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TLP Bonding of A Gamma Prime Strengthened Superalloy Using Ni-Si-B Interlayer at 1150°C-Part I: Microstructure

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Abstract: Transient liquid phase (TLP) diffusion bonding was used to join a nickel base superalloy GTD-111 using a Ni-Si-B amorphous interlayer. Bonding was carried out at 1150°C with different holding time under vacuum. Microstructure of joint region was studied by optical and scanning electron microscopy (SEM). Microstructural studies showed that before completion of isothermal solidification, bond region consists of three distinct zones: centerline eutectic structure due to athermal solidification, solid solution phase due to isothermal solidification, diffusion induced boride precipitates. Complete isothermal solidification, which prevented the formation of centerline eutectic constituent, occurred within 45min at 1150°C. Homogenization of isothermally solidified bonds at 1150°C for 240 min resulted in removing of secondary precipitates within the diffusion affected zone and formation of significant volume fraction of γ′ precipitates in the bond region.

Key words: TLP bonding · Nickel based superalloy · Isothermal solidification · Microstructure

INTRODUCTION

Gamma prime strengthened nickel base superalloys, such as GTD-111 are extensively used in hot section of aero-engine and power generation turbines. They offer excellent high temperature tensile strength, stress rupture and creep properties, fatigue strength, oxidation and corrosion resistance and microstructural stability at elevated temperature.

As the efficiency of turbine engines increases so does the complexity of the engine parts. In addition, increasing size of land-based turbines results in large section components which are prone to freckle formation. Hence, successful and economical manufacturing of high-performance gas turbine engines requires in many cases the ability to join the superalloy components using methods such as welding and brazing. On the other hand, a turbine blade or vane usually exhibits a combination of various types of damages such as thermal fatigue cracking, erosion, foreign object damage, hot corrosion, oxidation and sulphidation. Increasing cost of superalloy components has resulted in greater interest for repairing damaged components [1, 2].

Fusion welding, diffusion bonding and brazing are three main repairing/joining techniques that have been commonly applied in industry [3]. Brittle phases such as borides or silicides can be formed during brazing process and are known to detrimentally affect mechanical integrity of the joint [1, 4, 5]. Weldability of nickel base superalloys depends widely on their Al and Ti contents. Precipitation hardened nickel base superalloys which contain high Al and Ti concentration, are highly susceptible to microfissuring during welding and post weld heat treatment [6]. Also, microsegregation and non-equilibrium phase transformations which occur during non-equilibrium solidification of weld fusion zone can significantly affect performance of weldment [7]. Transient liquid phase bonding (TLP) or so called diffusion brazing considered as preferred repairing/joining process for nickel base superalloys [8-13], which is a hybrid process that combines beneficial features of liquid phase bonding and solid state bonding. This process differs from diffusion bonding in which the formation of the liquid interlayer eliminates the need for a high bonding pressure [14].

In general, it is considered that there are three distinct stages during TLP bonding, namely: base metal dissolution, isothermal solidification, solid state homogenization. Combining isothermal solidification with a subsequent solid state homogenization treatment, offers the possibility of producing bonds that are almost chemically identical to the parent material and have no discernable microstructural discontinuity at the bond line [15].

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Table 1: Chemical composition (wt.%) of base metal and interlayer

	Ni	Cr	Co	Ti	Al	W	Mo	Ta	Fe	C	B	Si
GTD-111	Balance	13.5	9.5	4.75	3.3	3.8	1.53	2.7	0.23	0.09	0.01	-
Interlayer	Balance	-	-	-	-	-	-	-	-	0.06	3.2	4.5

In this paper, the effect of bonding time and homogenization treatment on microstructure development during TLP bonding of GTD-111 superalloy was investigated. Effect of isothermal solidification and post bond heat treatment on mechanical properties, microhardness and shear strength of joints were also considered.

EXPERIMENTAL PROCEDURE

GTD-111 superalloy was used in the standard heat treatment condition as the base metal in this investigation. Also, a commercial Ni-Si-B alloy (MBF30), in the form of an amorphous foil with 25.4 µm thickness was used as the interlayer. Table 1 shows chemical composition of base metal and nominal composition of interlayer. 10mm×5 mm×5 mm coupons were sectioned using an electro-discharge machine. To remove oxide layer, contacting surfaces were ground using 600 grade SiC paper and then ultrasonically cleaned in acetone bath. Interlayer was then inserted between two base metal coupons. Stainless steel fixture was used to fix the coupons in order to hold this sandwich assembly and reduce metal flow during the TLP operation. Figure 1 shows a schematic representation of bonding set-up. Applied bonding pressure was about 0.2MPa. TLP bonding operation was carried out in a vacuum furnace under a vacuum of approximately 10^{-4} Torr. Liquidus and solidus temperatures of interlayer are 1054°C and 894°C, respectively [16]. Bonding temperature of 1150°C was chosen and bonding time varied from 30 to 45 min. According to previous experiments [13], the time required to ensure the completion of isothermal solidification at this bonding temperature was the lowest. Therefore, in this research the bonding temperature was selected as 1150°C. Complete isothermally solidified bonds were homogenized at 1150°C for 240 min in an argon gas atmosphere (99.999% Ar) using a tunnel furnace. Bonded specimens were sectioned perpendicular to the bond and joints microstructure were studied using optical microscope and SEM. For microstructural examinations, specimens were etched using two etchants. The Murakami etchant (10g KOH, 10g $K_3[Fe(CN)_6]$, 100 ml H_2O) preferentially etches Cr-rich phases and can therefore be used to reveal precipitates adjacent to interlayer/base metal interface. Molybdenum-acid etchant (0.5g MoO_3, 50ml Hcl, 50ml HNO_3, 200ml H_2O), which preferentially etches γ′ phase, has been used to indicate the γ-γ′ microstructure of isothermally brazed joints. Semi-quantitative chemical analyses of phases formed in the centerline of bond region and adjacent to the base metal conducted on a Cam Scan SEM, equipped with a beryllium window energy dispersive spectrometer (EDS) system using INCA standardless software.

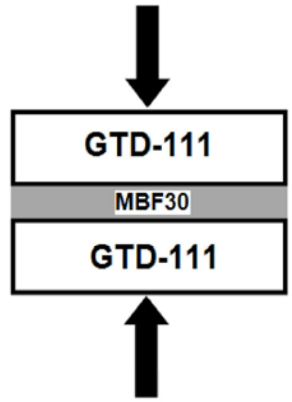

Fig. 1: Schematic representation of bonding set up

RESULTS AND DISCUSSION

Effect of Isothermal Solidification on Bond Microstructure: An ideal TLP bond microstructure would be free from eutectic structure and secondary precipitates with similar composition and microstructure to that of the base metal.

The experimental results indicate that bonding time has a significant effect on microstructure of the TLP joints. Figure 1 shows microstructure of a bond made at 1150°C with a holding time of 30 min.

In this bonding condition, bond region consists of three distinct microstructural zones:

- Isothermally solidified zone (ISZ) which formed by the interdiffusion induced compositional change resulting in isothermal solidification of the liquid. The ISZ microstructure consists of proeutectic nickel rich γ solid solution phase and is free from γ′ precipitates.
- Athermally solidified zone (ASZ) which formed due to insufficient time for isothermal solidification completion. Microstructure of the ASZ consists of

microconstituents with eutectic-like morphology and is made up of two distinct phases. Boron was detected in the intermetallic phase (Figure 2). The SEM/EDS analysis was suggested that the intermetallic phase is a nickel-rich boride and the second phase is identified as a nickel rich γ-solid solution. Microstructure of ASZ is governed by segregation of melting point depressant (MPD) elements during nonequilibrium solidification. At bonding temperature of 1150°C, B is the microstructure and rate controlling factor of TLP bond. Very low solubility of Ni in B (0.3at.%, according to the binary Ni-B equilibrium phase diagram [17]) and partition coefficient of B in Ni (~0.008 according to Ni-B binary phase diagram [17]) lead to rejection of B into adjacent melt shifting composition of the melt towards eutectic composition; thus, binary eutectic of γ-solid solution and nickel boride formed as solidification progressed.

- Diffusion affected zone (DAZ) which consists of extensive secondary precipitates. EDS compositional analysis of metallic elements was suggested that both precipitates are Cr rich carbo-boride [18]. Idowu *et al*. [19] also observed Cr-W-Mo based carbo-boride precipitates at the joint /base metal interface when bonding Inconel738 LC with a Ni-Cr-B interlayer at 1130°C.

These precipitates appear close to the joint interface where there is boron diffusion. However, at distances greater than 50-μm away from the joint interface, no carbo-borides were observed in this (almost boron free) region. Diffusion of boron from interlayer, with the fact that boron can reduce solubility of carbon in austenitic matrix interlayer, into the base metal and presence of Cr, which is a strong boride former, can explain formation of Cr rich carbo-borides.

Figure 3 shows microstructure of bonds made at 1150°C with a holding time of 45 min. As can be seen, eutectic structure is entirely eliminated. Therefore, it is concluded that 45 min holding time at 1150°C is sufficient for isothermal solidification completion. As can be seen, there is no crack within the joint region or joint interface. This can be related to the isothermal solidification which prevents solute rejection during solidification process, coupled with lower temperature bonding process in comparison to the conventional fusion welding processes, resulted in formation of a crack free bond.

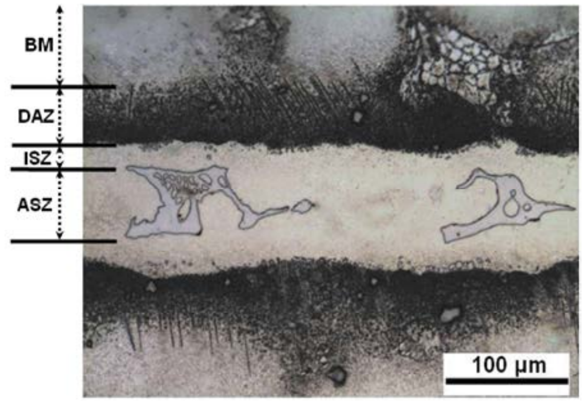

Fig. 2: Microstructure of bond made at 1150°C for 30 min.

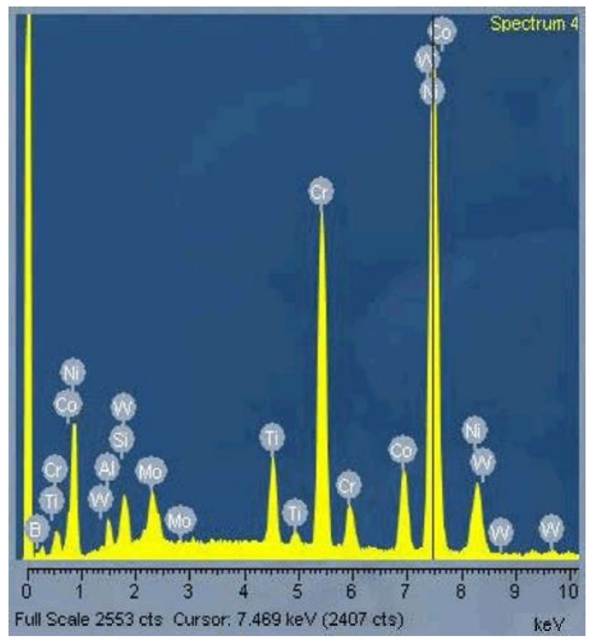

Fig. 3: Typical EDS spectrum of nickel-rich boride in ASZ

Effect of Post Bond Heat Treatment (PBHT) on Bond Microstructure: As mentioned above, isothermal solidification that prevents formation of hard eutectic structure in the joint centerline, was completed after 45 min of holding at 1150°C (Figure 3). In this condition, there are two dissimilarities between microstructure of the isothermally solidified zone and base metal.

- Lack of significant amount of γ′ phase in ISZ: As can be seen from Figure 3, there is no significant amount of γ′ phase within the ISZ of bond made at 1150°C for 45 min. This can be related to the low content of Al +Ti in the ISZ which could affect the γ′ phase stability. Presence of these elements is a key important factor for high temperature performance of the joint. Since the high temperature performance of precipitation hardened nickel based superalloy widely depends on the γ´ volume fraction; there is a need to design a proper PBHT to formation sufficient γ´ in bond region.

- Presence of borides in DAZ: As mentioned in the previous sections, isothermal solidification prevents the formation of eutectic structure in the bond region; however significant Cr-rich borides were still present in the DAZ. Despite the fact that the precipitates in DAZ have less detrimental effect on the joint shear strength due to their non-continuously distributed fashion along the joint/base metal interface, the high chromium content of DAZ precipitates, can lead to a significant depletion of chromium around this region, which may result in a decrease in the corrosion resistance [19].

Therefore, considering the lack of sufficient γ´ precipitation in ISZ and the presence of the large amount precipitates in DAZ, there is a need to design a proper PBHT to homogenize the bond. To pursue this purpose, isothermally solidified joints were homogenized at 1150°C in an argon atmosphere using a tunnel furnace. The holding time was 240 min. Figure 4 shows the microstructure of homogenized bond at 1150°C for 240 min. Figure 5 shows SEM micrograph of joint interface for homogenized bond. As can be seen, significant γ´ is formed in the bond region and the secondary precipitates in DAZ are almost removed. It should be mentioned that some γ´ coarsening was observed in the interface of bond region and the base metal.

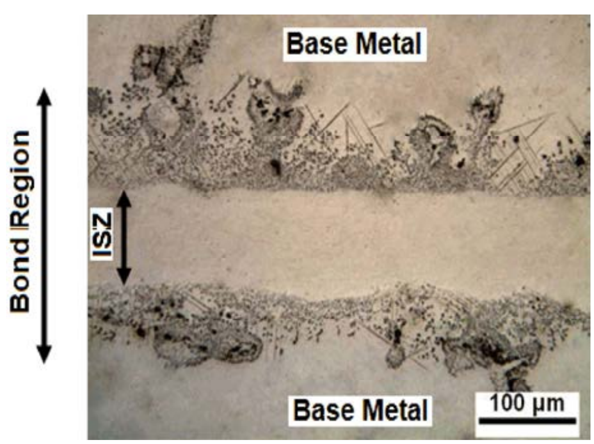

Fig. 4: Microstructure of joint bonded at 1150°C for 45 min.

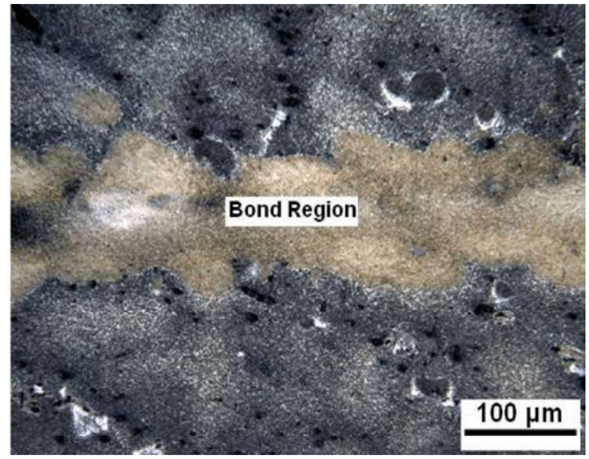

Fig. 5: Microstructure of homogenized bond

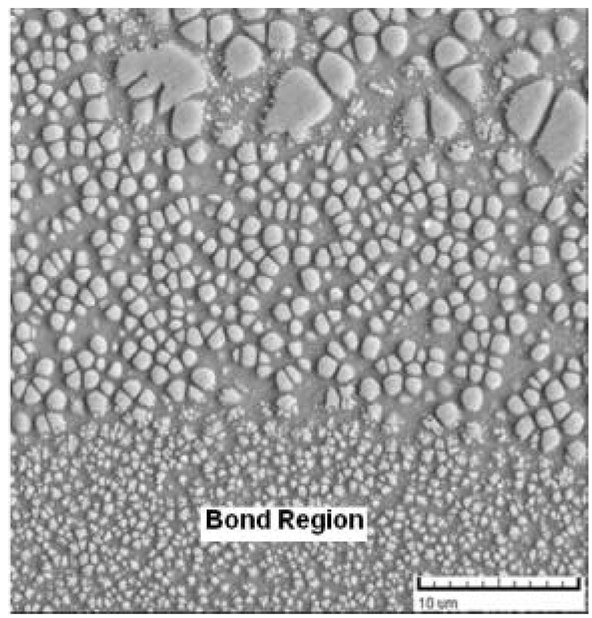

Fig. 6: SEM image showing interface microstructure of homogenized bond

CONCLUSION

From this research the following conclusions can be drawn:

- Before completion of isothermal solidification, bond region consists of four distinct zones: centerline eutectic structure due to athermal solidification, solid solution phase due to isothermal solidification, diffusion induced boride precipitates and base metal.
- Complete isothermal solidification, which prevents the formation of centerline eutectic constituent, occurred within 45min at 1150°C.

- Homogenization of isothermally solidified bonds at 1150°C for 240 min resulted in removing of secondary precipitates within the DAZ and formation of significant γ′ precipitates in the bond region.

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