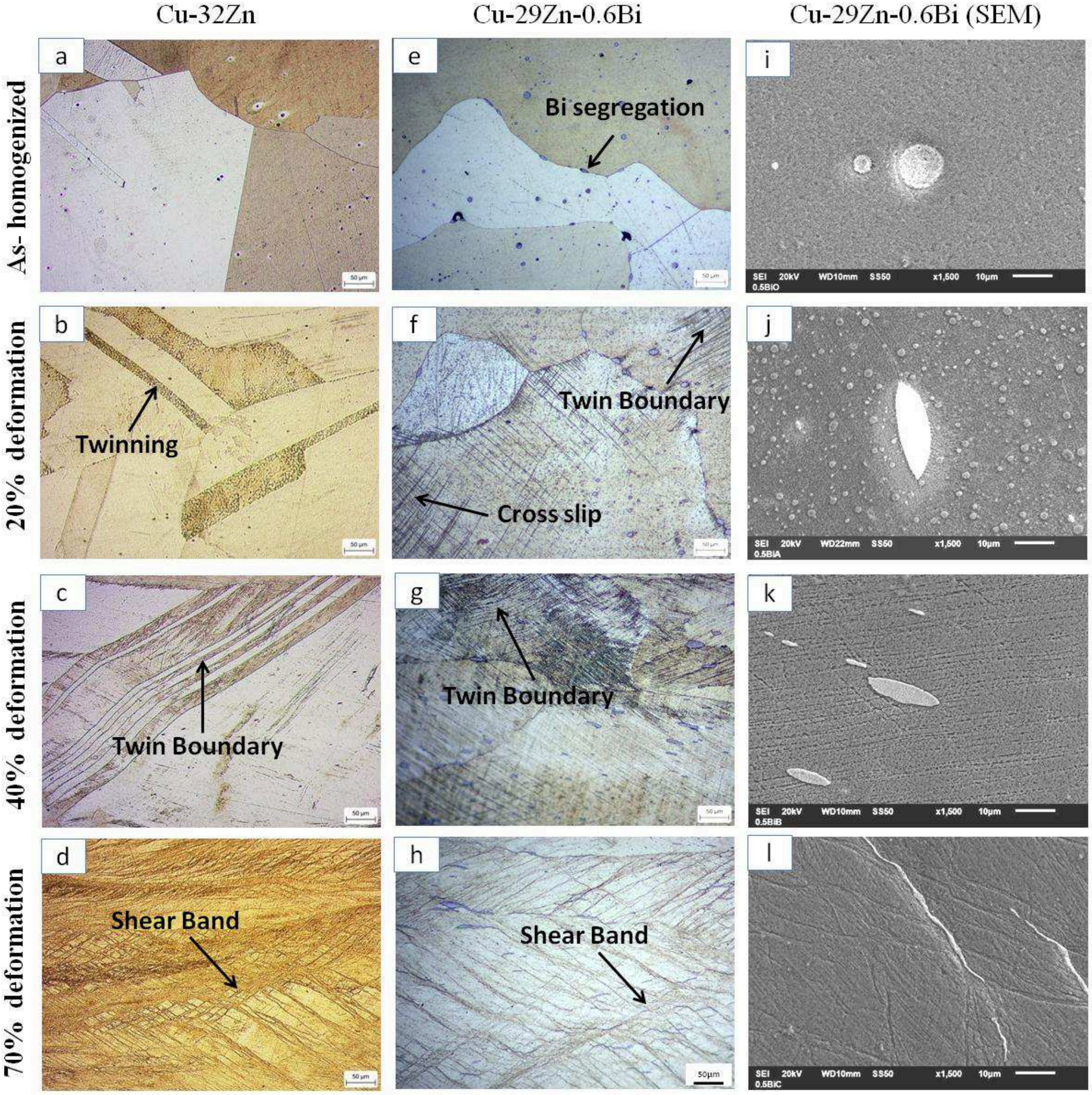


Fig. 1. Micrographs of (a-d) Cu-32Zn [8] and (e-l) Cu-29Zn-0.6Bi in as-homogenized condition and after cold rolling for 20, 40 and 70%.

Fig. 2 shows the microstructures of Cu-32Zn and Cu-29Zn-0.6Bi alloys after cold rolled for 70% and followed by annealing process at 300, 400, 500 ^{o}C for 30 minutes (for Cu-32Zn) [8] and 350, 400 and 450 ^{o}C for 15 minutes (for Cu-29Zn-0.6Bi). Fig. 2 (a) shows that recrystallization has started in Cu-32Zn alloy after annealing at 300 ^{o}C for 30 minutes. The recrystallization process started at the area of shear band, because this region is an area with high dislocation density and high energy [12]. The recrystallization was also prominent at the grain boundary, at which dislocations tended to interlock each other and promote dislocation density [8]. On the other hand, full recrystallization was already achieved by Cu-29Zn-0.6Bi after annealing process at 350 °C for 15 minutes. The faster recrystallization process in the Cu-29Zn-0.6Bi alloy compared to the Cu-32Zn alloy is thought to be due to the presence of Bi dispersoids, which act as nucleation site and promote the recrystallization. At the same time, the annealing temperature of 350 °C melted the Bi dispersoid, so that they dispersed into continuous structures in the grain boundary (Fig. 2 (g)). At the annealing temperature of 400 °C, the recrystallization process of Cu-32Zn is still running (Fig. 2 (b)) with resulting grain size bigger than that of the Cu-29Zn-0.6Bi (Fig. 2 (e)). This is due to the retardation of grain growth by the Bi dispersoids. Fig. 2 (c,f,i) illustrate the grain growth mechanism after recrystallization completed.

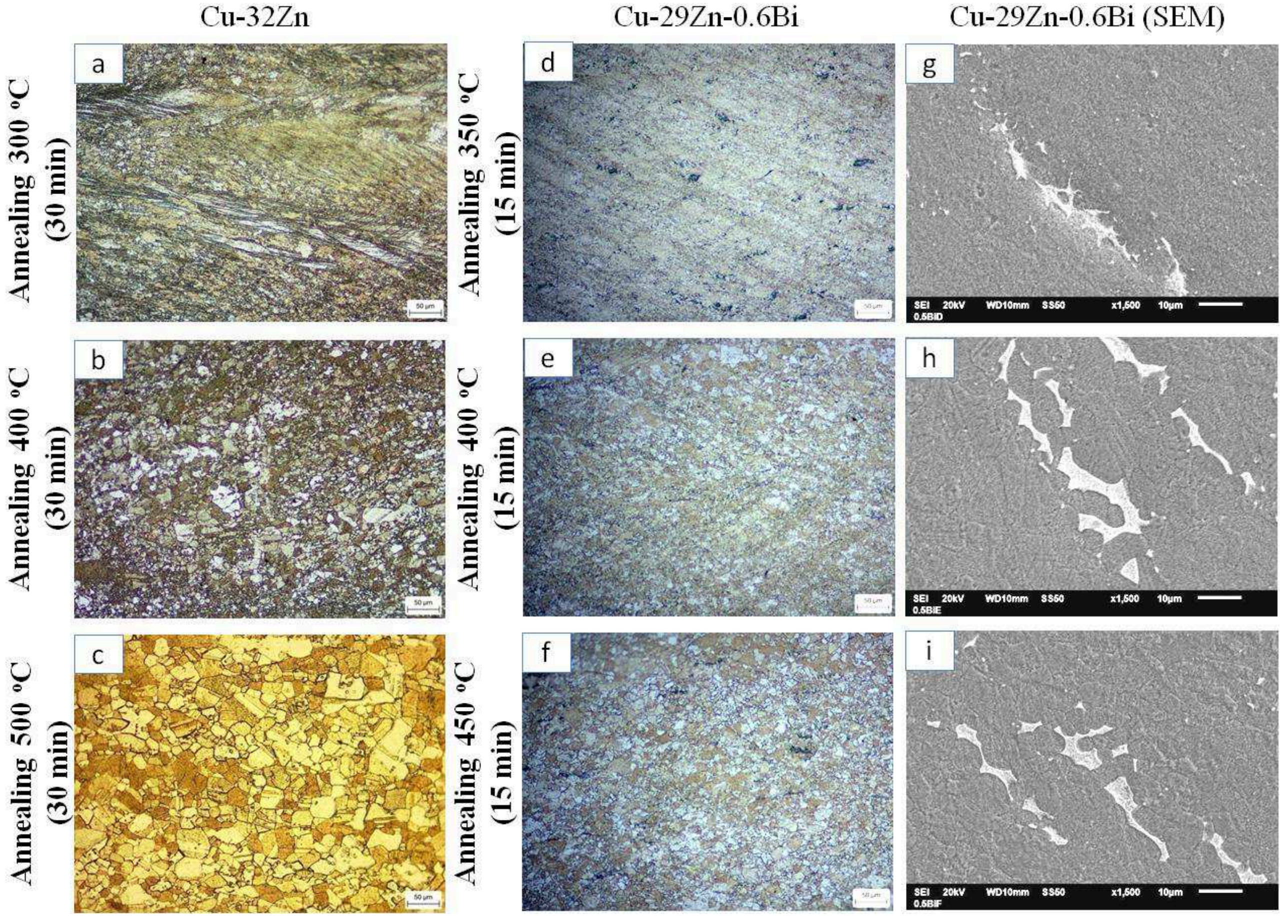
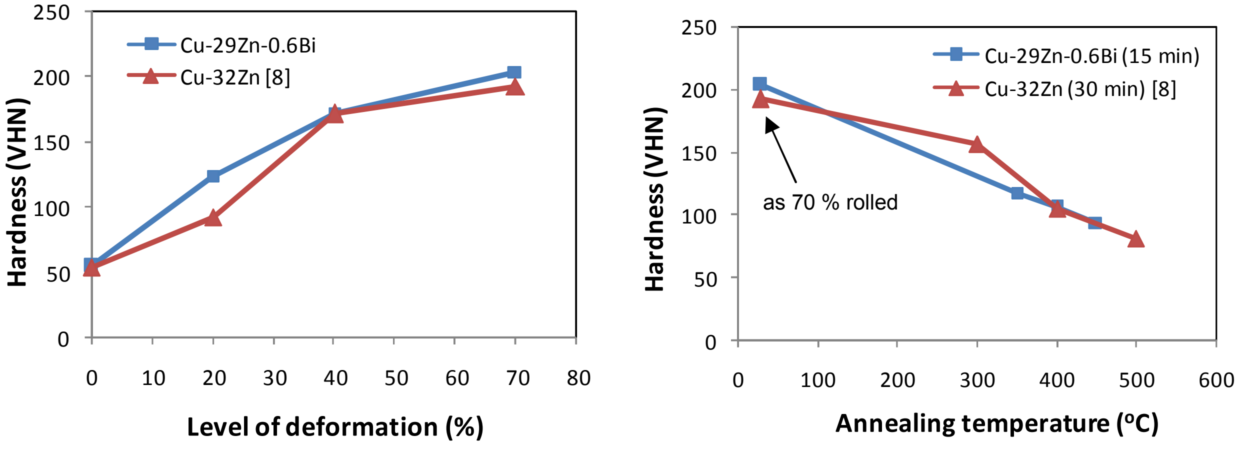


Fig. 2. Micrographs of (a-c) Cu-32Zn [8] and (d-i) Cu-29Zn-0.6Bi after cold rolling for 70%, followed by annealing at 300, 400, and 500 °C for 30 minutes (for Cu-32Zn) and 350, 400, and 450 °C for 15 minutes (for Cu-29Zn-0.6Bi).

Hardness

Fig. 3 (a) illustrates the hardness of Cu-32Zn [8] and Cu-29Zn-0.6Bi at various levels of deformation. The figure clearly shows that the hardness of samples increases with deformation level due to strain hardening. In general, the hardness of the Bi containing alloy is slightly higher than the base Cu-32Zn alloy. Both of undeformed samples have the lowest value of hardness (54 VHN). At 20 % deformation the two alloys show significantly different hardness, 92 and 124 VHN for Cu-32Zn and Cu-29Zn-0.6Bi, respectively. If we look at Fig. 1, at 20 % deformation, the base alloy undergoes twinning with large bands, while the Bi-containing alloy shows major cross-slip with a little amount of twinning along side with the flattening of Bi dispersoids. At 40% deformation, both alloys showed the increase in twinning density and resulted in higher hardness (172 VHN). The 70 % of deformation increased the hardness of the Cu-32Zn alloy to 192 VHN and the Cu-29Zn-0.6Bi alloy to 203 VHN. This is due to the presence of Bi dispersoids along the shear band structure, which makes the mechanism of homogeneous deformation is more difficult to form.

Annealing process reduces the hardness (Fig. 3 (b)) due to the recovery, recrystallization and grain growth mechanisms. Despite different rate of recrystallization and grain growth as shown in Fig. 2, the change of hardness of the two alloys after annealing is almost the same. The effects of Bi dispersoids somehow are nullified because of the annealing temperature is higher than the Bi melting temperature. The Bi dispersoids melted and formed continuous structures in the grain boundaries. Therefore, it reduces the effect of dispersion strengthening.



(a) (b)

Fig. 3. The change of hardness of Cu-32Zn [8] and Cu-29Zn-0.6Bi alloys (a) after cold deformation at 20, 40 and 70 % thickness reduction (b) after cold deformation for 70 %, followed by annealing at 300, 400, 500 °C for 30 minutes (Cu-32Zn) and 350, 400 and 450 °C (Cu-29Zn-0.6Bi) for 15 minutes.

Conclusions

The results of the observation on Cu-29Zn-0.6Bi can be concluded as follows:

1. The addition of Bi reduced the grain size and formed discrete Bi globules in the microstructure, so that increase the hardness of the alloy.
2. The increase of deformation degree was followed by the increase of hardness.
3. The Bi dispersoids deformed and filled intergranular spaces during rolling and promoted the formation of cross slip mechanism at the 20% deformation. At the 40% deformation, the presence of Bi globules resulted in the closely spaced twin lamellae and increased the twinning density. At the deformation level of 70%, the mechanism was dominated by shear band. Bismuth particles on the grain boundary flattened together to form continuous phase, resulting in more heterogeneities in the microstructure.
4. During the annealing process, Bi globules melted and dispersed into the interface of new grains. The presence of Bi dispersoid increased the rate of recrystallization during annealing due to the increase in potential nucleation sites. However, after recrystallization, the Bi dispersoids acted as the pinning agent for inhibition of grain growth. Therefore, in general the hardness of the Bi-containing alloy after annealing is relatively the same with that of the base Cu-32Zn.

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