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Microstructure evolution and mechanical properties of linear friction welded S31042 heat-resistant steel

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ABSTRACT

S31042 heat-resistant steel was joined by linear friction welding (LFW) in this study. The microstructure and the mechanical properties of the LFWed joint were investigated by optical microscopy, scanning electronic microscopy, transmission electron microscopy, hardness test and tensile test. A defect-free joint was achieved by using LFW under reasonable welding parameters. The dynamic recrystallization of austenitic grains and the dispersed precipitation of NbCrN particles resulting from the high stress and high temperature in welding, would lead to a improvement of mechanical property of the welded joint. With increasing the distance from the weld zone to the parent metal, the austenitic grain size gradually increases from ~1 μm to ~150 μm, and the microhardness decreases from 301 HV to 225 HV. The tensile strength (about 731 MPa) of the welded joint is comparable to that of the S31042 in the solution-treated state.

1. Introduction

The ultra-super critical (USC) plants remarkably improve the combustion efficiency and reduce the fuel consumption by increasing the steam parameter to 923 K and 34.3 MPa [1–3]. In the case of energy shortage and environmental pollution, the application of USC plants has been accelerated. Taking the advantages of corrosion-resistance and creep strength, S31042 steel is widely used in the manufacture of superheaters and reheaters of USC units [4,5]. The excellent and comprehensive properties of S31042 are originated from finely dispersed NbCrN particles, which are the main precipitates during creep process [6].

A variety of welding methods have already been applied to austenitic stainless, such as arc welding, electron beam welding and laser welding, and favorable mechanical properties of joints have been obtained [7,8]. Hexavalent chromium fumes were produced inevitably during these fusion welding processes. If the treatment is not proper, human health and environment are highly threatened. Nevertheless, LFW process is a promising solid phase joint technology [9] to avoid these harmful consequences.

In the LFW process, metallurgically sound joint is achieved in solid state due to the friction heat generated from the relative reciprocating motion of two components under a compressive force [10]. The microstructure of the joint is susceptible to heat input, which is usually proportional to friction pressure, oscillation amplitude and frequency [11]. The LFW process includes the initial, the transition, the equilibrium, and the forging stage [12]. Owing to the absence of liquid phase during the LFW process, the joint is free of typical solidification defects (pores, pinholes, shrinkage cracks, segregation, grain coarsening, etc.) [13]. Therefore, LFW has been reported as one of the promising welding techniques to join a range of materials including steel, alumium, copper, titanium alloys and aircraft engine alloys [14].

Ma et al. have reported that the tensile property of the LFWed 45 steel joint was significantly improved by superfine ferrite and pearlite compared with the quenched and tempered 45 steel [15]. Previous researches in alumium alloys have shown that the variation of the flow stress with temperature was a critical factor to achieve a larger process window and a stable process [16]. Buffa et al. have found a narrow range of the variation of the shear factor with temperature under different LFW process parameters, which can be used to predict the temperature of the 3D model [17]. Some investigations about LFW welding of aluminum on copper have also been reported, and the weld line was covered by a discontin-

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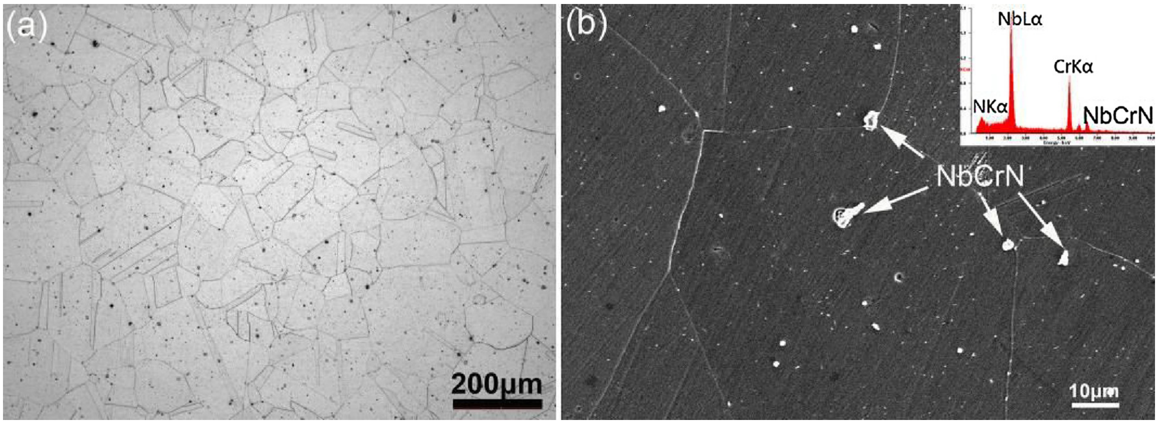

Fig. 1. Microstructure of the parent S31042 heat-resistant steel (a) OM and (b) SEM images.

uous layer of intermetallic compound, which was deleterious for the mechanical resistance of joint [18]. Chen et al. joined Ti2AlNb alloy by using LFW, and the tensile strength of the joint was comparable to that of the base metal [19]. Chen et al. also investigated the effects of post-weld heat treatment on LFWed Ti2AlNb alloy joint, and the mechanical properties of the joint were improved by the precipitation hardening of the orthorhombic-phase and the strengthening of the refined grain through the heat treatment at 815 °C for 1 h [20]. Ma et al. studied the LFW of nickel-based superalloy, and found that high temperature during welding induced the reversion of γ" and γ' and the segregation of some impurity elements along the grain boundaries, which impeded the suppression of the mechanical property of the joint [21].

In this study, LFW was used to join S31042 heat-resistant steel, which has been barely reported. The main object of this work is to concern the weldability of S31042 heat-resistant steel by LFW and investigate the weld quality by microstructure observation and mechanical property test. In addition, the influences of the frictional force and the frictional heat on the precipitation in weld zone, thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and parent metal are discussed in detail.

2. Experimental

The S31042 heat-resistant steel was solution treated at 1250 °C for 30 min and machined to rectangular blocks with nominal dimensions of 10 mm × 20 mm × 45 mm (with welding interface 10 mm × 20 mm) for the LFW experiment. The nominal chemical composition (mass percent, %) is C 0.07, Mn 1.16, Cr 24.94, Ni 20.49, Nb 0.44 and N 0.26. The microstructure revealed by optical microscopy (OM) is shown in Fig. 1. Particles with various sizes distribute in the austenitic matrix. Energy-dispersive X-ray spectroscopy (EDS) analysis shows that the contents of niobium and chromium are relatively high in these particles. According to previous study, the particles should be the undissolved NbCrN [1].

The welding experiment was implemented by a lab-scale LFW machine (type XMH – 250) developed by Northwestern Polytechnical University (China). Prior to welding, the welding surfaces of the samples were ground and cleaned in an acetone bath. Based on a series of preliminary experiments, the friction pressure was set as 80 MPa, forging pressure, 120 MPa, frequency and amplitude of oscillation, 25 Hz and 2 mm, respectively. The typical joint appearance is shown in Fig. 2.

Fig. 2. Appearance of the welded joint.

The polished metallographic specimens were etched in $CuCl_2 + HCl + CH_3CH_2OH$ solution. Field emission scanning electron microscopy (SEM, Hitachi S4800) and optical microscopy (Leica DMI 8) observations were performed to observe the morphology. The thin foils for transmission electron microscopy (TEM, JEM 2100f) analysis were prepared by a double-jet electrolytic polisher at a voltage of 50 V and the temperature of −25 °C, and the electrolyte contained 5 vol.% of perchloric acid and 95 vol.% of alcohol. The Vickers microhardness was measured using a hardness tester (Struers, Duramin-A300) under a load of 200 g for 10 s. The tensile test specimens were cut along the height direction (gauge length 30 mm), and uniaxial tensile was carried out with MTS C45 universal testing machine at a crosshead speed of 0.03 mm/s.

3. Results and discussion

3.1. Microstructure evolution

Fig. 3(a) shows an overall view of the microstructure of the joint, which is composed of weld zone, thermo-mechanically affected zone (regions A and B), heat affected zone (region C) and parent metal (region D). The weld zone appears as a dark line, which can be distinguished with the thermo-mechanically affected zone (TMAZ). With the increase of the distance from the weld zone, the austenitic grain size increases. In order to characterize the microstructure of TMAZ in detail, TMAZ is divided into two regions: the near-weld zone (region A) and the far-weld zone (region B). The near-weld zone (region A) consists of fine-equiaxed grains (about 10 μm in diameter) and second-phase particles (Fig. 3(b)). The grains within the far-weld zone (region B) are elongated along the direction of oscillation, and the grain boundary is sawteeth shape (Fig. 3(c)). In the heat affected zone (HAZ), the austenitic grain size is relatively larger than that of TMAZ, where precipitates distribute along the grain boundaries continuously (Fig. 3(d)). EDS analysis shows that these precipitates are chromium-rich but without niobium. According to previous studies, the chain-like precipitates

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