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Effect of stacking fault energy on mechanical properties and annealing behavior of brasses

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ABSTRACT

The effect of stacking fault energy (SFE) on mechanical properties and annealing behavior of brasses was studied in Cu–20Zn alloy (SFE ~18 mJ/m^2) and Cu–20Zn–1.2Si alloy (SFE ~9 mJ/m^2) as well as Cu–20Zn–1.9Si alloy (SFE ~6 mJ/m^2) alloy. These brasses have been rolled at room temperature up to different thickness reductions. The significant improvement of strength in Cu–20Zn–1.9Si alloy is attributed to the formation of fine grains and high densities of dislocations and deformation twins by decreasing the SFE. Thermal stability is enhanced due to the reductions of dislocation mobility and grain boundaries migration during annealing by a decrease in SFE and addition of Si. High fractions of the {236} ⟨385⟩ Brass–R and (55; 30; 0) in Cu–20Zn–1.9Si alloy with lower SFE should be ascribed to the substantial Brass texture in deformed microstructures. Fine grains, deformation twins and abundant annealing twins were introduced into Cu–20Zn–1.9Si alloy by decreasing the SFE, resulting in superior strength–ductility combination.

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1. Introduction

It has been widely acknowledged that the dislocation slip and twinning are two competitive plastic deformation mechanisms in face–centered cubic (fcc) metals [1,2]. Stacking fault energy (SFE) is an important parameter which has closely related to the deformation mechanisms. To date, most researches have concentrated on in metals with relatively high values for SFE so that dislocation slip would be the dominant deformation mechanism in plastic deformation [3–5]. With decreasing the SFE, the deformation mechanism will transfer from dislocation slip to twinning, and the grain refinement mechanism in plastic deformation will also change [6]. In metals with the high or medium SFE, the substantial dynamic recovery occurs by balancing multiplication and annihilation of dislocations, more interactions between dislocations and grain boundaries are in favor of the annihilation processes. Accordingly, no more dislocation boundaries can be formed, impeding the further subdivision of grains [7]. Twinning, a prevalent deformation mechanism in low SFE metals, plays a significant role in grain refinement. It primarily stems from the interactions between dislocations and twin boundaries resulting in the fragmentation of twin bundles. Meanwhile, the role of shear bands in refining the original coarse grains is also crucial. Therefore, it is reasonable to expect that the grain size can be refined down to the nanoscale for metals with low or extremely low SFE even under relatively gentle deformation conditions [8,9].

Previous study [7] indicated that the strength and uniform elongation were simultaneously improved by decreasing the SFE in Cu–Al alloys. This simultaneity was attributed to the formation of profuse deformation twins and shear bands, and their extensive intersections. Although the overall mechanical properties were improved with decreasing the SFE, the uniform elongation was still limited. Therefore, in recent years much attention has been paid to developing strategies for improving the limited ductility [10–14]. Thermal annealing has been found to be effective on improving the ductility. It was found that SFE plays crucial role in thermal annealing [15–17].

Therefore, in this work, regarding the significance of SFE in plastic deformation and thermal annealing, the effect of SFE on the

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mechanical properties and annealing behavior of Cu–Zn and Cu–Zn–Si alloys was investigated. Meanwhile, the effect of SFE on the recrystallization texture and strength–ductility combination of these alloys during annealing was also studied.

2. Materials and methods

Cu–20%Zn, Cu–20%Zn–1.2%Si and Cu–20%Zn–1.9%Si alloys (all compositions are in weight percent) were prepared by induction vacuum melting. The addition of Si, the valance of which is four, leads to a significant decrease in SFE [18]. The ternary alloy is especially designed to obtain minimum SFE in copper rich alloys. SFEs of the ternary alloys were calculated using the following equation and available data on the SFEs of binary alloys [19,20]:

$$\frac{\gamma - \gamma_{Cu-Zn}}{\gamma_{Cu-Si} - \gamma_{Cu-Zn}} = \frac{C_a - (Al)_E}{(Zn)_E - (Al)_E} = \frac{2C_a}{e/a - 1} - 1 \quad (1)$$

where γ_{Cu-Zn} and γ_{Cu-Si} are SFEs for binary alloys with the same electron/atom ratio (e/a) as the ternary solid solution and with the respective atomic fraction contents $(Al)_E$ and $(Zn)E.C_a$ is the total atomic fraction of solute content. SFEs of Cu–20Zn, Cu–20Zn–1.2Si and Cu–20Zn–1.9Si alloys are 18 mJ/m^2, 9 mJ/m^2 and 6 mJ/m^2, respectively.

In order to homogenize the composition, the casting ingots with thickness of 15 mm were heated at 830 °C for 1 h and then hot–rolled to thickness of 5.5 mm. The plates were finally annealed at 490 °C for 50 min and then quenched in water. These alloys were then rolled at room temperature up to different thickness reductions. The X-ray diffraction (XRD) measurements were carried out on a Rigaku X-ray diffractometer equipped with a Cu target. The Vickers hardness was measured at room temperature under a load of 1000 g and for a duration time of 30 s. Measurements at least 9 different points for each sample were taken to obtain an average hardness. Tensile specimens have gauge lengths of 6 mm and widths of 1 mm. Tensile tests were conducted at an initial strain rate of 3×10^{-3} s^{-1} at room temperature. Electron backscatter diffraction (EBSD) observations were made in the longitudinal plane containing the rolling direction (RD) and normal direction (ND), the rolling plane containing the RD and transverse direction (TD), and the cross plane containing the TD and ND. To make reliable measurements, all low angle grain boundaries with a misorientation less than 2° were excluded. The misorientation of 15° was used as the criterion to distinguish the low angle grain boundaries (LAGBs) and high angle grain boundaries (HAGBs). Microstructures in the rolling plane and longitudinal plane were also determined using the transmission electron microscope (TEM) technique. Thin foils were prepared by utilizing a conventional jet polishing technique in a solution of 25% HNO_3 and 75% Methanol.

3. Results and discussion

3.1. Deformed microstructures and tensile properties of brasses

The three–dimensional EBSD microstructures of the Cu–20Zn and Cu–20Zn–1.9Si alloys after a thickness reduction of 30% are shown in Fig. 1. Cu–20Zn alloy exhibits relatively coarse grains compared to Cu–20Zn–1.9Si alloy in all three planes. Cu–20Zn alloy shows deformed grains, which are elongated along the RD and TD in the longitudinal plane and cross plane, respectively. However, the severely fragmented and elongated grains were observed in Cu–20Zn–1.9Si alloy. As compared to Cu–20Zn alloy, the length of the elongated grain size is less in Cu–20Zn–1.9Si alloy.

Fig. 2 shows the micrographs of Cu–20Zn and Cu–20Zn–1.9Si alloys after a thickness reduction of 90%. A heavily deformed microstructure and dislocation cells were observed in Cu–20Zn alloy, as shown in Fig. 2a. The microstructures of Cu–20Zn alloy exhibit lamellar grains lying parallel to RD in Fig. b. As compared to Cu–20Zn alloy, a severely deformed microstructure with ill–defined grain boundaries and much higher dislocations density as well as lamellar grains were observed in Cu–20Zn–1.9Si alloy. Moreover, deformation twins (marked by circles in Fig. 2b, d) inclined to the RD by an angle of 45° were observed in Cu–20Zn–1.9Si alloy.

The dislocation density, twin density and grain size of the Cu–20Zn, Cu–20Zn–1.2Si and Cu–20Zn–1.9Si alloys were measured by using XRD analysis. The dislocation density ρ can be calculated based on microstrain, using the following equation [19]:

$$\rho = 16.1 \times \varepsilon^2 \Big/ b^2 \quad (2)$$

where ε is the microstrain, b is the Burgers vector and $b = (\sqrt{2}/2)a$, and a is the lattice constant in fcc metals. The twin density β, defined as the probability of finding a twin boundary between any two neighboring {111} planes, may be calculated based on the equation [21,22]:

$$\beta = \frac{\Delta C.G.(2\theta)_{111} - \Delta C.G.(2\theta)_{200}}{11 \tan \theta_{111} + 14.6 \tan \theta_{200}} \quad (3)$$

where $\Delta C.G.(2\theta)_{111}$ and $\Delta C.G.(2\theta)_{200}$ are the angular deviations of the gravity center from the peak maximum of the {111} and {200} XRD peaks, respectively. The grain size can be calculated by the Williamson–Hall method [23]. It is known that XRD analysis often yields a smaller grain size because it measures the sizes of coherent–diffraction domains [24]. The calculated results of these three main factors are shown in Table 1. An increase in the dislocation density and twin density from 1.6×10^{15} m^{-2}, 0.05% to 6.1×10^{15} m^{-2}, 0.26% when the SFE decreases from 18 to 6 mJ/m^2 for Cu–20Zn alloy and Cu–20Zn–1.9Si alloy, respectively. The grain size decreases from 103 to 42 nm with decreasing SFE from 18 to 6 mJ/m^2.

It is well known that SFE has close relationship with the deformation mechanisms [25]. On one hand, a decrease in SFE facilitates the full dislocations to split into two partials with a wide stacking fault between them, the lower the SFE, the wider the stacking fault [26]. The stacking fault can acts as a barrier for full dislocations to cross slip or climb, which suppresses the dislocation recovery via cross slip and climb [23]. On the other hand, with decreasing SFE, the stress necessary for dislocation slip is greater than that for twinning, and deformation twins would easily form with decreasing SFE [1]. Moreover, deformation twins caused by lowering SFE may serve as locations for dislocation accumulation [27]. Consequently, a lower SFE usually leads to a higher dislocation density and twin density. As proved by the results of TEM and XRD.

SFE determines not only the deformation mechanisms but also the grain refinement mechanisms. For metals with medium to high SFE, dislocation subdivision is the dominant grain refinement mechanism due to the extensive dislocation movement. With a decrease in SFE, deformation twins would be prevalent in plastic deformation [28,29]. The grain refinement mechanism gradually transfers from the dislocation subdivision to twin fragmentation. The twin fragmentation is more effective in grain refinement [30]. Therefore, finer grain size is achieved in metals with lower SFE.

Fig. 3 shows the engineering stress–strain curves of Cu–20Zn, Cu–20Zn–1.2Si and Cu–Zn–1.9Si alloys after a thickness reduction of 90%. A significant improvement in ultimate tensile strength (UTS) from 675 MPa to 1002 MPa, and an improvement in uniform elongation (UE) and total elongation from 3.8%, 8.5% to 5.4%, 9.6%

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