Materials Chemistry and Physics 216 (2018) 460–467

Contents lists available at ScienceDirect

Materials Chemistry and Physics

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

Microstructure and mechanical properties of hot rolled stainless steel clad plate by heat treatment

B.X. Liu*, S. Wang, W. Fang, J.L. Ma, F.X. Yin**, J.N. He, J.H. Feng, C.X. Chen

School of Materials Science and Engineering, Research Institute for Energy Equipment Materials, Tianjin Key Laboratory of Materials Laminating Fabrication and Interfacial Controlling Technology, Hebei University of Technology, Tianjin, 300130, China

HIGHLIGHTS

- Interface bonding strength can be enhanced by quenching treatment.
- Carburized layer thickness is decreased with the increasing quenching temperature.
- Reasonable quenching treatment can obtain a high strength-toughness balance.

ARTICLE INFO

Keywords:
Stainless steel clad plates
Quenching treatment
Interface
Ductile-brittle transition
Alloy element diffusion

ABSTRACT

Series of stainless steel clad plates were heat treated at the quenching temperatures ranging from 900 °C to 1150 °C for holding time of 6min and 60min, respectively. It was observed that the ferrite and pearlite phases in the hot-rolled carbon steel substrate changed into lath martensite and needle-like ferrite through quenching treatment. The carburized layer thickness was gradually decreased till disappeared, and the interfacial shear strength was firstly increased and then decreased with the increasing quenching temperature, which was attributed to the sufficient alloy element diffusion and matrix softening at the high quenching temperature. At the quenching time of 6min, the shear fracture zone transmitted from the interface into the decarburized layer with the increasing quenching temperature, and the severe interfacial delamination cracks all existed at the clad interface. However, the main shear cracks were all presented at the decarburized layer for the quenching time of 60min, and there were no interfacial delamination cracks in the tensile samples, revealing that strong interface can be obtained by prolonging quenching time. The tensile behavior and fracture characteristics showed the ductile-brittle transition with the increasing quenching temperature.

1. Introduction

Stainless steel clad plates combine the low cost, high weldability, strength, ductility, formability and thermal conductivity of carbon steel substrate with the high corrosion resistance, abrasion resistance, magnetic resistance and luxury decoration of stainless steel cladding, which have been widely applied in the nuclear, oil chemical industry, petroleum, pressure vessels, tanks, heat exchangers, water desalination, shipbuilding and other fields [1–6]. Actually, the saving of the cost and precious alloying elements (Cr and Ni etc) from using stainless steel clad plates rather than individual stainless steel is particularly valid when the total thickness increases or when the cladding metal becomes more complex and hence expensive [7–11]. Recently, the stainless steel clad plates have been mainly fabricated by three methods: overlayer welding [12–15], explosive welding [16–18] and hot rolling [19,20]. Herein, vacuum hot rolling is taken as a time-saving and environmental-friendly process among these various technologies, which is a solid phase bonding process to join carbon steel and stainless steel at elevated temperature for making clad plates [2,21].

However, the hot rolled stainless steel clad plates have many shortcomings. Firstly, the low carbon steel substrate comprising typical annealing microstructure (ferrite and pearite phases) always displays low yielding and ultimate strength compared with the stainless steel cladding, which can't match up with the practical service requirement of stainless steel [22–25]. Secondly, stainless steel cladding always contains deformation defects and deleterious secondary phases. For example, strain induced martensite phase and $Cr_{23}C_6$ particles can also decrease the mechanical properties and corrosion resistance of stainless

---

* Corresponding author.
** Corresponding author.
E-mail addresses: liubaoxi@hebut.edu.cn (B.X. Liu), yinfuxing@hebut.edu.cn (F.X. Yin).

https://doi.org/10.1016/j.matchemphys.2018.06.033
Received 25 March 2018; Received in revised form 1 June 2018; Accepted 12 June 2018

Table 1
Chemical compositions of Q235 carbon steel and 304 stainless steel materials.

material	Fe	Cr	Ni	C	Mn	Si	P	S
Q235 carbon steel	98.91	–	–	0.2	0.5	0.3	0.045	0.05
304 Stainless steel	68.95	18.5	8.5	0.025	2.0	2.0	0.025	0.001

steel [3,26–30]. Thirdly, a carburized layer with a thickness of 50–100 μm is formed in the stainless steel cladding due to carbon diffusion behavior, which can result in the formation of intergranular tunnel cracks and affect the fracture behavior and corrosion resistance of clad plates [2,31–33]. Fourthly, weak interface bonding strength can also induce the delamination crack, which seriously affects the practical application of stainless steel clad plates [2,34–38]. Therefore, it is necessary to determine the optimal heat treatment conditions to eliminate the above defects during hot rolling process and achieve the structure-function balance between the carbon steel substrate and the stainless steel cladding. It is useful to further comprehend the relationship between structure and performance and guide the microstructure design for property improvement of stainless steel clad plate or other laminated composites.

2. Experimental procedures

The stainless steel clad plate containing 304 austenite stainless steel cladding and Q235 carbon steel substrate was successfully fabricated by vacuum hot rolling method at 1100 °C, and the corresponding compositions of raw Q235 carbon steel and 304 stainless steel are listed in Table 1. Before assembly, the surface of substrate and cladding should be cleaned by angle grinder to remove the contaminants and oxide layer [39,40]. The sheets were symmetrically stacked together in an alternating sequence and then welded by argon arc welding as shown in Fig. 1a). Herein, symmetrically stacking method is chosen to be beneficial to straighten the plates and improve the production efficiency. The stacking sequence is taken as ABBA type. Carbon steel substrate is taken as A, and stainless steel cladding is taken as B. Two austenitic stainless steel plates were shielded with the high temperature isolate cloth and then spot-welded to fix together, the carbon steel plates were symmetrically stacked with austenitic stainless steel plates. 304 stainless steel plate has a dimension of 260 mm (length) × 160 mm (width) × 12 mm (thickness), Q235 carbon steel plate has a dimension of 300 mm (length) × 200 mm (width) × 60 mm (thickness), the thickness of isolate cloth is about 1 mm. Therefore, the thickness of symmetrically stacked plates is about 145 mm. The inner surfaces of two pieces of carbon steel plates were welded with four carbon steel seals, and a hole was drilled in the middle of one seal, which was joined with a stainless steel pipe by tungsten Inert Gas (TIG) Welding, and it is suitable to pump the air out of the green blanks and make a vacuum environment (10^{-2}Pa) using a triplex diffusion pump. Finally, the pipe was sealed and welded by hydraulic pressure clamp. The stainless steel clad plates were heated to the temperature of 1100 °C and the soaking time was 2 ~ 3 h. Afterwards, the stacked blanks were hot rolled to approximately 14.2 mm in thickness with a 2-high Φ550 × 350 mm hot rolling mill for eight passes at a speed of 288r/min, and the total reduction ratio was about 90.3% as shown in Fig. 1b). After cooling process in the air atmosphere, the symmetrical stainless steel clad plates were cut by sawing machine along the four edges, and the surrounding carbon steel welding seals were cut off as shown in Fig. 1c). Finally, two stainless steel clad plates were successfully separated along the original isolate cloth between surfaces of two stainless steels.

A portion of the hot-rolled stainless steel clad plates were subjected to the quenching treatments to improve the mechanical properties of carbon steel and corrosion resistance of stainless steel cladding. The water quenching was carried out at 900 °C, 950 °C, 1000 °C, 1050 °C, 1100 °C, 1150 °C after soaking for 6min and 60min, respectively.

Microstructural examination of hot rolled and heat treated clad plates was prepared by standard metallographic techniques. After the samples were mechanically polished to 1 μm flat, the carbon steel substrate was etched with 4% nitric acid alcohol solution, while the stainless steel cladding was exposed by electrochemical etching with chromic acid solution at 10 V for 15s. Then the samples were examined under a Axio Vert.A1 optical microscope for general microstructural features and under a JSM-7100F scanning electron microscope (SEM) for studying the structural changes near the bonding interface. Electron probe microanalysis (EPMA) was also carried out using a JXA-8530F electron probe micro analyzer for analysis of various alloying elements across the bonding interface.

Mechanical properties were evaluated using the test samples processed from as hot rolled and heat treated stainless steel clad plates. Tensile specimens of 18 mm gauge length processed as per ASTM E8 specification were tested in the Instron-5569 machine at a strain rate of 2 mm/min. All the thicknesses of tensile sample were 2.4 mm for base carbon steel substrate, stainless steel cladding and clad plates. Herein, the interface is located in the middle of tensile samples of clad plates as shown in Fig. 1d). In order to accurately measure the interfacial

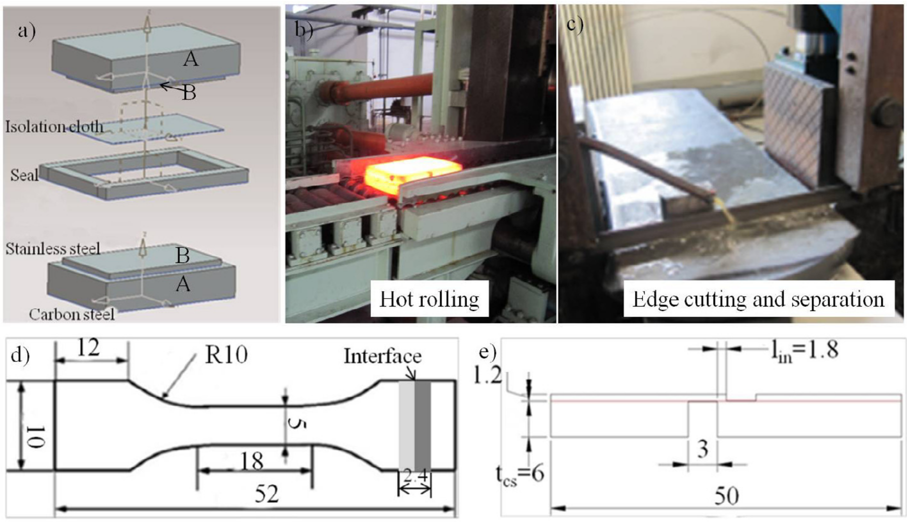

Fig. 1. The schematic diagram of fabrication process and dimensions of conventional tensile, tensile shear samples. a) The schematic illustration of stacking stainless steel clad plates symmetrically; b) hot rolling; c) edge cutting and separation process; d) tensile sample, e) shear sample.