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Microstructure and mechanical properties of UNS N10003 alloy welded joints

Shuangjian Chen[a,b], Xiang-Xi Ye[a], Kun Yu[a,b], Chaowen Li[a,*], Zhijun Li[a], Zhong Li[a], Xingtai Zhou[a]

[a] Center for Thorium Molten Salt Reactor System, Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, PR China
[b] University of Chinese Academy of Sciences, Beijing 100049, PR China

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ABSTRACT

Microstructure and mechanical performance of the welded joints of UNS N10003 alloy have been investigated in this work. Primary precipitates in base metal and eutectic precipitates in Heat Affected Zone (HAZ) and weld metal have been characterized and identified as M_6C type. The hardness value of HAZ (Eutectic zone) is significantly higher than the rest of joint, including weld and base metal. Tensile tests suggested the welded joints possess a very stable mechanical performance at elevated temperature from 650 °C to 725 °C. Moreover all the tensile samples were fractured in base metal, indicating that the eutectic carbides have no adverse effects on the short-time mechanical performance of joint. The fine carbides, acting as dispersion strengthening in weld metal, are main contribution to enhance the hardness and strength of weld. The good mechanical performance of HAZ is ascribed to the presence of eutectic carbides and twins.

1. Introduction

Molten salt reactor (MSR), which uses molten salt as coolant and nickel base alloy as metallic structural material, is one of the generation IV nuclear reactors [1–3]. Hastelloy N (ASME designated as UNS N100003) alloy, as a representative solid solution strengthened Ni-Mo-Cr alloy, was developed by Oak Ridge National Laboratory (ORNL) in 1950s specially as a structural material for Molten Salt Reactor Experiment (MSRE) due to its high molten salt corrosion resistance and excellent high temperature strength [4–8]. However, some challenges still exist in nuclear application of Hastelloy N, one of which is the welding issues of this alloy. Since the weldment is commonly considered as the weakest area of structural components, it is essential to study the weldability and evaluate the microstructure and mechanical performance of welded joints of Hastelloy N.

The weldability of Hastelloy N alloy was first studied by using Gas Tungsten Arc Welding (GTAW) in 1960s, and a good weldability and mechanical performance were obtained to this alloy [9–11]. McCoy [12] studied hot cracking in the welded joint with manual-TIG in a heavily restrained condition, and found the cracking was associated with the segregation of chemical elements in the HAZ. Additionally, some non-equilibrium intermetallic phases were formed in the heat-affected zone (HAZ) when thermal cycle peak temperatures >1300°C and microprobe analyses showed the brittle eutectic-type structure had a different composition from that of the matrix [13,14]. To the authors' knowledge, the types of precipitates in the welded joint are still subjected to debate.

D.Bhattacharyya et al [15] characterized the precipitates in different regions of the fillet weld of Ni-Mo-Cr-Si alloy, and found that the primary carbides in base metal and eutectic carbides in HAZ possess similar chemical composition closer to $Ni_2(Mo,Cr)_4(Si,C)$ and $Ni_3(Mo,Cr)_3(Si,C)$ by transmission electron microscopy equipped with energy dispersive spectrometer (TEM-EDS). The results could be better convinced if another identification method is applied since content of C cannot be measured accurately by TEM-EDS. He [16] studied the microstructure of eutectic carbides of Ni-Mo-Cr alloy through simulated heat-affected zone (HAZ) thermal cycle treatment and considered the precipitates in HAZ as M_3C_2 but without taking account of the type of precipitate in weld and base metal. In addition, the effects of precipitate carbides on the mechanical performance of welded joint and strengthening mechanism of welded joint are lacking in-deep understanding. Yang [17] investigated the influence of eutectic carbides on the mechanical performance of Ni-17Mo-6Cr alloy by using Gleeble simulator and found no adverse effect brought by eutectic carbides. On contrary, hot cracks caused by eutectic carbides were detected by Jiang [13] when Ni-Mo-Cr alloy with high silicon was heated to more than 1335°C. These contradictory conclusions cannot provide direct application guidance to a real welded joint of UNS N10003 alloy, further related experiments are needed to evaluate the effect of eutectic carbides on the mechanical performance of joints.

* Corresponding author.
E-mail address: lichaowen@sinap.ac.cn (C. Li).

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With the above problems in mind, to further accurately determine the types of precipitates in different regions of the welded joint, several analytical methods were used in this work, such as electro-probe micro analyzer (EPMA), electron backscattered diffraction (EBSD), X-ray diffraction (XRD). These methods were employed in a combined way to characterize and analyze the precipitates of as-welded joint of GH3535 alloy which belongs to the group of UNS N10003 alloy. In view of the narrow region of eutectic precipitates in the welded joint, Gleeble simulator was applied to simulate heat-affected zone (HAZ) thermal cycle treatment to produce a large sample with the same microstructure as the eutectic region near fusion line. Besides, we attempted to clarify the dependence of the eutectic precipitates on the hardness and tensile properties of the real welded joint and the strengthening mechanism of the weld metal and HAZ in the welded joint. The tensile tests were carried out at three typical service temperatures for TMSR, namely, 650°C, 700°C and 725°C. The results can substantially contribute to the understanding of microstructure and mechanical properties of welded joint involved in application of this alloy.

2. Experimental procedure

Automatic GTAW with pulsed current was employed as the welding method in this work. ERNiMo-2 filler wire with diameter of 1.2 mm was used as welding consumables and the GH3535 alloy plates with thickness of 16 mm were applied. The nominal chemical compositions for the parent alloy and filler wire are listed in Table 1. The GH3535 alloy plates in solution annealed state were procured from Special Steel Shares Co., LTD (China). Before welding, the plate was firstly cut into two test pieces with a sizes of 300 mm×100 mm×16 mm, then in each of which double V grooves with angle of 60° were prepared. The grooves and adjacent plates in the range of 20 mm were cleaned thoroughly. High purity Argon (99.99%) was used as welding shielded gas during the whole welding process. The optimized welding parameters used in this experiment have been qualified by the American Society of Mechanical Engineers (ASME) section IX [18] as presented in Table 2. The root pass and the final pass were inspected by visual inspection, and the surface morphology of the welded joint is shown in Fig. 1. It can be observed that a good appearance of weld was achieved without visual imperfection. Then the weld was inspected by penetration testing and x-ray, no weld defects were detected.

To characterize the microstructure, the cross-sections of welded joints were polished with 0.5 μm diamond paste after series of grinding procedures, and then etched with solutions including 70cc H_2O, 10ccHCl mixed with 10g$CuCl_2$ for 30 seconds at room temperature (RT). Microstructure characterization and analysis were carried out by ZEISS Axio Cam optical microscope (OM) and ZEISS LEO 1530VP SEM equipped with an Oxford EBSD system. The measurements of chemical compositions were conducted by EPMA and TEM-EDS. The polished specimens of welded joint were conducted on ZHV 30 micro Vickers under load of 500gf to measure the hardness values which were calculated automatically after measuring diagonal length of indentation on the machine software. Tensile tests with a set of 3 specimens were carried out in the temperature range of 25–725°C on a Zwick Z100 universal testing machine. The strain rates were respectively 0.005/min and 0.05/min before and after being yielded according to ASTM E21. Yield strength and ultimate tensile strength were defined at 0.2% offset and the maximum stress respectively. The elongation percentage was determined as the maximum elongated gauge length divided by the original gauge length. The gauge zone with a width of 50 mm was marked before tensile tests and then the elongation of gauge zone was measured manually after test. The geometry of tensile specimens is presented in Fig. 2. Fracture morphology after tensile tests was observed by SEM.

Table 1
Chemical compositions of GH3535 alloy and filler wire (wt%).

Alloy	Mo	Cr	Fe	C	Si	Mn	Ni
GH3535	16.5	7.0	4.0	0.06	0.27	0.5	Bal.
ERNiMo-2	16.4	8.0	5.0	0.05	1	1	Bal.

Table 2
Welding parameters.

Layer (Each side)	Current (A)	Welding speed (mm/min)	Pulse frequency (Hz)	Peak pulse duration (%)	Base pulse value/peak pulse value (%)	Gas flow rate (L/min)
1	230	90	2.5	50	50	15
2–6	240	110	2.5	50	50	15
7	230	100	2.5	50	50	15

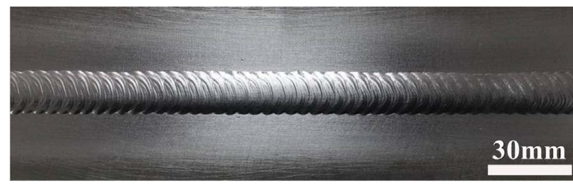

Fig. 1. Macroscopic morphology of the GH3535 welded joint.

The precipitates in different areas of the welded joint were analyzed by a Bruker D8 Advance XRD with a CuKα1 radiation source (λ=1.5406 Å) and an analyzed area size of 0.4×12 mm at step size of 0.02° in 0.15 s. Measurements were conducted in θ-2θ mode geometry at a tube power of 40 kV/40 mA to maintain linearity in the detector response. To analyze the narrow eutectic region in the welded joint, Gleeble3500 was applied to simulate heat-affected zone (HAZ) thermal cycle treatment. The detailed principle and application of Gleeble3500 have been described [19]. Fig. 3 displays the thermal cycle curve, in which the peak temperature is the key parameter to govern the final microstructure in the alloy. In this work, it was set to 1340 °C which is higher than the melting point of eutectic precipitate according to our previous work [16].

3. Results

3.1. Microstructure of the welded joint

Optical micrographs of the cross-section of as-welded GH3535 alloy joint are shown in Fig. 4. It is evident that three different zones can be observed, including base metal, heat affected zone (HAZ) and weld metal. The base metal is a single-phase austenite with chains of precipitates in the γ matrix. As for HAZ, it is divided into three parts, including eutectic zone, coarse grain zone and heat affected base metal zone with no significant change in microstructure. For the “eutectic zone” with width of about 300 μm near fusion line, it is noticeable to observe some much darker chains of carbides. HAZ (E) stands for the eutectic zone in HAZ. The range of “coarse grain zone” in HAZ is approximately 600 μm and a slight increase in grain sizes is observed compared with the adjacent out part of HAZ. The left part of HAZ is the area with no observed microstructure change and its width cannot be determined accurately from OM photos. HAZ(R) stands for the rest part of the HAZ except eutectic zone. In the weld, there exist precipitates in the matrix and columnar crystals almost perpendicular to the fusion line. Besides, migrated grain boundaries (MGBs) and solidification sub-grain boundaries (SSGBs) are observed. The presence of MGBs in the fusion zone may cause failure during tensile loading since some element segregation (S, P, B, O, etc.) can occur along MGBs