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The interface microstructure, mechanical properties and corrosion resistance of dissimilar joints during multipass laser welding for nuclear power plants

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ABSTRACT

This study presents the interface microstructure, mechanical properties and corrosion resistance of dissimilar joints between Inconel 52M overlays and 316L stainless steel during multipass laser welding for nuclear power plants. The results indicate that the microstructure at the interface beside 316L stainless steel consists of cellular with the width of 30–40 μm, which also exhibits numerous Cr and Mo-rich precipitates like flocculent structure and in chains along grain boundaries as a mixed chemical solution for etching. Many dendritic structure with local melting characteristics and Nb-rich precipitates are exhibited at the interface beside Inconel 52M overlays. Such Nb-rich precipitates at the interface beside Inconel 52M overlays deteriorate the tensile strength and toughness of dissimilar joints at room temperature. The tensile strength of 316L stainless steel at 350 °C significantly decreases with the result that dissimilar joints are fractured in 316L stainless steel. The correlation between corrosion behavior and microstructure of weld metals is also discussed. The difference in high corrosion potential between Nb-rich precipitates and the matrix could result in establishing effective galvanic couples, and thus accelerating the corrosion of weld metals.

1. Introduction

In nuclear power plants (NPPs), dissimilar joints are widely used to connect the ferritic steel of reactor pressure vessels, steam generators and pressurizers to austenitic stainless steel pipes [1]. For joining those dissimilar materials, nickel-base alloy buttering layers are usually applied to clad on the ends of the cold leg piping to impede the alloy carbon diffusion in the joins [2,3]. Recently, owing to high content of chromium, Inconel 52/52M alloys have started to be used both in new constructions as well as filler metals, which could provide extended service lives in nuclear engineering [4,5]. With the addition of Nb to resolve the ductility dip cracking, Inconel 52M alloys have drawn more attention in dissimilar joints for nuclear power plants [6].

As is well known, the large groove gap for joining thick section plates generally results in large residual stress and poor mechanical properties because of a lack of plasticity in the weld joints. Multipass laser welding technique with a narrow gap groove and a filler wire, with respect to low heat input, narrow heat-affected zone, low welding distortion and high welding speed, process controllability and weld quality, has shown great potential for thick section plates in engineering [7–9]. In recent years, many researchers have already made many significant contributions to this field. Elmesalamy et al. [10] successfully welded 316L stainless steel plates that were 20 mm in thickness using a 1 kW IPG single mode fiber laser with an ultra-narrow gap. They considered that the residual stresses were generally 30–40% lower in magnitude for the narrow gap laser welds in comparison to those for GTA welding. Alexander et al. [11] show that wire addition can enable relatively thick layers and electrical wire preheating increases the process performance and might facilitate wetting. Zhang et al. [12] studied microstructure and mechanical properties of super narrow gap joints of thick and high strength aluminum alloy plates welded by fiber laser. High power density laser welding show their unique advantages in the welding of thick section steels for potential nuclear pressure vessel manufacture [13–15]. In our research groups, the method of multipass laser welding has been put forward to join dissimilar materials between Inconel 52M overlays and 316L stainless steel for nuclear power plants. The defects

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and microstructure in the fusion zone of multipass laser welded joints with Inconel 52M filler wire have been reported [16].

Generally, the molten pool insufficiently mixed with the base metals results in a narrow interfacial region in dissimilar joints. Resulting from the convection and stirring of molten pool, the interfacial region significantly differs from the base metals and weld metals in composition, and sometimes even microstructure and properties [17,18]. As a result, it should be paid great attention to the interface microstructure. For dissimilar joints between Inconel 52M overlays and 316L stainless steel during multipass laser welding, it also experiences the diffusion of alloying elements and cause complex microstructure at the interface. It could thus involve mechanical properties and corrosion resistance of dissimilar joints for nuclear power plants. From the previous research, traditional welding approaches such as gas tungsten arc welding have been used to connect these dissimilar joints between Inconel 52M overlays and 316L stainless steel. However, it is rarely reported specific information on the interface microstructure, mechanical properties and corrosion resistance of dissimilar joints during multipass laser welding. For nuclear power plants, it should been revealed the interface microstructure, mechanical properties and corrosion resistance of dissimilar joints during multipass laser welding.

The objective of this study is to reveal the interface microstructure, mechanical properties and corrosion resistance of dissimilar joints between Inconel 52M overlays and 316L stainless steel during multipass laser welding for nuclear power plants. The interface microstructure, tensile strength, impact toughness, fracture behavior and microhardness of dissimilar joints are investigated. The corrosion behavior of the weld metals is also evaluated by potentiodynamic polarization studies.

2. Experimental procedure

The low alloy steel and 316L stainless steel used in the present study were provided in plate form with the thickness of 20 mm. Inconel 52M filler wire with the diameter of Φ1.2 mm was provided by Special Metals Company. Table 1 lists the chemical compositions. Prior to multipass laser welding, Inconel 52M overlays on low alloy steels were fabricated during electroslag cladding process with the strip in dimension of 60 × 60 × 0.5 mm. The parameters using in the electroslag cladding were: $I = 700–820$ A, $U = 26–30$ V, $v = 130–220$ mm/min, preheated temperature at 100–150 °C and the interlayer temperature at 120–150 °C. A butt joint configuration with a narrow gap groove was prepared for multipass laser welding with filler wire, as described in Fig. 1.

A fiber laser YLG10000 from IPG Company with the maximum output power of 10 kW, the output wavelength of 1.07 μm, power output stability of ±2%, modulation frequency of 5 kHz and the focus radius of 0.60 mm was employed for welding dissimilar materials between Inconel 52M overlays and 316L stainless steel. Prior to the welding test, the surfaces of plates were polished and the rust and oils were removed from the surface and groove of the samples. In the process of multipass laser welding with filler wire, argon gas with the flow rate of 25 L/min was used for protecting the joints. The spot size of laser beam was increased and the defocussed distance of 18 mm was chose to improve the action between the laser and filler wire in the welding test. In this study, three-pass laser welded joints were obtained and the optimum parameters of narrow gap multipass laser welding are given in Table 2.

Metallographic specimens were prepared from the transverse cross section of dissimilar joints for microstructural examination. All specimens were ground on silicon carbide papers of 80–2000 grit and then finally were polished. For revealing the interfacial microstructure beside Inconel 52M overlays, the specimens were electrolytic etched at the reagent of 10% chromic acid solution under a potential of 4 V (DC) for 30–60 s. For revealing the interfacial microstructure beside 316L stainless steel, the specimens were etched with two different solutions. The specimens are electrolytic etched at the reagent of 10% chromic acid solution and also chemically etched at a mixed chemical solution of 8g $FeCl_3$ + 90 ml HCl + 10 ml CH_3COOH. The microstructure and compositional analyses were characterized using scanning electron microscope (SEM) JEOL7600F equipped with an energy dispersive X-ray spectroscope (EDS). The tensile properties of the joints were evaluated according to the standard tensile method at room temperature and 350 °C on servo hydraulically controlled digital tensile testing machines (Zwick Z100 and Z50). Fig. 2 shows schematic illustration of specimen geometry of tensile test at room temperature and 350 °C. Charpy V-notch impact specimens with the size of 10 mm × 10 mm × 55 mm were prepared for impact test. The impact tests were performed on a SANS impact testing machine at room temperature. All the results of tensile strength and impact toughness are averaged from three sets of data. The fracture surfaces of tensile and impact specimens were also examined by SEM. The microhardness measurements, using Vickers hardness tester at a load of 200 g and a dwell period of 15 s, were made across the transverse joints to obtain the microhardness profiles on the weld transection.

Potentiodynamic polarization studies were performed to assess the corrosion behavior of weld metal. Specimens with the dimension of 10 mm × 10 mm × 3.5 mm cut from the welds metals, Inconel 52M overlays and 316L in the tests. And pitting tests were conducted on the potentiostat with the mode of Zahner Ennium in 3.5 wt.% NaCl + 0.05 M $Na_2S_2O_3$ mixture solution at the temperature of 25 °C. A three-electrode cell with Luggin capillary was used for the polarization studies, wherein the specimen, saturated calomel, and platinum were used as working, reference, and auxiliary electrodes, respectively. The potential scan rate was 1 mV s^{-1} in all the tests and three experiments were made to ensure the repeatability of results for each test condition.

3. Results and discussion

3.1. Microstructure in the interfacial regions

Fig. 3 shows the microstructure at the interface beside 316L stainless steel etched by 10% aqueous chromic acid solution and then by etched chemical solution of 8 g $FeCl_3$ + 90 ml HCl + 10 ml CH_3COOH. As shown in Fig. 3, the microstructure at the interface beside 316L stainless steel consists of cellular with the width of 30–40 μm approximately perpendicular to the fusion boundary, which related to the temperature gradient and constitutional supercooling. The brittle intermetallic compound layers are not

Table 1
Chemical composition of base metals and filler wire (wt.%).

Materials	Ni	Cr	Fe	Mn	Nb	Ti	C	Si	Mo
18MND5	0.96	0.17	Bal.	0.2	–	–	0.20	0.20	0.47
SUS316L	11.69	17.89	Bal.	1.36	–	–	0.025	0.52	2.43
Inconel 52M	Bal.	29.87	8.43	0.78	0.85	0.27	0.017	0.10	0.05