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LETTER

Mechanical Properties and Fracture Behavior of Laminated Heterostructured Composites Under Different Current Densities

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Abstract: The mechanical properties and fracture morphologies of Cu/Nb multilayer composites under electric-assisted tension (EAT) were investigated. Results show that the generated Joule-heat leads to obvious stress softening with the increase in current density. However, the elongation decreases, which is closely related to the characteristic fracture behavior of Cu/Nb multilayer composites during EAT. The fracture pattern is gradually transformed from ductile fracture to melt fracture with the increase in current density.

Key words: Cu/Nb multilayer composite; electric-assisted tension; mechanical properties; fracture behavior

In recent years, heterostructure materials have garnered increasing attention within the material science field[1–3]. The heterostructures, particularly those with lamellar structures, exhibit unique mechanical and physical properties[4–8]. Cu/Nb multilayer composites, produced via the accumulative roll bonding (ARB) process, overcome the traditional trade-off between strength and conductivity, showing great potential to develop composites with both high strength and high conductivity[9–10].

Electric-assisted forming (EAF) is a promising technique to form high-strength and difficult-to-deform alloys with high efficiency and low energy consumption[11–12]. The Joule heating effect of electric current is crucial in the process of electric-assisted tension (EAT), resulting in significant softening effect of some difficult-to-deform alloys, thereby reducing the flow stress[13–14]. This technique has been widely applied to the formation of titanium alloys[15–16] and superalloys[17].

However, the application of EAF to layered heterostructure composites is rarely reported. The Joule-heat temperature variations of Cu/Nb multilayer composites subjected to EAT at different current densities were investigated and the effects on mechanical properties and fracture behavior were also analyzed. This study provides a theoretical foundation for the reduction in flow stress and enhancement in formability of heterogeneous layered materials.

1 Experiment

The experiment material in this study was the Cu/Nb multilayer composites prepared by ARB process after 9 cycles, and the detailed process was reported in Ref.[6,9–10,18]. The dog bone-shaped tensile specimens were subsequently cut from the multilayer composites by electrical discharge machining with a nominal dimension of 5 mm×2 mm. EAT was conducted on EAT platform, which primarily consisted of a pulsed power supply (MicroStar CRSLFP20-500, Dynatronix Inc.), an infrared thermography (FLIR T660), and a material

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testing machine (AG-X 50 KN, Shimadzu Corp.). The strain rate applied for the tensile test was 1×10^{-3} s^{-1}. Additional experiment details were described in Ref. [19 – 20]. The morphology of Cu/Nb multilayer composites along the rolling direction-normal direction plane and the tensile fracture morphology were investigated by scanning electron microscope (SEM, Gemini 560). The element distributions were analyzed by energy dispersive spectroscope (EDS).

2 Results and Discussion

Fig. 1 shows the microstructures of Cu/Nb multilayer composites after 9 cycles of ARB process. Consistent with the results in previous studies, the specimen maintains its continuous laminar structure. Additionally, EDS results show that no significant phase transition or introduction of impurities occurs between the Cu and Nb layers of the multilayer composites after ARB process. This phenomenon indicates that the Cu/Nb multilayer composites exhibit superior coordinated deformation behavior and excellent structural stability throughout the ARB process. Furthermore, the interface between the Cu and Nb layers is clear with no cracks, indicating a tightly bonded state, i. e., a strong interfacial bonding.

Fig. 2 shows the temperature fields in Cu/Nb multilayer composites during EAT under different current densities. As shown in Fig. 2a, the temperature variation during EAT can be categorized into four stages: (A) temperature distribution before tension, (B) initial steady state, (C) crack initiation, and (D) crack propagation. The temperature increases rapidly from room temperature (RT) upon applying electric current to the specimen (stage A). Afterwards, the Joule-heat generated by the current achieves a dynamic

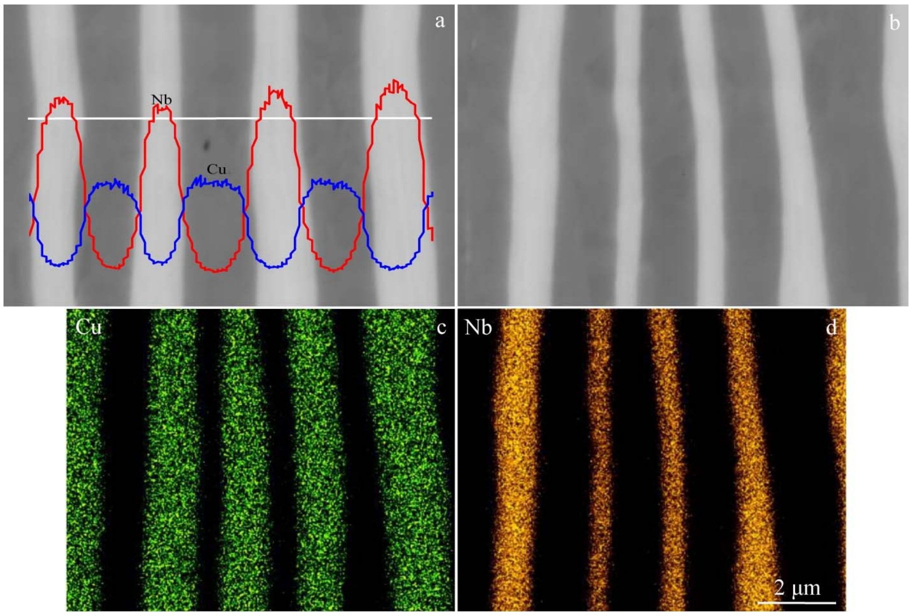

Fig.1 SEM cross-section morphologies (a – b) and EDS element distributions (c – d) of Cu/Nb multilayer composites after 9 cycles of ARB process

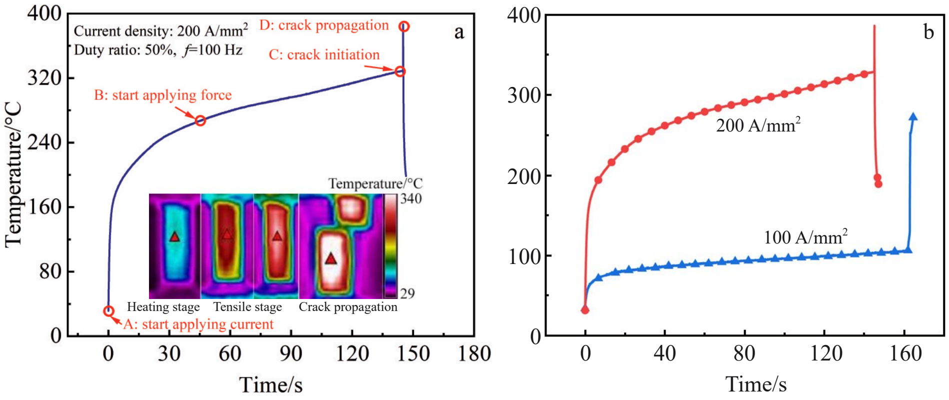

Fig.2 Temperature fields of Cu/Nb multilayer composites during EAT process: (a) typical four stages of temperature field variation; (b) temperature variation with time and current density

equilibrium with heat loss from thermal radiation and conduction, resulting in a steady state of temperature (stage B). Then, the current density gradually increases, leading to a slow rise in temperature until cracking occurs (stage C). Subsequently, the cross-sectional area of the specimen decreases significantly, causing the temperature to rise dramatically until the peak temperature is reached and the specimen ruptures (stage D). At the end of tensile process, the temperature decreases rapidly. The peak temperature is increased with the increase in current density. According to Fig. 2b, the peak temperatures during EAT process can reach approximately 100 and 320 °C at 100 and 200 A/mm^2, respectively.

Mechanical properties of Cu/Nb multilayer composites at different current densities during EAT process are shown in Fig. 3. Generally, both flow stress and elongation (EL) are decreased with the increase in current density. For example, the ultimate tensile strength (UTS) and EL at RT are 561 MPa and 0.13, respectively. During EAT process with current density of 100 A/mm^2, UTS decreases to 504.25 MPa with a normalized flow stress reduction of 10.1%. In this case, EL is 0.126, and the reduction in EL is less significant, compared with that at RT. However, when the current density increases to 200 A/mm^2, UTS decreases significantly to 371.15 MPa, and the normalized flow stress reduction increases sharply to 33.8%, indicating an obvious softening effect. Unfortunately, at 200 A/mm^2, EL is only 0.103, which is significantly lower than that at RT. The Joule heating effect is relatively obvious during EAT process, which accelerates the dislocation motion, reduces obstacles to dislocation movement, and diminishes strain hardening. Thus, Joule-heat is a primary factor contributing to the significant reduction of flow stress[11]. Additionally, the cross-sectional area of the specimen gradually decreases during EAT process, which leads to a gradual increase in the actual current density[17,21–22]. Therefore, the Joule-heat temperature distribution becomes uneven, resulting in the increase in localized temperature, intensification of inhomogeneous deformation, and earlier fracture. In the later stage of deformation, the specimen may even fuse. This phenomenon primarily accounts for the reduction in EL, and the similar results are reported in Ref.[17,21–22].

Fig. 4 shows the fracture surface morphologies of Cu-Nb multilayer composites after EAT process. As shown in Fig. 4a, cracks are visible in the surface morphology at RT. This morphology suggests that the bonding achieved through ARB is relatively weak[18]. Numerous dimples and microvoids can be observed in Fig.4b–4c, which indicates a ductile fracture mode. When EAT process is conducted at 100 A/mm², the resultant fracture morphology is quite similar to that in Fig. 4a, exhibiting a large number of dimples of ductile fracture. Meanwhile, some ablation and fusion traces can also be found at the tips of dimples, as shown in Fig. 4e. These ablation and fusion traces result from the presence of microvoids, which are formed during internal necking stage prior to fracture. At the edge of the microvoids, a sudden increase in the current density causes a sharp rise in the temperature, leading to the appearance of ablation and fusion traces. Additionally, the fracture morphology of the right half of the specimen is relatively smooth, only presenting some wavy patterns, as shown in Fig.4f. This phenomenon indicates that the fracture in the right half of the specimen involves fusion. Subsequently, the ablation and fusion traces appear at the local elevations due to the elevated current density around the dimples. With the deformation further proceeding, the effective current density is further decreased, leading to the direct fusion of the remaining portion of specimen. This results in the appearance of a smooth surface on the right half of the specimen. As shown in Fig.4g, when the current density increases to 200 A/mm^2, the rapid increase in the effective current density during the later stage of deformation causes a sharp rise in the temperature, ultimately leading to the fusion of specimen. Traces of oxides can also be found in Fig.4h–4i, which is attributed to the elevated temperature at the moment of fracture. A similar phenomenon was observed during EAT process of nanocrystalline pure titanium, as reported in Ref. [15]. Briefly, the fracture behavior is transformed from ductile fracture to melt fracture. These phenomena are responsible for the decrease in EL with the increase in

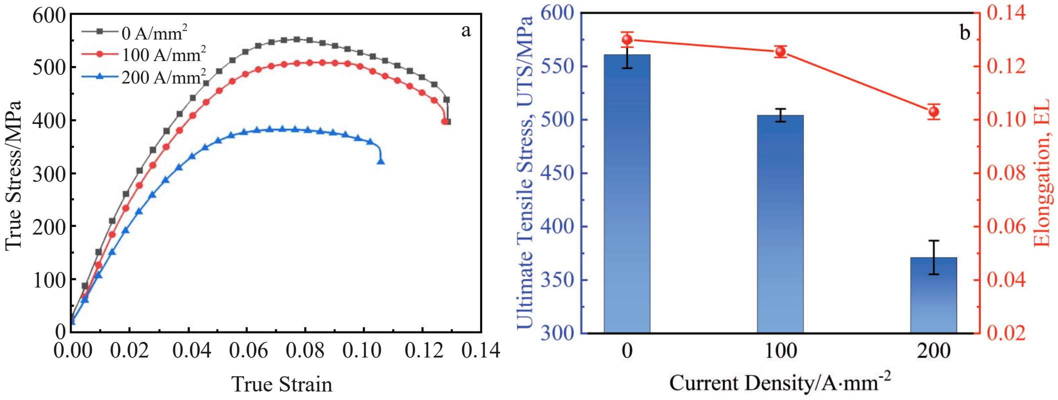

Fig.3 Mechanical properties of Cu/Nb multilayer composites at different current densities: (a) true stress-true strain curves; (b) variations of UTS and EL

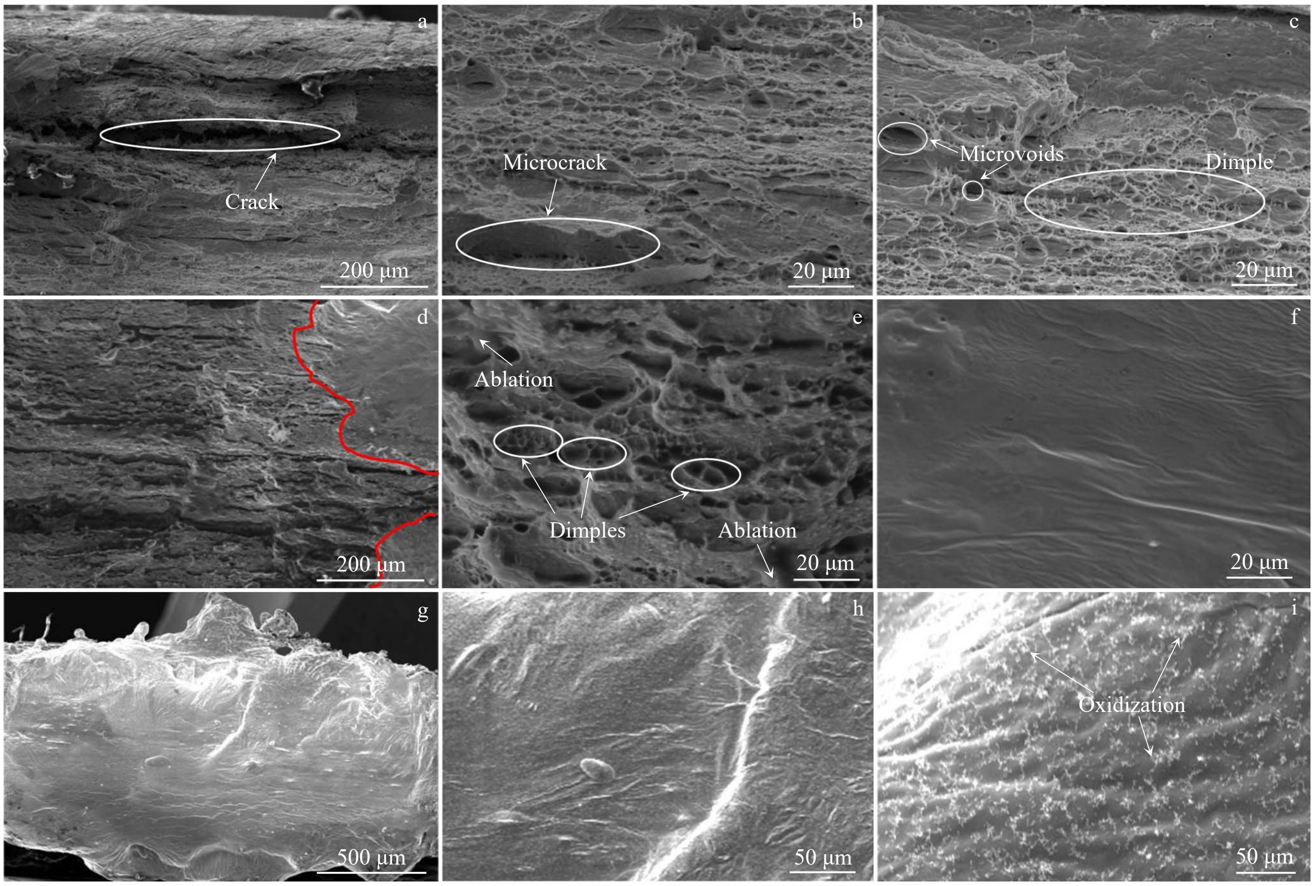

Fig.4 Tensile fracture surfaces of Cu/Nb multilayer composites at different current densities: (a – c) 0 A/mm^2, (d – f) 100 A/mm^2, and (g–h) 200 A/mm^2

current density.

3 Conclusions

1) With the increase in current density, the Joule heating effect becomes more pronounced, leading to the significant stress softening effect. The normalized flow stress decreases by 33.8% at 200 A/mm^2.

2) With the increase in current density, EL decreases from 0.13 to 0.103, and the fracture behavior is transformed from ductile fracture to melt fracture, which is the primary cause of the reduced EL in Cu/Nb multilayer composites.

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层状异质结构在不同电流密度下的力学性能和断裂行为

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摘　要：研究了Cu/Nb多层复合材料在电流辅助拉伸作用下的力学性能和断裂形貌。结果表明，随着电流密度的增加，产生的焦耳热导致应力显著软化。然而，材料的延伸率有所降低。这与Cu/Nb多层复合材料在电流辅助拉伸过程中的特征断裂行为密切相关。随着电流密度的增加，断裂模式逐渐由韧性断裂转变为熔断。

关键词：Cu/Nb多层复合材料；电流辅助拉伸；力学性能；断裂行为

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