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On the influence of boron-addition on TLP bonding time in a Ni_3Al-based intermetallic

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ABSTRACT

Transient liquid phase (TLP) bonding of boron-bearing and boron-free single crystals of a Ni_3Al-based intermetallic alloy IC 6 was performed to study the influence of boron addition to the base-material on isothermal solidification completion time, t_f, required to prevent formation of deleterious joint centerline eutectic microconstituent. The result showed that addition of boron to the intermetallic alloy did not prohibitively prolong t_f as predicted by theoretical TLP bonding models. The deviation from prediction is attributable to microsegregation behaviour of boron atoms during directional solidification of the cast alloy IC 6.

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1. Introduction

Conventional heat-resistant structural materials such as nickel based superalloys that are used in the aerospace and power generation gas turbines have nearly reached their upper temperature limit of application and, as such, research has been focused on alternative materials that are lighter and stronger, and have a higher temperature capability than the superalloys. Intermetallic-based alloys and compounds, such as, nickel aluminides, have evolved as prime alternate materials in this regard, and have been the subject of intense study in the past few decades. Welding is generally desired as a joining technique in the fabrication of turbine components and repair of service-damaged turbine parts. A substantial body of research on the fusion welding of intermetallics [1–5] has shown that while such high-energy beam welding techniques as electron-beam and laser-beam welding are attractive for joining these materials, their application is severely limited by the high susceptibility of the materials to cracking during welding. Transient liquid phase (TLP) bonding is being considered as a potential alternative for the successful joining and repair of components made from intermetallic materials. The process involves the formation of a joint between two solid substrates through the diffusion-induced isothermal solidification of the melting point depressant (MPD) solute-rich liquid phase that temporarily exists between the substrates at the bonding temperature.

Among the most investigated of the various intermetallics for commercial applications are the Ni_3Al-based alloys. A directionally solidified (DS) Ni_3Al-based alloy IC 6 has been developed at the Beijing Institute of Aeronautical Materials as a high temperature structural material for manufacturing advanced jet-engine components. It has been tested successfully as a turbine-vane material in two different types of aero-engines [6]. It exhibits superior creep-rupture resistance properties, and can withstand higher temperatures (1050–1100 °C) than the majority of the currently used nickel based superalloys. An important parameter in the consideration of TLP bonding for commercial joining applications is the holding time, t_f, required to complete the isothermal solidification of liquated insert and, hence, prevent the formation of deleterious solidification eutectic product. This parameter is a function of solute diffusivity in the solid substrate and the phase relationships between the filler alloy and the base metal. Addition of boron to Ni_3Al-based intermetallics, including alloy IC 6, is often desired to improve their high temperature creep properties. A review of the literature showed that very limited study is reported on the influence of base-material chemical composition on time t_f. According to current TLP bonding diffusion-based mathematical models, while boron addition is beneficial for enhancing high temperature performance of Ni_3Al-based intermetallics, it will, however, render application of TLP bonding to join the materials unattractive, due to prohibitive long time t_f required to produce reliable TLP joint. A recent careful experimental study has,

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however, showed that some inherent assumptions of current TLP bonding models can cause actual bonding behaviour to significantly depart from predicted pattern [6]. Therefore, in the present work, TLP bonding of two versions of single crystals of alloy IC 6, one with 1.18 at% wt boron content and the other one free of boron, was studied to experimentally verify the validity of theoretical model prediction, with regard to the effect of boron addition on time t_f.

2. Experimentals

The materials used in the present study were boron-free (BF) cast single crystal alloy IC 6 with chemical composition of Ni–15.9Al–7.78Mo (at.%) and a boron-bearing (BB) version with 1.18 (at %) of boron content. The filler alloy used was a Metglas Brazing Foil – MBF 80 with a composition of 14.4Cr, 16.2B, 0.12C balance Ni (at.%). The base alloy in the form of 8 × 9 × 12 mm test coupons was sectioned from as-received plates by using a numerically controlled wire electro-discharge machine (EDM). TLP bonding was carried out in a LABVAC II brazing furnace operating under a vacuum of 10^{-4}–10^{-5} Torr at 1100 °C for various holding time periods ranging from 30 to 180 min with gap sizes 80 and 120 μm. Bonded specimens were sectioned using EDM and prepared by standard metallographic techniques for microstructural assessment. The specimens were etched in a solution of 40 mL H_2O + 480 mL HCl + 48 mL $CuCl_2$ for 5 s. Preliminary general assessment of the joint microstructure was performed by an inverted-reflected light microscope equipped with a CLEMEX Vision 3.0 image analyzer. Scanning electron microscopic examination using secondary and backscatter electron imagine modes and compositional analysis of joint were conducted by a JEOL JSM-5900LV scanning electron microscope equipped with an ultra-thin window Oxford energy dispersive spectrometer (EDS) system and INCA software. A minimum of twenty measurements was taken to calculate the average centerline eutectic width in all the specimens. A rapidly growing technique for quantifying light trace elements like boron in nickel [6], laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), was used for determining boron concentration profile in the boron-bearing base-material.

3. Results and discussions

Fig. 1 shows microstructure of a TLP joint prepared at 1100 °C for 30 min in BF alloy IC 6. A continuous eutectic microconstituent can be observed along the centerline region of the joint. Semi-quantitative EDS compositional analysis indicated that the eutectic consisted of nickel rich boride phase, chromium rich boride phase and nickel base constituent similar to isothermally solidified pro-eutectic constituent. During TLP bonding, the filler alloy melts and rapidly attains equilibrium with the solid substrate. Inter-diffusion of alloying elements between the base-material and the liquid subsequently increases the melting point of the liquated insert and, thus, results in its isothermal solidification. As isothermal solidification progresses, the volume of the liquid decreases and the solid–liquid interface recedes toward the center of the joint. Insufficient holding time for boron diffusion to achieve complete isothermal solidification would result in residual liquid transforming into centerline eutectic microconstituent. Through the use of Scheil based simulation, Ohsassa et al. [7] studied the solidification behaviour of residual liquated insert during TLP bonding of pure nickel with Ni–B–Cr ternary filler alloy, and reported the formation of a ternary centerline eutectic consisting of nickel base solid solution (γ), nickel-boride and chromium boride at 997 °C. The centerline eutectic observed in the present work consists of nickel based solid solution, Cr-rich boride and Ni-rich boride (Table 1) similar to what was reported in other nickel based alloys [6–8]. The centerline eutectic is generally known to be deleterious to both mechanical and corrosion properties of TLP bonded materials [9,10]. Likewise, microstructural examination of the joint produced in BB alloy at 1100 °C for 30 min showed an occurrence of the centerline eutectic with similar width to that observed in BF alloy (Fig. 2a). Moreover, the eutectic width was found to be comparable in all joints prepared under the same bonding conditions in BF and BB alloy IC 6 (Fig. 2b). An increase in holding time to 3 h at the 1100 °C, to allow further diffusion of boron into the base-material, resulted in complete isothermal solidification of the liquid insert, which resulted in eutectic-free joints in both the BB and BF IC 6 specimens (Fig. 3).

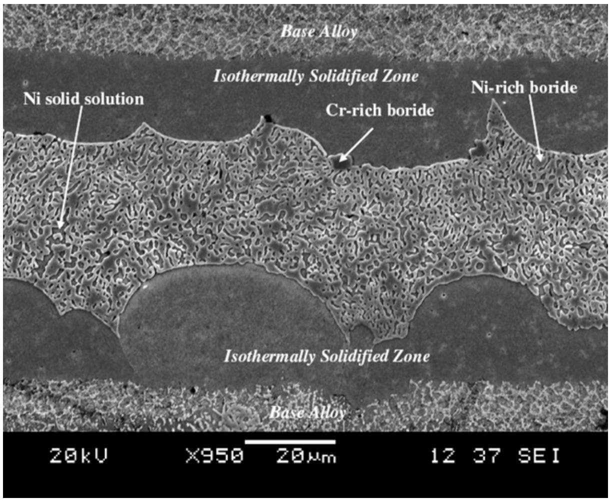

Fig. 1. Micrograph of a joint prepared at 1100 °C for 30 min in BF alloy IC 6 showing presence of centerline eutectic microconstituent.

A number of analytical and numerical models [11–13] have been proposed to represent underlying TLP isothermal solidification process. The models are based on analytical and numerical solutions to the standard Ficks second law of diffusion:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

where, $\partial C/\partial t$ is the rate of change in solute concentration with respect to time at a given position in the base metal, which could provide an indication of isothermal solidification rate, D is the diffusion coefficient, and $\partial^2 C/\partial x^2$ is the rate change of concentration gradient with respect to distance. Analytical models based on a migrating solid–liquid interface are developed to estimate the total time for complete isothermal solidification, t_f, and they generally follow the form:

$$t_f^{1/2} = \frac{2h}{4\gamma D^{1/2}} \tag{2}$$

where, γ is a dimensionless parameter, 2 h is the maximum width of the liquid insert, and D is the diffusion coefficient. The dimensionless parameter γ can subsequently be determined numerically by the following expression:

Table 1
Average metallic composition of centerline eutectic product as determined by SEM-EDS.

Phase	Composition (at.%)			
	Cr	Al	Mo	Ni
Cr-rich boride	66.54	–	19.11	14.35
Ni-rich boride	10.45	1.47	–	88.08
Ni solid solution	13.28	1.78	–	84.94

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