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Effect of homogenization on the TLP bonded joints of IN-738LC superalloy

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Abstract

This paper addresses simultaneously the effects of standard solution treatment on the microstructure and mechanical properties of IN-738LC superalloy bonded by transient liquid phase (TLP) using Ni-BNi-9 amorphous filler metal. TLP bonding was carried out at the bonding temperature of 1120 °C for 45 min and led to the formation of a nickel proeutectic solid-solution phase (γ) in the joint. The results revealed that after the standard heat treatment the microstructure of the bond and base metal is completely blended together, and γ' precipitates in the joint are similar to those in the base metal. Mechanical test results indicated high joint shear strength of the sample post-bond heat-treated, approximately 99% of the base metal.

Keywords*:* IN-738LC, TLP bonding, Standard heat treatment, Isothermal solidification.

1- Introduction

Gas turbine engines come in a wide variety of shapes, sizes and types and are extensively used in aircrafts and land-based power generators. Aero-engine and power generation turbine components made from γ′ strengthened nickel-based superalloys such as IN-738LC operate at high temperatures [1]. IN-738LC faces numerous challenges in terms of weldability because of considerable amounts of Al and Ti (more than 6 to 7 wt.%) in its composition [2,3]. Segregation of Al and Ti in IN-738LC along with non-equilibrium phase transformations during non-equilibrium solidification in welding result in the formation of heat affected zone (HAZ) intergranular liquation cracking which in turn lead to a reduction in the mechanical properties of the joint [4,5]. Moreover, in high temperature brazing, melting point depressants (MPDs) namely phosphorus, silicon and boron are added to the braze alloy in order to increase its fluidity. These elements lead to the production of detrimental phases (e.g. borides, silicides and phosphides) during non-equilibrium solidification of the remaining liquid phase in the cooling stage [6].

Diffusion brazing (DB) was developed by Duvall et al. [7] in order to move past the aforementioned limitations and produce ideal joints. This method is based on diffusion of melting point depressant (MPD) elements such as silicon, boron and phosphorus from the filler metal to the base metal (BM). The TLP bonding is performed at a temperature between the liquidus and the solidus of the filler metal and BM, respectively. During holding at bonding temperature, interdiffusion of alloying elements occurs between the base metal and

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the liquid filler metal. TLP bonding progresses through isothermal solidification of the liquid phase initiating from the base metal/bond region interface towards the center of the joint [8,9]. Heat treatment is carried out on bonded components for commercial applications to create a microstructure and chemical composition similar to the base metal in the bonding area. Pouranvari et al. [10] have reported that PBHT at 1150 °C for 12 hours in TLP bonded IN718 components leads to a boride-free joint with a uniform chemical composition. There are many reports on the effects of joining parameters on the microstructural and mechanical properties of the bond [11–15]. Studies focusing on the effects of standard heat treatment cycles on the diffusion brazed joints or a combination of diffusion brazing and standard heat treatment are still scarce. Therefore, the aim of the present research is set to study the influence of standard heat treatment of IN-738LC on the microstructure and mechanical properties of isothermally solidified specimens.

2- Experimental

In this investigation, cast Ni-based superalloy IN-738LC was used as the base metal. The chemical composition of the superalloy as determined using spark emission spectroscopy was: Ni-15.1 Cr-8.3 Co-3.4 Al-3.6 Ti-2.7 W-1.9 Mo-1.7 Ta-0.9 Nb-0.11 C-0.07 Fe-0.04 Zr-0.01 B-0.01 Si (in wt.%). BNi-9 alloy with the chemical composition of Ni-15.2 Cr-3.94 B (in wt.%) was chosen as the filler alloy. The filler metal with 38 μm thickness was inserted between two pieces of substrate in the form of an amorphous foil. Test specimens with dimensions of 10×10×5 mm were sectioned from the BM using an NC wire electro-discharge machine (EDM). The filler metal was cut to the dimensions of the base metal. To eliminate the oxide layers on the mating surfaces of the specimens and reduce the roughness of the surfaces, the substrate material was polished using 800-grit SiC paper. A fixture made from CrNiMo heat resistant steel was used to fix the specimens during the bonding process.
Bonding was performed in a furnace under a vacuum of approximately 3.5×10-5 torr. The joints were then heat-treated for homogenization using three distinct and consecutive steps of standard IN-738LC heat treatment (SHT) namely full-solution, partial-solution and aging. The heat treatment scheme for each specimen is summarized in Table 1.
The bonded specimens were sectioned perpendicular to the joint line using spark machining. Standard metallography techniques were used for specimen preparation. The bonded specimens were etched with a Marble solution (50 ml HCl, 50 ml H_2O, 10 g $CuSO_4$) for microstructure observations. The microstructural investigations were done using optical microscopy (OM) and field emission scanning electron microscopy (FE-SEM).
Shear tests were performed at room temperature as per ASTM D1002 [16] using a Zwick Z250 tensile machine. The cross-head speed of the tensile tester was set at 1 mm/min. Three shear tests were done for each joint ID listed in Table 1.

Table 1: Bonding and PBHT conditions of TLP specimens.

Joint ID	Bonding Temperature (˚C)	Bonding Time (min)	Post Bond Heat Treatment (PBHT)
NHT-45	1120	45	-
HT-45	1120	45	SHT (1200°C/4h/AC+1120 °C/2 h/AC+845 °C/24 h/AC)

3- Results and Discussion

3-1- Microstructure of the base metal

Figure 1 shows FE-SEM images of γ´ precipitates before and after standard heat treatment of the substrate material. According to Figure 1a, before SHT, γ´ precipitates are shapeless, tightly packed and also nonhomogeneous. After SHT, the γ´ precipitates are separate, block-shape and have an ordered structure (Figure 1b). The reason for the block-shape can be attributed to the elastic strain energy associated with the formation of the second phase overpowering the interface energy between the matrix and precipitates that leads to altering the shape of γ´ particles from spherical to blocky [17].

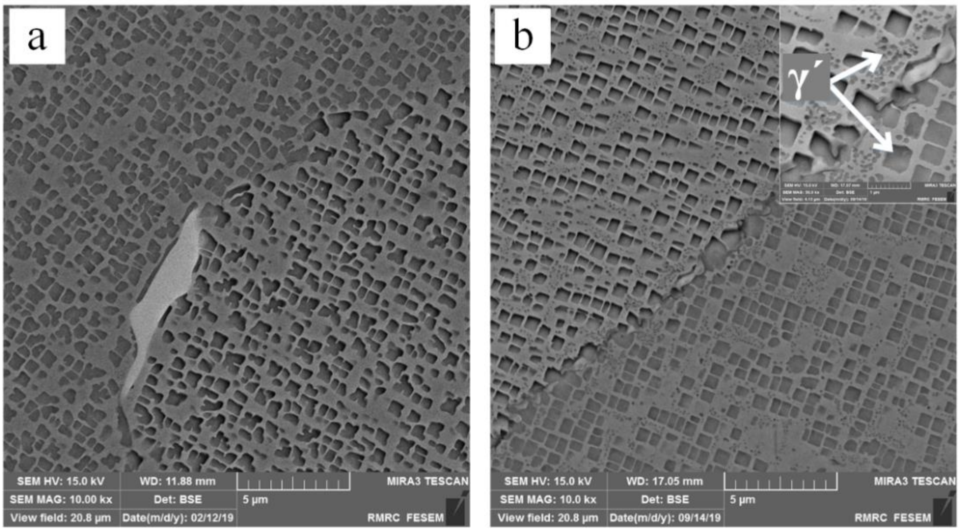

Figure 1. FE-SEM images of γ' precipitates in the IN-738LC substrate material: (a) before SHT and (b) after SHT.

3-2- Microstructure of TLP joints

3-2-1- Before SHT

Figure 2 presents representative FE-SEM images of the joint region after completion of isothermal solidification at 1120 °C for 45 minutes (NHT-45). As can be seen, bonding for this longer time has resulted in development of a single- γ phase in the joint (Figure 2a). Moreover, as shown in Figure 2b, γ´ precipitates are formed in the bond region close to the joint/BM interface. The number of γ´ precipitates drops with increasing distance from the joint/BM interface towards the joint centerline.

Microstructure of the HT-45 specimen joint after SHT is displayed in Figure 3 (a-c). According to this figure, the microstructure of the bond and base metal have completely blended together after SHT. This seamless transition from the joint to the BM can be attributed to complete diffusion of alloying elements into the joint region. In addition, complete elimination of the boride precipitates in the DAZ during SHT (especially solution annealing) contributes to the observed uniformity. As can be seen in Figure 3c and 1b, the primary γ' precipitates are similar to those in the base metal in terms of shape, density and size. Applying full solution annealing at 1200˚C has resulted in complete dissolution of γ' precipitates of the substrate material adjacent to the bond and the diffusion of their constituent elements especially Ti and Al into the joint region. Moreover, diffusion of Al and Ti in the HT-45 specimen takes place in liquid ISZ (at full solution temperature) on the contrary to NHT-45 specimen where diffusion occurs in solid ISZ (at bonding temperature). Aging treatment has led to the formation of small and spherical secondary γ' precipitates in the bond region [18].

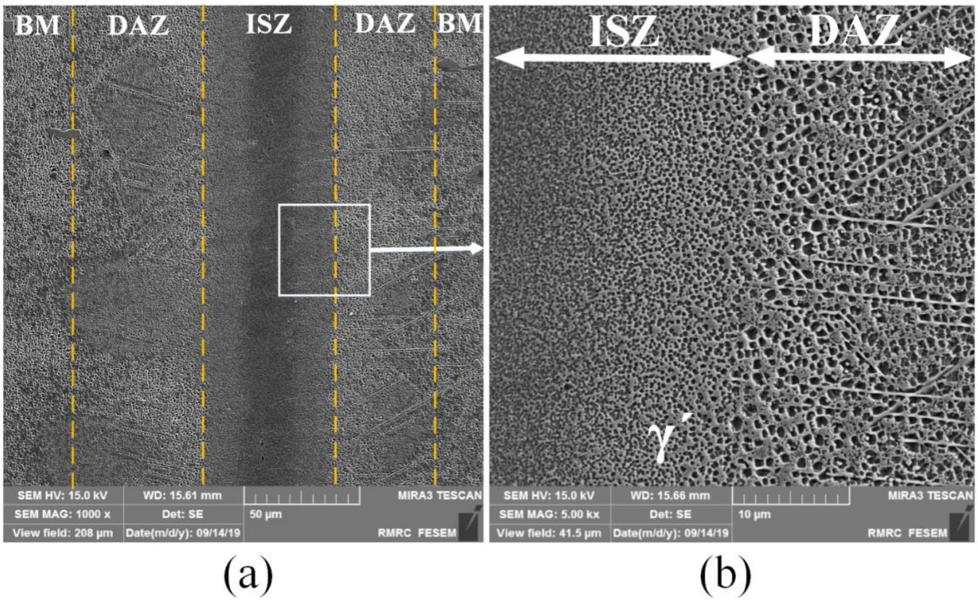

Figure 2. FE-SEM images of the joint region carried out at 1120 °C for 45 mins (NHT-45 specimen): (a) Bond region and (b) higher magnification of the joint/SM interface.

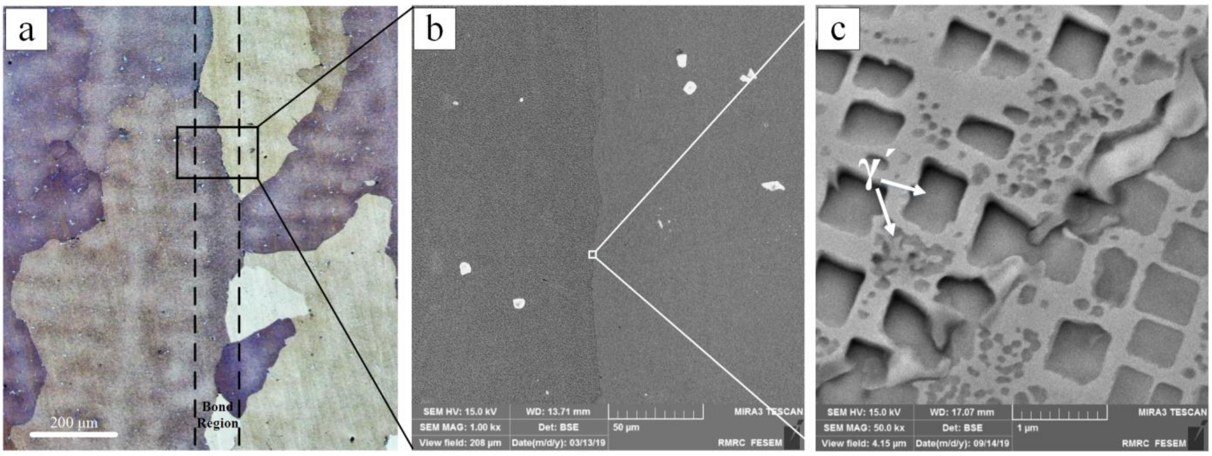

Figure 3. Microstructure of the bond region in the HT-45 TLP joint sample: (a) Optical micrograph, (b) FESEM image, and (c) higher magnification of the joint.

3-3- Mechanical properties

3-3-1- Shear strength

Figure 4 displays summarizes the maximum shear stress and toughness achieved from shear tests carried out on the joints before and after SHT and also BM after SHT. The area under the load-displacement curve for each of the joints was calculated as the toughness. The shear strength of the IN738LC was measured as ~811 MPa after SHT. After completion of isothermal solidification (NHT-45 specimen), the shear strength of the joint was 74% of the BM. The application of SHT to HT-45 sample, led to improvement of shear strength, and toughness, approximately 99% of the base metal. This is due to complete removal of DAZ precipitates and also the formation of the primary and secondary γ' precipitates in the joint district similar to the base metal.

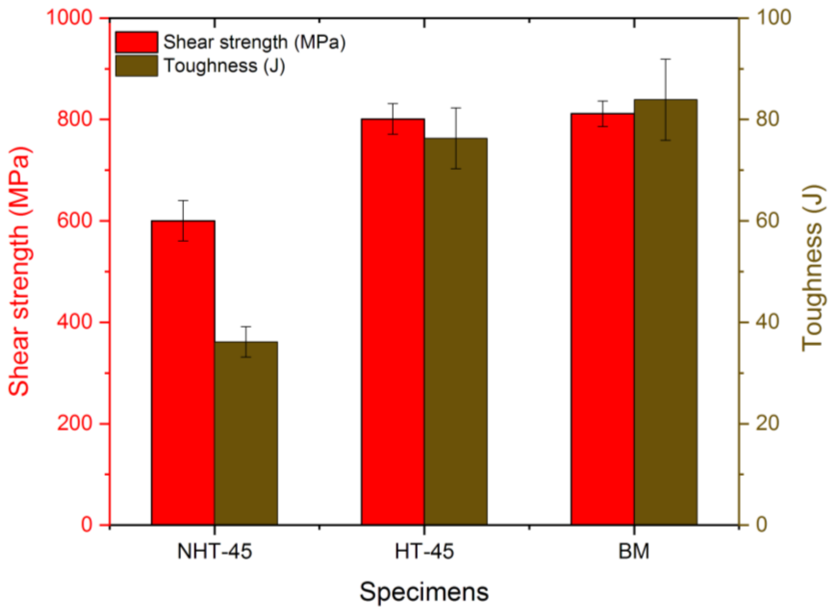

Figure 4. Shear test results carried out on bonded specimens and BM.

4- Conclusions

Microstructure and mechanical properties before and after applying standard heat treatment on isothermally solidified specimens of IN-738LC/BNi-9 TLP joints were studied. The main conclusions drawn from the results of this research are summarized below:

1. A distinct growth of the ISZ was observed in the specimen bonded at 1120 °C for 45 minutes due to the extension of boron diffusion from the joint region into the substrate. γ′ precipitates were formed in the bond region close to the joint/BM interface.
2. The isothermally solidified joint after SHT showed very high similarities between joint and BM in terms of microstructure and also γ' precipitates. This uniformity can be attributed to complete diffusion of alloying elements into the joint and complete elimination of the borides in the DAZ during SHT.
3. The specimen with complete isothermal solidification and SHT indicated high joint shear strength (approximately 99% of the BM) and toughness.

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