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The effect of interlayer thickness, bonding temperature and atmosphere on transient liquid phase bonding of GTD-111 to FSX-414

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ABSTRACT

The amount of γ/nickel boride/Ni-B-Si ternary eutectic in the athermally solidified zone of joints was increased with increased thickness of the filler metal. By increasing the temperature from 1130 °C to 1160 °C, isothermal solidification was completed and no harmful phase was found in the middle of the joints. At higher temperatures, the dissolution of substrate elements prevented the diffusion of melting point depressants and the eutectic phase reappeared. Solidification cracks were observed when transient liquid phase bonding was done in non-vacuum atmospheres. The peak hardness in diffusion affected zones remained even when isothermal solidification was completed. The maximum shear strength of 412 MPa was achieved for a specimen with complete isothermal solidification (50 μm/1160 °C/45 min).

1. Introduction

Superalloys are applied in aerospace and power generation industries (Abdelfatah and Ojo, 2009). Although conventional welding procedures can be applied to join superalloys, solidification cracking is a major concern. High nickel weld metals are susceptible to cracking along the fusion line (Shojaati and Beidokhti, 2017).

Ghoneim and Ojo (2011) claimed that transient liquid phase (TLP) bonding yields proper properties of joints compared to other joining techniques. Furthermore, the TLP joint has a higher melting point than the bonding temperature (Grant et al., 2011).

During TLP bonding, the isothermal solidification of liquid phase can take place by diffusion of melting point depressant (MPD) elements into the base metal (Lee et al., 2007). Good mechanical properties of TLP bonds cannot be achieved without completion of isothermal solidification. Intermetallic compounds could be formed due to athermal solidification. These constituents degrade the mechanical properties and corrosion resistance of joints (Pouranvari, 2014). Different factors affect the isothermal solidification process. Liu et al. (2017) showed that the high amount of refractory elements in the filler material hinders isothermal solidification. Maleki et al. (2016) found that the increased gap size increases the bonding time required for achieving isothermal solidified joints.

It has been shown that the intermetallic phases during TLP can be represented by a diffusion model (Campbell and Boettinger, 2000). Bai et al. (2017) simulated TLP joining and found that the strength of joints was improved by post-bond heat treatment (PBHT). An increase of 34% in shear strength of TLP joint has been reported by Hadibeyk et al. (2018). It has been shown that homogenizing treatment of the joint removes harmful phases (Pouranvari et al., 2017). On the other hand, Cao et al. (2014) have declared that the precipitation of second phases induced by PBHT could be useful for the properties of joints.

Zhang et al. (2017) have reported that the precipitations in the diffusion zone of Ni-based bonds were M_6(C, B), M_{23}(C, B)$_6$, M_5B_3 and M_3B_2 types. Sheng et al. (2015) found that fine M_3B_2 particles could be formed even near the boundary of the isothermal solidification zone and matrix. It has been claimed that borides act as boron sink and promote isothermal solidification (Sheng et al., 2014). However, it is believed that borides are the preferential sites for nucleation and growth of cracks during both low and high temperature tensile tests (Zhang et al., 2016).

In this work, dissimilar TLP bonding of GTD-111 Ni-based superalloy to FSX-414 Co-based superalloy is carried out. In particular, the effects of filler metal thickness, temperature and atmosphere on the microstructure and mechanical properties of dissimilar joints are investigated in detail.

2. Materials and experimental procedure

Co-based FSX-414 and Ni-based GTD-111 superalloys were cut into 10 × 10 × 10 mm coupons and used as base metals. A commercial Ni-Si-B interlayer (MBF30) in the form of an amorphous foil with liquidus temperature (T_L) of about 1054 °C was applied as the filler material. Table 1 shows the chemical composition of the base and filler materials.

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Table 1
Nominal composition of the base and filler metals (wt.%).

Material	Co	Ni	Cr	Ti	Al	W	Mo	Ta	B	Si	Fe	C
FSX-414	Rem.	10	30.5	–	–	7.5	–	–	0.01	1	2	0.25
GTD-111	9.5	Rem.	13.5	4.75	3.3	3.8	1.53	2.7	0.01	–	0.23	0.09
MBF30	–	Rem.	–	–	–	–	–	–	3.2	4.5	–	–

Table 2
Summary of the bonding conditions.

`Specimen	Filler Metal Thickness (μm)	Temperature (°C)	Time (min)	Atmosphere
F30	30	1130	45	Vacuum
F50	50	1130	45	Vacuum
F75	75	1130	45	Vacuum
F50-6	50	1160	45	Vacuum
F50-9	50	1190	45	Vacuum
F50-Air	50	1130	45	Air
F50-Ar	50	1130	45	Ar

Before joining, FSX-414 superalloy was subjected to solution treatment at 1150 °C for 4 h followed by aging at 980 °C for 2 h. However, the solution treatment of GTD-111 superalloy was done at 1205 °C for 4 h and the specimens were subsequently aged at two stages (1120 °C/2 h and 845 °C/24 h). The mating surfaces of test coupons were polished using different grades of emery paper and then they were ultrasonically cleaned for 15 min. The cleaned coupons were kept in an ethyl alcohol solution until they were bonded. For TLP bonding, the filler alloy with thicknesses of 30, 50 and 75 μm was placed between two dissimilar coupons of the base metals. These specimens were designated F30, F50 and F75, respectively. The coupons were fixed between two plates of AISI 314 high temperature stainless steel. Considering the temperature T_L, the pre-assembled specimens were joined at bonding temperature (T_B) of 1130 °C for 45 min using a vacuum furnace. The process was repeated at bonding temperatures of 1160 °C and 1190 °C for specimen F50 in order to study the effect of temperature. These bonded coupons were designated specimens F50-6 and F50-9. To investigate the atmospheric effects, two specimens with the conditions similar to specimen F50 were prepared and TLP joining was performed in air as well as in argon (specimens F50-Air and F50-Ar, respectively). Table 2 shows the summary of bonding conditions.

The bonded specimens were sectioned perpendicular to the bonding line and were polished. Thereafter, they were etched in a Murakami solution (10 g KOH, 10 g $K_3[Fe(CN)_6]$, 100 ml H_2O). The microstructure of the samples was studied using an Olympus BX60M optical microscope (OM) and a LEO 1450VP scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). The quantitative analysis of microstructural constituents was carried out by microstructural image processing (MIP) software. Hardness tests with a constant load of 50 g were performed on a Buehler Vickers microhardness tester 1600-6125 to measure hardness values across the joints. Shear tests with a crosshead speed of 1 mm/min were carried out using a Zwick Z250 testing machine at room temperature to compare shear strength values of the joints.

3. Results and discussion

Each bonded coupon could be divided into four zones based on their morphologies: athermally solidified zone (ASZ), isothermally solidified zone (ISZ), diffusion affected zone (DAZ), and base metals (BM). The main regions for specimen F50 (bonded at 1130 °C for 45 min) are shown in Fig. 1.

At 1130 °C, 45 min was not sufficient to complete isothermal solidification. The athermally solidified zone (ASZ) was formed in the middle of the joint and it contained the ternary eutectic of Ni-solid

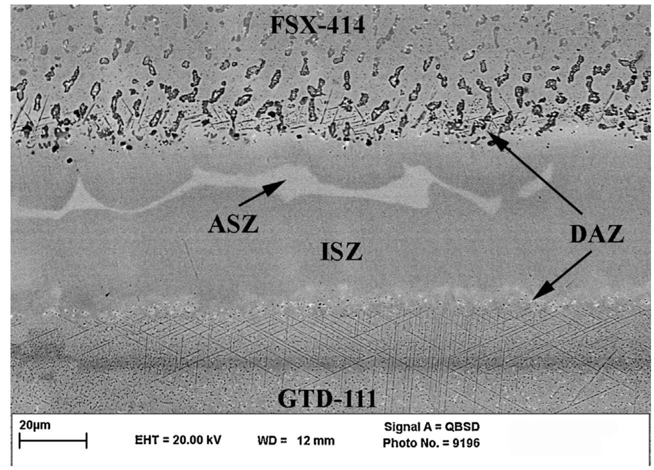

Fig. 1. SEM micrograph of the TLP joint (1130 °C, 45 min) showing different regions; athermally solidified zone (ASZ), isothermally solidified zone (ISZ) and diffusion affected zone (DAZ).

solution (γ), nickel boride and Ni-B-Si constituents as shown in Fig. 2(a). According to the Ni-B (Teppa and Taskinen, 1993) and Ni-Si phase diagrams (Oikawa et al., 2007), the solubility limit of boron and silicon in nickel are 0.2 at.% and 14 at.%, respectively. Therefore, a mixture of γ and nickel boride was formed in this region. The remaining liquid was enriched in silicon and formation of Ni-B-Si constituents was also encouraged.

The diffusion of melting point depressants (MPDs) into the base metals is the main reason for the formation of the isothermal solidification zone (ISZ). The dissolution of the base metals has occurred simultaneously during TLP and some amounts of substrate elements (e.g. Co, Cr, Ti and Al) were found in the ISZ. The microstructure of ISZ was Ni-solid solution (γ).

Two morphologies of precipitations, i.e. round and acicular types, were observed in the diffusion affected zone (DAZ) of GTD-111 as shown in Fig. 2(b).The EDS results reveal that both morphologies could be Cr-rich carbo-borides (Fig. 2(c) and (d)). The percentage of Al in the DAZ on the GTD-111 side was about 2 at.% and it was lower than the value of 12 at.% which is required to form γ´. On the FSX-414 side, Co-Cr carbides were found in the DAZ.

3.1. *The effect of filler metal thickness*

The thickness of the interlayer determines the joint gap. The volume fraction and continuity of eutectic phase in the middle of the joints were increased by increasing the joint gap. As mentioned before, the formation of nickel boride facilitated the formation of ternary eutectic through Si-enrichment of the remaining liquid. For the thin interlayer, boron could easily diffuse into the base metals. Consequently, the boride phases were reduced and the remaining liquid was not enriched in silicon. It seems that ternary eutectic cannot be formed in TLP joints when a thin filler metal is applied. In these conditions, solidification was completed with the formation of only two phases (γ and Ni-boride) in the ASZ. Maleki et al. (2016) have reported that perhaps nickel silicide cannot be formed in narrow gap joints. They mentioned that the more residual liquid phase in wide gap TLP joints could intensify the