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Effect of the steel sheet surface hardening state on interfacial bonding strength of embedded aluminum–steel composite sheet produced by cold roll bonding process

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ABSTRACT

Three kinds of surface hardening states of the steel sheet were obtained by different mechanical surface preparation methods with flap disc and steel circumferential brushes before cold roll bonding of embedded 1060 aluminum-08Al steel composite sheets, and the influence of steel sheet surface hardening state on the interfacial bonding strength of the composite sheet and the related mechanism were studied. The results showed that numerous cracks formed between the broken work-hardened surface layer and its steel matrix during cold roll bonding, resulting in a large number of fragments at the interface, which was the main reason for the reduction of the bonding strength. It is an effective method for reducing the work-hardened surface layer hardness to improve the bonding strength of the composite sheet. The nano-hardness of the steel surface treated by flap disc was 4.5 GPa which was close to that (4.4 GPa) of the steel matrix, while the nano-hardnesses of the steel surfaces treated by the steel brushes made of Φ 0.3 mm wires and Φ 0.1 mm wires were 8.6 GPa and 5.7 GPa, respectively. For the thickness reduction of 25%, the peel strengths of the composite sheets whose original steel sheet surface were treated by the steel brush made of Φ 0.3 mm wires and Φ 0.1 mm wires were 0.9 N/mm and 2.9 N/mm, respectively, while the peel strength of the composite sheet whose steel sheet surface was treated by flap disc significantly rose to 14.9 N/mm.

1. Introduction

Embedded aluminum–steel composite sheet combines high strength of steel and good thermal conductivity, corrosion resistance of aluminum, and works as a key material to manufacture aluminum–steel composite finned tube used in large air-cooling system of the thermal power plant. Embedded aluminum–steel composite sheet has characteristics of thin aluminum layer, great thickness difference between aluminum layer and steel layer. 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 large-scale production of the embedded aluminum–steel composite sheet, however, the poor interfacial bonding strength of the composite sheet leads to aluminum–steel separation and low yield of the products.

Surface preparation before CRB is an effective method to improve the bonding strength of bimetal composite sheet produced by CRB [1–3]. Proper surface preparation can not only decrease the threshold reduction but also increase the bonding strength of the composite sheet [2,3]. Surface preparation is mainly classified as chemical cleaning [4–6] and mechanical cleaning [7–9]. Mechanical cleaning is widely used for producing the composite sheets by CRB due to simple process, low cost and continuous production. Scratch brushing is most commonly utilized in the surface mechanical preparation. In general, scratch brushing not only cleans the metal surface but also forms a work-hardened surface layer [3,10–12]. During CRB, the hardened surface layer fractures and different virgin metals exposed near the interface are extruded from the cracks to be contacted and bonded together [13,14]. However, due to the difference of mechanical properties and plastic deformation behaviors between the work-hardened surface layer and its matrix, cracks may form between them during CRB, even resulting in the separation of them, which may reduce the bonding strength. Therefore, suitable surface mechanical preparation should be adopted to obtain proper surface hardness for preventing

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the occurrence of crack and separation between the work-hardened surface layer and its matrix, which is of great importance to improve the interfacial bonding strength of the composite sheet.

In the present work, taking the embedded 1060aluminum-08Al steel composite sheets produced by CRB as object, the effects of steel sheet surface hardening state by surface preparations of flap disc and steel circumferential brushes on the interfacial bonding strength of the composite sheet and the related mechanism were studied, which may provide a guidance of selecting proper surface preparation method for enhancing the bonding strength of the embedded aluminum–steel composite sheet.

2. Experimental procedure

2.1. Materials

Annealed commercial purity aluminum sheets (1060) and annealed steel sheets (08Al) were used in this study. The aluminum sheets were 500 mm in length, 75 mm in width, 1 mm in thickness, and the steel sheet was 500 mm in length, 95 mm in width, 3.75 mm in thickness. The mechanical properties and chemical compositions of the aluminum strip and the steel sheet were listed in Table 1.

2.2. Surface preparation

The steel sheets were first pickled by 5 wt% hydrochloric acid solution to remove the grease and oxide. Our previous research showed that the hardness of scratch brushed surface decreased by reducing the wire diameter of steel brush, and the hardness of flap disc brushed surface was much lower than that of scratch brushed surface. In order to investigate the effect of steel surface hardening state on the bonding strength, three kinds of steel surface hardening states were obtained by the different surface mechanical preparation methods. The acid pickled steel sheets were respectively treated by rotating flap disc and steel circumferential brushes 90 mm in diameter with Φ 0.3 mm wires and Φ 0.1 mm wires until fresh metal was exposed throughout the entire surface. The rotational speed was fixed at 11000 r/min by referring to industrial processing in order to avoid the effect of rotational speed on the bonding strength. The aluminum sheets were just degressed 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.

2.3. Cold roll bonding process

The heads of the aluminum sheet and the steel sheet were riveted after surface preparation to ensure symmetrical 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 20–55% without lubrication, using a four-high laboratory rolling mill with a loading capacity of 2000 kN. Diameters of the backup roll and the work roll were 350 mm and 170 mm, respectively, and the roll width was 500 mm. The rolling speed was 3 m/min.

2.4. Peeling test

Peeling tests were carried out to evaluate the bonding strength of the composite sheets in this paper. Samples with a length of 150 mm and a width of 5 mm were cut from the cold roll bonded sheets parallel to the rolling direction. According to ASTM-D3167-10, the peeling tests were performed using a WDW-1 tensile testing machine. As shown in Fig. 1(a), the peeling speed v was 25 mm/min, the peeling force F was shown in Fig. 1(b), and the average peel strength was determined using the following Eq. (1):

$$\text{Average peel strength} = \frac{\text{Average peeling force (N)}}{\text{Sample width (mm)}} \tag{1}$$

2.5. Surface and interface morphology observation and nano-hardness test

Roughness of the steel sheet surface was measured by tektak 150 surface profile instrument. Nano-indentation tester was employed to detect the nano-hardness of the samples. The steel surface and the composite interface morphologies were observed by Zeiss Auriga scanning electron microscope (SEM). The morphology of the aluminum layer of the samples after peeling were examined by Leica S440i scanning electron microscope (SEM) and the chemical composition was detected by energy dispersive spectrometer (EDS).

3. Results

3.1. The interfacial bonding of the CRBed aluminum–steel composite sheet under surface preparation by scratch brushing

Fig. 2 displayed the interface morphologies of the cold roll-bonded aluminum–steel composite sheets under the condition of steel surface treated by steel brush with Φ 0.3 mm wires (commonly used in industry) with different thickness reductions. A few cracks were observed on the scratch brushed surface of the steel sheet, as shown in Fig. 2(a). After CRB, a large number of steel fragments formed at the aluminum–steel interface. With increasing the reduction, the size of the fragments decreased and the interspace between them increased (Fig. 2(b)–(d)). In addition, the rolling pressure increased with an increase of reduction, which was favor to the combination of fresh aluminum and steel metals and improved the peel strength.

Fig. 3 showed the back scattered electron (BSD) images and chemical composition distribution (detected by EDS) of the aluminum layer with different CRB reductions after peeling, where the gray part was steel and the dark gray part was aluminum in Fig. 3(a)–(c). There were a large number of residual steel fragments on the aluminum layer after peeling. With the increase of the thickness reduction, the fragment size reduced and the interspace between them increased, which was in a good agreement with the results of Fig. 2. It is indicated that the steel fragments embedded

Table 1
Mechanical properties and chemical compositions of the aluminum strip and steel sheet.

Materials	Temper	Yield strength, MPa	Tensile strength, MPa	Elongation, %	Chemical composition, wt%
Al	O	33	68	25	99.810Al, 0.020Si, 0.120Fe, 0.003Mn, 0.005Zn, 0.042others
Steel	O	268	327	44	99.681Fe, 0.004C, 0.209Mn, 0.014Si, 0.005S, 0.019P, 0.068others