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Formation mechanism and control of aluminum layer thickness fluctuation in embedded aluminum−steel composite sheet produced by cold roll bonding process

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Abstract: The influences of rolling reduction and aluminum sheet initial thickness (AIT) on the thickness fluctuation of aluminum layer (TFA) of embedded aluminum−steel composite sheet produced by cold roll bonding were investigated, the formation mechanism of TFA was analyzed and method to improve the thickness uniformity of the aluminum layer was proposed. The results showed that when the reduction increased, TFA increased gradually. When the reduction was lower than 40%, AIT had negligible effect on the TFA, while TFA increased with the decrease of AIT when the reduction was higher than 40%. The non-uniformities of the steel surface deformation and the interfacial bonding extent caused by the work-hardened steel surface layer, were the main reasons for the formation of TFA. Adopting an appropriate surface treatment can help to decrease the hardening extent of the steel surface for improving the deformation uniformity during cold roll bonding process, which effectively improved the aluminum thickness uniformity of the embedded aluminum/steel composite sheets.

Key words: aluminum−steel composite sheet; cold roll bonding; work-hardened surface layer; thickness fluctuation

1 Introduction

Embedded aluminum−steel composite sheet has the characteristics of thin aluminum layer and great thickness difference between aluminum layer and steel layer, and works as a key material to manufacture aluminum−steel composite base tube used in large air-cooling system of the thermal or nuclear power plant. In order to conveniently weld the composite sheet into the composite tube, in which the thin aluminum layer is covered outside the tube for being soldered with aluminum fins, symmetric no-aluminum layer on each side of the composite sheet is also needed. Cold roll bonding (CRB) process is an effective method for industrial production of the embedded aluminum–steel composite sheet due to its advantages of simple process, easy scale production and low cost [1,2]. Thickness fluctuation of aluminum layer (TFA) is a very important technical indicator for the composite sheet due to the extremely thin aluminum layer (<100 μm). Large thickness fluctuation can easily lead to perforation of the thin aluminium layer during CRB or during the annealing or brazing due to the formation of Fe_2Al_5 and $FeAl_3$ [3] intermetallic compounds, which reduce the reliability and service life of the composite sheet.

Straight interface shape is easy to be changed into large undulating waves during CRB of dissimilar metals [4,5]. MOZAFFARI et al [6] found that during the accumulative roll bonding of aluminum/nickel laminated composites, large undulating waves appeared at the aluminum/nickel interface after secondary rolling and some fractures happened in some local areas in the nickel layer. YU et al [7] found that in the rolling process of titanium clad copper composites, the titanium layer protruded towards copper layer at the copper/titanium

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interface, and the titanium layer experienced breakage in the following rolling. For most bimetal laminated composite sheets, the fluctuating (non-straight) interface morphology has negligible influence on performance of the composite sheets due to the thick cladding layer. However, for the embedded aluminum/steel composite sheets with ultra-thin aluminum layer, interface fluctuation formed during CRB has a significant impact on the thickness uniformity of the aluminum layers, which may reduce the product yield of the composite sheet during the subsequent annealing and brazing.

Interface morphology changes are closely related to the deformation behaviors of aluminum layer and steel layer on both sides of the interface during the CRB of aluminum/steel composite sheets. A higher level of deformation uniformity leads to smaller fluctuation of aluminum/steel interface and more uniform aluminum layer thickness. The factors affecting deformation behaviors of the cladding layer and the base layer mainly include reduction ratio [8−11], initial thickness of sheet [11−13], the relative yield stresses [14], and rolling speed [15]. Since aluminum is much softer than steel, coordinated deformation behaviors of the aluminum layer and the steel layer during CRB may be mainly responsible for the aluminum layer thickness uniformity. In the present work, the influences of reduction ratio and aluminum sheet initial thickness (AIT) on the TFA in the embedded aluminum/steel composite sheets prepared by CRB were studied, the formation mechanism of the TFA was analyzed, and a method for improving the aluminum layer thickness uniformity was proposed from the viewpoint of changing steel surface hardness, which provides a guidance of producing high-quality embedded aluminum/steel composite sheets with ultra-thin aluminum layer.

2 Experimental

Steel sheets of 475 mm in width, 3.75 mm in thickness and aluminum sheets of 455 mm in width, 0.10−0.50 mm in thickness were commonly used in industrial production. The sheet edge without aluminum layer was 10 mm in width after the aluminium sheet was superposed on the steel sheet before CRB. Both the steel layer and aluminum layer were in plane strain state during the CRB.

According to the above information, annealed commercial purity aluminum sheets (1060) and annealed steel sheets (08Al) were used in this study. The steel sheets were 500 mm in length, 95 mm in width, 3.75 mm in thickness, and the aluminum sheets were 500 mm in length and 75 mm in width. Three kinds of aluminum sheets with thickness values of 0.10, 0.25 and 0.50 mm were used to investigate the influence of AIT on the TFA.

The steel sheets were stress relief annealed at 600 °C for 1 h followed by acid pickling by 5% (mass fraction) hydrochloric acid solution to remove the grease and oxide, and then washed by absolute alcohol. The aluminum sheets were annealed at 600 °C for 1 h and degreased by acetone to remove the dust particles and greases without any surface mechanical preparation which would destroy the flatness of the soft and thin aluminum sheets and was bad for the CRB. In order to investigate the effect of steel surface hardening state on the TFA, the surfaces of acid pickled steel sheets were respectively treated by rotating flap disc and steel circumferential (rotational speed was 11000 r/min) brushes with 90 mm in diameter and *d*0.3 mm wires referring to industrial processing.

The heads of the aluminum sheet and the steel sheet were riveted after surface preparation to ensure symmetric non-aluminum region width (10 mm) on both sides of the composite sheet. The sheets were then cold roll bonded at the thickness reduction of 20%−60% using a four-high laboratory rolling mill. Diameters of the backup roll and the work roll were 350 and 170 mm, respectively, and the roll width was 500 mm. The deformation zone was obtained with a sudden stop during the CRB.

Samples were taken on the vertical symmetry plane along the rolling direction of the CRB deformation zone and cold roll bonded composite sheets, and a metallographic microscope was used to examine the morphology of the vertical symmetric plane of the composite sheets. For each sample, 20 points were selected to observe the wavy aluminum/steel interface morphology. The height differences between the peaks and valleys were measured, and half of the average of the 20 height difference data was taken as the TFA.

The scanning electron microscope was used to observe the interface wave variation between the aluminum layer and the steel layer on the vertical symmetric plane along the rolling direction from the rolling entrance to exit in the CRB deformation zone. The grain orientation distribution of the aluminum layer and steel layer at the interface was analyzed with electron back scattering diffraction (EBSD) technique, and the formation mechanism of TFA in the embedded aluminum/steel composite sheets was discussed.

3 Results and discussion

3.1 Effect of reduction on aluminum layer thickness fluctuation

Figure 1 shows the morphology of the aluminum/steel interface after CRB at different reductions under the

condition of AIT 0.25 mm and the steel surface treated by steel brush. It can be seen that after CRB, the composite sheets exhibited obvious wavy interface. When the reduction increased, the interface fluctuation became more significant and the aluminum layer thickness fluctuation increased gradually.

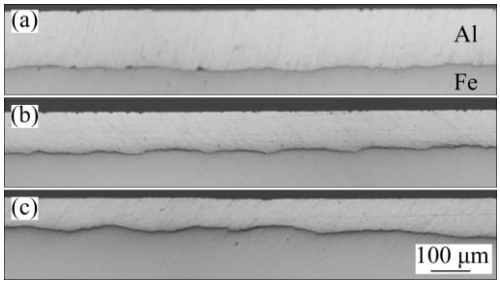

Fig. 1 Interface morphologies of composite sheets prepared by CRB with different reductions under condition of AIT 0.25 mm and steel surface treated by steel brush: (a) 20% reduction; (b) 40% reduction; (c) 55% reduction

Figure 2 displays the aluminum layer thickness fluctuation of the embedded aluminum/steel composite sheets prepared at different reductions under the condition of AIT 0.25 mm and the steel surface treated by steel brush. From Fig. 2, the reduction had a significant impact on the aluminum layer thickness fluctuation. As the reduction increased, both the amplitude and percentage of aluminum layer thickness fluctuation gradually increased (percentage of aluminum layer thickness fluctuation stands for the ratio of TFA to average aluminum thickness). When the reduction rose from 20% to 60%, the aluminum layer thickness fluctuation amplitude increased from ±4.0 to ±11.9 μm. For the reduction of 60%, the aluminum layer thickness fluctuation percentage reached ±17%, indicating poor aluminum layer thickness uniformity.

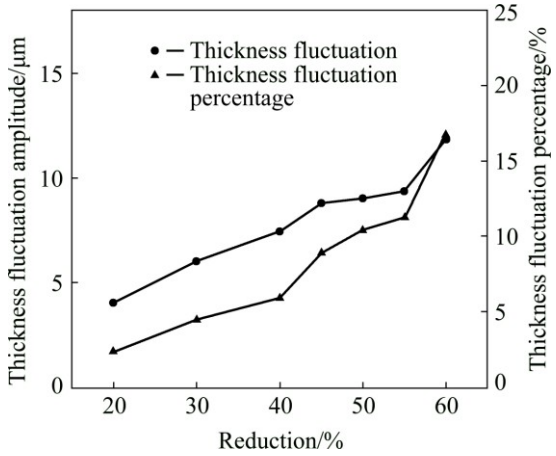

Fig. 2 Aluminum layer thickness fluctuation of composite sheets CRBed in condition of AIT 0.25 mm and steel surface treated by steel brush

3.2 Influence of initial aluminum sheet thickness on aluminum layer thickness fluctuation

Figure 3 shows the interface morphologies of the aluminum/steel composite sheets prepared with different AIT values under the condition of steel surface treated by steel brush. For the reduction of 30%, as AIT decreased, the interface morphology of the composite sheets changed little, and the aluminum layer thickness fluctuation basically remained unchanged. For the reduction of 60%, as AIT decreased, the interface fluctuation of the composite sheets became more significant. For further analysis of TFA in the aluminum/steel composite sheets, the thickness fluctuation was shown in Fig. 4. It is indicated that when the reduction was lower than 40%, the AIT had negligible influence on the aluminum layer thickness fluctuation of the composite sheets. When the reduction was higher than 40%, the thickness fluctuation of the aluminum layer increased with a decrease of AIT.

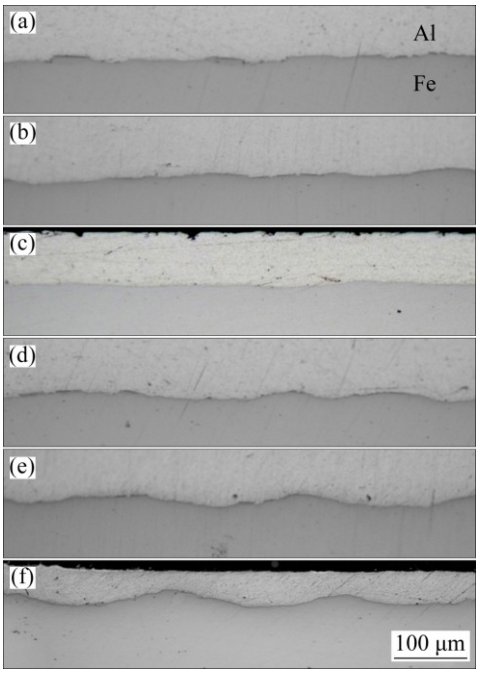

Fig. 3 Interface morphologies of composite sheets prepared with different initial AIT under condition of steel surface treated by steel brush: (a) 0.50 mm AIT, 30% reduction; (b) 0.50 mm AIT, 60% reduction; (c) 0.25 mm AIT, 30% reduction; (d) 0.25 mm AIT, 60% reduction; (e) 0.10 mm AIT, 30% reduction; (f) 0.10 mm AIT, 60% reduction

3.3 Formation mechanism of aluminum layer thickness fluctuation of composite sheet

Experimental results showed that the TFA in the embedded aluminum/steel composite sheet was closely related to the deformation behavior of the aluminum layer and steel layer during CRB. Before CRB, a certain thickness of work-hardened surface layer formed on the steel surface during the scratch brushing treatment [16].

The work-hardened layer had a significant impact on the deformation behavior of the steel layer and the aluminum layer in the process of the CRB, which affected the TFA. Figure 5 shows the interface morphology and the distribution of steel work-hardened layer at the interface of aluminum/steel composite sheet. In Fig. 5, the black blocks were the fragments of steel work-hardened surface layer which was broken during CRB. The fragments of steel work-hardened surface layer obviously protruded to the aluminum layer, and thus the aluminum layer thickness in the corresponding region was thin.

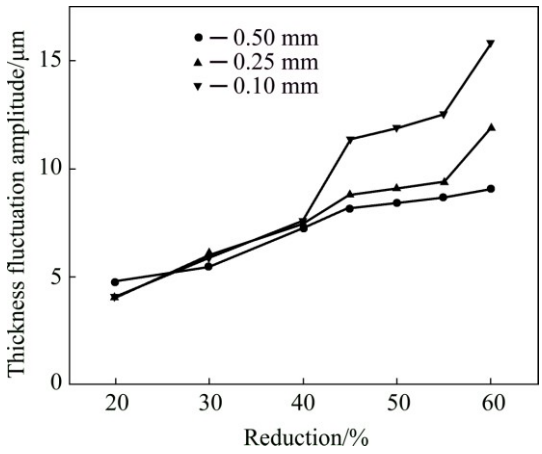

Fig. 4 Aluminum layer thickness fluctuation of composite sheets with different AIT values under condition of steel surface treated by steel brush

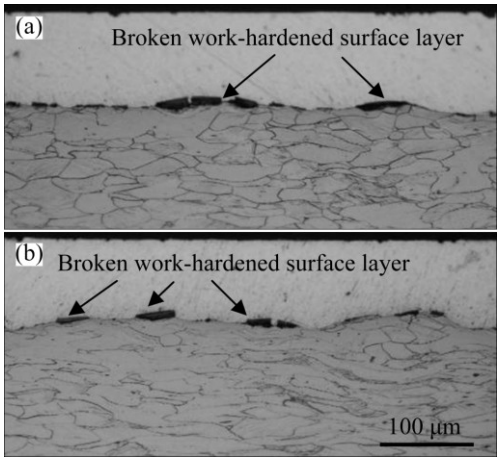

Fig. 5 Interface morphologies of composite sheet with AIT 0.25 mm and steel surface treated by steel brush: (a) 45% reduction; (b) 60% reduction

To analyze the evolution of TFA in the embedded aluminum/steel composite sheet during CRB, the interface morphology of the composite sheet was observed in the deformation zone of the CRB, as shown in Fig. 6. Before CRB, the surface of the aluminum sheet and steel sheet was straight. With the increase of the rolling deformation, the straight interface gradually evolved into wavy shape, and the interfacial fluctuation increased significantly. A lot of broken work-hardened layer fragments appeared at the interface and the region of steel layer containing work-hardened layer fragments

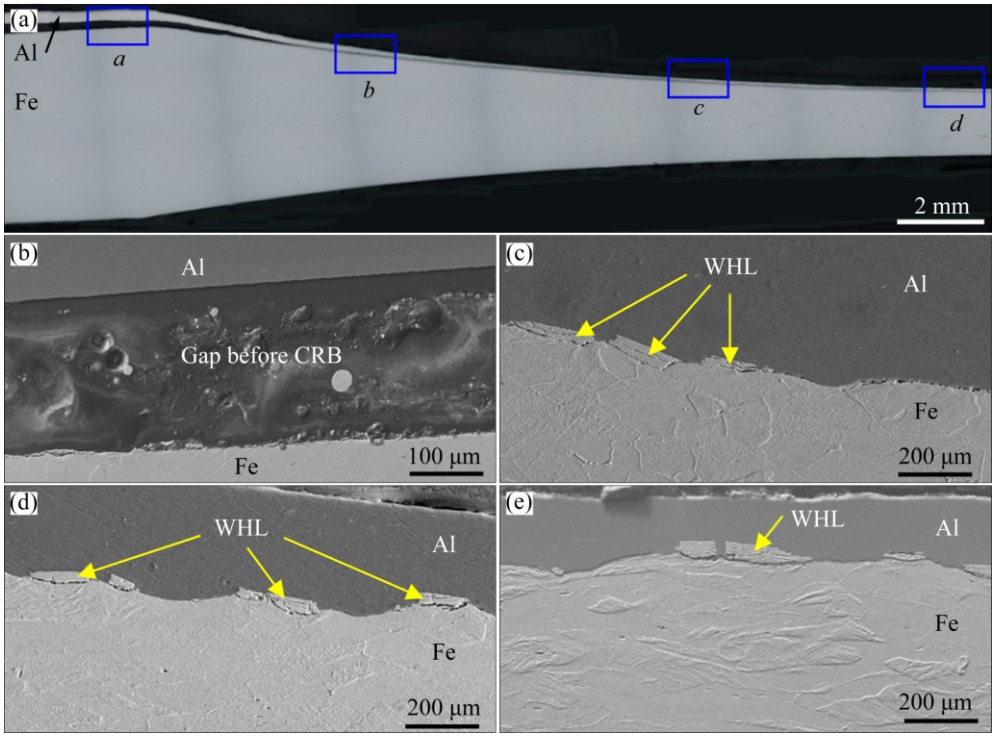

Fig. 6 Interface morphologies of composite sheet in deformation zones of CRB with reduction of 60% and AIT 0.25 mm and steel surface treated by steel brush (WHL stands for work-hardened surface layer): (a) Total interface morphology; (b−e) Interface morphologies of zones *a*−*d* in Fig. 6(a), respectively

was convex to the aluminum layer, which was consistent with the experimental results in Fig. 5. The above experimental results indicated that the work-hardened surface layer of the steel sheet generated during the scratch brushing had an important influence on the TFA.

Based on the above experimental results, schematic diagrams concerning the influence of the steel work-hardened surface layer on the interface morphology of the composite sheet and the aluminum layer thickness fluctuation during the CRB were drawn, as shown in Fig. 7. After surface treatment with steel brush, a certain thickness of work-hardened surface layer appeared on the steel sheet surface. The hardness of the work-hardened surface layer was up to 8.6 GPa, which was much greater than that of the steel substrate (4.4 GPa) [16]. The work-hardened surface layer was broken and scattered along the interface during the CRB, and the broken fragments of the work-hardened surface layer hardly deformed, thus they protruded towards the aluminum layer, which induced the greater deformation of the aluminum layer and the thinner aluminum in the corresponding region. In contrast, the aluminum deformation in the region without hardening layer fragments was weaker and the thickness of the aluminum layer was thicker, causing the wavy interface morphology and aluminum layer thickness fluctuation, as shown in Fig. 6.

Figure 8 shows the interface morphology, microstructure and orientation distribution of the aluminum layer and the steel layer near the interface of the aluminum/steel composite sheet after CRB with a reduction of 45%, where the gap at the aluminum/steel interface in Fig. 8(b) was due to the galvanic cell effect that occurred at the interface between the aluminum

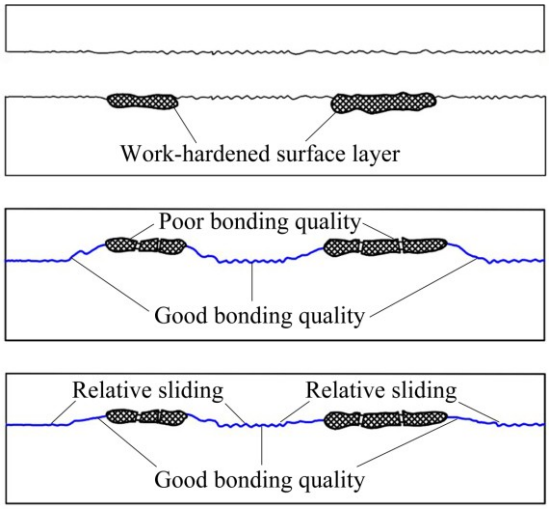

Fig. 7 Schematic diagrams showing influence of work-hardened steel surface layer on aluminum thickness fluctuation during CRB

layer and the steel layer during the sample preparation with electrolytic polishing methods. From Fig. 8, [111] oriented grain (blue grain A) of the steel layer near the interface after CRB was almost equiaxed grain with a small deformation. The steel layer containing the [111] oriented grain protruded towards to the aluminum layer, resulting in a smaller aluminum layer thickness. [100] oriented grain (red grain B) was elongated along the rolling direction with a great deformation, and the corresponding aluminum thickness near the grain was larger. Since the steel sheets used in this study had equiaxed grains with random orientation and the aluminum layer was softer than the steel layer, deformation degree of the grains with different

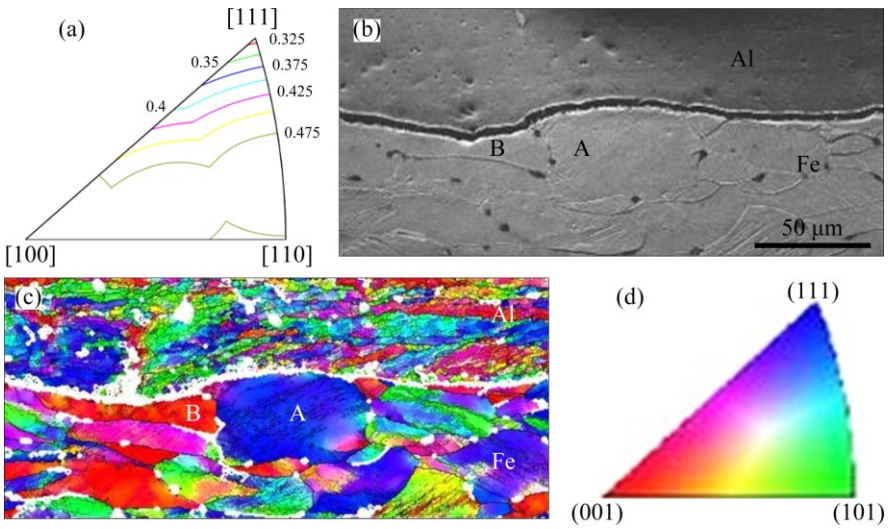

Fig. 8 Schmid factor distribution of BCC metal, interfacial morphology and micostructure of composite sheet produced by CRB with reduction of 45% along rolling direction (RD) and normal direction (ND): (a) Schmid factor distribution; (b) Interfacial morphology (gap at interface was due to electrolytic polishing process); (c, d) ND orientation map of aluminum/steel interface

orientations varied in the steel layer near the interface during the CRB, which resulted in non-uniform deformation of the aluminum layer. Steel belongs to BCC crystal structure, and Schmid factor distribution of different grain orientations of the BCC metal is shown in Fig. 8(a). The Schmid factor of [111] oriented grains was the smallest, which were classified as hard oriented grains. [111] oriented grains formed in the steel layer during CRB (including the [111] oriented grains exposed after breakage of the hardening layer) were not liable to deformation, hence deformation of the aluminum layer corresponding to such oriented grains was greater, which induced the thinner aluminum layer in such regions. In contrast, the Schmid factors of [100] and [110] oriented grains were greater, which were classified as soft oriented grains. Under the same CRB conditions, [100] and [110] oriented grains in the steel layer near the interface were more liable to deformation. The deformation of aluminum layer corresponding to these oriented grains was fewer, which formed the wavy interface and TFA. From the above experimental results, it is indicated that the non-uniform deformation of the steel surface (between hardening layer and substrate, and between grains with different orientations) was an important reason for the formation of aluminum layer thickness fluctuation in the embedded aluminum/steel composite sheets.

In addition, the interfacial bonding state had a significant influence on the aluminum layer thickness fluctuation in the steel/aluminum composite sheets during CRB. After surface treatment by steel brush, a certain thickness of work-hardened surface layer appeared in the local region of the steel strip surface. During the cold roll bonding, the work-hardened surface layer was broken and fresh steel without oxidation was exposed. The aluminum layer was then extruded into the cracks to be contacted and bonded with the fresh steel layer. The work-hardened surface layer hardly deformed and was liable to crack with the steel matrix during the CRB, thus the interface containing the work-hardened surface layer was invalid bonding [16−18]. While on the interface without work-hardened surface layer, compatibility deformation between aluminum layer and steel layer was more likely to occur, and the interface contact area increased, which induced increase of the interface bonding strength. Thus, the interface without work-hardened surface layer had higher bonding strength than the interface with work-hardened surface layer, and the schematic diagram was shown in Fig. 7(b).

In the process of the CRB, the bonding between the steel layer and the aluminum layer in the region with the work-hardened steel surface layer was weak with a low interface bonding strength, and thus relative sliding between the steel layer and the aluminum layer was prone to happen in these regions. On the contrary, the bonding between the steel layer and the aluminum layer in the regions without hardening layer fragments was stronger with a higher interface bonding strength, which means that relative sliding between the steel layer and the aluminum layer was not prone to happen in the corresponding regions. Since the deformation resistance of the aluminum layer was greatly different from that of the steel layer, under the same rolling pressure, the aluminum layer was easier to experience plastic deformation, and the aluminum layer corresponding to the region containing work-hardened surface layer fragments was bound by the interface bonding force to a less extent, and such behaviour enabled the aluminum layer to move toward both sides of the work-hardened surface layer, which resulted in a thinner aluminum layer in those regions. On the contrary, the aluminum layer corresponding to the region without hardening layer fragments was bound by the interface bonding force to a more extent, which limited relative sliding between the steel layer and the aluminum layer, meanwhile, the aluminum layer corresponding to the region with the hardening layer fragments moved toward and stacked in these regions, which resulted in thicker aluminum layer in these regions. Therefore, the non-uniformity interfacial bonding state which was caused by the work-hardened steel surface layer resulted in the non-uniform deformation of aluminum layer during CRB, which was another important reason for the formation of wavy interface and aluminum layer thickness fluctuation of the composite sheets. With the increase of the reduction, the total deformation of the aluminum layer increased, and the variations of aluminum layer deformation corresponding to the regions with hardening layer fragments and without hardening layer fragments became more significant, resulting in larger aluminum layer thickness fluctuation.

For the aluminum sheet with different initial thickness values, when the reduction was lower than 40%, the interfacial bonding extent of the aluminum/steel composite sheets was low, and the difference of the interface bonding extents between the regions with work-hardened surface layer fragments and those regions without work-hardened surface layer fragments was small, which means that the aluminum layer thickness fluctuation caused by the non-uniformity of the interfacial bonding state was lower. For a higher reduction (>40%), the interfacial bonding extent of the aluminum/steel composite sheets was higher, and the difference of the interface bonding extents between them was larger, which means that the aluminum layer thickness fluctuation caused by the non-uniformity of the interfacial bonding extent was larger. In particular, as the AIT decreased, the effect of the interfacial bonding state

on deformation behavior of the aluminum layer increased and the aluminum layer exhibited a higher level of non-uniformity deformation, which induced the greater aluminum layer thickness fluctuation. Therefore, when the reduction exceeded 40%, the aluminum layer thickness fluctuation of the composite sheet increased apparently with the decrease of AIT.

3.4 Method to improve thickness uniformity of aluminum layer

From the above experimental results and analysis, the work-hardened surface layer which was generated on the steel sheet surface during scratch brushing had a significant impact on the aluminum layer thickness fluctuation of the embedded aluminum/steel composite sheets. Different deformation extents between the work-hardened steel surface layer and the steel substrate and the non-uniformity of the steel/aluminum interfacial bonding extent were the main reasons for the formation of the wavy interface and aluminum layer thickness fluctuation of the composite sheet. Therefore, the improvement of uniform deformation of aluminum layer through decreasing the surface work-hardening state of the steel sheet is an effective method to reduce the aluminum layer thickness fluctuation of the embedded aluminum/steel composite sheets produced by CRB. In this work, it was proposed that an appropriate surface treatment for decreasing the surface work-hardening extent of steel sheet was used to reduce the aluminum layer thickness fluctuation and improve the uniformity of aluminum layer thickness in the aluminum/steel composite sheets.

Our previous study indicated that the surface hardening extent of the steel sheets treated by flap disc was much lower than that of the steel sheet treated by steel brush. The nano-hardness of the steel surface treated by steel brush was 8.6 GPa, which was much higher than that of the steel matrix (4.4 GPa), while the nano-hardness of the steel surface treated by flap disc was 4.5 GPa, which was close to that of the steel matrix [16]. In this study, therefore, the surface of the steel sheet was treated by steel brush and flap disc, respectively, the CRB was employed to produce the embedded aluminum/steel composite sheets and the effect of the surface hardening methods on the aluminum layer thickness fluctuation was comparatively studied.

Figure 9 showed the aluminum/steel interface morphology and the relationship between TFA and reduction for the initial aluminum sheet of 0.25 mm in thickness using different surface treatment methods. From Fig. 9, for the same reduction, the composite sheet produced by the CRB with steel surface treated by steel brush exhibited obvious wavy interface, while the composite sheet subjected to flap disc treatment had

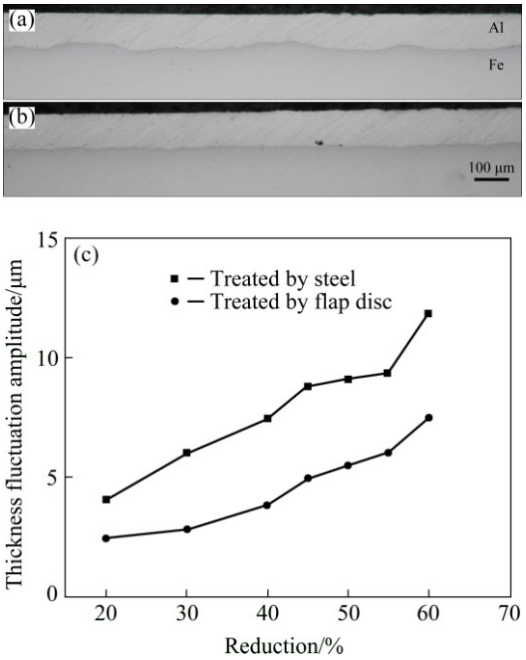

Fig. 9 Interface morphologies and aluminum layer thickness fluctuation of aluminum/steel composite sheet produced by CRB with AIT 0.25 mm and different surface treatment methods: (a) Treated by steel brush, 45% reduction; (b) Treated by flap disc, 45% reduction; (c) Aluminum layer thickness fluctuation

straighter interface. With the increase of the reduction, the aluminum layer thickness fluctuation of the composite sheet increased, and the composite sheets subjected to flap disc treatment had lower aluminum layer thickness fluctuation than the composite sheets subjected to steel brush treatment. For the reduction of 60%, the average TFA of the composite sheets subjected to steel brush treatment was ±11.9 μm (the average thickness of aluminium layer was 71 μm), while that of the composite sheets subjected to flap disc treatment was ±7.5 μm (the average thickness of aluminium layer was 73 μm). Based on the above experimental results and the analysis in Section 3.2, it is indicated that adopting an appropriate steel sheet surface treatment (e.g., flap disc treatment) can help to decrease the hardening extent of the steel sheet surface for improving the deformation uniformity of the aluminum layer during CRB, which effectively reduced the TFA and improved the aluminum thickness uniformity of the embedded aluminum/steel composite sheets.

4 Conclusions

1) After CRB, the embedded aluminum/steel composite sheets exhibited obvious wavy interface. As the reduction increased, the aluminum layer thickness fluctuation increased gradually. The initial thickness of aluminum sheet had negligible influence on the

aluminum layer thickness fluctuation for the reduction lower than 40%, while for the reduction higher than 40%, the thickness fluctuation of the aluminum layer increased with a decrease of AIT.

2) The non-uniformities of both the steel surface layer deformation and the steel/aluminum interfacial bonding extent, which were caused by the work-hardened steel surface layer, were the main reasons for the formation of the aluminum layer thickness fluctuation of the composite sheets. The thickness of aluminum layer in the region containing the work-hardened layer is thin and thick in the other region without the work-hardened layer.

3) Adopting an appropriate steel sheet surface treatment (e.g., flap disc treatment) can help to decrease the hardening extent of the steel sheet surface for improving the deformation uniformity of the aluminum layer during CRB, which effectively reduced the aluminum thickness fluctuation and improved the aluminum thickness uniformity of the embedded aluminum/steel composite sheets.

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嵌入式铝/钢冷轧复合带材铝层的厚度波动形成机理与控制

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摘 要：研究压下率和铝带初始厚度对冷轧复合嵌入式铝/钢复合带材铝层厚度波动的影响，分析铝层厚度波动的形成机理，提出改善复合带材铝层厚度均匀性的措施。结果表明，随着压下率的增加，铝层厚度波动逐渐增大。当压下率低于40%时，初始铝带厚度对复合带材铝层厚度波动量的影响较小；当压下率高于40%时，随初始铝带厚度的减小，复合带材的厚度波动量增大。表面处理形成的钢带表面硬化层引起钢带表层变形和钢/铝界面结合程度不均匀是导致复合带材铝层厚度波动的主要原因。采用合适的钢带表面处理方式降低钢带表面硬化程度，改善钢带表层变形和钢/铝界面结合程度的均匀性，可有效降低铝/钢复合带材的铝层厚度波动。

关键词：铝–钢复合带材；冷轧复合；表面硬化层；厚度波动

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