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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 d0.3 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