Applied Surface Science 463 (2019) 121–131

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Full Length Article

Interface characteristics and fracture behavior of hot rolled stainless steel clad plates with different vacuum degrees

B.X. Liu*, S. Wang, C.X. Chen**, W. Fang, J.H. Feng, X. Zhang, F.X. Yin

Research Institute for Energy Equipment Materials, Tianjin Key Laboratory of Materials Laminating Fabrication and Interfacial Controlling Technology, School of Materials Science and Engineering, Hebei University of Technology, Tianjin 300132, China

ARTICLE INFO

Keywords:
Stainless steel clad plate
Hot rolling
Vacuum degree
Interface
Mechanical properties

ABSTRACT

In order to investigate the effect of vacuum degree on the interface microstructure and mechanical properties of stainless steel clad plate, series of 316L/Q235 clad plates were successfully fabricated by hot rolling with different vacuum degrees of 10^5 Pa, 400 Pa, 10 Pa, 10^{-1} Pa and 10^{-2} Pa. Interestingly, with the increase of vacuum degree, the interface oxides distribution changed from continuous wall/film to dispersed refined particles, and the thicknesses of martensite layer, decarburized layer and carburized layer were gradually increased. Meanwhile, the interface bonding strength of clad plates can be effectively enhanced by improving the vacuum degree. Due to thin decarburized and carburized layers, the stainless steel clad plate with a low vacuum degree of 10^5 Pa reveals superior yield strength and ultimate strength, while a low fracture elongation was obtained due to severe interface delamination. However, the stainless steel clad plate with a high vacuum degree can obtain a superior tensile ductility, which is attributed to the strong interface and localized necking delaying effect.

1. Introduction

Corrosion-resistant stainless steel clad plates have been available in various forms over 60 years and are widely applied in the nuclear, oil and gas production [1–3]. The stainless steel cladding layer which will be in contact with the corrosion fluids whilst the less expensive backing carbon steel substrate can provide the strength and toughness required to maintain the mechanical integrity. The cost saving from using cladding rather than monolithic stainless steel is particularly valid when the total thickness increases or when the cladding grade becomes more complex and hence expensive [4].

Stainless steel clad plates have been utilized with great success in processing vessels, heat exchangers, tanks and a variety of material handling and storage facilities as well as making longitudinally welded clad pipe [4–6]. Recently, appropriate stainless steel clad plates synthesizing processes for industrialization mainly contain three kinds of bonding methods: overlay welding, explosive welding and hot rolling. Herein, due to the controllable cladding thickness, high efficiency and continuity compared to the other above two methods, more than ninety percents of stainless steel clad plates are produced by vacuum hot rolling [7–9].

Interface bonding status and bonding strength are taken as main factors to evaluate the quality of stainless steel clad plate, and the interface bonding strength and toughness determine the usefulness of stainless steel clad plates in subsequent forming processes, such as cutting, forging, rolling, bending, joining, deep drawing and stretch forming etc [10–15]. The interface bonding strength of stainless steel clad plates mainly depends on several rolling parameters, including rolling reduction ratio [16], rolling temperature [1], vacuum degree [17] and interlayer etc [18]. Liu et al [1] reported that the interface bonding strength of stainless steel clad plate is gradually increased with the increase of rolling reduction ratio and rolling temperature. The tensile fracture characteristics reveal the transition from a weak interface with long delamination cracks to a strong interface without defects, and shear fracture zone transmits from the interface to the decarburized layer. Xiao et al [19] reported that the addition of DT4 interlayer can effectively inhibit carbon alloy element diffusion, which is beneficial to strengthen the clad interface of TA2/Q235B clad plate. Zhu et al [17] found that interface oxides turn from the blocky shape into the spheroidal, rod-like, irregular linear shape with the increase of vacuum degree. However, the intuitive effect of vacuum degree on interface microstructure, shear fracture zone, tensile properties and fracture characteristics has not been investigated in detail. This work will further provide the relationship between microstructure and performance and guide the interface design for property improvement of stainless steel clad plates.

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* Corresponding author.
** Corresponding author.
E-mail addresses: liubaoxiliubo@126.com (B.X. Liu), karenccx@126.com (C.X. Chen).

https://doi.org/10.1016/j.apsusc.2018.08.221
Received 28 April 2018; Received in revised form 4 August 2018; Accepted 24 August 2018

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

Elements	Fe	Cr	Ni	C	Mn	Mo	Si	P	S
Q235	Bal	–	–	0.2	0.5	–	0.3	0.045	0.05
SUS316L	Bal	16.03	10.03	0.017	1.26	1.95	0.42	0.031	0.0025

2. Experimental procedures

Stainless steel clad plates were prepared by vacuum hot bonding with plain carbon steel as the substrate and SUS316L stainless steel as the cladding. The chemical compositions of both base and cladding steels 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 × 16 mm were prepared for hot-rolling process. 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 different vacuum degrees of 10^5 Pa, 400 Pa, 10 Pa, 10^{-1} Pa, 10^{-2} Pa and then sealed. The rolling process was carried out after soaking the built-up slab at 1200 °C for 120 min. The thicknesses of the five clad plates were reduced after ten passes, and total rolling reduction ratio was 93.75%. 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 solutions of 10% CrO_3 + 90% H_2O and 4% nitrate alcohol were used as the etchant to display the microstructure of stainless steel cladding and carbon steel substrate, respectively. Moreover, the EBSD sample was electropolished for 40 s at 2A and 5 °C. The electrolyte contained 800 ml acetic acid (CH_3COOH) and 200 ml perchloric acid ($HClO_4$). The microstructure and distribution of interface alloying elements were observed by Axio Vert.A1MAT optical microscope (OM), JSM-7100F scanning electron microscope (SEM), JXA-8530F electron probe microanalysis (EPMA) and electron back scattering diffraction (EBSD). The martensite zone analysis was carried out by TEM. 3-mm-diameter discs with the interface at the centre were milled by the ion-beam at 4 kV using an initial incidence angle of 15° and subsequently a shallower angle to obtain an electron transparent region at the clad interface.

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. 1(a). Tensile dog bone samples have dimensions of 18 × 5.0 × 2.0 mm as shown in Fig. 1(b). Herein, the symmetrical layer thickness of carbon steel substrate is about 1.0 mm. Moreover, non-symmetrical tensile specimen along the layer thickness can be used to observe the profile fracture characteristics and fracture damage as shown in Fig. 1(c). In order to provide a clear surface, the specimens were glued to a metallic plate and polished using a specialized polishing machine, then a total of five samples were tested for each mode.

3. Results

3.1. Microstructure and interface characteristics

Fig. 2 shows the optical and SEM interface oxides of stainless steel clad plates with different vacuum degrees. It is observed that the number of interface oxides is gradually decreased with the increase of vacuum degree as shown in Fig. 2(a–e). At a low vacuum degree of 10^5 Pa, loose coarse oxide clusters accompanying with many refined oxide particles are stacked on the clad interface and form a thick ceramic wall as shown in Fig. 2(a). Zhu et al [17] reported that coarse interface oxides were formed due to high oxygen partial pressure. However, with the increase of vacuum degree, the number and size of interface oxides are gradually decreased as shown in Fig. 2(b–d). Fig. 2(b) shows that many coarse blocky shaped oxides with the size of 3–5 μm are presented at the clad interface, and some refined spherical oxides with nanometer size are still located at the interface. Fig. 2(c) shows the interface oxides morphologies of clad plate at the vacuum degree of 10 Pa, herein, many coarse blocky shaped oxides and partial continuous belt-like shaped oxides exist at the clad interface. At the vacuum degree of 10^{-1} Pa, spheroidal, rod-like and spinel structure oxides with submicro or nanoscale size are dispersed at the clad interface as shown in Fig. 2(d). At a high vacuum degree of 10^{-2} Pa, it is hard to detect the interface oxides in the macro scale. However, in the microscale, there are a few refined spinel and spheroidal-like oxides presented at the clad interface as shown in Fig. 2(e). That is to say, the high vacuum degree can obviously inhibit the interface oxidation.

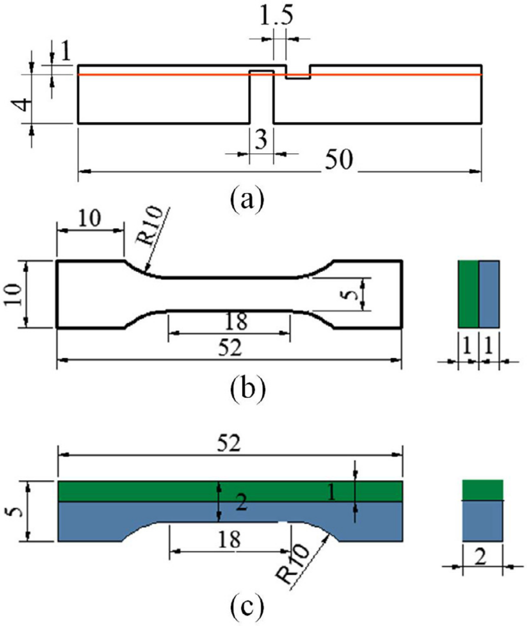

Fig. 1. Schematic of specimen shape under testing. (a) tensile-shear specimen; (b) tensile specimen; (c) non-symmetrical tensile specimen.

Fig. 3 shows the EPMA map distribution of stainless steel clad plates with different vacuum degrees. Clearly, it is observed that the interface oxidation zone is gradually shortened with the increase of vacuum degree. At a low vacuum degree of 10^5 Pa, EPMA map shows that Cr, Mn, Si, O elements are all enriched in the clad interface, and based on the selective oxidation theory, these coarse ribbon-like oxides may be Cr_2O_3 and Mn-Si oxides, which form a thick oxides film or wall as shown in Fig. 3(a). With the increase of vacuum degree, oxides shape turns from a continuous thick wall into the dispersed spherical and rod-like morphologies as shown in Fig. 3(b), (c). At a high vacuum degree of 10^{-1} Pa, only Mn, Si, O elements are enriched in the clad interface as shown in Fig. 3(d), and dispersed oxides are uniformly distributed at the clad interface, revealing a strong interface bonding. Fig. 3(e) shows the clad interface of stainless steel clad plate with the vacuum degree of 10^{-2} Pa, and only refined SiO_2 oxides are detected. Herein, a complex oxidation system is formed at the clad interface at the high rolling temperature of 1200 °C, and various alloy elements containing Si, Mn, Cr, Fe, Ni all take part in the oxidation system. According to thermodynamic calculation and Ellingham diagram, the formation Gibbs free energies of corresponding oxides resulting from the above alloy elements at the rolling temperature of 1200 °C are sorted as follows [20]:

$$\Delta G_{SiO_2} < \Delta G_{MnO} < \Delta G_{Cr_2O_3} < \Delta G_{FeO} < \Delta G_{Fe_3O_4} < \Delta G_{NiO} < \Delta G_{Fe_2O_3}$$