Inhomogeneous Deformation of Multilayered Roll-Bonded Brass/Cu Composites

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Abstract The deformation gradients in multilayered hot roll-bonded composite materials incorporating two dissimilar face-centered cubic metals, i.e., brass and Cu, were investigated by characterizing the deformation microstructure, hardness and texture at different thickness positions of the composites. For the constitutive metals, the center part of each metal sheet forms the substructure containing coarse grains, while the ultrafine grains and significant shear banding form in the outer part. As deformation increases, the cross-interface shear occurs in the Cu sheet of the composites. Then, grain fragmentation, shear banding and dynamic recovery become the main factors that influence hardness of the metal. Moreover, in the co-deformed composites, the interface between brass and Cu plays a role in texture developments of the individual metals.

KEY WORDS: Deformation; Multilayers; Brass/Cu composites; Texture

1 Introduction

Multilayered metallic composites incorporating different metals belong to a new class of materials. In such materials, multiple layers of dissimilar metals are combined together to form one single unit with ultrafined microstructures. As the unit combines advantages of the constitutive metals, better properties, e.g., mechanical, electrical and magnetic

properties, can be obtained for one composite material than that for the individual metals [1–3].

Fabrication of multilayered metallic composites can be accomplished by either the “bottom-up” methods such as direct current magnetron sputtering [4] or the “top-down” methods by performing severe plastic deformation (SPD) [5, 6]. With the development of SPD techniques, accumulative roll bonding (ARB), involving repetitive cutting, stacking and roll bonding of sheet metals under non-lubricated conditions, becomes most promising in producing multilayered composites [7, 8]. This is because with this method multilayered materials on a bulk scale can be obtained. In the past decade, deformation of the ARB-processed composite materials has been widely investigated [9–17]. In addition to the plane strain compression loading applied by the rollers, the ARB-processed metal surfaces also undergo shear deformation, due to the large friction between the metal and the roll surfaces. Consequently, a strong gradient of deformation through the thickness of sheets as well as through-thickness gradients in the microstructure occur [8, 13]. On the other hand, due to the inhomogeneous deformation of the materials, texture

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distributions during ARB also vary among the different thickness positions. As textures may strongly influence the mechanical properties and formability of metals, recently, some attention has been placed on understanding texture gradients in the multilayered metal sheets during ARB [13, 18, 19]. However, most of the research is focused on the multilayers incorporating only one single metal, while the study on correlations between structural morphologies, properties and texture distributions in the multilayers incorporating dissimilar metals is quite limited.

Therefore, in this work, we utilize confocal laser scanning microscopy (CLSM), hardness tests and X-ray diffraction (XRD) to study the inhomogeneous deformation of the roll-bonded composites incorporating two dissimilar face-centered cubic (fcc) metals, i.e., brass and Cu. It should be mentioned that, for the individual fcc brass and Cu under conventional rolling conditions, the texture development ranges between two types, i.e., the brass-type [containing the $\{011\} \langle 211 \rangle$ (brass) and $\{011\} \langle 100 \rangle$ (goss) texture components] and the copper-type [containing the $\{112\} \langle 111 \rangle$ (copper) and $\{123\} \langle 634 \rangle$ (S) texture components], depending on the stacking fault energy (SFE) [20–23]. For the fcc materials like Cu with high SFE, dislocation glide is the main mechanism during cold rolling, and accordingly, the copper-type textures are developed. In contrast, in the metals like brass with low SFE, mechanical twinning and shear banding occur together with dislocation glide as main deformation carriers particularly at large plastic deformations. The resulting rolling textures are characterized by the brass-type texture components. By studying microstructures, hardness and textures of the roll-bonded brass/Cu composites, the current research will bring insights into the characteristics of the deformation gradients in microstructures constituting the hetero-phase interfaces between brass and Cu. Besides, it is hoped that the results are helpful in exploring the correlation between the inhomogeneous deformation and the

formability of the multilayered composites under ARB and other deformation modes.

2 Experimental

The starting materials are brass (Cu-38 wt% Zn) and pure Cu (99.99% purity), which are in the form of commercially hot-rolled sheets, with 0.8 and 0.2 mm in thickness, respectively. First, the as-received metals were annealed at 600 °C for 1 h to reduce the residual stress, which was taken as the initial states of the materials in the current study. The microstructures obtained by employing the optical microscope on the longitudinal sections containing the rolling direction (RD) and the normal direction (ND) of the both metals at the initial state are displayed in Fig. 1. Brass contains an fcc α -CuZn matrix which is equiaxed and has the minor B2-structured β' second phase dispersed at the α grain boundaries. The average grain size of the α phase is about 35 μm , and the volume fraction of the β' phase is $<2\%$. Cu also presents an equiaxed but fine microstructure with the average grain size of about 15 μm . Subsequently, two pieces of Cu sheets and two pieces of brass sheets were degreased, wire brushed and mutually stacked for the roll-bonding experiment. The rolling mill was furnished with two rollers with a diameter of 92 mm and a rolling speed of 7 m/min without lubricate. The rolling process was carried out at 200 °C to reach several different reductions, i.e., 52%, 57%, 66% and 73%, of the initially stacked specimen thickness, and only one cycle was applied for each of the above-mentioned thickness reductions. After rolling, four sheets of multilayered Cu/brass specimens were obtained.

To clearly reveal slip and shear band morphologies of the deformed brass/Cu specimens, CLSM with a planar resolution (namely, in the observed plane) of 120 nm and a height resolution (in the direction perpendicular to the

Fig. 1 Optical micrographs on the longitudinal section containing RD and ND of brass **a**, Cu **b** at the initial state

observed plane) of 10 nm was applied. The CLSM observation was made on the longitudinal section of the rolled sheets. The Vickers hardness measurements were taken from the transverse direction (TD), namely on the plane parallel to RD and ND. A 401 MVDTM digital sclerometer was used on the polished surfaces under an applied load of 0.1 N for 15 s. To test the hardness of the brass sheets, indents were only made on the α matrix. Moreover, for the specified thicknesses of a stacked specimen, at least ten measurements were taken to obtain an average hardness value. To reveal the orientation distributions in both brass and Cu in the co-deformed metal sheets, the pole figures for {111}, {200} and {220} at different thicknesses of the 73% rolled specimen were measured by the laboratory XRD technique, with a radiation of $\text{CuK}\alpha$ in reflection geometry. A plane specimen with a size of 20 mm (RD) $\times$ 20 mm (TD) was extracted from the rolled sheet by an electro-discharge machine. The textures were then measured sequentially after careful grinding and polishing the specimen to different thickness positions. As schematically shown in Fig. 2, textures of three layers (-surface, center and interface) of the outer metals adjacent to the rollers and those of two layers (center and interface) of the internal metals away from the rollers were measured. The experimental pole figures, after defocusing and background corrections, were used to determine crystallographic orientation distribution functions (ODFs), i.e., $f(g)$, for each layer by using the Labo-Tex texture analysis software [24]. The orientations were expressed by a triple of Euler angles (φ_1 , Φ , φ_2) in Bunge's notation, and $\{hkl\} \langle uvw \rangle$ was used for characterizing the texture type with $\{hkl\} // \text{ND}$ and $\langle uvw \rangle // \text{RD}$.

Fig. 2 Schematic of a roll-bonded brass/Cu specimen

3 Results and Discussion

3.1 Microstructure

Confocal laser scanning microscopy observations on the longitudinal sections of the specimens at different thickness reductions are given in Fig. 3. For all the specimens, an elongated microstructure along RD is observed in both brass and Cu. In brass, obvious grain subdivision and shear bands that form an angle of $\sim 35^\circ$ to RD are clearly identified, which is generally consistent with the previous work performed on highly rolled fcc metals of low SFE such as Ag and brass [20, 22]. One may note that for the softer Cu, unlike the outer metal sheets, the internal Cu that is away from the rollers undergoes the less rigid constraint forced by the rollers. Therefore, a significant curvature can be found in the internal Cu sheets in all the specimens. Besides, as deformation increases, the internal Cu becomes to be more severely curved, and then the localized necking of the Cu sheet occurs in the 66% and 73% rolled specimens. In the rolling process of the brass/Cu multilayered materials, the whole sheet thickness follows the roller movement and necking may occur in a single metal with the interaction between the adjacent metals. Formability of the hard metal with relatively high strength and work harden ability is reported to be the determining factor that controls necking and layer continuity [25]. However, in this case, the soft metal, Cu, shows necking preferentially. This is because in addition to the flow properties of the constitutive metals, the larger initial thickness of the hard metal (brass) in the stack prevents necking of the brass sheets.

Figure 4 shows the detailed microstructures of the 73% rolled specimen under different magnifications. As it can be seen that, in the center layer of the brass sheets, some dispersed large grains are commonly observed, which is due to the fact that the center part within the metal bears much less shear stresses compared with the edge part adjacent to the Cu sheet or the rollers. Therefore, the heterogeneity of deformation is observed on the mesoscale. Namely, for the constitutive metals, the center part of each sheet forms the substructure containing coarse grains, while the ultrafine grains and significant shear banding form in the outer part. Moreover, shear banding is also clearly identified in the Cu Sheet (Fig. 4b). This is quite different from the deformation structure expected for rolled pure Cu with medium SFE [21, 22], which will be discussed later. The shear bands in Cu corresponding to the highly localized strain also induce severe curvature of the Cu/brass phase boundary. Finally, some β' grains are identified in Fig. 4c. The appearance of these grains altered the original direction of the shear bands that is inclined at approximate 35° to RD.

Fig. 3 CLSM micrographs observed on the longitudinal sections of the brass/Cu specimens after different rolling reductions: **a** 52%; **b** 57%; **c** 66%; **d** 73%

Fig. 4 CLSM micrograph observed on the longitudinal sections of the 73% rolled brass/Cu specimen **a** and the magnified images of the selected regions in **a** of Cu **b** and brass **c** areas

3.2 Vickers Hardness

Figure 5 shows the Vickers hardness of the specimens after different rolling reductions measured as a function of specimen thickness. The hardness of brass and Cu at the initial state is 198 HV and 194 HV, respectively. The following features are noteworthy.

In the 52 and 57% deformed specimens, the hardness of the both metals increases with increasing rolling reductions. Moreover, the hardness in both brass and Cu layers shows inhomogeneous distributions. Namely, the hardness in the region adjacent to the brass/Cu boundaries is lower than those in the interior of the metals (Fig. 5a, b). This may be attributed to the localized strain in regions closed to the brass/Cu interfaces. One may note that significant shear bands occur in the brass layers because of its low SFE. Then, it is assumed that the activation of the shear banding induces the very large shear stress concentration at the brass/Cu interfaces, and thus, strongly affects the hardness of the neighboring metals. Besides, the hardness in brass is generally greater than that in the Cu sheets, due to the much larger strain hardening in the former metal [26, 27]. Even though brass is stronger than Cu, as seen in the distribution of the hardness values, the shear banding region of the hard metal (brass) is severely narrowed along

ND. This leads to the necking of the hard metal in composite materials. As indicated by the current study, the localized plastic instability in the shear banding region leads to the curved lamellar structure. Accordingly, when deformation is large enough, the shear can propagate along the shear band direction. This explains the cross-interface shear found in the Cu sheet of the specimens at large rolling reductions. Similar behavior has also been reported to occur in some other ARB-processed multilayer composites, such as Al/Ni [10] and Al/Cu [25]. In these materials, when necking forms in the hard layer of the multilayer, localized deformation of the soft layer occurs in the vicinity of the neck.

When the reduction is larger than 57%, the hardness of brass decreases with deformation increasing (Fig. 5c, d). Regarding this phenomenon, two factors should be considered: First, as rolling reduction increases, shear banding is more extensively activated in brass. In particular, in regions adjacent to the rollers, the high density of shear bands leads to the significant decrease in hardness compared to that in the 52% and 57% deformed specimens. Second, for the specimens rolled at 200 °C, dislocation motion and even dynamic recovery might occur in the both metals and this tendency becomes more apparent with deformation. So the stress relaxation induced by dislocation motion acts as the

Fig. 5 Vickers hardness (HV) obtained at different thicknesses of the 52% **a**, 57% **b**, 66% **c** and 73% **d** rolled brass/Cu specimens. In the plots, the x-axis indicates the distances from “surface” layer of the outer Cu sheet to positions where the hardness indentations locate

other reason for the decrease in hardness in the brass sheets. On the other hand, the hardness of the Cu sheets shows a continuously increasing tendency with deformation, even though recovery also occurs in this metal. The hardness of the Cu sheet adjacent to the rollers reaches a maximum at 73% deformation and is even greater than that of the brass layers. This can be attributed to the larger shear stress undertaken by the outer Cu adjacent to the rollers than that by the central parts of the specimen. To this stage, it is clear that grain fragmentation induced by large shear stress, shear banding and dynamic recovery is the main factor that influences the hardness of the specimens. Grain subdivision contributes to an increase in hardness of both brass and Cu sheets, whereas shear banding and recovery induce the softening of the metals. Then, the three factors compete against each other during deformation, leading to the inhomogeneous distribution of hardness in the same specimen at different thicknesses as well as the variation of hardness among the specimens after different rolling reductions.

3.3 Texture Distribution

To clearly see texture development in the co-deformed brass and Cu, the measured orientation densities at the

different thickness positions of the 73% rolled specimen along the α fiber composing of the $\{011\} \langle 100 \rangle$ (goss) and $\{011\} \langle 211 \rangle$ (brass) components, the β fiber composing of the $\{112\} \langle 111 \rangle$ (copper), $\{123\} \langle 634 \rangle$ (S) and brass components, and the τ fiber composing of the $\{001\} \langle 110 \rangle$ (rotated-cube), copper and goss components are presented as functions of the Euler angles φ_1 , φ_2 and Φ , respectively (Figs. 6, 7). Textures of the both metals at the initial state (after the preprocessing of hot rolling by the manufactory and annealing by us) are also shown. Before roll bonding, the main orientations in brass and Cu are brass and copper components, respectively. These orientations belong to the textures typically found in rolled fcc metals and alloys [20, 21]. It should be mentioned that the $\{001\} \langle 100 \rangle$ (cube) orientation is also found in Cu without roll bonding, indicating that recrystallization has occurred in the metal during annealing at 600 °C. However, as the cube texture component does not belong to the deformation textures of fcc materials, we do not pay much attention to this orientation in the current research.

The fiber plots for the different thicknesses of the brass sheets show that goss component is the main texture in the various layers of the metal, whereas in the internal brass sheet, the brass component is much stronger than that in the

Fig. 6 Textures at different thickness positions of brass in the 73% deformed specimen, using α and τ fiber representation: **a** α fiber with constant Euler angles $\Phi = 45^\circ$ and $\varphi_2 = 0^\circ$; **b** β fiber with local maximum texture intensity along a *skeleton line* (with variable coordinates); **c** τ fiber with constant Euler angles $\varphi_1 = 90^\circ$ and $\varphi_2 = 45^\circ$

Fig. 7 Textures at different thickness positions of Cu in the 73% deformed specimen, using α and τ fiber representation: **a** α fiber with constant Euler angles $\Phi = 45^\circ$ and $\varphi_2 = 0^\circ$; **b** β fiber with local maximum texture intensity along a *skeleton line* (with variable coordinates); **c** τ fiber with constant Euler angles $\varphi_1 = 90^\circ$ and $\varphi_2 = 45^\circ$

outer sheet. Both the goss and brass texture components are typical for the conventionally rolled (under plane strain condition) fcc materials with low SFE; thus, it is inferred that deformation in the brass sheet away from the rollers is more homogeneous than that in the sheet adjacent to the rollers. For the outer Cu sheet, some shear textures,

including the $\{111\} \langle 112 \rangle$ (brass-R) and $\{001\} \langle 110 \rangle$ (rotated-cube) orientations, are found in the three layers (surface, center and interface) of the metal. It should be mentioned that after deformation no significant change in the sample dimension in TD is found, so the transverse shear during roll bonding is neglected in this work. The

above orientations belong to the typical texture components of simple shear in the ND–RD plane for fcc materials [28]. Moreover, textures in the surface and interface layers are stronger than that in the center layer, indicating that as rolling proceeds both the roller and the brass sheet adjacent to the outer Cu give a significant shear to the outer Cu sheet. For the center and interface layers in the internal Cu, the main rolling textures consist of the copper, goss and brass components. As mentioned before, these characteristics of textures are typical of conventional rolling. However, it is obvious that in the center layer, the copper component dominates over all other components, while in the interface layer, the intensity of the copper orientation has been reduced and is comparable to that of the goss and brass orientations. As the texture components in the center layer of the internal Cu should represent the copper-type rolling texture expected for the rolled pure fcc metals with medium or high SFEs, the rolling textures found in the interface layer of the same Cu sheet are found quite interesting. This result suggests that the adjacent brass or brass/Cu interface may play a role in the texture development of the Cu sheet when the two metals are under co-deformation. Consistent results have also been reported in a 75% rolled Cu–Ag eutectic composite, in which the Cu and Ag phases develop the similar textures, i.e., the less copper-type but the more brass-type texture components [29]. Actually, textures developed in ARB-processed composite materials are often evaluated in comparison with those of conventional rolling or simple shear deformation [13, 18], which indicates that strong texture gradient exists through the rolled sheet thickness from rolling-type textures at the center to shear-type textures near the surface. In the current study on the roll-bonded composites with dissimilar metals, however, in addition to those general agreements, the new finding is that the brass/Cu interface leads to the unique textures at the interface between the constitutive metals. The similar finding in two-phase lamellar composites during ARB is rarely reported in literature as the research on texture evolution in these materials is quite limited. Such phenomenon needs to be clarified in understanding the correlation between the texture evolution and the deformation behavior of the metals.

Considering the characteristic texture evolution in the co-deformed brass/Cu or Cu–Ag eutectic composites [29], two implications emerge: First, Cu deforms via the similar relative proportions of dislocation slip and twinning as brass or Ag. Then, in the Cu sheet, twinning would contribute to the weakening of copper-type textures and the strengthening of brass-type textures. However, the studies on the rolled Cu–Ag composite place this idea in question, because twinning is not identified as an important deformation mechanism in the Cu phase [29]. Second, for fcc materials at large deformations, non-crystallographic

deformation in the form of shear banding can be initiated by a mechanical instability that contains band-like dislocation cells in high SFE metals [30, 31] or twin-matrix lamellae in low SFE metals [21]. In both cases, shear banding leads to the weaker copper-type but the stronger brass-type textures. More specifically, even though significant fine twins have formed at moderate deformations, the elevation of twin volume fraction gives a minor contribution to the texture change with further deformation. Instead, at high strains shear bands that cut through the profuse twin boundaries have a decisive effect on the texture transition from the copper type to the brass type. This would mean that in the Cu sheet of the studied brass/Cu specimens more shear banding may be activated at the interface layer compared to that at the center layer. According to the recent finite element modeling of plane strain compressed Cu–Ag and Cu–Nb metal matrix composites [32], pronounced shear bands are triggered by stress concentration at the phase boundaries, due to the fact that deformation has to be accommodated between the adjacent metals. Also as observed in the deformation structures of the brass/Cu composite (Fig. 4), the curved lamellar structure is a result of local plastic instability in the shear banding region, and, as rolling reduction increases, the shear further propagates along the shear band direction. Then, when a large amount of shear bands are activated in either metal (brass) of the composite, highly localized strains that correspond to a softening of the shear banding regions and lattice reorientations within the bands would occur in both the metal and its neighboring material (Cu).

4 Conclusions

Inhomogeneous deformation at different thickness positions of the roll-bonded brass/Cu composite specimens was investigated. The main results can be summarized as follows:

- (1) The heterogeneity of the deformation can be observed on the mesoscale. Namely, for the constitutive metal sheets, the center part of each sheet forms the substructure containing coarse grains, while the ultrafine grains and significant shear banding form in the outer part.
- (2) The shear banding that is not expected for rolled pure Cu occurs in the Cu sheet of the composite materials and induces severe curvature of the Cu/brass phase boundary. This is attributed to the fact that, at large rolling reductions, shear propagates along the shear band direction from brass to Cu.
- (3) Grain fragmentation, shear banding and dynamic recovery are the main factors that influence the

hardness of the specimens. During deformation, the three factors compete against each other, leading to the inhomogeneous distribution of hardness in the same specimen at different thicknesses and the variation of hardness among the specimens after different rolling reductions.

- (4) The adjacent brass or brass/Cu interface plays a major role in the texture development of the Cu sheet when the two metals are under co-deformation. In the Cu sheet of the studied brass/Cu specimens, more shear banding may be activated at the interface layer compared to that at the center layer, which leads to the reduced copper texture component in the former.

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