

Article

Size Effect on Tensile Properties and Fracture Mechanism of Micro-Rolled Ultra-Thin Cu/Al Composite Sheet

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Abstract

In this study, a laboratory-precision four-high micro-rolling mill was employed to investigate the influence of grain size on the deformation behavior and fracture mechanism of a micro-rolled Cu/Al composite ultra-thin sheet. Analytical testing techniques including scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM+EDS), X-ray diffraction (XRD), and unidirectional tensile experiments were utilized. The experimental results indicate that the grain size of the Cu/Al composite ultra-thin sheet increases with increasing annealing temperature and extended holding time while undergoing the first and second micro-rolling processes. Under identical annealing conditions, secondary micro-rolling leads to an increase in the grain size of Cu, while the growth rate of Al grains is reduced. Tensile tests and fracture surface observations reveal that as the annealing temperature increases, the grain size of the once-micro-rolled Cu/Al composite ultra-thin sheet also increases. When annealing at 400 °C for 40 min, the elongation reaches a maximum of 25.6%, with a tensile strength of 106.3 MPa. For the second micro-rolled samples, a maximum tensile strength of 114.8 MPa is achieved after annealing at a temperature of 360 °C for an 80 min holding time, although the elongation is significantly lower at 3.4%. This indicates that the fracture mode of the once-micro-rolled ultra-thin Cu/Al composite sheet is ductile fracture, whereas that of the second micro-rolled sample is brittle fracture.



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Keywords: micro-rolling; composite interface; tensile properties; fracture mechanism

1. Introduction

With the rapid development of high-precision micro-devices, especially driven by the rapid growth of industries such as micro-electromechanical systems [1] and medical [2], aerospace [3] and other industries, the demand for micro-parts is increasing [4–7]. Due to the excellent specific strength, high working temperature, and good corrosion resistance of ultra-thin metal composite materials, they have been widely applied in fields such as automobiles, electronic equipment, medical equipment, military industry, aerospace, robotics, and household appliances [8–11].

When the size of a part is reduced to the microscopic scale, the material is composed of only a small number of grains and the properties and deformation patterns of the material are quite different from those at the macroscopic scale [12,13]. Especially at micro-dimensions, the proportion of surface atoms increases, and the influence of surface defects, grain boundaries, and other factors becomes more prominent. The size effect will

significantly affect the performance of materials and directly determine the reliability of their engineering applications [14].

Fu et al. [15] investigated the influence of size effects on the fracture behavior of annealed pure copper foils with varying thicknesses and grain sizes through tensile experiments. Zhang et al. [16] examined the impact of size effects on the tensile properties and fracture behavior of pure copper specimens with thicknesses of 0.1, 0.2, and 0.3 mm that had undergone annealing treatment at different temperatures. Wang et al. [17] investigated the effect of size on the tensile properties and fracture behavior of Cu/Ni composite foils with different heat treatment processes using uniaxial tensile experiments, and the common influence of the microstructure and interface on the plastic deformation behavior of Cu/Ni composite foils under different heat treatment processes was also investigated. Gau et al. [18] aimed to investigate the mechanism of dimensional effects on the flow stress and forming properties of materials through bending and tensile tests on brass and aluminum sheets. Zhang et al. [19] studied size effects on the flow stress and forming characteristics of materials with different average grain sizes on a 0.10 mm thick 316 L stainless steel ultra-thin sheet through uniaxial tensile tests.

Chen et al. [20] studied the microstructure and tensile properties of 0.6 mm thick Cu/Al composite thin strips at different annealing temperatures. With the annealing temperature increasing from 300 °C to 500 °C, the tensile strength decreased significantly while the elongation increased significantly. Li et al. [21] investigated the interface effect and fracture process of Cu/Al laminated composites by characterizing the microstructure of the Cu/Al composites and conducting uniaxial tensile tests. Wang et al. [22] investigated the microstructure, tensile properties, and forming properties of Cu/Al composite strips during melt flow tests.

Fu et al. [23] present the effect of annealing temperature on the evolution of the phase composition of the interface diffusion layer, as well as the tensile properties. The results show that the tensile strength decreases and the elongation increases and then decreases with increasing annealing temperature. Chen et al. [24] systematically studied the influence of annealing temperature. As the annealing temperature increased, the thickness of the interface diffusion layer increased, and the interface bonding mode changed from mechanical bonding to metallurgical bonding. The micro-hardness increased, but the tensile strength and elongation decreased significantly. Peel strength showed a trend of first decreasing and then increasing, reaching a peak at 400 °C. In the field of micro-scale rolling, Xie et al. [25] found that the size effect significantly affected forming resistance. When the diameter of the copper wire decreased, the difference in forming resistance between the experiment and the simulation increased. The surface roughness increased as the wire diameter decreased after rolling.

At present, there are more studies on the effect of initial rolling annealing on the properties of ultra-thin Cu/Al composite sheets, but there are fewer studies on the effect of the annealing size on the microstructure and properties of ultra-thin Cu/Al composite sheets after initial rolling annealing and secondary rolling. Crystallographic texture, a key microstructural parameter in Cu/Al composites, is not addressed herein, as our focus is on grain size-dependent effects—specifically, how grain evolution, interface diffusion, and intermetallic formation under micro-rolling and annealing influence tensile behavior. This targeted scope prioritizes clarifying size effect mechanisms in ultra-thin sheets, with texture investigations planned for subsequent work. In this paper, the influence of grain size on the deformation behavior and fracture mechanism of a micro-rolled ultra-thin Cu/Al composite sheet was studied by using a laboratory-precision, four-roll micro-mill through (SEM+EDS) X-ray diffractometry (XRD) and other analytical testing techniques, alongside uniaxial tensile tests.

2. Materials and Methods

2.1. Materials and Equipment

The chemical composition of the experimental materials, namely a Cu thin sheet with a thickness of 0.10 mm and purity of 99.9% and a 1060 Al thin sheet with a purity of 99.6%, is shown in Tables 1 and 2.

Table 1. Chemical composition of ultra-thin T2 Cu sheet, wt.%.

Cu	Bi	Sb	As	Fe	Ni	P	Pb	Sn	S	Zn
99.90	<0.0004	<0.0010	<0.0010	0.0074	0.0013	0.0017	0.0037	0.0023	0.0015	0.0099

Table 2. Chemical composition of ultra-thin 1060 Al sheet, wt.%.

Al	V	Mn	Mg	Zn	Si	Ti	Fe	Cu
99.60	0.05	0.03	0.03	0.05	0.25	0.03	0.35	0.05

The annealing process was carried out in a vacuum tube furnace (GR.TF60, Shguier, Shanghai, China) under an argon atmosphere. Rolling experiments were carried out using an in-house-designed, four-roll, laboratory-scale micro-roller (working roll diameter: 30 mm; support roll diameter: 120 mm). An inlay machine (XQ-2B, Hangzhou, China) was used to heat the sample (150 °C). A universal tensile testing machine (WDW-300, Zhong LuChang, Jinan, China) was used to complete the uniaxial tensile test with a tensile speed of 0.1 mm/min. Metallographic analysis was conducted using a super depth-of-field microscope (VHX-5000, KEYENCE, Osaka, Japan). Compositional analysis was performed using an XRD analyzer (Bruker D8-ADVANCE, Bruker AXS GmbH, Karlsruhe, Germany). Scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) were utilized (Zeiss Sigma 300, Carl Zeiss AG, Oberkochen, Germany).

2.2. Experimental Methods

Ultra-thin Cu/Al composite sheets were prepared by first micro-rolling using a rolling mill, and their thickness after the first micro-rolling procedure was 0.09 mm. After micro-rolling, the ultra-thin Cu/Al composite sheet samples were subjected to annealing heat treatment; the annealing temperature was set at 360 °C, 400 °C, and 440 °C, the heating gradient was 5 °C/min, and the holding time was 80 min. Micro-rolling-annealed ultra-thin Cu/Al composite sheets were selected for a second round of micro-rolling, and double-micro-rolled ultra-thin Cu/Al composite sheets with a thickness of 0.04 mm were obtained. The obtained samples of double-micro-rolled ultra-thin Cu/Al composite sheets were subjected to the same annealing heat treatment.

The samples selected for microstructural observation were cut into dimensions of 20 mm × 10 mm. The specimens were mounted using a hot mounting machine, and the mounted specimen blocks were sequentially ground with 600-mesh, 800-mesh, 1000-mesh, 1200-mesh, 1500-mesh, and 2000-mesh sandpaper. Subsequently, the samples were polished by applying a small amount of 2.5 µm polishing paste to a tweed cloth and polishing with water in the direction perpendicular to the scratches until all scratches were removed, followed by etching.

To simultaneously observe the microstructures of copper and aluminum, two etching agents were used to etch the surface. The copper etchant was prepared with a ratio of Fe(NO₃)₃·9H₂O to anhydrous ethanol of 1 g:25 mL, with an etching time of approximately 5 s. The aluminum etchant was formulated as HF:HNO₃:H₂O = 1:1:8 mL, with an etching time of about 20 s.

The microstructure of the ultra-thin Cu/Al composite sheets was observed and analyzed using an optical microscope (OM) (VHX-5000, KEYENCE, Osaka, Japan). The grain sizes of Cu and Al were determined using the intercept method: a set of equidistant parallel test lines were drawn on the microscopic images, the number of intersections (P) between the test lines and grain boundaries was counted, and the total length of the test lines (L_T) was measured. Combined with the magnification (M), the average grain sizes of the Cu and Al phases were calculated using the formula $d = L_T / (P \cdot M)$. For each sample, five fields of view were selected along both the rolling direction and transverse direction, and the results were averaged.

Rectangular specimens of the rolled ultra-thin Cu/Al composite sheets were cut to dimensions of 50 mm $\times$ 6 mm with a thickness of 0.08 mm. Tensile specimens were cut along the rolling direction (Rd) [20–22], as shown in Figure 1 (unit: mm). Three samples were tested for each condition, and the average values were used to plot the true strain–true stress curves.

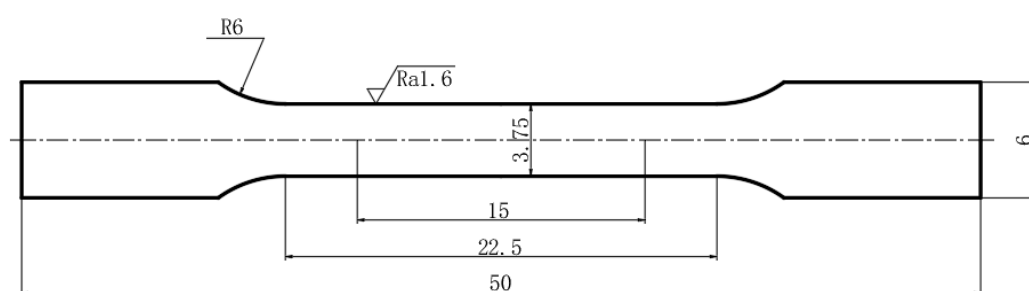


Figure 1. Sample diagram of tensile test (mm).

Scanning electron microscopy (SEM) was employed to perform surface scans on the samples (after regrinding and polishing) to observe elemental diffusion, and the fracture morphologies retained after tensile testing were observed and analyzed. For XRD analysis, samples were prepared by stacking several ultra-thin Cu/Al composite sheets, curling them to a uniform size, polishing the cross-section, and then examining the cross-section.

3. Experimental Results

3.1. Effect of Annealing Process on Grain Size of Micro-Rolled Cu/Al Composite Thin Sheets

3.1.1. Effect of Annealing Temperature on the Microstructure of Cu/Al Composite Thin Sheets Made by One Round of Micro-Rolling

The microstructure of Cu/Al composite thin sheets created through one round of micro-rolling at different annealing temperatures is shown in Figure 2a–c. Through the truncation method, when the holding time is 80 min and the annealing temperature is 360 °C, the Cu grain size is 6.80 μm and the Al grain size is 8.98 μm ; the Cu grain size is 7.50 μm and the Al grain size is 18.89 μm when the annealing temperature is 400 °C; and when the annealing temperature is 440 °C, the Cu grain size is 8.20 μm and the Al grain size is 27.61 μm .

The dimensional changes of the Cu and Al grains in the once-micro-rolled ultra-thin Cu/Al composite sheet at different annealing temperatures are shown in Figure 3. From the figure, it can be seen that the Cu and Al grains increase in size with increasing annealing temperature. The standard deviation of the grain size is sufficient, so no additional error experiments are needed.

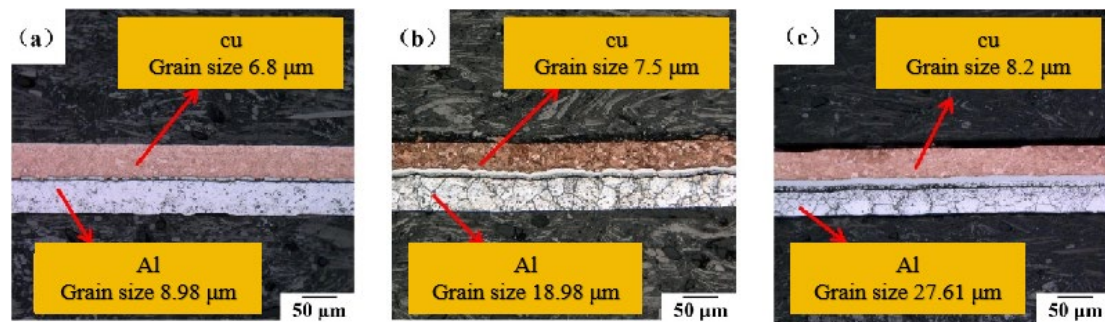


Figure 2. Microstructure diagram of first micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures: (a) 360 °C, (b) 400 °C, and (c) 440 °C.

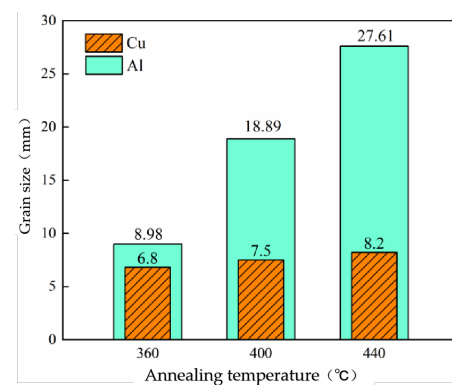


Figure 3. Grain size change diagrams of Cu and Al for the once-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures.

3.1.2. Effect of Annealing Temperature on the Grain Size of Double-Micro-Rolled Cu/Al Composite Thin Sheets

The microstructure of the double-micro-rolled Cu/Al composite thin sheets at different annealing temperatures is shown in Figure 4a–c. Through the truncation method, the holding time was 80 min, and when the annealing temperature was 360 °C, the Cu grain size was 11.75 μm and the Al grain size was 14.20 μm; when the annealing temperature was 400 °C, the Cu grain size was 12.3 μm and the Al grain size was 15.5 μm; and when the annealing temperature was 440 °C, the Cu grain size was 16.02 μm and the Al grain size was 19.12 μm.

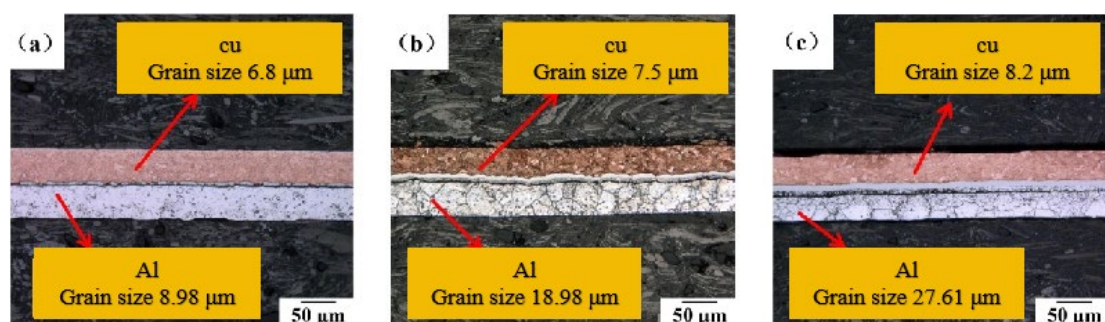


Figure 4. Microstructure diagram of double-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures: (a) 360 °C, (b) 400 °C, and (c) 440 °C.

The size changes of the double-micro-rolled Cu and Al grains at different annealing temperatures are shown in Figure 5. It can be seen that the Cu and Al grain sizes increase with increasing annealing temperature. The standard deviation of the grain size is adequate, requiring no extra error tests. The Cu grain size increased from 11.75 μm to 16.02 μm while

the Al grain size increased from 14.2 μm to 19.12 μm when the annealing temperature was increased from 360 $^{\circ}\text{C}$ to 440 $^{\circ}\text{C}$ after secondary micro-rolling.

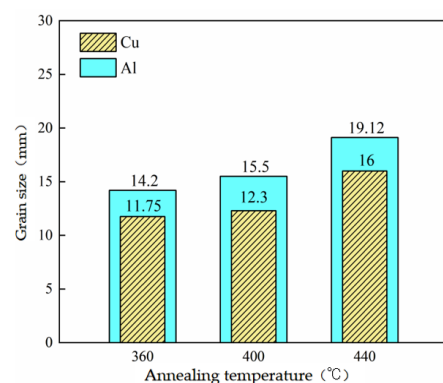


Figure 5. Grain size change diagrams of double-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures.

3.2. Effect of Annealing Temperature on the Tensile Properties of Micro-Rolled Cu/Al Composite Thin Sheets

3.2.1. Effect of Annealing Temperature on the Tensile Properties of Cu/Al Composite Thin Sheets Made Through One Round of Micro-Rolling

The true stress–true strain curves of the once-micro-rolled Cu/Al composite thin sheets at different annealing temperatures are shown in Figure 6. When the holding time is 80 min and the annealing temperature is 360 $^{\circ}\text{C}$, the tensile strength is 119.9 MPa and the elongation is 14.9%; when the annealing temperature is 400 $^{\circ}\text{C}$, the tensile strength is 85.7 MPa and the elongation is 21.7%; and when the annealing temperature is 440 $^{\circ}\text{C}$, the tensile strength is 78.8 MPa and the elongation is 13.4%.

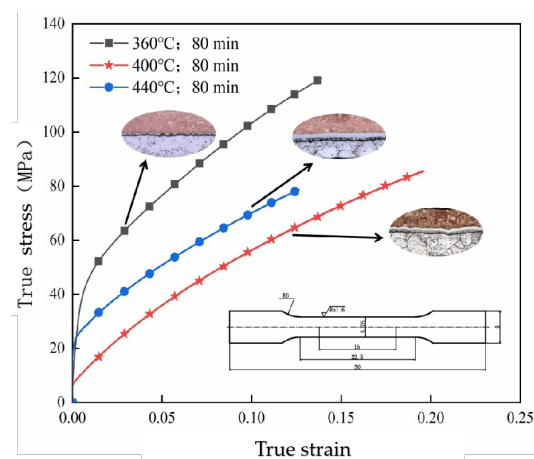


Figure 6. True stress–true strain curves of once-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures.

The experimental data showed that the tensile strength decreased from 119.9 MPa to 78.8 MPa with increasing annealing temperature. Combined with the previous microstructure analysis, it can be observed that the grain size increased gradually with increasing annealing temperature, which is in line with the Hall–Petch relationship, i.e., the larger the grain size, the lower the strength [26].

It can also be observed in Figure 6 that both the elastic region and yield strength of the ultra-thin Cu/Al composite sheets annealed at 400 $^{\circ}\text{C}$ are smaller than those of the sheets annealed at 360 $^{\circ}\text{C}$ and 440 $^{\circ}\text{C}$. This is because the grain sizes of Cu and Al are larger at 400 $^{\circ}\text{C}$ than at 360 $^{\circ}\text{C}$. According to the Hall–Petch relationship, the hindering effect

of grain boundaries on deformation is weakened, which reduces the stress required for initiating plastic deformation (yield strength) and shortens the elastic deformation stage accordingly. At the same time, the interfacial diffusion layer changes from a discontinuous state at 360 °C to a continuous state at this temperature, and the generation of brittle intermetallic compounds is lessened, which promotes coordinated deformation between the Cu and Al substrates and the possibility of grain boundary slipping, which further contributes to the transition from elastic deformation to plastic deformation earlier on.

At 360 °C, the smaller grain size significantly enhances resistance to deformation by increasing the grain boundary density, resulting in a higher yield strength and a longer elastic region; at 440 °C, although the grain size increases further, the high temperature intensifies interfacial diffusion, resulting in a thicker diffusion layer and the formation of more brittle intermetallic compounds (CuAl phases). These brittle phases limit plastic deformation and require higher stresses to initiate yielding, resulting in a slightly longer elastic region and a relatively higher yield strength than the 400 °C sample. The standard deviations for tensile properties are sufficient, so no additional error experiments are required.

3.2.2. Effect of Annealing Temperature on the Tensile Properties of Double-Micro-Rolled Cu/Al Composite Thin Sheets

The true stress–true strain curves of the double-micro-rolled Cu/Al composite thin sheets at different annealing temperatures are shown in Figure 7. When the holding time is 80 min and the annealing temperature is 360 °C, the tensile strength is 114.8 MPa and the elongation is 3.4%; when the annealing temperature is 400 °C, the tensile strength is 89.7 MPa and the elongation is 1.6%; and when the annealing temperature is 440 °C, the tensile strength is 51.3 MPa and the elongation is 0.8%.

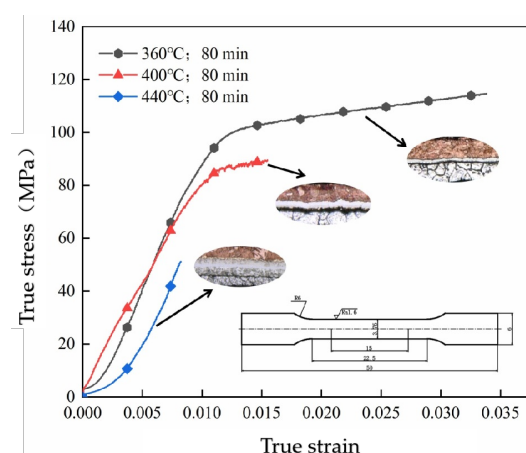


Figure 7. True stress–true strain curves of double-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures.

The experimental data show that for a holding time of 80 min, with increasing annealing temperature, the grain size of Cu and Al increased and the tensile strength and elongation showed a significant decreasing trend. The significant decrease in both tensile strength and elongation after secondary rolling suggests that secondary rolling may have introduced defects, such as dislocations, which reduced the plasticity of the material. Combined with the previous analysis of microstructure and interface diffusion behavior, it can be observed that, with increasing annealing temperature, the grain size of Cu and Al increases and the surface layer thickness increases, which usually leads to lower strength and plasticity. The intense interface diffusion improves to form more brittle intermetallic compounds, especially CuAl compounds, which greatly reduces the strength, and all these

factors together lead to a decreasing trend in tensile strength and elongation. The standard deviations for the tensile properties are adequate, requiring no extra error tests.

3.2.3. Effect of Grain Size on the Tensile Properties of Cu/Al Composite Thin Sheets

As can be seen from Figure 8, with increasing annealing temperature, the thickness of the interface diffusion layer increases, while the grain sizes of Cu and Al also increase, which is attributed to the fact that the increase in annealing temperature enhances the atomic thermal motion, thus accelerating the diffusion process and forming a wider diffusion layer.

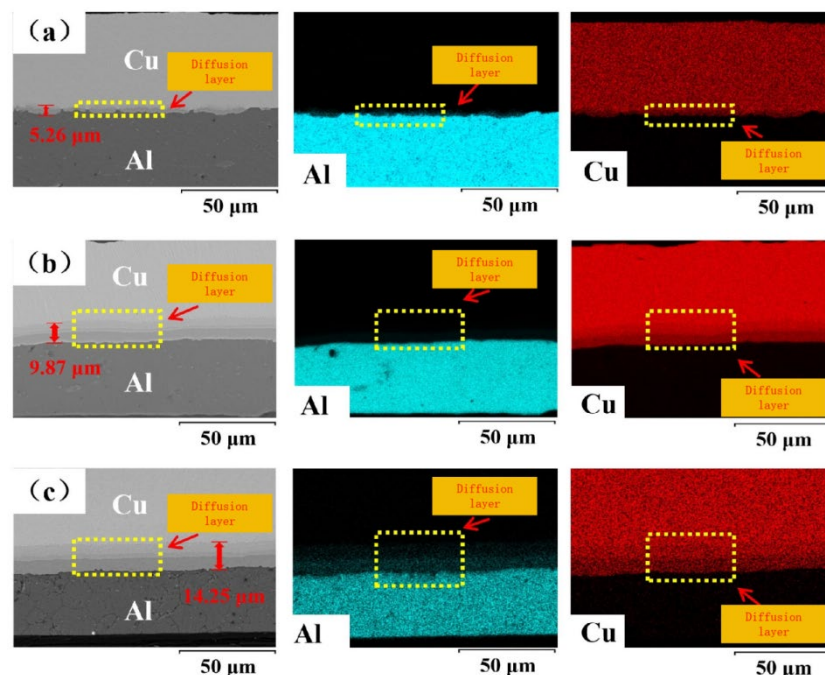


Figure 8. Interface element diffusion maps of once-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures: (a) 360 °C, (b) 400 °C, and (c) 440 °C.

In summary, the grain size increases with increasing annealing temperature; meanwhile, elongation increases first and then decreases. This phenomenon is closely related to the microstructure evolution and interface diffusion behavior. At a lower annealing temperature of 360 °C, as shown in Figure 8a, the Cu and Al grains are small, and the interface diffusion layer is only 5.26 μm. Intermetallic compounds are dispersed, with a high density of grain boundaries, and the plugging dislocation leads to restricted plasticity, which results in less elongation and maximum tensile strength. [27] When the annealing temperature is 400 °C, the Cu and Al grain sizes increase, the interface diffusion layer becomes continuous, the grain boundary strength is reduced, and grain boundary slipping is more likely to occur, which improves elongation. At the higher annealing temperature of 440 °C, the grain sizes of Cu and Al increase, with the proportion of surface grains exceeding 50%, resulting in a shift in the size effect from surface strengthening to overall weakening. In addition to the thickening of the diffusion layer, the interfacial diffusion is intensified, and more brittle intermetallic compounds may be formed, reducing the interfacial bond strength and elongation. For a holding time of 80 min, the grain sizes of Cu and Al increased, and the tensile strength and elongation showed a significant decline with increasing annealing temperature.

The secondary rolling may have introduced defects, such as dislocations, which reduced the plasticity of the material; furthermore, both tensile strength and elongation decreased significantly after secondary rolling. Meanwhile, as the annealing temperature

increased, the grain sizes of Cu and Al and the surface layer thickness increased. However, the surface layer had lower plasticity.

3.2.4. Effect of Secondary Rolling on the Tensile Properties of Cu/Al Composite Thin Sheets

Compared with the first rolling, the tensile strength and elongation were significantly lower after secondary rolling. Secondary rolling produces more defects, such as dislocations, due to the work-hardening effect, which greatly reduces the plasticity of the material. As the annealing temperature increases, the grain sizes of Cu and Al increase and the interfacial diffusion becomes more intense. The XRD analysis shown in Figure 9 indicates that the intermetallic compounds are CuAl_2 , Cu_4Al , and Cu_9Al_4 when the holding time is 80 min and the annealing temperature is 360 °C. When the annealing temperatures are 400 °C and 440 °C, a new intermetallic compound appears, CuAl , in addition to CuAl_2 , Cu_4Al , and Cu_9Al_4 . Lv et al. [23] calculated the diffusion kinetics using the Arrhenius relation and concluded that the diffusion activation energies of the intermetallic compounds are in the order of CuAl_2 , CuAl , and Cu_9Al_4 from smallest to largest, but the intermetallic compounds do not appear in this order. Since the order of formation of intermetallic compounds depends not only on the diffusion activation energy but also on the thermodynamic condition G_0 , Cu_9Al_4 , which has a smaller G_0 , is the easiest to form according to the thermodynamic analysis of the phase transition.

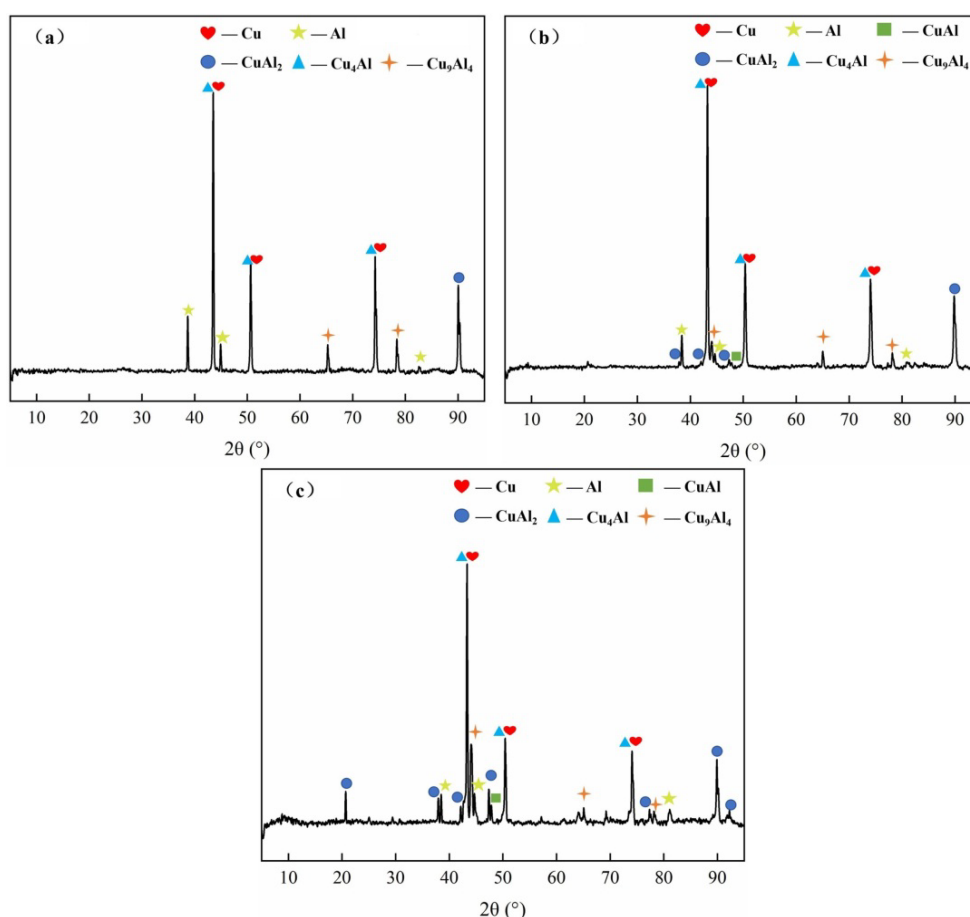


Figure 9. X-ray diffraction patterns of double-micro-rolled ultra-thin Cu/Al composite sheets at different annealing temperatures: (a) 360 °C, (b) 400 °C, and (c) 440 °C.

In addition, the diffusion kinetics, phase transition thermodynamics, and thinning of the ultra-thin Cu/Al composite sheet after secondary micro-rolling were considered. It was

concluded that thinner composite sheets are more favorable for the further reaction of intermetallic compounds at the interface [28], which explains the appearance of the intermetallic compound CuAl at higher temperatures after secondary micro-rolling. The appearance of this new intermetallic compound may significantly change the interfacial bond strength and mechanical properties of the composites. The increase in brittle intermetallic compounds, especially the formation of CuAl compounds, greatly reduces the strength, and these factors together lead to a decreasing trend in tensile strength and elongation.

3.3. Effect of Annealing Temperature on the Tensile Fracture of Micro-Rolled Cu/Al Composite Thin Sheets

3.3.1. Effect of Annealing Temperature on the Tensile Fracture of Cu/Al Composite Thin Sheets Made by One Round of Micro-Rolling

The tensile fracture morphology of Cu/Al composite thin sheets micro-rolled once at different annealing temperatures is shown in Figure 10a–c. From the figure, it can be seen that with increasing annealing temperature, the thickness of the diffusion layer increases. This indicates that the increase in annealing temperature promotes the mutual diffusion of Cu and Al atoms at the interface. At the same time, it can be observed that the interface diffusion layer undergoes an obvious delamination phenomenon, which is evident from the formation of different intermetallic compounds. Meanwhile, through the phenomenon of micropores appearing at the interface between the interface diffusion layer and the Al matrix, it was analyzed and found to be related to the Kirkendall effect.

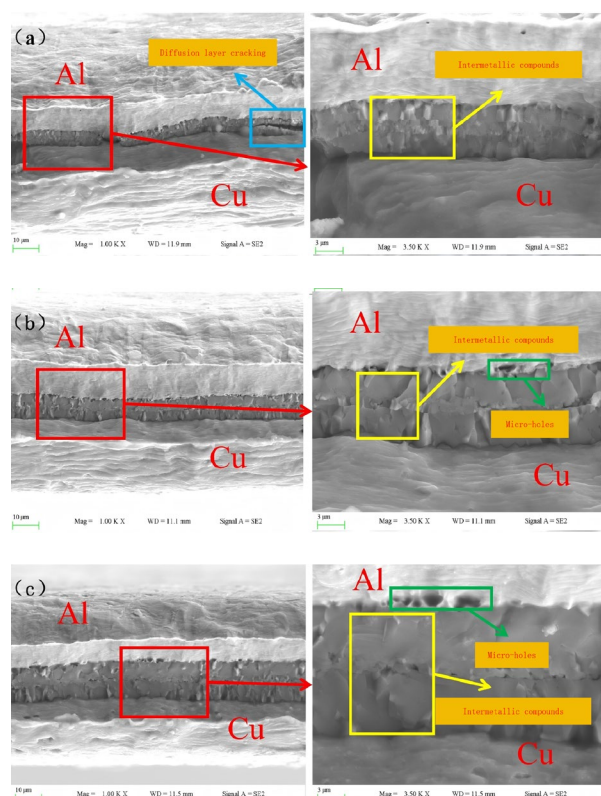


Figure 10. Tensile fracture of Cu/Al composite ultra-thin sheets after one micro-rolled at different annealing temperatures: (a) 360 °C; (b) 400 °C; (c) 440 °C.

3.3.2. Study on the Fracture Mechanism of Cu/Al Composite Thin Sheets Produced by One Round of Rolling

At different annealing temperatures, the elongation of the once-micro-rolled ultra-thin Cu/Al composite sheet becomes greater than 5%, and it can be concluded that its fractures are ductile fractures. In the process of micro-rolling, the Cu and Al metal matrix layers

are preferentially deformed under tensile load, and the extension of the matrix is larger than that of the interface diffusion layer. The intermetallic compounds in the diffusion layer are highly brittle relative to the base material and have a weaker ability to resist crack propagation, which in turn induces inhomogeneous deformation and the rupture of the Cu and Al metal matrix as deformation proceeds. Meanwhile, the phenomenon of micropores appearing at the interface between the diffusion layer and the Al matrix, as shown in Figure 10, was analyzed and found to be related to the Kirkendall effect. Due to the significantly higher diffusion rate of Al than Cu, the migration speed of Al atoms to the Cu side is faster than the reverse migration of Cu atoms, resulting in excess vacancies on the Al side of the matrix. These vacancies gradually accumulate to form Kirkendall holes [29,30].

The existence of these holes reduces the interfacial bonding strength and facilitates crack initiation and propagation. As the annealing temperature increases, the diffusion layer becomes continuous at annealing temperatures of 400 °C and 440 °C, indicating more adequate interfacial diffusion, more complete formation of intermetallic compounds and consequently greater deformation, more coordinated deformation between the matrix and the interfacial layer, increased elongation, and less tendency to fracture.

In summary, the fracture mechanism under the first rolling condition is ductile fracture, which is mainly caused by microporous aggregation and uneven deformation of the matrix and diffusion layer.

3.3.3. Effect of Annealing Temperature on the Tensile Fracture of Double-Micro-Rolled Cu/Al Composite Thin Sheets

The morphology of a tensile fracture of a double-micro-rolled ultra-thin Cu/Al composite sheet at different annealing temperatures is shown in Figure 11a–c. From the figure, it can be seen that the interface diffusion layer of the tensile fracture of the double-micro-rolled ultra-thin Cu/Al composite sheet is smooth, and there is obvious uneven deformation of the Cu and Al metal matrix. The elongation of the double-micro-rolled ultra-thin Cu/Al composite sheet at different annealing temperatures is less than 5%, which is an obvious characteristic of brittle fracture. After secondary micro-rolling, with increasing annealing temperature, the size of the Cu and Al grains increases and the thickness of the interface diffusion layer increases.

The thickness of the interface diffusion layer decreases slightly when the annealing temperature is 360 °C or 400 °C in the double-micro-rolled sheet compared with the once-micro-rolling sheet, but the interface diffusion layer increases in thickness when the annealing temperature is 440 °C, which signifies a more significant diffusion enhancement effect. This is because the thickness of the interface diffusion layer of the ultra-thin Cu/Al composite sheet is reduced by the second micro-rolling process under the same annealing temperatures of 360 °C and 400 °C, and it is further diffused after the second annealing heat treatment, but due to the formation of intermetallic compounds after the first annealing heat treatment, which impedes atomic thermal motion, the interface diffusion layer is thinner after the second annealing treatment than after the first annealing treatment. At the same annealing temperature of 440 °C, the thermal motion of the atoms was strong enough to easily pass through the potential barrier of the intermetallic compounds at the interface, resulting in a thicker interface diffusion layer after the second micro-annealing than after the first micro-annealing.

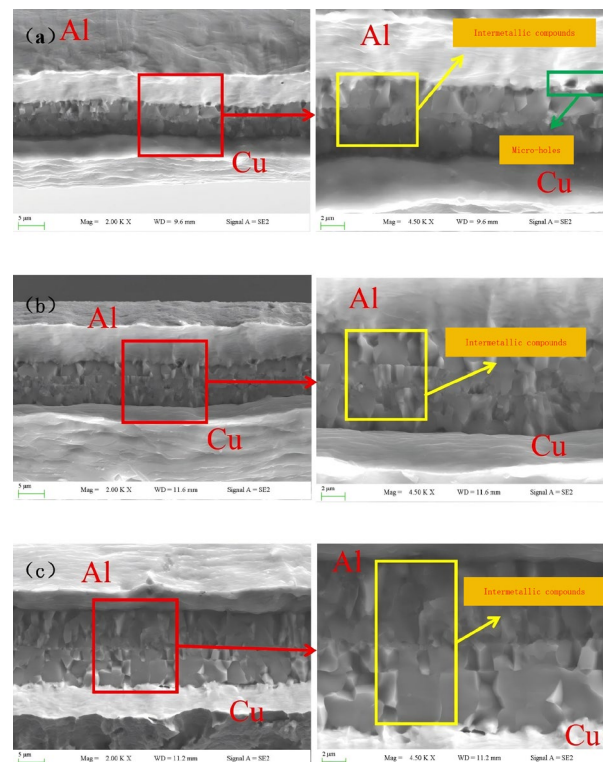


Figure 11. Tensile fracture of Cu/Al composite ultra-thin sheets after double micro-rolled at different annealing temperatures: (a) 360 °C; (b) 400 °C; (c) 440 °C.

3.3.4. Study of the Fracture Mechanism of Cu/Al Composite Thin Sheets After Secondary Rolling

The fracture mechanism of extremely thin Cu/Al composite sheets after secondary micro-rolling at different annealing temperatures is brittle fracture. Compared with the tensile fracture morphology of the extremely thin Cu/Al sheets after the first micro-rolling process, the number of micro-holes at the interface between the Al matrix and the diffusion layer is reduced. This indicates that the fracture after secondary rolling is no longer a micro-hole aggregation fracture but rather a brittle fracture caused by the overly thick composite interface layer and the presence of a relatively large CuAl brittle phase.

As can be seen in Figures 9 and 11, when the annealing temperature is 400 °C, the CuAl phase precipitates from the interfacial diffusion layer, but the CuAl phase is more brittle, resulting in a decrease in elongation. At an annealing temperature of 440 °C, CuAl phase precipitation increased, the interface diffusion layer accounted for a very large proportion of the sheet, the matrix layer consisted of only a single grain in the thickness direction, the brittle interfacial diffusion layer thickness was greater than the thickness of the two sides of the substrate, and the brittle phase became the dominant factor in the fracture, which ultimately led to brittle fracture triggered by the brittle phase.

4. Conclusions

The effects of different annealing temperatures on the tensile properties and tensile fracture of the once-micro-rolled ultra-thin Cu/Al composite sheet and the double-micro-rolled ultra-thin Cu/Al composite sheet are as follows:

(1) As the annealing temperature increases, for the once-micro-rolled ultra-thin Cu/Al composite sheet, the grain size of Cu and Al increases, the tensile strength decreases, and the elongation first increases and then decreases, while for the secondary micro-rolled Cu/Al composite sheet, tensile strength and elongation are significantly reduced.

(2) Micro-rolling conditions: As the grain size of both Cu and Al increased, the surface grains accounted for more than 50%, resulting in the size effect changing from strengthening the surface to weakening it overall, and at the same time, the diffusion layer continued to increase in thickness, the interface diffusion intensified, and brittle phase enhancement reduced the elongation.

(3) With increasing annealing temperature, the Cu and Al grain sizes increased. The fracture mechanism of the once-micro-rolled ultra-thin Cu/Al composite sheet was mainly due to the brittle phase and microporous aggregation leading to ductile fracture. The fracture mechanism of the double-micro-rolled ultra-thin Cu/Al composite sheet was mainly due to the thick interfacial layer and the large proportion of the brittle phase, causing brittle fracture.

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