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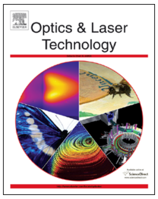

Modern fiber laser beam welding of the newly-designed precipitation-strengthened nickel-base superalloys

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ABSTRACT

In the present research, the modern fiber laser beam welding of newly-designed precipitation-strengthened nickel-base superalloys using various welding parameters in constant heat input has been investigated. Five nickel-base superalloys with various Ti and Nb contents were designed and produced by Vacuum Induction Melting furnace. The fiber laser beam welding operations were performed in constant heat input (100 J mm^{-2}) and different welding powers (400 and 1000 W) and velocities (40 and 100 mm s^{-1}) using 6-axis anthropomorphic robot. The macro- and micro-structural features, weld defects, chemical composition and mechanical property of 3.2 mm weldments were assessed utilizing optical and scanning electron microscopes equipped with EDS analysis and microhardness tester. The results showed that welding with higher powers can create higher penetration-to-width ratios. The porosity formation was increased when the welding powers and velocities were increased. None of the welds displayed hot solidification and liquation cracks in 400 and 1000 W welding powers, but liquation phenomenon was observed in all the heat-affected zones. With increasing the Nb content of the superalloys the liquation length was increased. The changing of the welding power and velocity did not alter the hardness property of the welds. The hardness of welds decreased when the Ti content declined in the composition of superalloys. Finally, the 400 and 1000 W fiber laser powers with velocity of 40 and 100 m ms^{-1} have been offered for hot crack-free welding of the thin sheet of newly-designed precipitation-strengthened nickel-base superalloys.

1. Introduction

Precipitation-strengthened nickel-base superalloys are extensively utilized in the important industrial applications such as land-based and aero gas turbines due to their excellent high temperature strength. These alloys mainly obtain their high temperature strength due to formation of dispersive γ'-$Ni_3(Ti,Al)$ and γ''-Ni_3Nb intermetallic particles in the austenite phase [1]. High content of titanium and niobium in the composition of nickel-base superalloys not only causes the γ' and γ'' strengthening phases to form, but also can lead to formation of various types of other phases and secondary precipitations in the microstructure. Carbide precipitations such as TiC, NbC, and (Ti,Nb)C, Laves eutectic structures such as γ-Ni_3Nb and γ-$Ni_3(Ti,Al)$ and other eutectic structures like γ-NbC, or δ-Ni_3Nb intermetallic compounds are examples of these secondary phases [2–5]. Secondary phases and structures can strongly deteriorate the weldability of superalloys. TiC, NbC and (Ti,Nb)C precipitations melt when they react with the austenite phase and reach to the eutectic composition. These molten regions can facilitate the liquation cracking in the heat-affected zone of the superalloy by constitutional liquation mechanism. Austenite–Laves and austenite–carbide liquid eutectic structures solidify at lower temperatures in comparison to the austenite phase solidification temperature [6–8]. Thus, these compounds increase the solidification temperature range of the superalloys and sensitize them to the hot solidification cracking. The solidification temperature range (ΔT) is measured by the $\Delta T = T_l - T_s$, in which, T_l is the liquidus, and T_s is the solidus temperatures. When the final liquid of the weld metal solidifies as the above eutectics, the liquidus temperature of weld decreases, because the temperature of eutectic formation is significantly lower than formation temperature of austenite single phase. As a result, the solidification temperature range (ΔT) of the weld containing the above eutectics increases. When these phases are present in the heat-affected zone (HAZ) of the welds, the liquation cracking occurs by remained eutectic mechanism melted during

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Table 1
Chemical composition of the newly-designed superalloys.

Alloy designation	Composition of elements (wt%)							
	Ni	Cr	Co	Fe	Mo	Al	Ti	Nb
Alloy 1	52.7	19	14.8	–	3.5	3	7	–
Alloy 2	52.4	19	11.1	4.6	3.5	2.4	5.5	1.5
Alloy 3	52	19	7.4	9.4	3.5	1.8	4	2.9
Alloy 4	51.8	19	3.7	13.9	3.5	1.2	2.5	4.4
Alloy 5	51.4	19	–	18.6	3.5	0.6	1.1	5.8

the welding. Moreover, this is reported that the γ' and γ'' strengthening precipitations and δ phase cause liquation cracking in the HAZ by constitutional liquation mechanism. Therefore, the precipitation-strengthened nickel-base superalloys are severely susceptible to the hot cracking, and significant efforts are carried out to design new superalloys by optimizing the alloy chemical composition in order to achieve improved weldability [9–12].

On the other hand, considerable researches have been performed to substitute the conventional welding processes by the newer welding methods for welding the nickel-base superalloys [13–17]. Usual welding processes such as Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW), and Gas Tungsten Arc Welding (GTAW) can impose significant damages to the nickel-base superalloys weldability due to low heat concentration; low heat transfer efficiency and wide weld metal and heat-affected zones. Thus, the welding processes with high energy concentration and deep penetration-to-width ratio are strongly spreading for joining the susceptible nickel-base superalloys [18–20]. Beam welding processes such as Electron Beam Welding (EBW) and Laser Beam Welding (LBW) are examples for the new welding techniques with deep penetration. Appropriate penetration, low heat input, small weld and heat-affected zone, improved efficiency, clean welding, welding speed and thin sheet welding are the most important advantages of the beam welding processes. The researchers correlated the laser welding heat inputs to the size of heat-affected zone, the liquation cracking and solidification cracking in the Inconel 625 and Inconel 718 nickel-base superalloys such. They found that in the lower heat inputs, smaller heat-affected zones and cracks are obtained [21–23]. The laser beam welding techniques such as CO_2-laser and Nd:YAG laser have found more applications for nickel-base superalloys welding than electron beam welding [24–26].

Nowadays, with innovation of the Fiber Laser Beam (FLB), modern welding of the nickel-base superalloys with the fiber laser beam has been provided. However, the Fiber Laser Beam Welding (FLBW) of the precipitation-strengthened nickel-base superalloys has not experimentally been studied. So, the purpose of the present research is systematic investigation of the welding and weldability of the newly-designed superalloys welding using the modern fiber laser beam welding. In this organized research, the fiber laser beam welding of newly-designed precipitation-strengthened nickel-base superalloys has been fulfilled utilizing various welding powers and welding velocities in constant heat input. The geometrical evaluations of the welds (i.e. penetration-to-width ratio), microstructural aspects, weld defect assessments, weldability evaluation and mechanical investigation of fiber laser beam-welded newly-designed superalloys have been carried out in detail.

2. Experimental procedure

One of the current research aims is to investigate the effect of Nb,Ti variations on the microstructure and weldability of obtained fiber laser-welded superalloys. The precipitation-strengthened superalloys are specially hardened by the gamma-prime and gamma-double prime intermetallics which are enriched in the above mentioned elements. The other elements such as Ni, Co, Fe, Cr and Al form the austenite matrix, whose variations in the composition of superalloys have minor effects on the microstructure and weldability. Therefore, five different nickel-base superalloys with pre-specified composition have been designed. A vacuum induction melting (VIM) furnace with the vacuum of 10^{-4} bar, the frequency of 3.6 KHz and maximum power of 60 KW was employed for melting and adjusting the composition of the superalloys. Pure alumina crucibles with volume of 1000 ml, and steel die with dimensions of 150 mm × 100 mm × 50 mm were used for pouring the resultant molten alloys. The temperature of 1450 °C was selected for full melting of alloys, and the ingots were cooled at the ambient temperature. The chemical composition of newly-designed superalloys is shown in Table 1. The Ti content decreases and the Nb content increases from Alloy 1 to Alloy 5.

Before the welding, the strips with dimensions of 150 mm × 25 mm × 3.2 mm were extracted from the newly-designed as-cast superalloy ingots by wire cutting. Then, the samples were deoxidized and degreased by a stainless steel brush and acetone solution.

The Fiber Laser Beam Welding equipment was utilized without adding the filler metal (i.e. autogeneous welding) to produce samples containing bead-on-plate welds. The Fiber Laser Beam Welding (FLBW) set up was composed of an IPG YLR-1000 fiber laser source with maximum power of 1000 W, frequency of 5 kHz, and 1070 nm wavelength; a HIGHYAG BIMO welding head with 200 mm focus lens diameter and 100 mm collector; and an ABB IRB 2400 6-axis anthropomorphic robot as a positioning machine. The essential parts of FLBW setup are shown in Fig. 1. Two different laser powers and welding velocity values were used in constant input energy applied to the weld pool. The details of FLBW parameters are provided in Table 2. The input heat energy per unit square millimeter (i.e. input heat surface density) was calculated on the basis of the following equations:

$$E\left(\frac{\mathrm{J}}{\mathrm{mm}^2}\right)=\frac{P\ (\mathrm{J}/s)}{V\ (\mathrm{mm}/s)\times d\ (\mathrm{mm})} \tag{1}$$

$$\text{For } P=400\ \mathrm{W}\rightarrow E=\frac{400\ (\mathrm{J/s})}{40\ (\mathrm{mm/s})\times 0.1\ (\mathrm{mm})}=100\left(\frac{\mathrm{J}}{\mathrm{mm}^2}\right) \tag{2}$$

$$\text{For } P=1000\ \mathrm{W}\rightarrow E=\frac{1000\ (\mathrm{J/s})}{100\ (\mathrm{mm/s})\times 0.1\ (\mathrm{mm})}=100\left(\frac{\mathrm{J}}{\mathrm{mm}^2}\right) \tag{3}$$

where P is fiber laser beam power, E is input heat energy, V is speed of welding, and d is the focused laser beam diameter on the surface.

After the welding operations, abrasive cutting and cleaning, the specimens were prepared according to the standard metallographic procedures. At least 3 different perpendicular cross-sections from each weld are used for the microscopic and mechanical evaluations, and the average values are reported as the results. For revealing the weldment microstructures, four different etching solutions were used. The type, chemical composition and the corrosivity of the etchants have been presented in Table 3. The identification of the microstructural characteristics was carried out by a Leitz Wetzlar Aristomet optical microscope equipped with Nikon ACT Version 2.70 software. Further microstructural investigations were performed by a Zeiss EVO 50XVP scanning electron microscope (SEM) with accelerating voltage of 30 kV equipped with an Oxford Instrument 7060 energy dispersive X-ray spectrometer (EDS) for spot, line and map weight analysis.

For measurements of mechanical properties i.e. hardness, a Vickers Microhardness Tester of Future-Tech Corporation FM-700 model, with indentation weight of 1000 gf and indentation time of 15 s was utilized. The Vickers microhardness tests were fulfilled in