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The bonding properties and interfacial morphologies of clad plate prepared by multiple passes hot rolling in a protective atmosphere

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ABSTRACT

SUS304 stainless steel and plain carbon steel were first bonded by hot rolling in an argon atmosphere and were subsequently hot-rolled by multiple passes in air. Shearing and peeling tests were performed according to appropriate standards to evaluate the bonding results. The interfacial microstructures, composition diffusion and peeling fractographies of the clad plate samples were used to examine the bond quality. The effects of bond parameters on the bond properties of clad plate were studied. The experimental results indicate that the shear strength reaches 266 MPa, and the peel strength is up to 322 N/mm at 1323 K in the first pass, representing a reduction of 24.3%. Both the shear strength and the peel strength increase with increases in bonding temperature and total reduction ratio. The maximum shear strength reaches 361 MPa, and the peel strength is up to 510 N/mm at 1323 K after six passes with a total reduction ratio of 74.8%. Both the dimension and number of interfacial pores decrease rapidly with increasing rolling passes. Multipass hot rolling generates a number of local embedments at the interface and improves the interfacial bonding strength.

1. Introduction

Stainless clad plates are commonly made by joining stainless steel and structural steel and successfully combine the surface properties of the stainless steel layer with the satisfactory mechanical properties of the structural steel substrate. Clad plates are made of a relatively thin stainless steel layer and a thick structural steel substrate with a thickness ratio of 1:3–1:10 and are usually less expensive than stainless steel according to Ramazan and Mustafa (2004). As stated by Wang et al. (2007), clad plates have become increasingly popular for engineering applications and have been used widely in many fields in transfer pipes, reservoirs, vessels, heat exchangers, kitchen utensils, decorative trade, and other products. Many technologies have been used to manufacture stainless clad plates, such as explosion welding, diffusion bonding, vacuum brazing, transient-liquid-phase bonding, inversion casting, common casting, and roll bonding. Among these various approaches, roll bonding is the most economical and productive manufacturing process for large clad metal sheets. According to Chen et al. (2005) and Kang et al. (2007), roll bonding is a solid state welding process joining similar or dissimilar metals, and it is a well-established and widely used manufacturing technology. In roll bonding, two or more metal sheets, plates or strips are stacked together, passed through a pair of rolls, and finally jointed tightly when the proper deformation is achieved. In general, there are two types of roll bonding: hot roll bonding and cold roll bonding. Cold roll bonding has several advantages over hot roll bonding, including a more uniform individual layer thickness ratio, good surface quality and no surface oxidation. However, cold roll bonding also has some disadvantages. First, a high reduction is expected in the thickness of the material (up to 60% or more in a single rolling pass) under the high pressure needed at the roller to bond two metals. It is difficult for a common mill to bond two metals with a high strength and a large thickness. Second, annealing is normally performed to obtain a metallurgical bond after roll bonding. This process also leads to significant energy consumption. Compared with cold roll bonding, two metals can be easily bonded with only a slight reduction in thickness in hot roll bonding, and a metallurgical bond can be easily achieved due to the plastic deformation and recrystallization of interfacial metals. However, the interfacial metals will be oxidized in a non-protective atmosphere at high temperature. As a result, the bond strength between materials will be drastically decreased when the metal surface is oxidized, and it is likely that these two metals will not be able to be bonded together. A study of warm and cold rolling to bond a two-layered aluminum alloy presented by Yan and Lenard (2004) demonstrated that the shear strength reached a maximum at 553 K and decreased at higher temperatures due to the increase in the oxide layer. Peng et al. (1999) investigated the

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Table 1
The chemical composition of the substrate and superficial layer (wt.%).

Elements	C	Si	Mn	P	S	Ni	Cr	Fe
Layer	0.08	0.06	1.28	0.019	0.001	9.30	17.61	71.65
Substrate	0.21	0.30	0.22	0.012	0.009	0.002	0.01	99.20

effect of rolling temperature on the interface and bond strength of copper/aluminum metal laminates prepared by hot rolling in a single pass. The peel strength of laminates increased with the roll bonding temperature and reached a maximum at 703 K and then decreased at 773 K. Based on these results, these authors inferred that the decrease in peel strength resulted from the oxidation of the aluminum surface. Masahashi et al. (2006) fabricated iron aluminum alloy/steel laminates by pre-bonding the slab by applying a pressure of 1 MPa in a vacuum of less than 2×10^{-3} Pa and then welding the edge of the stacked plates to prevent oxidation of the metal surface, followed by rolling at 873–1273 K, leading to a reduction of approximately 75% after several passes. The accumulative roll-bonding process developed by Krallics and Lenard (2004) also indicated that the roll bonding of two-layered strips was conducted at 773 K in high vacuum in the first pass to limit the oxidation of the metal surface, and the adhesion increased with increases in load, contact time and temperature. Quadir et al. (2008) found that a bond was not easily achieved in aluminum alloys after heating to elevated temperatures of 573–823 K in air due to the increasing rate of surface oxidation. These results demonstrate the importance of preventing oxidation of the metal to improve the bond strength following hot roll bonding. The present study reports the preparation of stainless steel/plain carbon steel clad plates by hot roll bonding in a protective atmosphere. The multipass rolling process is employed to improve bond strength further. The shear strength and peel strength are examined by a custom-made testing device. The interfacial morphologies are measured after every pass by separating the stainless layer from the plain carbon steel. The effects of process parameters on bond strength and interfacial morphologies are discussed based on the experimental data.

2. Experiments

2.1. Sample preparation

Clad plate was prepared by hot roll bonding with plain carbon steel as the substrate and austenitic stainless steel (SUS304) as the layer in an argon atmosphere. The chemical compositions of both materials are provided in Table 1. The yield strength of carbon steel is 220 MPa, and that of austenitic stainless steel is 320 MPa, as determined by a uniaxial tension test at room temperature. The schematic of the roll bonding process is shown in Fig. 1. The bonding system includes a four-high mill and a 6 kW electrical resistance furnace. The four-high mill is driven by a 65 kW DC motor with a roll size of Φ110/Φ220 mm in diameter and 350 mm in length. The

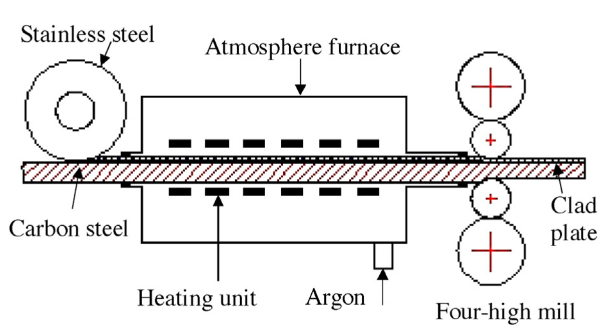

Fig. 1. Schematic of the hot roll bonding system.

maximum rolling speed of the mill is approximately 32 rpm, and the maximum roll force is 1200 kN. The electrical resistance furnace was filled with argon as a protective atmosphere. The furnace exit was located close to the mill entrance to reduce the heat loss of the stacked steel plates. The thickness of the carbon steel plate was 5.8 mm, and it was cut into 60 mm wide samples. The thickness of the austenitic stainless steel plate was 2.8 mm, and it was also cut into 60 mm wide samples. The surfaces of the steel plates were cleaned by appropriate mechanical and chemical methods to remove contaminants and organic matter. The carbon steel plate was pickled in 8–10% HCl solution at 60–80 °C to remove oxide scales. The surface of the austenitic stainless steel plate was roughened by a wire brush 0.15 mm in diameter to remove the thin oxide layer and to create a fresh surface with a Ra of 1.0–2.0 μm. Ra is referred as the arithmetic mean deviation of the roughness profile. The carbon steel plate and stainless steel plate were stacked together against the clean surfaces, and the leading heads were spot-welded to enter smoothly into the roll gap. The stacked plates were then put into the atmosphere furnace, purged by argon gas and heated to the temperature range of 1173–1323 K, and then rolled under the reduction of 24.3% in the first pass to obtain the primary bonding. Subsequently, the bonded plates were rapidly rolled for another five passes in air by the same mill, resulting in a total reduction ratio of 74.8%.

2.2. Microstructural characterization

Specimens were cut from bonded plates after each pass and prepared using conventional metallographic techniques. A 4% nitric acid alcohol solution was used as an etchant to reveal the interfacial microstructures. The interfacial microstructures and the peeling fractographies were observed using scanning electron microscopy (SEM). The diffusion of alloy elements near the interfacial region of the clad plate was determined by energy dispersive spectroscopy (EDS).

2.3. Testing mechanical properties

The shear and peel tests were adopted to evaluate the bond quality in this paper.

The shear tests were conducted on an 810–100 kN Material Test System to determine the bonding qualities with reference to the ASTM A 264 standard and the Chinese standard GB/T 6396-2008. According to these two standards, the shear test is to be performed as indicated in Fig. 2. The minimum cladding thickness for the shear tests is 1.9 mm. However, the substrate steel produces plastic buckling under the test compression force before the cladding layer is sheared off when the thickness (t) of substrate steel is less than 2-3 mm, leading to test failure. Thus, the tensile shear specimen should be used to test shear strength when the thickness of the clad plate is less than 10 mm according to Chinese standard GB/T 6396-2008, as shown in Fig. 3. However, it is difficult to machine notches on the specimen just at the bond interface, so the result is inaccurate or even completely wrong. In addition, the specimen is easily broken at position A because the tensile strength of position A may be less than the shear strength of position B. This also leads to test failure.

To determine the shear strength of the thinner clad plate (thickness <3 mm), a custom-made testing device was designed based on the two standards above. The testing device is composed of the punch, head, down mold, up mold, seat and bolt, consulting the patent by Jing et al. (2012), as shown in Fig. 4. First, the test specimen is cut along the cross section of the clad plate approximately 1 mm in thickness and 10–20 mm in length using an electric discharge machine. The specimen is clipped using a punch and head fastened by a bolt, and then held between the down mold and up