Materials Chemistry and Physics 114 (2009) 415–419

Contents lists available at ScienceDirect

Materials Chemistry and Physics

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

Induction-assisted laser welding of IN-738 nickel–base superalloy☆

M.F. Chiang, C. Chen*

Department of Materials Science and Engineering, National Taiwan University, 1 Roosevelt Road, Sec. 4, Taipei 106, Taiwan

ARTICLE INFO

Article history:
Received 15 January 2008
Received in revised form 22 April 2008
Accepted 19 September 2008

Keywords:
Laser welding
IN-738 nickel–base superalloy
Microstructure
Tensile test

ABSTRACT

Induction-assisted laser welding was performed with filler metal additions to weld IN-738, a nickel–base superalloy. IN-738 powder was added through a coaxial nozzle to the weld pool in order to reduce the weld defects, such as underfill and porosity in the welds. This was particularly important for the square-groove butt joints due to the presence and opening of gaps in the welding process. Crack-free laser welds were obtained by induction preheating at approximately 800 °C, however, some scattered pores were still observed in the welded specimen. Tensile testing indicated that the strength of the weld metal was comparable to that of the base metal at 850 °C. Stress-induced precipitation of fine γ' particles was also observed on IN-738 specimens subjected to tensile loading. The preliminary results of this study demonstrated that the quality and performance of laser-welded IN-738 specimens were acceptable. However, more works on the process optimization are required to further improve the weld quality.

1. Introduction

Nickel–base superalloys are developed mainly for high temperature applications, and the cast IN-738 is one of the most widely used materials for hot sections in the industrial gas turbines. IN-738 is strengthened by the precipitation of the ordered $Ni_3(Al,Ti)$ γ' phase, and it exhibits excellent elevated temperature creep-rupture strength and superior hot corrosion resistance. As a result, it is often selected as the blade and vane material for land-based gas turbines. The sophisticated blade design of industrial gas turbines, in an effort to achieve increased efficiency, inevitably leads to a high blade. Therefore, the restoration of damaged blades and other components becomes an important task for most power plants in order to reduce operating costs. Welding is one of the most commonly used methods for repairing damaged gas turbine components.

The weldability of IN-738 is known to be poor due to the formation of hot cracks in the weld metal (WM) and liquidation cracks in the heat-affected zone (HAZ) [1–4]. In addition, strain-age cracking in the HAZ of the weld might also occur during the post-weld heat treatment (PWHT). Consequently, the welding or repair of IN-738 blades has advanced very slowly and is regarded to some extent as unweldable [5]. Some techniques, such as the employment of lower strength filler metals and low heat input processes, have been tried to prevent cracking problems [6,7]. For instance, laser repairing (a low heat input process to reduce HAZ cracking) of IN-738 blades with IN-625 (a relatively soft metal to avoid WM hot cracking) is frequently performed. However, this method is limited to the surface build-up at low-stressed regions owing to the lower strength of the filler metal. A study of high-temperature electron beam welding of IN-738LC indicated that welding at elevated temperatures helps to overcome severe hot cracking [5]. Electron beam welding requires a vacuum and is not convenient for most engineering applications. On the other hand, laser beam welding is similar to electron beam welding and has the advantage of operating under normal atmosphere. It also gives a narrow HAZ and less distortion of the weld than conventional welding processes, so laser beam welding has become of great interest in the refurbishment of expensive components such as turbine blades.

In this investigation, a laser induction welding process with the addition of filler metal was used to conduct high-temperature welding of IN-738 specimens. Laser welding parameters to affect the quality of welds were carefully studied, with special attention paid to the preheat temperature and weld cracks. Furthermore, tensile tests at 850 °C were conducted to evaluate the soundness of welded joints after PWHTs. The results obtained from this study could be helpful for repair welding of damaged IN-738 blades using the same material as the filler metal.

2. Material and experimental procedures

The material employed in this investigation was old IN-738 blades (25,000 service hours), which were provided by Taiwan Power Company. The chemical composition in weight percent of the alloy, as determined by a glow discharge spectrometer (LECO GDS-750 QDP), was 16.82% Cr, 0.41% Nb, 1.4% Mo, 0.28% C, 8.53% Co, 2.77% W, 3.33% Ti, 3.51% Al, 1.75% Ta, and the balance Ni. The 3.6 mm thick

☆ This manuscript has neither been published previously nor submitted for publication elsewhere.

* Corresponding author. Tel.: +886 2 23925330; fax: +886 2 23634562.
E-mail address: gchen@ntu.edu.tw (C. Chen).

0254-0584/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.matchemphys.2008.09.051

Table 1
Laser welding parameters used in the experiment.

Laser power	3200 W
Travel speed	1500 mm min^{-1}
Focal length	200 mm, Cu mirror
Focal point	0.5 mm below the surface
Powder flow rate	10–12 L min^{-1}
Preheat temperature	800 °C

specimens were cut by an electrode-discharge wire cutter to about 70 mm × 35 mm, and then hot isostatically pressed at 1180 °C/1 h, with Ar pressure of 147 MPa. After hot isostatic pressing (HIP), the specimens were solution-treated at 1120 °C/2 h under vacuum, followed by Ar-assisted cooling to room temperature.

Laser welding was carried out using a 6-kW CO_2 laser with metal powder additions through a coaxial powder feed nozzle which has been described elsewhere [8]. NI-284-10 alloy powder, a trademark of Prixair Surface Technologies, Inc., was added to the weld pool during the welding process to reduce the tendency of forming underfill (a geometry defect) and porosity in butt-jointed IN-738 specimens. The nominal chemical composition of NI-284-10 powder (45–90 μm) was similar to IN-738 composition, and in weight percent was: 16% Cr, 9% Co, 4% Al, 4% Ti, 3% W, 2% Mo, 2% Ta, 1% Nb, and the balance Ni. Prior to laser welding, the specimens were placed on a fixture in a chamber that had been purged with Ar continuously from the bottom. The specimens were then heated to approximately 800 °C and maintained at that temperature by an induction heating system, followed by laser welding. Table 1 lists the laser welding parameters utilized in the experiment. PWHTs were performed on all welded specimens, which included a solution treatment at 1120 °C/2 h and an aging treatment at 850 °C/16 h under vacuum.

After PWHTs, the laser welds were sectioned and prepared for metallographic examination and microhardness measurement. The evaluation of tensile behavior of the welds was carried out using an MTS machine at 850 °C, with a strain rate of 6.67×10^{-4} s^{-1}. Fig. 1 shows the configuration of the tensile specimens, which were made according to the specifications of ASTM E8-90a. The soundness of welded specimens was assessed by both radiographic and metallographic methods. Each specimen was X-ray inspected to ensure the absence of weld defects prior to mechanical tests. The detailed microstructure of various specimens was examined by scanning electron microscopy (SEM).

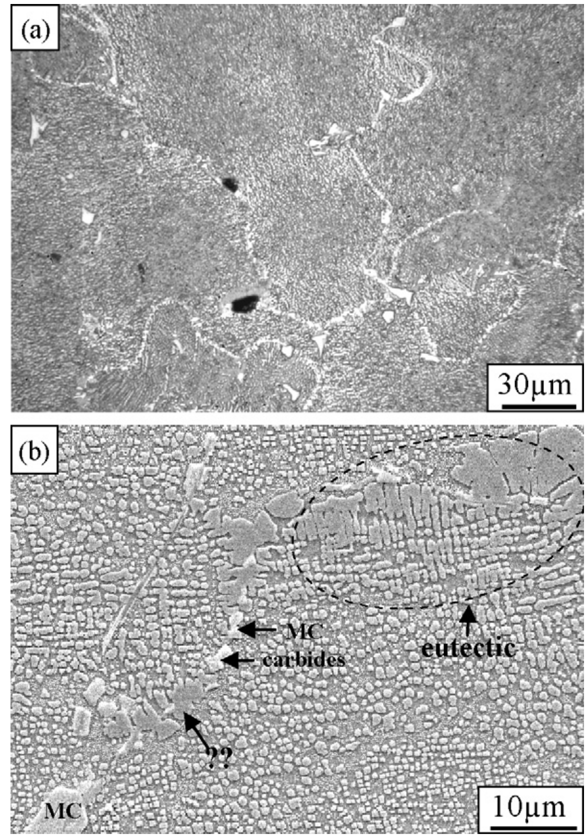

Fig. 2. Micrographs of the blade after 25,000 h of service exposure at high temperatures showing (a) the inherent casting defects and (b) the decoration of grain boundaries with γ′ and MC carbides.

3. Results and discussion

3.1. Specimen and heat treatment

Fig. 2 displays micrographs of the blade after 25,000 h service exposure at high temperatures, showing the inherent casting defects including porosity and shrinkage voids (Fig. 2(a)) and the decoration of grain boundaries with γ′ and MC carbides (Fig. 2(b)). γ′ precipitates at the grain boundary are irregular in shape and appear to form a continuous path with scattered MC carbides along the grain boundary. Within the matrix, γ′ precipitates are either cubical or spherical particles of the size 0.5–1 μm, and MC carbides of various sizes (1–5 μm) are found. γ + γ′ eutectics are often observed in the nearby region of the grain boundary as shown in Fig. 2(b). Long-term exposure was reported to cause MC carbide degeneration and precipitation of $M_{23}C_6$ at the grain boundaries, resulting in weakening of the boundaries [9]. However, such a degeneration to form $M_{23}C_6$ carbides was not observed on the material used in the present study.

Generally, precipitation–hardenable nickel alloys are welded in the solution-treated condition [10]. In order to obtain meaningful tensile results, all specimens were hot isostatically pressed (Hipped) to seal casting defects as well as creep voids, if any. Hipped specimens were then solution treated at 1120 °C/2 h which is the recommended procedure prior to repair welding of IN-738 blades [11]. Fig. 3 reveals that casting defects in the used blade are healed, and the amount of γ′ at grain boundaries is significantly reduced after HIP and solution heat treatments. It should be noted that γ′ at the grain boundaries was completely dissolved during solution treatment at 1120 °C/2 h and then re-precipitated upon cooling. MC carbide, γ′ and eutectic phases at the grain boundaries are reported to cause intergranular liquation cracking in the HAZ of IN-738 welds [2,12]. Consequently, the reduction of such phases at grain boundaries would help to lower the cracking tendency in the welding of IN-738.

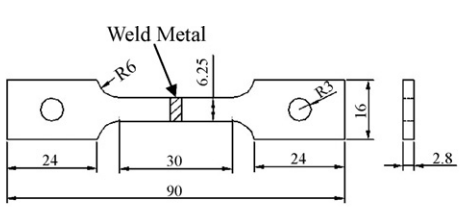

Fig. 1. Schematic diagram showing the dimensions of laser-welded specimens used in tensile tests.

3.2. Characteristics of the process and the resultant weld

The advantages of laser powder technology over conventional welding techniques have been discussed elsewhere [13]. The coaxial nozzle used in the current study was similar to that in a previous report on the welding of 2205 duplex stainless with nickel powder additions to modify the ferrite/austenite ratio of the WM [8]. In order to reduce the attenuation of lasers by metal powder, laser powder welding is processed with the focused powder stream, to form a cavity of an inverse cone just above the top surface of the specimen as shown in Fig. 4. The powder stream at the outlet of nozzle was confined by circumferential shroud gas, which helped to focus it. By adjusting the flow rate of the central and shroud gases, the position of the focused powder stream could be altered relative to the focal point of the laser beam. This process is somewhat different from the laser powder cladding process, which has the focal