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Microstructure, mechanical properties and interface bonding mechanism of hot-rolled stainless steel clad plates at different rolling reduction ratios

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ABSTRACT

The microstructure, interfacial characteristics, shear behavior, tensile properties and fracture morphologies of stainless steel clad plates fabricated by vacuum hot rolling at different rolling reduction ratios of 20%, 40%, 70%, 90% and 93.75% are investigated using optical microscope (OM), ultra-depth microscope, scanning electron microscope (SEM), electron probe microanalysis (EPMA) and universal testing in detail. With the increasing rolling reduction ratio, the refinement degree of microstructure is increased, while the thicknesses of interface alloy element diffusion zones including the decarburized, carburized layers and martensite zone are decreased. Due to the different interface bonding status, the shear fracture of clad plate rolled at a low reduction ratio of 40% is located at interface, while clad plates with high reduction ratios of 70% and 90% fracture at the decarburized layers. Therefore, interface shear strength is sharply and then slightly increased. Moreover, the interface bonding strength, tensile strength and interface deformation coordination are increased, while fracture elongation is increased firstly and then decreased with the increasing rolling reduction ratio, which are attributed to the competing mechanisms of grain refinement, work hardening, interface strengthening and intergranular cracks of carburized layer. Overall, the interfacial bonding mechanism can be related to the Mn-Si oxide inclusions rupture, alloying elements diffusion, phase transition and severe plastic deformation at high rolling temperature.

1. Introduction

Stainless steel clad plates, exhibiting their predominance on mechanical properties, corrosion resistance and low cost, are widely used for high-end defense field, such as nuclear, shipbuilding, petrochemical, armor and desalination sectors involving corrosion issue [1–3]. Stainless steel clad plates contain carbon steel or low alloy steel taken as substrate and stainless steel taken as cladding, and the clad interface may be metallurgically bonded by methods of explosive bonding, hot rolling and overlaying welding [4–6]. Due to low cost, low time consuming and high efficiency, vacuum hot rolling is expected to replace the explosive bonding and overlaying welding methods in pressure vessels. Recently, ninety percents of stainless steel clad plates were produced by vacuum hot rolling method [7].

Hot rolling process can obtain complete metallurgical interface bonding under the high temperature, rolling pressure and severe plastic deformation. Meanwhile, there are obvious interface alloying elements diffusion zones around the actual interface. Carbon diffusion behavior results into the formation of decarburized layer and carburized layer, which severely deteriorate the mechanical properties and corrosion resistance of stainless steel clad plate, whereas the diffusion behavior of other alloy elements (Fe, Ni, Cr) plays an important role in strengthening and toughening clad interface [8–10]. Alloy element diffusion, interface microstructure and mechanical properties are related to the fabrication parameters, such as vacuum degree, rolling reduction ratio and rolling temperature. Zhu et al. [1,11] has reported that the interface bonding strength and toughness can be enhanced by improving the vacuum degree. Liu et al. [12,13] investigated the effect of rolling temperature on the interface microstructure and mechanical properties of stainless steel clad plates in detail, and concluded that

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the interface shear strength and tensile ductility are increased with the increasing rolling temperature. However, the topic about the effect of rolling reduction ratio has yet to be studied systematically.

From ancient times, the Damascus steel containing multilayer soft/hard steel structure were fabricated by repeated annealing and forging method. High plastic deformation during multiple annealing and forging process can not only remove impurities and serious work hardening, but also refine the grain size and improve the interface bonding strength [14–16]. Recently, accumulative roll bonding (ARB) is used to fabricate laminated metal composites with microscale and nanoscale layer thickness. Because of the relative simplicity and low cost nature of this process, and the enhanced mechanical properties are attributed to the mechanisms of grain refinement, interface toughening, size effect and dislocation strengthening during the multiple rolling process with super-high rolling reduction ratio [17,18]. Therefore, the rolling reduction ratio plays an important role in strengthening and toughening laminated metal composites including stainless steel clad plate. Investigating the effect of rolling reduction ratio on interface microstructure and mechanical properties can be a guide to improve the loading capacity and service applications.

2. Experimental procedures

Stainless steel clad plates were prepared by vacuum hot bonding with plain carbon steel as the substrate and SUS304 stainless steel as the cladding. The chemical compositions of both base and cladding steel are listed in Table 1.

Carbon steel plates with dimension of 200 × 240 × 60 mm and 304 stainless steel plates with dimension of 160 × 200 × 12 mm were prepared for hot-rolling preparation. After cleaning up the oxide scale and contaminant layer on the surface by angle grinder or other grinding machines, two groups of square billets were symmetrically assembled in a mirror. All round welding of four plate edges was carried out to form a sealed chamber with a reserved air exhaust hole, then pumping was performed with 10^{-2}Pa and then sealed. The rolling process was carried out after soaking the built-up slab at 1200 °C for 120min. The thicknesses of the five clad plates were reduced after one, three, five, eight and ten passes, and total rolling reduction ratios are 20%, 40%, 70%, 90% and 93.75%, respectively. Finally, the hot products were naturally cooled in air and afterwards cut for testing.

Samples were cut from the rolled stainless steel clad plates and prepared using conventional metallographic technologies. The solution of 10% CrO_3+90% H_2O and 4% nitrate alcohol was used as the etchant to display the microstructure of stainless steel cladding and carbon steel substrate, respectively. The microstructure and distribution of interface alloying elements were observed by Axio Vert. A1MAT optical microscope (OM), JSM-7100F scanning electron microscope(SEM), and JXA-8530F electron probe microanalysis (EPMA).

The tensile and tensile shear samples are shown in Fig. 1. The samples were carried out using an AGS-50kNX universal testing machine at a constant crosshead speed of 2 mm/min. The widths of all the tensile shear samples are 5.0 mm, and the notch distance is 1.5 mm as shown in Fig. 1a). Tensile dog bone samples have dimensions of 18 mm × 5.0 mm × 2.4 mm as shown in Fig. 1b).

Table 1
The chemical compositions of the carbon steel and stainless steel (wt. %).

Elements	Fe	Cr	Ni	C	Mn	Si	P	S
Q235	98.91	–	–	0.2	0.5	0.3	0.045	0.05
SUS304	68.95	18.5	8.5	0.025	2	2	0.025	0.001

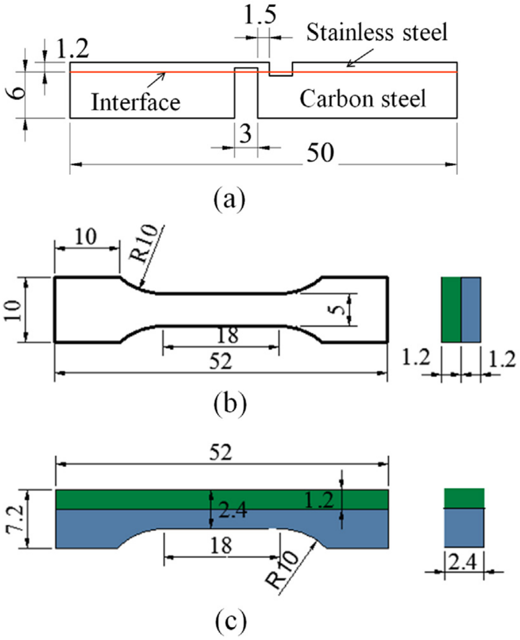

Fig. 1. Schematic of specimen shape under testing. a) tensile-shear specimen; b) tensile specimen; c) non-symmetrical tensile specimen.

Herein, the symmetrical layer thickness of carbon steel substrate is about 1.2 mm. Moreover, non-symmetrical tensile specimen along layer thickness should be used to observe the profile fracture characteristics and fracture damage as shown in Fig. 1c). In order to provide a clear surface, the specimens were glued to a metallic platen and polished using a polishing machine, a total of five samples were tested for each mode.

3. Results and discussions

Fig. 2 shows the optical microstructure of stainless steel clad plates with different rolling deformation reduction ratios, and the corresponding statistical grain sizes of different zones are listed in Table 2. At a low rolling reduction ratio of 40%, the austenite grains with the size of about 152 μm in the stainless steel cladding, the ferrite grains and pearlite phases in the carbon steel substrate are rather coarse. Especially, an abnormal growing grain is presented at the cladding layer as shown in Fig. 2a). Moreover, a thick decarburized layer with the thickness of 108 μm and a carburized layer with the thickness of 230 μm are located at the interface zone as shown in Fig. 2a) and b), which is attributed to the severe diffusion behavior of carbon element [13]. In addition, the interface zone shows gradient grain distribution. Grain size of decarburized layer is larger than that of the carbon steel substrate. The reason is that pearlite can effectively encourage the nucleation of ferrite in carbon steel during the cooling process. Therefore, the grain of decarburized layer with the grain size of 82 μm is hard to refine due to the absence of pearlite. Grains of the carburized layer adjacent to the interface zone are effectively refined compared to the grains in the cladding far away of the interface, which may be attributed to the mutual diffusion of Cr and C elements, and many chromium carbide ($Cr_{23}C_6$) particles are formed at the carburized layer. The $Cr_{23}C_6$ precipitates display a gradient distribution perpendicular to the clad interface, and pin effect of the carbides in the grain boundary keep grain boundary from coarsening, which maintains the refined grain structure. Therefore, the grain size of carburized layer reveals a gradient distribution.