Optics & Laser Technology 81 (2016) 18–25

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Full length article

Effects of post-weld heat treatment on microstructure and mechanical properties of laser welds in GH3535 superalloy

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ARTICLE INFO

Article history:
Received 18 September 2015
Accepted 18 January 2016
Available online 25 January 2016

Keywords:
Laser beam welding
GH3535 superalloy
Post-weld heat treatment
M_6C carbides

ABSTRACT

In this study, the microstructure and mechanical properties of laser welds before and after post-weld heat treatment processes were studied. The results show that the tensile strength of the joints can be increased by 90 MPa by a post-weld heat treatment process at 871 °C for 6 h, exceeding the strength of the original state of the base metal. Besides, elongation of the joints are also increased to 43% by the process, whereas the elongation of as-welded joints are only 22%. In addition, the Charpy impact properties of laser welds almost do not change. Second phase precipitates, which were identified as Mo–Si rich M_6C-type carbides by transmission electron diffraction and scanning electron microscope, were observed at solidification grain boundaries and solidification subgrain boundaries. These carbides can pin dislocations during the following tensile deformation, hence are responsible for the strengthening of tensile properties of the joints.

1. Introduction

Nickel-based alloys are widely used in the nuclear and chemical industries because of their excellent corrosion resistance and high-temperature mechanical performance [1–3]. Hastelloy N, whose grade of ASME is UNS N10003, was used in molten salt nuclear reactor system in the 1960s by the Oak Ridge National Laboratory (ORNL) [4,5]. But the reactor project had been disrupted for several decades. GH3535 superalloy, whose ingredients are similar as that of Hastelloy N, is a solid solution strengthened nickel-based alloy. GH3535 superalloy is made in China with excellent high-temperature molten salt corrosion resistance, radiation resistance and oxidation resistance. GH3535 superalloy is identified as the primary materials of the Thorium Molten Salt Reactor (TMSR) that is a suitable candidate reactor of the fourth-generation nuclear reactors [6,7].

It is important to evaluate the microstructure and mechanical properties of welds before manufacturing nuclear reactors. The ORNL had studied the weldability of Hastelloy N by Gas Tungsten Arc Welding (GTAW). They had found that the tensile strength and elongation of as-welded joints have some extent lower than that of the base metal. In addition, they also studied the effect of post-weld heat treatment (PWHT) on mechanical properties and residual stress of weldments of GTAW [8–11]. They found that the residual stress of weldments treated at 650 °C/100 h was not effective reduced. Although the PWHT at 760 °C/6 h could reduce the residual stress, it did not recover the properties of weldments unless heat treatment time is beyond 90 h. In addition, the PWHT at 871 °C/6 h could reduce the residual stress and improve ductility and stress rupture life of weldments. From above, the PWHT at 871 °C/6 h may be seen as an high effective process. However, they did not study the evolution of microstructure and the relationship between microstructure and properties. As for TMSR, the sleeve of control rod used at about 650 °C which requires very small post-weld deformation will be manufactured by welding. Nevertheless, the traditional GTAW could not satisfy the deformation requirement of the welded sleeve because the large width of the fusion zone (FZ) and the large heat input leading to large deformation. Due to high welding efficiency, small structural deformation and narrow heat affecting, laser beam welding (LBW) is considered as an attractive joining technique, which is widely used for some industrial manufacturing systems [12–15]. Besides, the post-weld heat treatment comes to be an option because it may restore or improve the mechanical properties of welds as previous researches of GTAW studied. However, there are few studies on laser beam welding of Hastelloy N or GH3535 superalloy. Thus this paper studies the microstructure and mechanical properties of laser welds before and after post-weld heat treatment. The results are reported in detail.

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http://dx.doi.org/10.1016/j.optlastec.2016.01.029
0030-3992/

2. Materials and experimental procedures

GH3535 superalloy used in this study was provided by material manufacturer in the form of solid-solution annealed plates with dimensions of 2200 mm × 600 mm × 4 mm. The chemical composition of this alloy is present in Table 1. The metallurgical microstructure shows that the grain dimension of the base metal is approximately 100 μm as shown in Fig. 1, in addition, quantities of twins and chain-like carbides distribute in the grain. It is suggested that these chain-like carbides are M_6C type carbides, according to some research reports on Hastelloy N [16,17] and GH3535 superalloy [18].

An IPG YLS.10000 fiber laser with a maximum power of 10 kW was used in the laser welding experiments. The laser beam was delivered to the welding head through an optical fiber with a 200 μm core diameter. The laser beam was focused onto the specimen surface by a lens with a 200 mm focal length. The schematic of laser beam welding setup is shown in Fig. 2, the laser welding head mounted on a 6-axis KUKA robot moved on when the welding began. Two plates with dimensions of 300 mm × 100 mm × 4 mm were machined from as-received plates and cleaned using sand blasting to remove the surface oxide. Acetone was used to clean the surface, and then the plates were clamped on the work table with the device of backing gas. The welding direction was parallel to the rolling direction of the base metal. The plates were butted and autogenously welded with the welding parameters listed in Table 2. It can be seen that there are no visual defects such as cracks, surface pores and so on from the appearance of face and back welds as are shown in Fig. 3.

After passing acceptance requirement of ASME BPVC-III NB-5320 about radiographic inspection, the welded specimen was sectioned into two parts. One was as-welded specimen, the other one was prepared for heat treatment at 871 °C for 6 h followed by water quenching. The metallographic specimens were etched with a mixture solution contained 3 g $CuSO_4$ and 80 ml HCl for 30 s to reveal their microstructure. The preliminary study of microstructure was performed by optical microscopy (OM) with use of a ZEISS AxioCam microscope. The further study of microstructure and fracture surface morphology was carried out by a LEO 1530VP scanning electron microscope (SEM). The qualitative analysis of specimen composition was done by an SHIMADZU electron probe microanalyzer (EPMA) equipped with an Oxford energy-dispersive spectrometer (EDS). The type of carbide was identified by a Tecnai G2 F20 S-TWIN transmission electron microscopy (TEM). The tensile properties of specimens were tested by a Zwick/Roell Z100 universal material machine. The Charpy impact properties of specimens were tested by a Zwick/Roell RKP450 pendulum impact test machine.

Table 1
Chemical composition (wt%) of as-received GH3535 superalloy.

Ni	Cr	Mo	Fe	C	Si	Mn	Al	Ti	B	W
Bal.	7.07	17.0	4.02	0.018	0.40	0.75	0.026	< 0.01	0.005	< 0.05

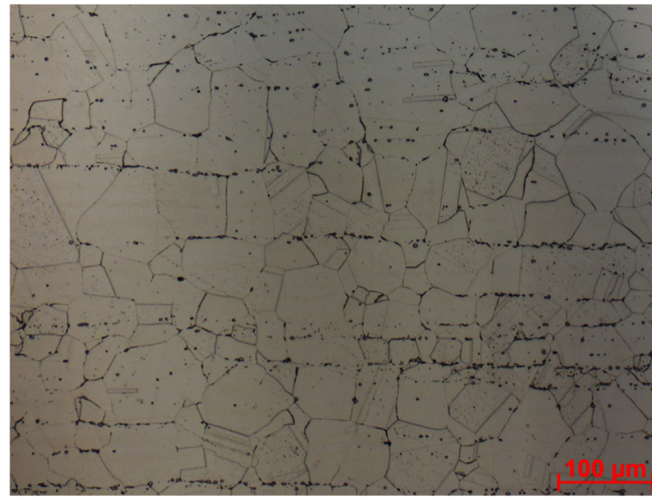

Fig. 1. Microstructure of GH3535 superalloy by optical microscopy.

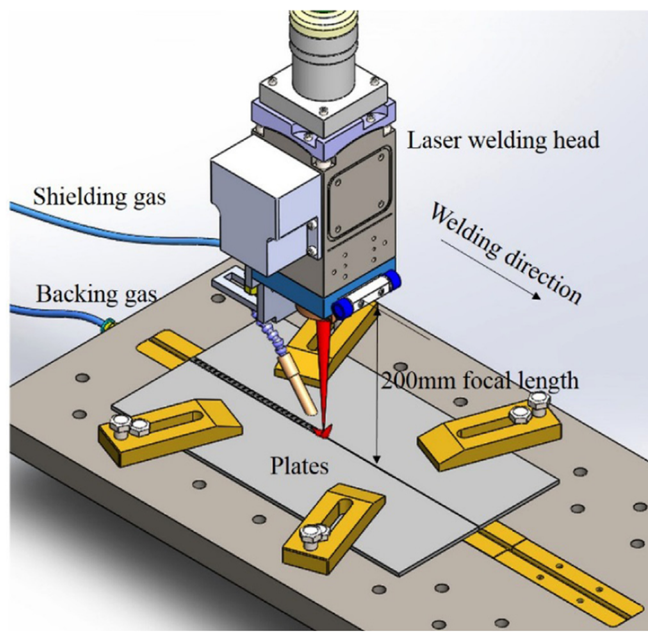

Fig. 2. Schematic of laser beam welding setup.

3. Results and discussion

3.1. The microstructure of joints

Fig. 4 shows the OM images of the FZ in the transverse joints under as-welded and PWHT condition. The microstructure of FZ of as-welded specimen consists of a great deal of subgrains, which present as cells and dendrites (Fig. 4a and b). The columnar dendrites grow along transverse direction from both sides, and the dimension of cells is very fine. It is hardly found that there are any solidification grain boundaries (SGBs) resulting from the intersection of packets of subgrains in FZ of as-welded joint. In addition, it is also hardly found that there are any particles in interdendritic region (Fig. 4a and b). The interdendritic region was known as solidification subgrain boundary (SSGB) separating adjacent subgrains [19]. Comparing with the FZ of as-welded joint, as is shown in Fig. 4c and d, there are many SGBs and quantities of black particles at SSGBs in PWHT joint. In addition, the subgrains of PWHT joint are less evident than that of the as-welded joint shown in Fig. 4b and d because the composition differences between subgrain and SSGB are reduced when the joints suffer the high-temperature treatment.

In order to further study the elements distribution and microstructure of precipitates, the SEM and EPMA analysis were carried out. As is shown in Fig. 5, precipitates are hardly observed at SSGB of the as-welded joint (Fig. 5a) while quantities of precipitates emerge at SSGB and SGB of PWHT joint (Fig. 5b). It is reckoned that the composition of SSGB under as-welded condition is different from that of the bulk microstructure because of solute redistribution under the non-equilibrium solidification