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Transient liquid phase bonding of Inconel 718 and Inconel 625 with BNi-2: Modeling and experimental investigations

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Abstract

In this study, a combination of direct experimentation and computational modeling approach was used to predict the time required to complete isothermal solidification during the transient liquid phase bonding of Inconel 718 and 625 superalloys, two most commonly used superalloys in aero-engine hot section components, with nickel based filler alloy, BNi-2. However, unlike conventional modeling, the diffusion of solute atoms was modeled by the Random Walk Modeling technique which can take into account the physical and chemical uncertainties associated with the transient liquid phase bonding experiments. The model equations for migrating solid/liquid interface and solute distribution approaches have been modified and presented in this article. Cumulative probability distribution and probability density function of predicted isothermal solidification times were calculated for different process conditions. The predicted isothermal solidification time range with different confidence levels has been verified with experimental data. Good agreement was observed. The times required for complete isothermal solidification were found to be significantly less than those of other nickel superalloys with different nickel based brazing fillers. Further, significant reduction of holding time was observed with increasing bonding temperature and with decreasing joint gap and no significant grain growth has been observed in the temperature range being investigated (1325–1394 K).

Keywords: Transient liquid phase bonding; Random Walk Modeling; Inconel 718; Inconel 625; BNi-2

1. Introduction

Inconel 625 and 718 superalloys are extremely versatile austenitic nickel based superalloys with excellent strength and good ductility at very high temperature. Typical applications include aero-engine hot section components, miscellaneous hardware, tooling and liquid rocket components involving cryogenic temperatures. However, like other austenitic nickel based superalloys that contain a substantial amount of Ti and Al, they are highly susceptible to heat affected zone cracking during welding [1,2]. Typical high temperature brazing with nickel based filler alloys, containing boron and silicon as melting point depressants, evolved as an effective way to join these superalloys. However, these melting point depressants form eutectic structures that are extremely hard and contain very brittle intermetallic compounds with nickel and chromium which are detrimental to the mechanical properties of the brazed joint [3–5]. One method to prevent the formation of these deleterious phases is transient liquid phase bonding (TLP), also known as diffusion brazing [6,7]. The TLP bonding process uses a low melting filler alloy to wet the contacting base material and that subsequently solidifies isothermally via a fast diffusing element, e.g. boron. Unlike conventional brazing, the thermal exposure used for the TLP bonding cycle is sufficient to induce isothermal solidification at the bonding temperature [8]. Thus, at a relatively low melting temperature, diffusion brazing produces a joint that has a uniform composition profile, relatively more tolerance to surface oxides, geometrical defects and wide gaps [6,9]. These advantageous features have been exploited in a wide range of applications, from the production and repair of turbine engines in the aerospace industry to the connection of circuit lines in the microelectronic industry [7–9].

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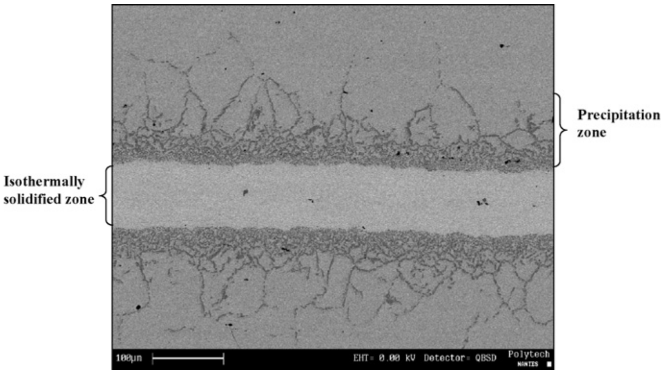

Fig. 1. SEM micrograph of an Inconel 625/BNi-2 joint showing complete isothermal solidification.

For a given operating temperature, TLP bonding process relies on the time required to complete the isothermal solidification to prevent the formation of the brittle eutectic phases in the resulting brazed joints, an example is shown in Fig. 1. Boron composition reached the solidus value during the holding period because of diffusion towards the base metal and thus, the formation of eutectic phases was avoided during cooling.

Tuah-Poku et al. [10] derived an expression for the holding time for silver/copper/silver sandwich joints based on stationary solid/liquid interface and their predicted values were found to be much higher than the experimentally determined values. Lee et al. [11] suggested that diffusion of the solute atoms could take place during liquid homogenization, which could result in the precipitations of second phases in the base metal and thus the holding time required for complete isothermal solidification would be considerably reduced. Other models based on migrating solid/liquid interface and solute distribution law have been used by several researchers [2,4,12–15] to predict the isothermal solidification completion times and the formation of second phase precipitates in the substrates for pure nickel, nickel based single crystal superalloys, Inconel 738 and duplex stainless steel base metals with binary Ni–P and Ni–B, or ternary Ni–Cr–B, or multi-component Ni–Cr–B–Fe–Si filler alloys, and good agreement with the experimental values have been reported. However, modeling studies and experimental investigations of isothermal solidification during TLP bonding of Inconel 625 and 718 superalloys with BNi-2 filler alloy, could not be found in the literature.

Although TLP bonding is an excellent bonding technique, the time required to complete isothermal solidification is usually long enough to discourage their potential applications in many industries. Therefore, a better understanding of the effect of other process variables, such as bonding temperature and joint gap, on the time required to complete isothermal solidification, is imperative to reduce the time requirement and thus to optimize the process. By a combination of direct experimentation with computational modeling, the optimum joining parameters, such as joint gap, bonding temperature and holding time can be set prior to actual field trials.

Mathematical modeling coupled with experimental data is widely used to determine the kinetic parameters such as diffusion coefficient of solute atoms into the base alloys during TLP bonding. However, when coupling experimental data with the mathematical model, the physical and chemical uncertainties associated with the diffusion brazing experiments should be addressed in a way that it best reflects the diffusion characteristics of the solute atoms into the base alloy. Taking only one or two sets of experimental data, often sufficient to solve the governing diffusion equations, will lead to erroneous results because another set of experimental data will result into a different value. Therefore, in such a situation, several sets of experimental data should be used to determine the range of diffusion coefficients and it should be then modeled as a random number based on the statistical distribution profile being observed, such as normal, weibull, uniform, or any other distribution. Such modeling approach is known as Random Walk Modeling and is widely used to simulate the diffusion characteristics of solute atoms in diffusion governing processes [16–19]. However, no such approach has been used so far to simulate the diffusion characteristics of solute atoms into the base alloys during TLP bonding and, single sets of kinetic parameters for diffusion of solute atoms, which is not representative for real life experiments, continue to appear in the literature.

Hence, the objectives of this work are to calculate the time required to complete isothermal solidification during TLP bonding of Inconel 718 and 625 superalloys with BNi-2 filler alloy using mathematical models based on migrating solid/liquid interface and solute distribution law taking the random diffusion of solute atoms into considerations, and to verify the predicted isothermal solidification times with experimental investigations.

2. Experimental investigations

2.1. Procedures

This research was conducted on both wrought Inconel 625 and 718 alloys. The microstructures of the as-received base metals are shown in Fig. 2. Wedge shape joint gap specimens with identical base alloys, shown in Fig. 3, were utilized to form an edge groove where the BNi-2 brazing filler paste was placed. The nominal compositions of the base and filler alloys are given in Table 1. The specimen was fixed by tack welds to form a variable brazing gap (0–250 μm).

The samples were nicro-blasted and then acid cleaned. To prevent the oxide build-up, the base alloy was pre-plated with very thin layer of nickel (nickel flash) and subsequently vacuum brazed at a vacuum pressure of 1.33 mPa (10^{-5} torr) according to the matrix shown in Table 2. The brazed samples were prepared metallographically and studied under the optical and scanning electron microscope (SEM) equipped with electron dispersive spectrometry (EDS).

2.2. Microstructures of the brazed joint

A typical micrograph of the Inconel 625/BNi-2 brazed joint and the corresponding EDS analyses are shown in Fig. 4. Intermetallic phases were formed along the centerline of the joint as