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Delaying premature local necking of high-strength Cu: A potential way to enhance plasticity

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A cold-rolled metal sheet is usually of high strength but low plasticity due to the onset of premature local necking. Here, we reveal that the tensile plasticity of cold-rolled Cu can be effectively enhanced by a layered structure stacked alternately by thicker Cu and thinner Al layers. The layer interface in the composite strongly constrains and delays the development of premature local necking of the cold-rolled Cu layer. A potential way to improve plasticity without losing strength is suggested.

Keywords: Plasticity; Cu/Al laminated composite; Cold-roll bonding; Uniform elongation

Strength and plasticity are usually a pair of paradoxical mechanical properties. The improvement in strength of a material through continuously decreasing the scale of its microstructure has to be at the cost of losing plasticity [1–5]. The physical reason for the paradox is that the decrease in microstructure scale inevitably results in the degradation of the material's strain-hardening ability, which triggers plastic strain localization in the form of necking or shear banding. Thus a strategy how to prevent or delay the onset of premature local necking or shear banding so as to sustain a large uniform deformation may be effective against the degradation of the plasticity of the material.

Laminated structures found in biological materials, such as nacre, have stimulated attempts to optimize the mechanical properties of conventional structural materials [6,7]. With regard to nanoscale multilayers, Misra and co-workers [8,9] showed that deformability of a few nanometers can be enhanced by adjusting the constituent layers and interfaces. Here we design and produce a laminated structure stacked alternately by thicker Cu and thinner Al layers through a cold-roll bonding method [10]. The tensile plasticity of the laminated composite can be enhanced effectively by introducing a stronger interface between the layers, which can strongly constrain and delay the development of premature local necking of the cold-rolled Cu layer. A potential way to improve plasticity without losing strength is proposed based on the present study.

We designed two kinds of materials to examine comparatively the variation in plasticity and strength. One is an annealed 460 μm thick copper sheet (a commercial purity of 99.9%), which was subjected to three passes of cold-rolling. The other one is also a copper sheet, but was stacked alternately with annealed 10 μm thick Al 8011 sheets, then cold roll-bonded into a Cu/Al laminated composite. The laminated composite was also rolled for three passes to reduce the number of voids at the interface, which could enhance shear localization in tension [11]. Both the Cu/Al laminated composite and the cold-rolled Cu were deformed severely through three-pass cold-rolling. The reduction of each rolling pass was about 50% (equivalent strain $\varepsilon = 87.5\%$). The laminated composites and the cold-rolled Cu were then annealed at 160, 200, 240 and 280 °C, respectively, for 8 min under a vacuum condition of 10^{-3} Pa to get different interface bond toughnesses.

Uniaxial tensile tests of the materials were performed on a testing machine (Instron E1000 Microtester) at a strain rate of $10^{-4}\ s^{-1}$ at ambient temperature, and the tensile direction was parallel to the rolling direction of the sheet. The bond toughness of the Cu/Al interface

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was also measured using double-cantilever beam testing method [12]. The cross-head speed was 2 mm min^{-1}, and the dimensions of the specimen were $0.24 \times 10 \times 80$ mm^3. The in-plane microstructures of the laminated composite were characterized by transmission electron microscopy (TEM) using a JOEL FX2000 II transmission electron microscope operating at 200 kV. Cross-section morphologies, fracture surfaces and interface compositions of the multilayer composite were observed by scanning electron microscopy (SEM) using a ZEISS Supra 35 scanning electron microscope with an Oxford Inca energy-dispersive X-ray spectrometer.

Figure 1(a) and (b) presents SEM cross-sectional views of the Cu/Al laminated composite after three-pass roll bonding and annealing at 240 °C, respectively. During roll bonding of a laminated composite, the hard constituent layer can neck due to the different properties of the two constituent layers, leading to plastic instability [13–15]. Here, both the Cu and Al layers in the composite could be deformed uniformly and were bonded well. The thicknesses of the rolling-deformed Cu and Al layers are about 61 and 1.35 μm, respectively. Energy-dispersive X-ray spectrometry (EDS) analyses revealed that, after heat treatment, intermetallic compounds, Cu_3Al_2, have formed at the Cu/Al interface, as determined subsequently by X-ray diffraction. The thinner Al layer is consumed gradually with increasing annealing temperature, and is completely depleted to generate the brittle intermetallic compound layer at 280 °C.

TEM plan-views of microstructures of the Cu layer after three-pass roll bonding and annealing at 240 °C

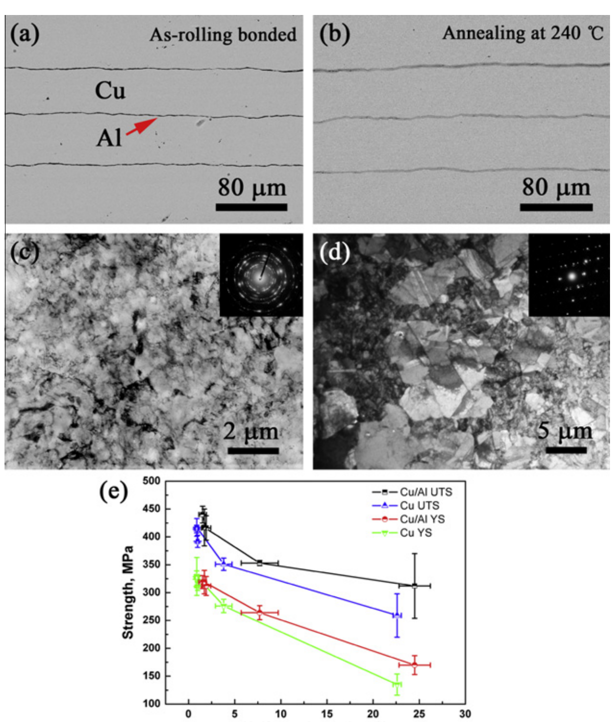

Figure 1. SEM morphologies of (a) three-pass roll-bonded Cu/Al laminated composite and (b) that annealing at 240 °C observed from the tensile direction. (c and d) Corresponding TEM observations of the Cu layers. (e) Plots of uniform elongation vs. strength for the roll-bonded Cu/Al laminated composite and the cold-rolled Cu.

shown in Figure 1(c) and (d), respectively, indicate that typical dislocation cells or subgrain structures were formed within the grains. The grain size of the Cu layer is about 1.88 μm. With increasing annealing temperature, the volume fraction of the micrometer-sized grains increases gradually and could reach about 80% after annealing at 240 °C. Complete recrystallization, which occurred at 280 °C, resulted in the microstructure of the Cu layer consisting of micrometer-sized grains with some annealed twins. For the individual Cu layer, which was about 60 μm thick, the length scale effects on recrystallization could be neglected [16]. The recrystallization procedure was thought to be the same for both the Cu/Al laminated composite and the cold-rolled Cu.

Figure 1(e) presents uniform elongation vs. strength for the roll-bonded Cu/Al laminated composite and the cold-rolled Cu. One can find that the as-roll-bonded Cu/Al laminated composite has an ultimate tensile strength (UTS) of about 440 MPa, which is slightly higher than that of the cold-rolled Cu under the same conditions, and the as-rolled samples have nearly the same yield strength (YS), at about 320 MPa. However, the uniform elongation of the composite is enhanced compared with that of the cold-rolled Cu. With increasing annealing temperature, both the laminated composite and cold-rolled Cu exhibit a continuous increase in uniform elongation and a decrease in strength. It is worth noting that the strength of the laminated composites are somewhat higher than that of the corresponding cold-rolled Cu, but the uniform elongation of the laminated composite is clearly larger than that of the corresponding cold-rolled Cu. It is clear that the uniform elongation of the composite annealed at 240 °C is about twice that of the cold-rolled Cu annealed at the same temperature. Thus, the laminated composite consisting of thicker Cu layers stacked alternately with much thinner Al layers produced by the cold-roll bonding method can have not only higher strength but also better plasticity.

To understand the underlying reasons, the deformation and fracture behavior of the roll-bonded Cu/Al laminated composite and the cold-rolled Cu were examined by SEM and are shown in Figure 2. Both the cold-rolled Cu and the Cu layers in the composite exhibited ductile necking before fracture, as shown in Figure 2(a) and (b). Some small dimples were formed at the necking-induced fracture surface (Fig. 2(c) and (d)). This indicates that, after strain hardening and a certain amount of plastic deformation, the composite fractured through the local necking of the Cu layers. Some small Al fragments identified by EDS remained on the facture surface, as indicated by the dashed lines in Figure 2(d). This implies that the normal stress caused by local necking of the Cu layers tears the Al layer into a number of pieces which remain at the fracture surface. As a result, local necking was inhibited by debonding of the Cu/Al interfaces and deformation of the Al layers, as observed in Figure 2(e). The bond toughness of the Cu/Al interface appears to play an important role in constraining and delaying the development of the local necking of the Cu layers. Thus, it is expected that the higher the interface bond toughness, the larger the uniform elongation.