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Effect of interface oxides on shear properties of hot-rolled stainless steel clad plate

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ABSTRACT

This paper aims at determine the effect of interface oxides on shear properties of 316L stainless steel/HSLA steel clad plate by studying interface microstructure, characteristics of interface oxides and shear fracture model. It was found that carbon element diffusion caused the forming of a decarburized ferrite zone (DFZ) of the substrate and a carburized austenite region (CAZ) of the clad metal, and between those two metals, a high-hardness band (HHB) with rapid element component change are formed in the solid-state diffusion bonding process. It was revealed that, at the micro-scale, when oxides concentrated area on the boundary of CAZ reaches up to a threshold size, DFZ crack may carve across the rigid HHB and propagate along CAZ boundary during the shear test. Thus macro-scale nonuniform distribution of oxides led to massive competitive cracking between the plastic DFZ and the high-strength CAZ, and statistically maintain the shear strength at a high level for test samples with a medium oxidation level. Nevertheless, those clad plates may still fail to meet the performance request of products, since the cladding interface tended toward a low fracture toughness failure during the process of deformation.

1. Introduction

Stainless steels clad plates are widely used for vessels in chemical and petroleum industries involve corrosion issue, and displaying its predominance on mechanical properties, corrosion resistant and low cost. Those composite plates cover plate of a carbon steel or low-alloy steel base to which is bonded on one or both sides a layer of stainless steel, and the alloy-cladding metal may be metallurgically bonded to the base metal by methods of explosive cladding, rolling cladding and weld overlay cladding [1]. Bond quality is one of the most important specifications for clad plate product, and the cladding metal shall be integrally and continuously bonded to the base metal. Bending and shearing tests are usually applied for evaluating bond integrity and strength of the cladding interface prior to shipment in accordance with the procedures and methods of standard specification [2].

Since most of the producing methods for stainless steel clad plate involved the interface solid diffusion process under high-temperature [3], such as hot-rolling, cold-rolling and explosive cladding with post heat treatment after forming, a lot of work had been done on microstructure characteristic and element diffusion associated with the interface forming under those hot bonding processes [4–7], and the relevant bonding properties have also been studied. Those works mostly concerned with the bonding strength change with different technological parameter involving temperature and reduction, under conditions of a relatively clean interface with a little oxide, and supposed that interface oxidation is an adverse factor for the important reliability indicator of bond quality, which may result in significantly reduction of bonding strength. Clean interface indeed ensures the steady quality of clad plate, but the fact is that interface oxidation is inevitable due to the metal oxidation nature, and also it is difficult to keep the oxidation at a low level with the simple manufacture process in commercial production of large gauge clad plates. However, there are no investigations on the integrated role of the interface oxides on bonding properties of stainless steel clad plates have been reported. For this purpose, we studied on the interface microstructure, characteristics of interface oxides and shear fracture mechanism to find the effect of interface oxidation on shear properties of hot-rolling stainless steel clad plates. It may provide guidance for the control of clad plate quality and improvement to the manufacture process with the necessary connection between interface oxidation and production conditions.

2. Materials and experimental procedures

The base and clad materials of seven groups of clad plates (No. 1–7) used in this research were respectively HSLA steel and 316L stainless steel, and chemical compositions of those commercial

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Table 1
Chemical composition (weight percent) of raw materials.

Alloy	C	Si	Mn	Cr	Ni	Mo	P	S	Fe+Others
HSLA	0.17	0.27	1.40	0.023	0.018	–	0.011	0.0074	Bal
316L	0.017	0.42	1.26	16.03	10.03	1.95	0.031	0.0025	Bal

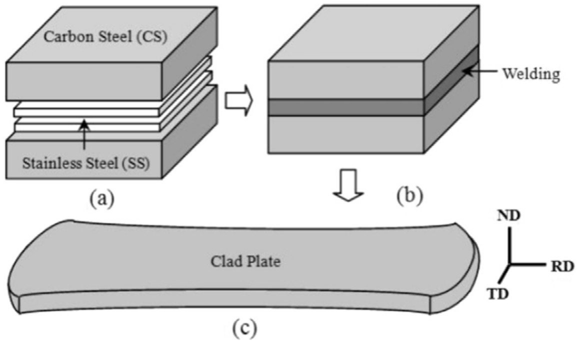

Fig. 1. Simplified diagrams of the clad plate production process. (a) Surface finishing and assembling; (b) Welding and vacuuming; (c) Hot rolling.

hot-rolling plates are given in Table 1.

HSLA steel plates with dimension of 300 × 300 × 85 mm and 316L steel plates with dimension of 300 × 300 × 15 mm were prepared for hot-rolling practice. As shown in Fig. 1, two groups of square billets were mirror symmetrically assembled after cleaning up the oxide scale and other foreign matters on the surface by machining the surfaces flat (Fig. 1a). All-round weld of plate edges was carried out to form a sealed chamber with a reserved air exhaust hole, then vacuuming was performed with various vacuum degrees and sealing state for interface oxidation controlling through the hot-rolling process (Fig. 1b and Table 2). The rolling process was carried out after soaking the built-up slab at 1200 °C for 120 min (Fig. 1c). The thickness of the clad plate was reduced from 200 mm down to 50 mm after five passes in about 5 min, and then hot products in air were naturally cooled and afterwards cut for test.

Cross sections perpendicular to the rolling direction of the sample with 20 mm interface were ground and finished to statistically measure characteristics of the oxides. Oxides area and length fraction of each cross section were assessed from 12 microstructure pictures each about 0.2 mm. And then the samples were sequentially etched with 4% ethanol solution of nitric acid and 10% chromic acid electrolytic method for microstructure observation. Interface characteristics and fracture examinations were also conducted using a scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS) and electron probe microanalyses (EPMA) with wavelength dispersive spectroscopy (WDS). Diffusion distances of element Cr and Ni were measured by fitting composition profiles using the Boltzmann function, and the location with 1 pct composition difference to the matrix were set for diffusion start or end position. Vickers microhardness tests (load 10 g) were carried out through the plate thickness to evaluate mechanical property variations near the interface. Bending specimens (270 × 40 × 24 mm) were machined perpendicular to the rolling direction with clad material thickness of 4 mm. And bend and shear tests were carried out using a universal testing machine to determine the quality of the bond, and test methods were according to the ASTM standard.

Table 2
Vacuum degree and sealing state of cladding plates.

Group number	Vacuum degree (Pa)	Sealing state
No. 1	0.66	Vacuuming and fully sealed
No. 2	0.10	Vacuuming and fully sealed
No. 3	100,000	Vacuuming and fully sealed
No. 4	100,000	No vacuuming and fully sealed
No. 5	133	Point leakage simulation
No. 6	25,000	Point leakage simulation
No. 7	133	Surface leakage simulation

3. Results

3.1. Interface characteristics

Optical microscopy studies of the interface microstructure of stainless steel clad plates revealed that the bi-material interface was nearly flat, decarburization of HSLA steel and carburization of stainless steel were observed near the interface, as shown in Fig. 2a. The base metal had an 80 μm wide DFZ adjacent to the interface, and ferrite plus pearlite structure away from the interface. The stainless steel exhibited a 200 μm wide CAZ with poor performance of intergranular corrosion resistant near to the interface. In Fig. 2b, the higher magnification image of the transitional zone showed a 1–2 μm wide band consists of light gray contrast strip which was hard to distinguish from the austenite matrix and dark contrast long ribbon-like bar which seems to be more easily to etch. At the band boundary near CAZ, crushed oxides distributed at the original metal surface (OMS) in dot, block and irregular shape.

The elevated composition gradient of alloying elements existed between HSLA steel and stainless steel could result in remarkable element changes near the interface of clad plates during the high temperature diffusion process. The element transfer results are given in Fig. 2c, element content of Cr and Ni decreased when it was moving from stainless steel to carbon steel. Concentration gradients and diffusion coefficients difference between Cr and Ni elements led to the diffusion distances of 12–13 μm and 3–4 μm

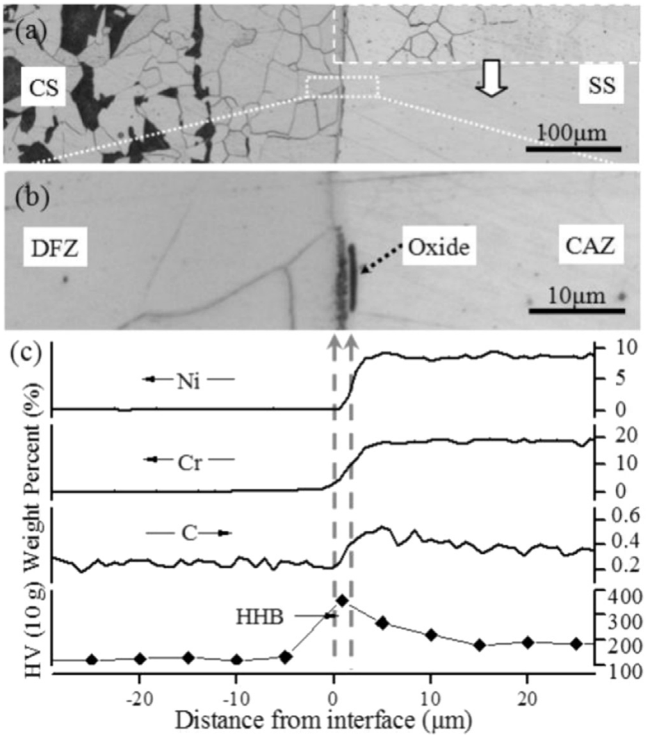

Fig. 2. Characteristics of bi-metal interface. (a) Micrographs of the interface; (b) at enlargement; (c) compositional profile via EPMA and microhardness variation.