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ARTICLE

Influence of Reduction Levels on Microstructure and Mechanical Properties of Rolled Cu/Al Corrugated Composite Plates

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Abstract: The corrugated cold rolling bonding (CCRB) process, as a new rolling technique, has gained widespread attention in the preparation of metal composite plates. However, the mechanical properties of corrugated composite plates and the microstructure of the interface at different reduction levels are not yet clear. Numerical simulation and experimental methods were employed to investigate the preparation of Cu/Al corrugated composite plates under reduction levels of 55%, 60%, 65%, and 70%. A three-dimensional model was established by finite element simulation software ABAQUS to simulate the normal stress and strain curves during the rolling process. The interface morphology of the composite plate was characterized by scanning electron microscopy, electron backscatter diffraction, and X-ray energy dispersive spectroscopy. Results show that the ultimate tensile strength and shear strength reach the maximum values at a reduction level of 65%, measuring 221.08 and 79 MPa, respectively; while they reach the minimum values at a reduction level of 55%, measuring 169.34 and 45 MPa, respectively. Particularly, at reduction levels of 65% and 70%, the composite plate exhibits elongated grains and fine equiaxed grains due to severe plastic deformation. At a reduction level of 70%, excessive rolling force causes microcracks in the matrix metal, leading to a decrease in tensile performance, which is consistent with the mechanical test results.

Key words: Cu/Al corrugated composite plate; corrugated cold rolling bonding (CCRB); reduction level; ABAQUS finite element simulation; mechanical property; microstructure

With the rapid development of industry, the demands for material performance have become increasingly stringent in the new era. With the advancement of technology, composite materials have come into existence. Cu/Al composite plates combine the lightweight, corrosion resistance, affordability, and excellent electrical and thermal conductivity of Al alloys, thus becoming a lightweight, wear-resistant, and corrosion-resistant outstanding material[1–6].

In modern industry, composite plates are often fabricated by methods such as explosive bonding[7–8], diffusion welding[9–11], casting, rolling[12], and asymmetric rolling. Currently, most metal materials, including Al/St, Cu/St, Al/Al, Mg/Al, Mg/Cu, Cu/Cu, Cu/Al, etc, can be produced through rolling[13]. Among rolling methods, the corrugated roll-bonding process has become the most popular technique due to its advantages like simplicity, high productivity, and stable product quality[14]. Research of Li[15] et al shows that two-pass rolling of Cu/Al composite plates yields better bonding performance compared to single-pass rolling, and requires lower equipment requirements. Wang[16] discovered that corrugated roll-bonding can significantly reduce the curvature of the sheet compared with traditional rolling methods. Bai[17] proposed that the peel strength of Cu/Al laminated composites is linearly related to interface compounds. Chen[18] et al cold-rolled Al/08Al composite plates at different reduction levels and found that the bond strength is primarily dependent on the extent of fracture in the Al surface hardening layer. Cheng[19] et al

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investigated the interface bonding of Cu/Al composite plates using an energy spectrum analyzer and analyzed the mechanical properties of the composite plates through peel-off tests. Liu[20] et al conducted corrugated roll-bonding on Ti/Al composite plates and discovered that it can increase the bonding area at the interface, thus effectively improving the bonding quality and achieving excellent bending resistance. In addition, our research group[21–22] successfully applied a novel corrugated cold roll bonding (CCRB) process to produce Mg/Al and Ti/Al corrugated composite plates. Through our research, we observed significant differences in the mechanical properties of corrugated roll-bonded composite plates prepared at different reduction levels. For corrugated roll-bonded composite plates, the first rolling pass is crucial as it exerts a significant influence on the microstructure and mechanical properties of the base material. In the first rolling pass, the selection of the reduction level is of paramount importance. Different reduction levels have varying effects on the stress-strain characteristics, microstructure, and overall mechanical properties of the composite plate. In this study, the ABAQUS finite element method was employed to simulate the Cu/Al corrugated composite process under different reduction levels. By analyzing the normal stresses at each reduction level, the bonding conditions of the Cu/Al corrugated composite plates under different reduction levels were assessed. To more accurately describe the micro-structural characteristics and mechanical properties, four Cu/ Al composite plates with different reduction levels were selected. This analysis focuses on the microstructure in the rolling deformation zone and the differences in their mechanical properties.

1 ABAQUS Finite Element Simulation

1.1 Simulation process

This study used ABAQUS finite element software to simulate the rolling process and to analyze the forces, deformation, and microstructure at the interface under different reduction levels. To ensure the accuracy of the simulation, a two-dimensional plane strain condition was performed through a three-dimensional dynamic/explicit mode[23]. To successfully complete the simulation of the rolling process, several conditions were preset: (1) applying constraints to the upper and lower rolls as rigid bodies to prevent deformation; (2) simulating the rolling process under isothermal conditions without considering heat generation and heat transfer; (3) using an explicit dynamic procedure for simulation; (4) material following the Mises yield criterion and deformation following the Levy-Mises flow rule[24–26]. The material ' s physical parameters, roller diameter, and Cu/Al plate specifications used in the model were consistent with the experimental setup. The rolling model is shown in Fig.1.

The friction coefficients between the roll and the Cu plate, between the roll and the Al plate, and between the Cu plate

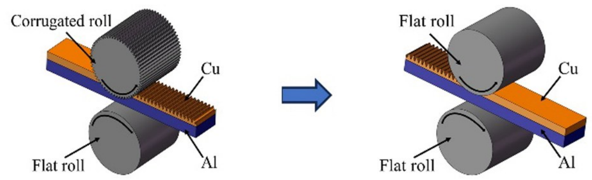

Fig.1 Schematic of rolling with corrugated roller and flat roller

and the Al plate were set to 0.20, 0.20, and 0.30, respectively. For the meshing of the Cu plate and Al plate, both C3D8R hexahedral elements and R3D4 tetrahedral elements were used. The model was divided into 75 860 R3D4 elements and 11 200 C3D8R elements.

1.2 Stress-strain distribution in the rolling deformation zone

Fig. 2 and Fig. 3 depict the time-dependent curves of equivalent strain and normal stress in ABAQUS simulations under four reduction levels. The maximum normal stress and equivalent strain occur at a 70% reduction level, and the equivalent strains at 65% and 70% reduction levels are very close, differing by only 8%. Wang[27] et al found that the normal stress at the interface of corrugated composite plates exhibits a positive correlation with the bonding strength of the composite plates within a certain range. Govindaraj proposed a bonding strength model, as shown in Eq.(1)[28].

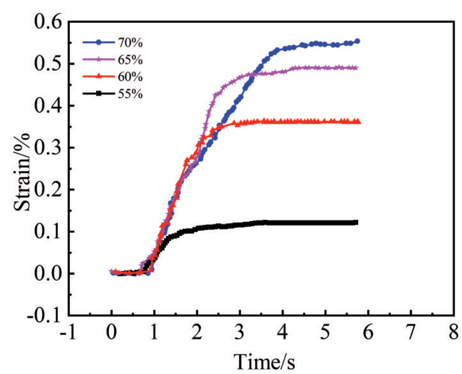

Fig.2 Equivalent strain under different reduction levels

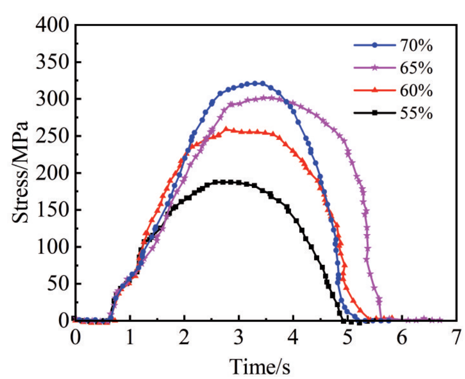

Fig.3 Normal stress under different reduction levels

$$\sigma_b = k_1 \sigma_0 \exp\left(-\frac{\sqrt{3}}{2} k_2 \varepsilon_e \right) \quad (1)$$

where k_1 and k_2 are constants depending on the plate material, σ_b represents bonding strength, σ_0 is the tensile stress for stress-strain curve, and ε_e is the equivalent strain of the rolled plate[29]. This indicates a positive correlation between equivalent strain and bonding strength. Additionally, the normal stress at the interface is also an important criterion for evaluating bonding strength. To precisely analyze the mechanical properties of Cu/Al corrugated composite plates prepared under different reduction levels, the following experiments were conducted.

2 Experimental Results and Discussion

2.1 Experimental process

This study used industrial pure 1060 Al and T2 Cu. Table 1 and Table 2 provide the chemical composition of these Al and Cu materials, respectively.

The specifications of the Cu plate were 150 mm×25 mm×2 mm, and the Al plate had dimensions of 150 mm×25 mm×3 mm. Before rolling, the surfaces of the Cu and Al plates were polished to a matte-finish by a wire brush, which removed the oxide layer and exposed fresh metal to facilitate bonding during rolling[30]. Oil and particles of both the Cu and Al plates were cleaned by acetone and alcohol. They were then assembled together, with holes drilled at the ends and riveted, and 1060 Al wire was bundled to prevent misalignment during the rolling process. The assembled billet was rolled by a two-roll mill, and the first pass was corrugated roll bonding. The upper roll was a corrugated roll with a roll curve given as $\rho(t)$ =75+0.5sin(100t) (0⩽t⩽2π) and the lower roll was a flat roll.

Table 3 lists the physical properties of the Cu/Al composite plate. Fig. 4 is a schematic representation of the Cu/Al corrugated composite plates prepared by CCRB

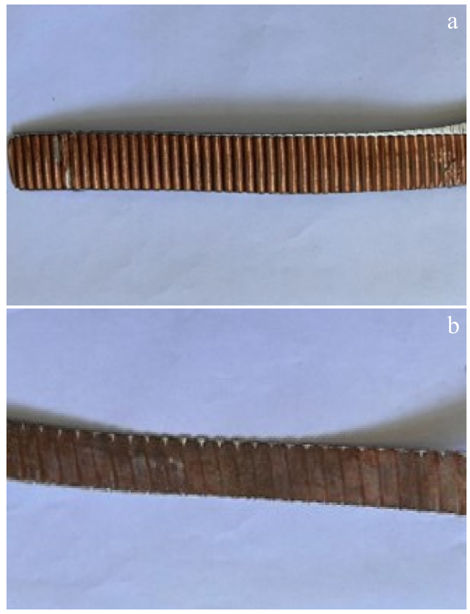

Fig.4 Cu/Al corrugated composite plates after 1-pass (a) and two-passes (b) CCRB

process. In this study, four corrugated composite plates were prepared under different reduction levels. Four tensile test samples were cut from these plates to analyze their tensile limits under different reduction levels. Energy-dispersive X-ray spectroscope (EDS), electron backscatter diffractometer (EBSD), and scanning electron microscope (SEM) were employed to analyze the morphological characteristics of the shear-cut slices and the microstructures near the interface.

Table 1 Chemical composition of 1060 Al (wt%)

Fe	Mn	Mg	Si	Zn	Ti	Cu	Al
0.35	0.03	0.03	0.25	0.05	0.03	0.05	⩾99.6

Table 2 Chemical composition of T2 Cu (wt%)

Bi	Sb	As	Fe	Pb	S	Cu
0.001	0.002	0.002	0.005	0.005	0.005	⩾99.9

Table 3 Physical properties of Cu/Al sheets

Material	Elastic modulus/GPa	Poisson's ratio	Yield strength/ MPa
1060 Al	69	0.35	79
T2 Cu	115	0.325	90

2.2 Mechanical properties

Strain hardening is an important strengthening method to enhance the bonding strength of composite materials. Tensile tests were conducted on specimens extracted from the corrugated composite plates produced at different reduction levels along the rolling direction. Fig. 5 and Fig. 6 present the stress-strain curves, shear strength, and elongation curves under different reduction level conditions. It can be observed that the corrugated composite plate produced at 65% reduction level exhibits higher tensile strength and shear strength, while the plate produced at 55% reduction level has a higher elongation.

During the rolling process of Cu/Al corrugated composite plates, especially at the corrugated composite interface in the rolling direction, intense plastic deformation occurs under the action of rolling force at room temperature. This leads to the formation of a large number of fine-grained structures and twinning structures. Grain refinement can improve the strength, plasticity, and toughness of the Cu/Al composite plate. The formation of twinning structures is due to the presence of partial dislocations. Under the influence of rolling force, dislocation appears, and slip occurs due to perfect dislocation motion. When slip motion cannot continue, dislocation jamming occurs, causing

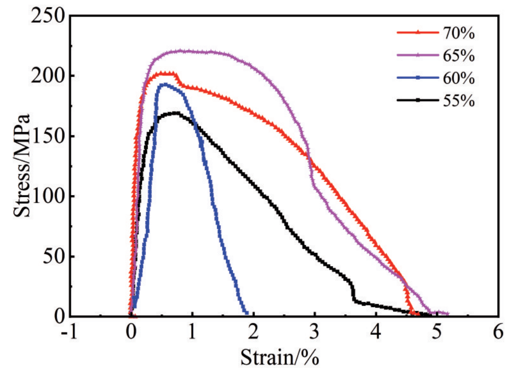

Fig.5 Stress-strain curves under different reduction levels

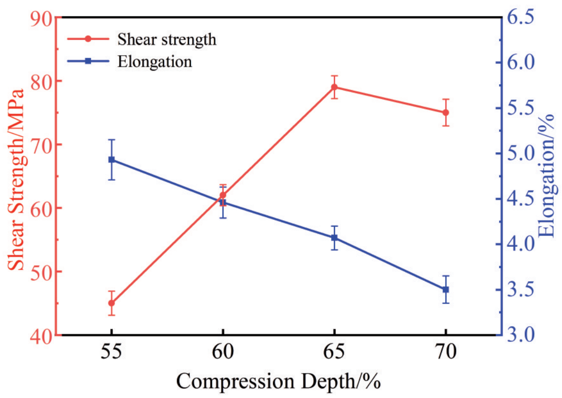

Fig. 6 Shear strength and elongation under different reduction levels

stress concentration and making it prone to twinning structure formation. In the case of Cu/Al composite plates rolled at a 70% reduction level, the excessive rolling force leads to the generation of a large number of twinning structures. The presence of twinning structures in turn causes stress concentration in some interface areas, affecting its tensile performance. At or below 65% reduction level, twinning structures are very rare, which is the reason why the Cu/Al composite plate rolled at 65% reduction level exhibits the best tensile performance. Table 4 shows the mechanical properties of the composite plates at different reduction levels.

Table 4 Mechanical properties of composite plates at different reduction levels

Reduction level/%	Tensile strength/MPa	Elongation/%	Shear strength/MPa
55	169±3	4.93±0.22	45±1.9
60	202±2	4.46±0.17	62±1.67
65	221±3	4.07±0.13	79±1.78
70	215±4	3.50±0.15	75±2.11

It can be observed that as the rolling reduction level increases from 55% to 65%, the tensile strength of the composite plate also increases from 169 MPa to 221 MPa. This tensile strength rises with the increase in the reduction level of the composite plate, which is due to the phenomenon of strain hardening. As the reduction level continues to increase, the dislocation density in the composite plate intensifies, leading to slip phenomena and gradual increase in strength. However, due to strain hardening, the plasticity and toughness of the composite plate decrease, resulting in a gradual reduction in elongation.

When the reduction level increases from 65% to 70%, the intensified rolling force leads to the formation of partial dislocations and twinning structures, causing dislocation jamming and stress concentration in some areas, which results in a decrease in tensile performance. Additionally, the excessive rolling force causes microcracks in certain regions of the Cu layer, leading to a decrease in its elongation and shear strength. Furthermore, the stronger shear forces at the 65% reduction level provide additional vacancies and more energy for atomic diffusion.

2.3 Microstructure

The mechanism of the CCRB followed by flat rolling can be explained by the thin film theory. This theory suggests that during the CCRB process, the metal surface expands, and brittle layer cracking occurs, leading to the formation of cracks. Fresh metal is squeezed out from these cracks, and under the action of rolling force, layer atomic-level bonding forms at localized regions in the interface between Cu and Al elements with a certain bonding strength. Fig. 7 shows SEM morphologies along with EDS mappings of the corrugated composite plates produced at different reduction levels, and there are significant differences due to varying reduction levels. Because Cu has higher deformation resistance than Al, during the rolling deformation, the plastic deformation behavior in the Al matrix is much more severe than that in the Cu layer. As a result, a large amount of fresh Al is extruded into the cracks generated due to plastic deformation. Since the bonding strength of the Cu/Al composite plate is primarily influenced by the degree of tearing in the Cu layer during the rolling process, the microstructure at the interface of the Cu layer is the main focus of observation. From EDS mappings, it is evident that the differences in the distribution of Al on the Cu layer surface at different reduction levels correspond to the variations in the mechanical properties of the Cu/Al composite plate. At 55% reduction level, there are small amounts of point-like Al debris and traces of Al ridges on the Cu layer surface, indicating relatively weaker bonding between Cu and Al under this condition. At 60% reduction level, more Al metal is extruded into the Cu layer, resulting in a widespread distribution of Al ridges on the Cu layer surface, signifying an increase in the bonding strength between Cu and Al. At 65% reduction level, a mesh-like pattern of Al ridges

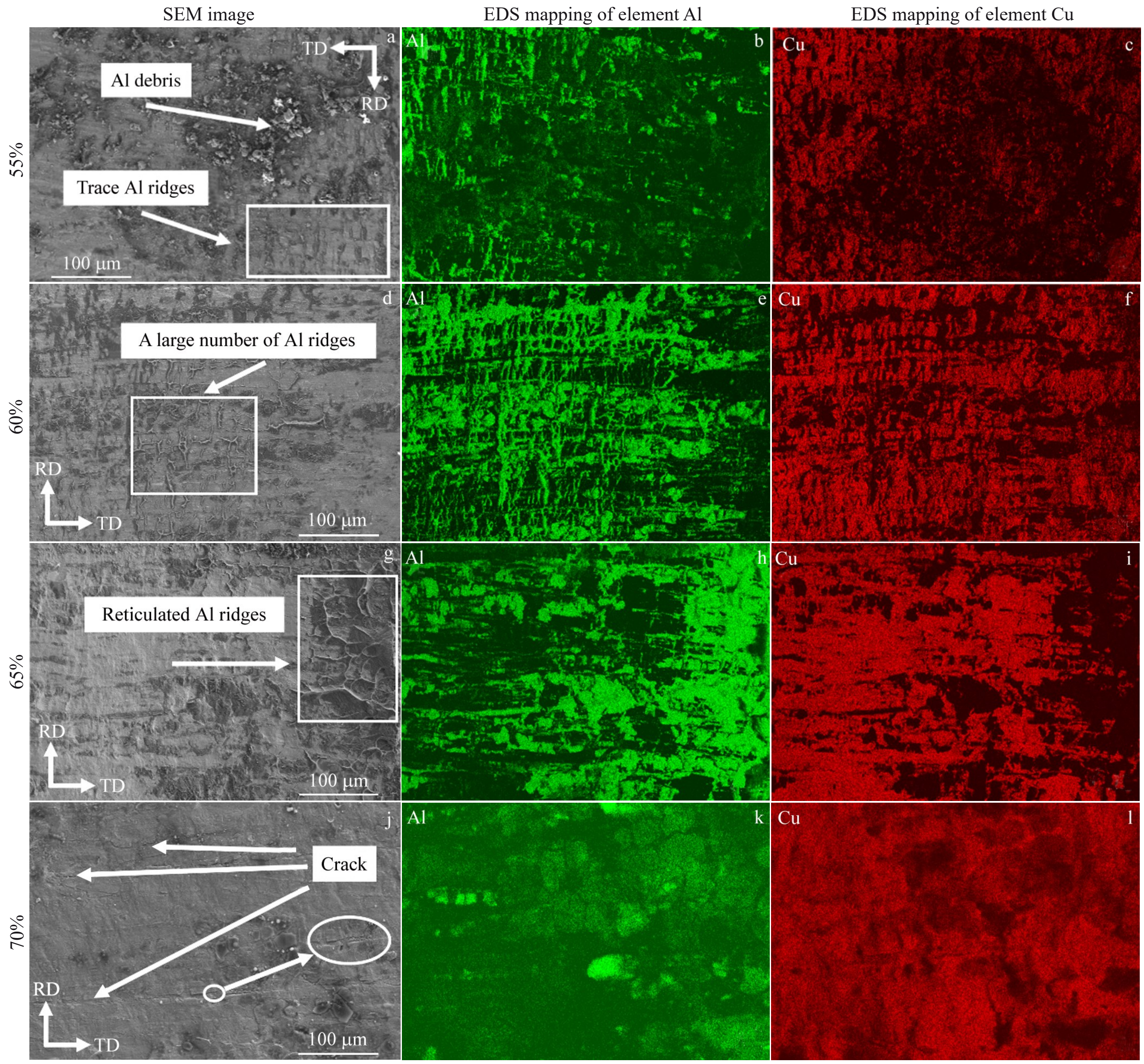

Fig.7 Microscopic morphologies of Cu matrix and corresponding EDS mappings at reduction levels of 55% (a–c), 60% (d–f), 65% (g–i), and 70% (j–l)

appears on the Cu layer surface, indicating a further improvement in bonding quality with a tighter connection between Cu and Al. However, at 70% reduction level, due to excessive rolling force, microcracks appear with crack widths ranging from 0.5 μm to 4.5 μm, leading to a decrease in bonding quality and a subsequent impact on mechanical performance. These observations align with the changes in the mechanical properties of the Cu/Al corrugated composite plate, highlighting a positive correlation between the Al content on the Cu layer surface and bonding quality. This information is valuable for understanding the preparation and performance optimization of composite plates.

Enhancing the work hardening is a crucial approach to improve the bonding strength of metal composite plates. As clearly observed from previous mechanical tests, severe plastic deformation occurs in the Cu/Al corrugated composite plates under 65% and 70% reduction levels. Fig. 8 presents EBSD images of the Cu/Al corrugated interface under different reduction levels. It is evident that grain elongation and refinement of varying degrees occur at the interface region under different reduction levels, which results from the combined effects of high shear strain and intense tensile stress. At reduction levels of 55% and 60%, grain refinement primarily occurs at the interface region. However, under 65% and 70% reduction levels, the grain refinement and elongation are more pronounced due to the higher levels of tensile stress in

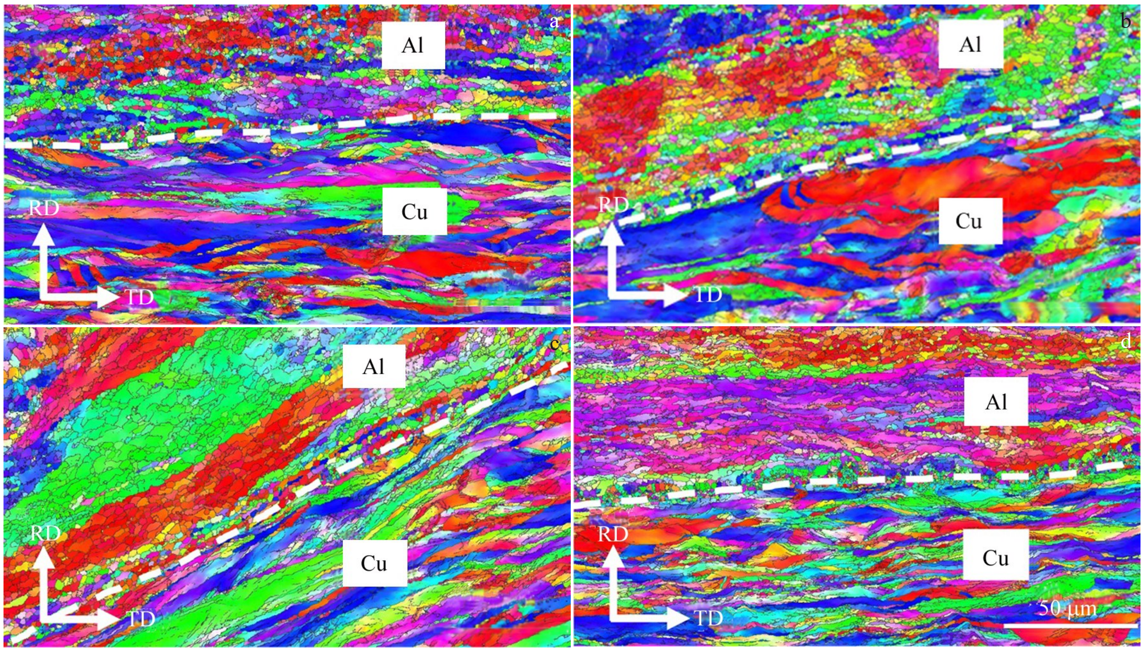

Fig.8 EBSD images of Cu/Al corrugated composite plate interface under different reduction levels: (a) 55%, (b) 60%, (c) 65%, and (d) 70%

these cases.

Fig. 9a – 9d illustrate the distribution of low-angle grain boundaries (LAGBs, 2° – 10° , in green) and high-angle grain boundaries (HAGBs, >10° , in black) at different reduction levels. As shown in Fig. 9i – 9k, as reduction levels increase from 55% to 65%, the quantity of LAGBs in the Cu matrix gradually increases, and the average misorientation angle of grain boundaries decreases from 12.28° to 9.42°. This indicates that the Cu layer undergoes a process of grain refinement. In contrast, as shown in Fig. 9e – 9g, the quantity of HAGBs in the Al matrix gradually increases as reduction levels increase from 55% to 65%, and the average misorientation angle of grain boundaries increases from 10.33° to 12.78°, implying that the grains in the Al layer start to refine during the corrugated rolling process.

During the rolling process, various microstructural changes in the Cu and Al layers are closely associated with the stacking fault energy of the metals and the degree of deformation. For Cu and Al, both having fcc crystal structures, the microstructural evolution during rolling deformation involves the proliferation of dislocations, slip, and grain refinement. Cu has a lower stacking fault energy, around 33 mJ/m^2, while Al possesses a higher stacking fault energy of about 142 mJ/m^2[31]. In the case of Cu, due to its lower stacking fault energy, it is more challenging for dislocations within the Cu layer to slip and cross-slip during plastic deformation. As plastic strain increases, a large number of dislocations begin to intertwine within the grains, forming dislocation tangles and cells, ultimately leading to the generation of subgrains. Consequently, with the gradual increase in the reduction ratio, plastic deformation intensifies, and the average grain boundary misorientation angle in the Cu layer gradually decreases. When the reduction level reaches 70%, severe plastic deformation occurs, leading to an increase in the temperature of the interface region, along with an increase in the average grain boundary misorientation angle. For the Al matrix with a higher stacking fault energy, the dislocation expansion area is relatively small. Through the process of deformation, the number of dislocations significantly decreases due to dislocation multiplication and interaction. At the same time, the temperature of the interface region rises significantly with the increase in plastic deformation, providing a strong driving force for grain refinement. Particularly, at a reduction level of 70%, the strong positive stress promotes further grain refinement. As a result, a large number of equiaxed grains appear near the Al interface, leading to a significant increase in HAGBs, as shown in 9d.

The interface images and EDS line scan results of Cu/Al corrugated composite plates at different reduction levels exhibit significant differences, as clearly observed in Fig. 10. As the reduction level gradually increases, the height of the corrugation peaks decreases, the wavelength becomes longer, and the corrugated interface gradually becomes smoother. It is worth noting that the thickness of the diffusion layer at the corrugated interface of the composite plate is positively correlated with the reduction level, increasing from 1.28 μm (55%) to 3.11 μm (60%, 65%, and 70%). According to classical kinetic theory, the diffusion coefficient D of atoms is influenced by temperature

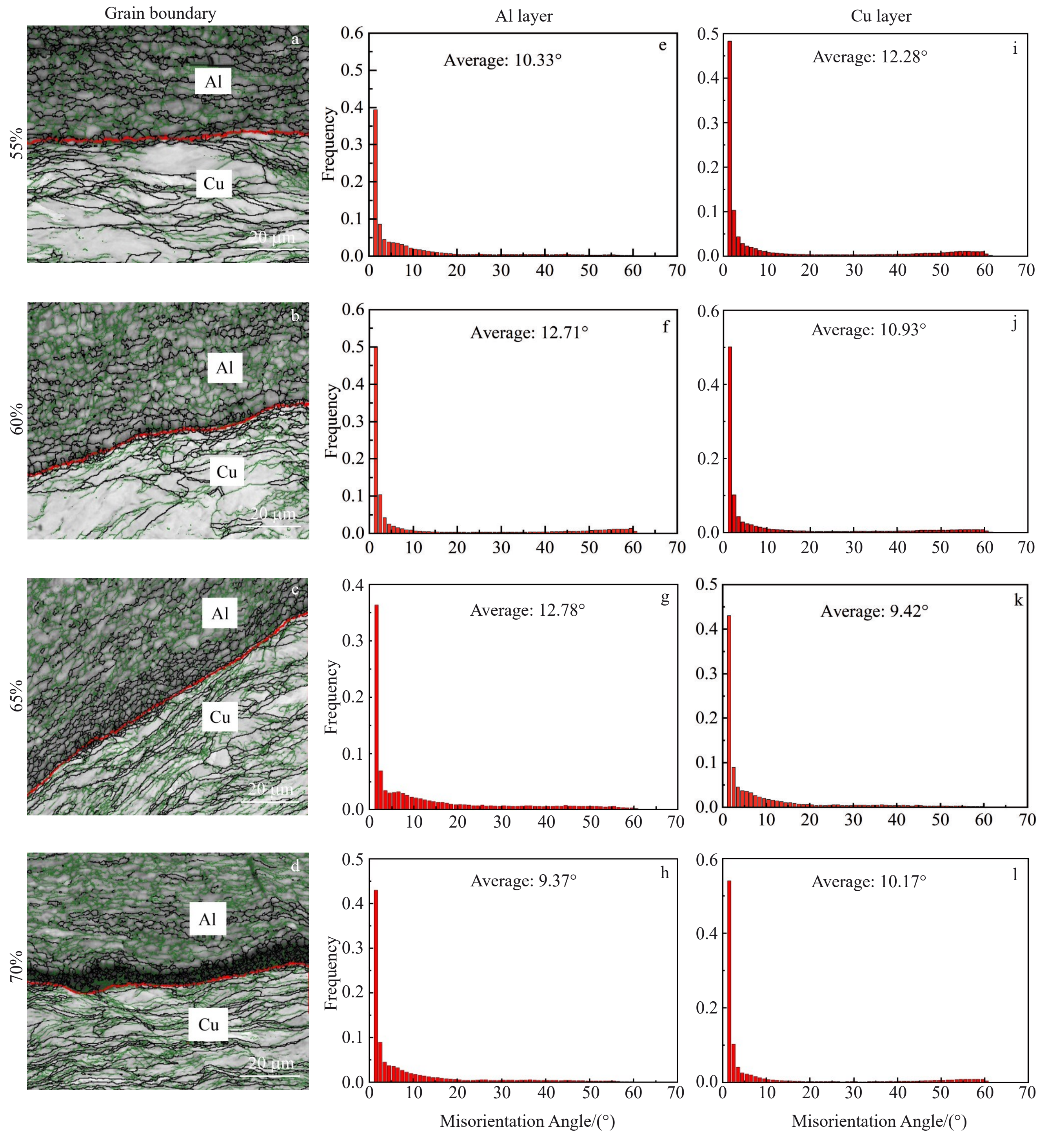

Fig.9 Distribution of LAGBs (green) and HAGBs (black) of Cu/Al composite panels with different reduction levels and the average grain boundary orientation difference

and activation energy, and its relationship is shown in Eq.(2)[32].

$$D = D_0 \exp\left(-\frac{\Delta H}{RT}\right) \quad (2)$$

where D_0 represents the diffusion coefficient, ΔH represents the activation energy for diffusion, R is the thermodynamic constant (R=8.314 J·mol^{-1}·k^{-1}), and T represents the temperature during the rolling process. This is consistent with the EBSD results, indicating that during the CCRB process, the progressively increasing reduction levels lead to more pronounced plastic deformation. This deformation, in turn, results in a gradual temperature rise, thereby promoting the diffusion of atoms at the corrugated interface of the composite plate[33].

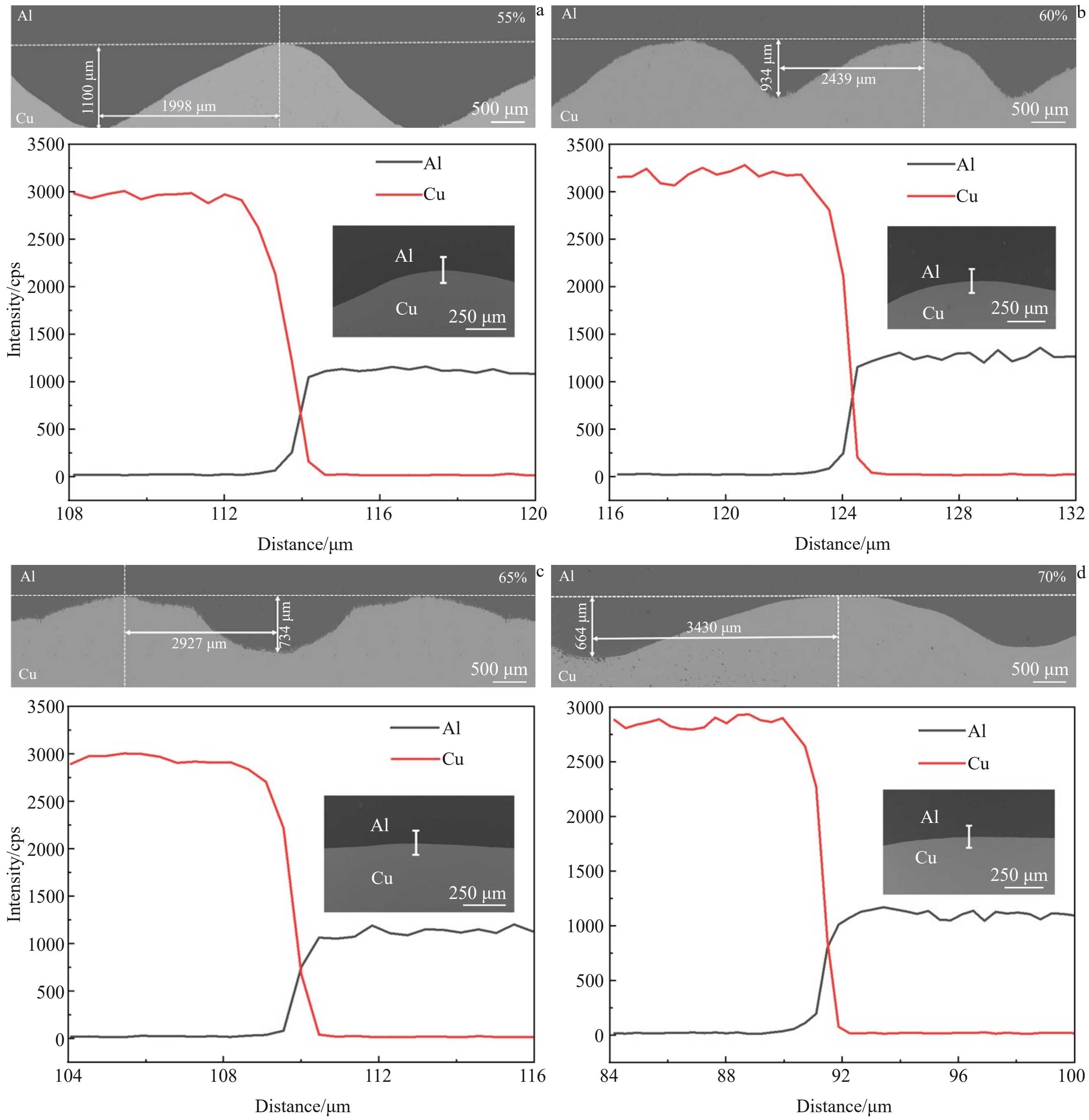

Fig.10 SEM images and EDS line scan results of the Cu/Al corrugated rolled composite interface under different reduction levels: (a) 55%, (b) 60%, (c) 65%, and (d) 70%

3 Conclusions

1) The bonding strength of Cu/Al corrugated composite plates increases as the reduction level increases, exhibiting better mechanical performance. At 65% reduction level, the tensile strength of the Cu/Al corrugated composite plate reaches 221 MPa, and the shear strength reaches 79 MPa, reaching their maximum values. However, when the reduction level reaches 70%, the rolling force becomes too high, resulting in microcracks in the matrix during the rolling process, thus leading to a decline in the mechanical properties of the composite plate.

2) The peak stresses generated by corrugated roller rolling, along with intense frictional shear stresses, promote plastic deformation at the corrugated interface, accelerate grain refinement, and enhance atomic diffusion capability, thus improving the bonding performance of the interface.

3) Different reduction levels lead to significant changes in the microstructure of corrugated composite plates. At reduction levels of 55% and 60%, due to limited plastic deformation, the matrix grains are relatively coarse. Conversely, under reduction levels of 65% and 70%,

influenced by severe plastic deformation and shear stress, the microstructure is primarily composed of elongated grains and equiaxed grains.

References

1 Liu Yanxiao, Wang Zhenhua, Liu Yuanming *et al. Journal of Taiyuan University of Technology*[J], 2022, 53(4): 759 (in Chinese)

2 Chen Cai, Kong Cheng, Wang Mingchuan *et al. Forging Technology*[J], 2023, 48(7): 82 (in Chinese)

3 Zuo Xiaojiao, Lv Jiayin, Huang Hongjun. *Journal of Shenyang University of Technology*[J], 2023, 45(2): 161 (in Chinese)

4 Wang Zhixia, Hou Jie, Gao Xiangyu. *Hot Working Technology*[J], 2022, 51(20): 71

5 Wu Yufeng, Cui Yanan, Ge Wenchao *et al. Heat Treatment Technology and Equipment*[J], 2021, 42(4): 23 (in Chinese)

6 Wang Pengju, Zhao Shujie, Zhong Ning *et al. Rare Metal Materials and Engineering*[J], 2023, 52(4): 1259

7 Zhang Haibo, Zhang Linjie, Liu Jiangzhe *et al*. *Journal of Materials Research and Technology*[J], 2020, 9(5): 10498 (in Chinese)

8 Chen Guoqing, Gan Zhanhua, Zhang Ge *et al. Aeronautical Manufacturing Technology*[J], 2023, 66(19): 93 (in Chinese)

9 Jiang Xiaosong, Li Jingrui, Liu Wanxia *et al*. *Asian Journal of Chemistry*[J], 2014, 26(17): 5682

10 Xu Jiujian, Fu Jinyu, Li Shiju *et al. Journal of Materials Research and Technology*[J], 2022, 16: 530

11 Babayev Y, Kahraman F, Karadeniz S. *Materials and Manufacturing Processes*[J], 2010, 25(11): 1292

12 Wen D X, Lin Y C, Li H B *et al. Materials Science and Engineering A*[J], 2014, 591: 183

13 Shi Wenchao, Lin Yuan, Xu Fuchang *et al. Materials Characterization*[J], 2018, 138: 98

14 Zhang Fengyi. *Study on Laser Ultrasonic Imaging Method of Cu/Al Corrugated Composite Plate Interface Defects*[D]. Taiyuan: Taiyuan University of Technology, 2022 (in Chinese)

15 Li Sha, Gao Xiangyu, Wang Tao. *Hot Working Technology*[J], 2018, 47(23): 30 (in Chinese)

16 Wang Yuelin. *Numerical Simulation and Experimental Study on Roll Forming of Mg/Al Composite Sheets by Corrugated Roll*[D]. Taiyuan: Taiyuan University of Technology, 2022 (in Chinese)

17 Bai Yuliang. *Research on the Interface Behavior and Technological Basis of the Titanium/Steel Composite Thin Plate Formed by Cold-Hot Rolling*[D]. Beijing: University of Science and Technology Beijing, 2022 (in Chinese)

18 Chen Xin, Li Long, Zhou Dejing. *Chinese Journal of Plastic Engineering*[J], 2015, 22(3): 127

19 Cheng Mingyang, Wang Aiqin, Mao Zhiping *et al*. *Journal of Henan University of Science and Technology (Natural Science Edition)*[J], 2017, 38(1): 10 (in Chinese)

20 Liu Chang, Jia Yi, Li Sha *et al*. *Chinese Journal of Plastic Engineering*[J], 2020, 27(12): 66 (in Chinese)

21 Li Yajie, Ma Chengrui, Li Cuirong *et al. Rare Metal Materials and Engineering*[J], 2023, 52(9): 3264 (in Chinese)

22 Li Sha, Jia Yi, Liu Xinyang *et al. Journal of Netshape Forming Engineering*[J], 2021, 13(6): 1 (in Chinese)

23 Ma Tao, Liao Gongyun, Huang Xiaoming. *Application of Finite Element Software Abaqus in Road Engineering*[M]. Nanjing: Southeast University Press, 2021 (in Chinese)

24 Wang Tao, Gao Xiangyu, Zhang Zhixiong *et al. Rare Metals*[J], 2021, 40(5): 1284

25 Wang Tao, Gao Xiangyu, Zhang Zhixiong *et al. Journal of Materials Research and Technology*[J], 2021, 13(40): 216

26 Han Jianchao, Li Sha, Gao Xiangyu *et al. Journal of Materials Research and Technology*[J], 2023, 23: 284

27 Wang Yifan. *Study on Mechanical Properties and Failure Mechanism of Vibration Cast-Rolling Ti/Al Composite Strip*[D]. Yanshan: Yanshan University, 2022 (in Chinese)

28 Nagaraj Vinayagam Govindaraj, Steinar Lauvdal, Bjorn Holmedal. *Journal of Materials Processing Technology*[J], 2013, 213(6): 955

29 Gao Xiangyu, Huang Zhiquan, Jiang Lianyun *et al*. *Rare Metal Materials and Engineering*[J], 2023, 52(4): 1447 (in Chinese)

30 Peng Haijian, Hu Jie. *Rare Metal Materials and Engineering*[J], 2021, 50(12): 4218

31 Yu Huihui. *Research on the Relationship Between Boundary Character and Strengthening in Mg Alloys*[D]. Chongqing: Chongqing University, 2018 (in Chinese)

32 Li Bin, Shen Yingying, Feng Qiong *et al. Rare Metal Materials and Engineering*[J], 2023, 52(6): 2189 (in Chinese)

33 Li Yajie, Ma Chengrui, Liu Cuirong *et al. Rare Metal Materials and Engineering*[J], 2023, 52(9): 3264 (in Chinese)

不同压下量对波纹辊轧制铜/铝复合板微观组织及力学性能的影响

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摘 要：波纹辊冷轧粘合（CCRB）作为一种新型轧制工艺，在金属复合板的制备过程中受到广泛关注，但不同压下量下波纹复合板的力学性能及界面的微观形貌尚不明确。采用数值模拟和实验方法，研究了在55%、60%、65%和70%压下量下制备铜/铝波纹复合板的情况。通过ABAQUS有限元模拟仿真软件建立三维模型，模拟了轧制过程中的应力和应变曲线。通过扫描电子显微镜、电子背散射衍射、X射线能谱仪等方法研究了波纹复合板界面形貌。结果表明，复合板的极限抗拉伸强度和剪切强度在65%压下量下达到最大值，分别为221.08和79 MPa，在55%压下量下达到最小值，分别为169.34和45 MPa。在65%和70%压下量下，由于剧烈的塑性变形作用，复合板形成拉长的晶粒和细小的等轴晶。但70%压下量下，由于轧制力过大，基体金属产生微裂纹，导致拉伸性能下降，这与力学实验结果一致。

关键词：铜/铝波纹复合板；波纹辊冷轧粘合（CCRB）；压下量；ABAQUS有限元模拟；力学性能；微观形貌

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