Materials Science & Engineering A 562 (2013) 96–100

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Interface strengthening of laminated composite produced by asymmetrical roll bonding

Xiaobing Li [a,b], Guoyin Zu [a,*], Ping Wang [b]

[a] *School of Materials and Metallurgy, Northeastern University, Shenyang 110004, China*
[b] *Key Laboratory of Electromagnetic Processing of Materials, Ministry of Education, Northeastern University, Shenyang 110004, China*

ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form
5 November 2012
Accepted 7 November 2012
Available online 17 November 2012

Keywords:
Layered structures
Interfaces
Mechanical properties
Tension test
Asymmetrical rolling

ABSTRACT

We investigate the tensile properties of Al/Cu/Al laminated composites produced by asymmetrical roll bonding. In comparison with the conventional rolled composites, the strengthening of asymmetrical rolled composites with slightly reduced elongation arises from the improved interfacial microstructure and intermetallic compounds. Moreover, the interface strengthening effect causes higher strain rate sensitivity.

1. Introduction

Laminated composites are under extensive theoretical and experimental studies due to their promising mechanical properties and potential applications [1–5]. The interface strengthening mechanism and complementary properties of these materials have been investigated. And the methods of manufacturing of laminated composites have been developed rapidly, such as vapor deposition, magnetron sputtering, thermal spraying, diffusion bonding, roll bonding and hot press welding [6,7].

A recently discovered laminated composite Al/Cu/Al has attracted much attention. Owing to its high strength, effective corrosion resistance and perfect thermal and electromagnetic characters, it can be utilized in mechanical–thermal–electromagnetic applications [3,8,9]. Unfortunately, the performance differences of copper and aluminum restrict the preparation procedure, e.g. the excess intermetallic compounds and Kirkendall voids by diffusion bonding [10], the oxide inclusion by hot roll bonding [11]. This has not prevented researchers from pursuing creative proposals that rely on a combination of carefully crafted materials and devices.

Was and Foecke [12], and Heathcote et al. [13] have studied and summarized the deformation mechanism and mechanical properties of microlaminate materials, focusing on fracture micromechanics and toughness improvement. Misra has studied the mechanical behavior of metallic nanolayered composites via physical vapor deposition and roll procedure on the basis of interfacial dislocation theory [6,14–16]. Nevertheless, the effect of interface and other characteristic microstructures on the mechanical properties are far from clear. Except for the precise manufacturing techniques of nanostructure multilayered composites, the roll bonding and annealing technique can be used to produce long scale laminated materials, e.g. clad sheet, functional converter, and physical joint [17–19]. Asymmetrical rolling technique regarded as a severe plastic deformation route has been used in the manufacture of ultrafine grain materials [20–22]. The severe shear deformation and interfacial improvement of copper/aluminum clad sheet through asymmetrical cold roll bonding and annealing have been discussed in our previous work [23]. In service as an electrical joint, the Al/Cu/Al laminated composites may be subjected to various external impacting. The mechanical performances of asymmetrical rolled composites have not been studied before. Considering the interface strengthening effect, asymmetrical rolled laminated composites are fabricated and investigated by tension tests at a wide range of strain rate. It aims to explore a better preparation procedure and analyze the interface deformation behavior.

2. Experiments

The Al/Cu/Al laminated composites were produced through cold roll bonding in an asymmetrical laboratory mill with work-rolls diameter of 92 mm and annealing in a resistance furnace.

---

[*] Corresponding author. Tel.: +86 24 83686462; fax: +86 24 83682912.
E-mail addresses: lxbing2009@126.com (X. Li), zugy@smm.neu.edu.cn (G. Zu).

0921-5093/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msea.2012.11.028

Table 1
Characteristics of copper and aluminum sheets.

Raw material	Chemical composition (wt%)	Tensile strength (MPa)	Elongation (%)	Initial thickness (mm)	Final thickness (mm)
AA1100	99.60Al, 0.12Cu	153	10.8	0.9	0.25
C11000	99.90Cu, 0.04O	286	23.0	0.8	0.25

The characteristics of raw materials are shown in Table 1. The surface of copper and aluminum specimens was degreased in acetone and then scratched by a circumferential brush with 0.3 mm diameter stainless steel wires running at 1200 rpm. The asymmetrical roll bonding was conducted at a speed ratio 1.31 of lower to upper roll. Stacked layers were rolled at a velocity of ~5.7 m/s without any lubrication. The rolled laminated composites were annealed at 350 °C for 30 min.

The initial microstructure and fractograph of the interfacial region of laminated composites were observed to demonstrate interfacial deformation behavior by a scanning electron microscope SUPERSCAN SSX 550. The final thicknesses of copper and aluminum specimens in laminated composites were measured as shown in Table 1. The phases of the interfacial region were measured by X'Pert Pro with Cu target through scanning the cross section of composite. Tension tests of the laminated composites were conducted on a SANSCMT 5000 materials testing system at room temperature. Five duplications of tensile specimen with gauge of 20 mm length and 10 mm width were made according to ASTM D882-10 from the center of the clad sheets along the rolling direction. The nominal strain rates were set as $8.3\times10^{-4}\ \mathrm{s}^{-1}$, $8.3\times10^{-3}\ \mathrm{s}^{-1}$, $8.3\times10^{-2}\ \mathrm{s}^{-1}$ and $2.1\times10^{-1}\ \mathrm{s}^{-1}$. The ultimate strength and elongation were obtained based on the stress–strain curves. The experimental results were used to analyze the mechanical properties and interface effect of laminated composites.

3. Results and discussion

3.1. Interfacial microstructure and fracture analysis

Fig. 1 shows the interfacial microstructure of two types of rolled laminated composites with different thicknesses and structure of interlayer. The interlayer of asymmetrical rolled composite with a thickness of 1 μm may have arisen from the following factors. The severe plastic deformation of interfacial region resulted from the dramatic shear action in asymmetrical roll bonding removes contamination and improves subsequent diffusion [22]. During asymmetrical roll bonding, different rotational velocities of the rolls make a mismatch metal flow and cause friction between the component metals. Therefore, the bonded interface gets a significant shear deformation and deformation-induced heat accumulation. Recently, several studies [24,25] have indicated that the bonding of metallic multilayer largely depends on the surface crack and virgin bond. Owing to the shear deformation, a large number of cracks form on the unbonded surface and promote the underlying virgin metal extrusion.

After low temperature annealing, the laminated composite releases residual stress and work-hardening. More importantly, an interlayer is formed due to the interfacial diffusion. The interface of conventional rolled composite, verified in Fig. 1(a), contains some contaminations and prevents the interfacial diffusion. The diffusion determined by the annealing and roll process influences the interfacial microstructure and properties. Some brittle intermetallic compounds may be developed due to the diffusion. Therefore, the interlayer should be controlled to obtain a certain thickness and chemical phases [26]. The phases in interlayer are measured through XRD analysis as shown in Fig. 1(e). It can be noted that few intermetallic compounds CuAl and $CuAl_2$ exist together with solid solutions at the interface.

Fig. 2 represents the fracture microstructure of laminated composites at a strain rate $8.3\times10^{-3}\ \mathrm{s}^{-1}$. With regard to the crack degree observed from the fractograph in Fig. 2(a) and (b), it is clear that the interface of asymmetrical rolled composite possesses a better fracture resistance than another one. A different fracture mode can be seen from the magnification of interface. There are lots of voids and dimples shown in Fig. 2(c) on the torn surface of component metals. In contrast, the torn interface of asymmetrical rolled composite contains few dimples and tear ridges.

During tension tests, the laminated composites first have an integral deformation, and then get damaged at the interface due to the mismatch elongation of copper and aluminum. After that, the individual component continues to be drawn into failure. It is clear that the interface provides an important transition to the deformation between components. If the interlayer is negligible, as shown in Fig. 1(a), the damage of interface would occur easily. Some cracks are initiated at the interface and propagate along the tensile direction. It causes interface cleavage once the composite ruptures. The magnification in Fig. 2(c) shows that some combinations are kept at the interface, which can be ascribed to local metallic bonding due to the interfacial friction. The dimples existing on the torn interface of components show the characteristic fractures of individual copper and aluminum, indicating the slight effect of diffusion and compounds. However, the asymmetrical rolled composite shows a better interfacial fracture without remarkable delamination. The influence of interlayer is demonstrated in Fig. 2(d) based on the fractograph. Owing to the weak ductility of the interlayer containing some intermetallic phases, dimples barely exist on the fracture of components. Hence, the fracture of the interface reveals a brittle behavior.

3.2. Tension tests of composites

The tension tests of pure metals and rolled composites at a strain rate $8.3\times10^{-3}\ \mathrm{s}^{-1}$ are conducted to investigate the influence of interface. The engineering stress–strain curves are illustrated in Fig. 3. The ultimate tensile strength (UTS) values of pure copper and aluminum sheet are 297 MPa and 159 MPa, respectively while it is 210 MPa and 215 MPa for conventional and asymmetrical rolled laminated composite, respectively. According to the mixed rule, Al/Cu/Al laminated structure with the same thickness of component reaches the ultimate strength of 205 MPa [5]. It is most likely due to the interface strengthening in laminated composites. Based on the interfacial microstructure of composites in Fig. 1, asymmetrical roll bonding improves the tensile strength. It is noted that, however, an elongation decrease of asymmetrical rolled composite is obvious. In the magnification inset, the yield stress of laminated composites is found to be higher than that of pure metals, and it is the highest value for asymmetrical rolled composite.

According to the deformation behavior of composites in the tension test, the interface provides a pin strengthening to dislocations and causes the formation of dislocation pile-up region to delay the plastic deformation. The interfacial diffusion without remarkable compounds is able to transit the dislocations and accommodate them, in a way of dislocation pile-up at interfacial interlayer. Moreover, severe plastic deformation in asymmetrical roll bonding can cause grain fragmentation and refinement in the interfacial region for a contribution to the strengthening.