Journal of Alloys and Compounds 653 (2015) 386–394

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Effect of bonding time on the microstructure and isothermal solidification completion during transient liquid phase bonding of dissimilar nickel-based superalloys IN738LC and Nimonic 75

M. Khakian, S. Nategh*, S. Mirdamadi

Department of Materials Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Article history:
Received 1 August 2015
Received in revised form
29 August 2015
Accepted 6 September 2015
Available online 9 September 2015

Keywords:
IN738LC
Nimonic 75 superalloy
TLP bonding
Isothermal solidification
Microstructure
Mechanical properties

ABSTRACT

Joining of dissimilar nickel base superalloys IN738LC to Nimonic 75 by use of transient liquid phase bonding with Ni–15Cr-3.5B interlayer (MBF-80) was carried out at temperatures of 1080 °C, 1120 °C, 1150 °C and 1180 °C for different bonding times. Joint microstructure was surveyed by optical and scanning electron microscopy. Microstructural examinations showed those in short bonding times, the joint microstructure consists of continuous eutectic intermetallic phases and longer times lead to eutectic free microstructure. It was shown that bond shear strength increases with holding time increment. Fick's equations were used for prediction the time required for completion of isothermal solidification. It was seen that there was a good correspondence between the results of modeling and experimental data.

1. Introduction

IN738LC is one of the most practical precipitation hardened casting nickel-base superalloys due to its excellent mechanical properties and high corrosion and oxidation resistance at high temperatures. It is widely used in gas turbine power plants and aircraft engines [1]. Nimonic 75, On the other hand, is one of the simplest solid solution strengthened nickel base superalloy. It is now mostly used for sheet applications calling for oxidation and scaling resistance coupled with medium strength at high operating temperatures. It is still used in gas turbine engines and also for industrial thermal processing, furnace components and heat-treatment equipment [2].

Due to the complex configuration of the components used in gas turbines, integrate production of these parts is not possible through casting, forging and machining. So, the manufacturers have to use the joining and assembling processes [1]. Fusion welding, brazing and diffusion bonding are the most common joining processes of the Ni base superalloys [3]. Welding of IN738LC is very difficult due to the presence of high amount of γ' formers in this widespread superalloy ($Al + Ti > 6$wt.%). Haafkens and Matthey [4] showed that the shrinkage stresses caused by rapid precipitation of γ' during fusion welding, leads to the formation of cracks in HAZ. On the other hand, because of the nature of brazing, the formation of brittle phases during the brazing of the alloy is inevitable, leading to the loss of the integration of the base metals and decreasing the mechanical properties of the joint [5]. So, these difficulties associated with brazing and also fusion welding can limit the industrial application of these processes for IN738LC alloy [6,7].

Transient liquid phase (TLP) bonding is the one of the most effective joining process of similar and dissimilar superalloys. In this process, the formation of brittle intermetallic phases which are formed during the brazing process, which can decrease the mechanical properties and service temperature of the joint, is prevented. In TLP process, a filler metal that contains some melting point depressant (MPD) elements (such as B and Si) is put between joint faying surfaces and then whole of the assembly is heated at temperatures upper than liquidus temperature of interlayer and also lower than solidus temperature of base metals [8].

Bonding temperature of superalloys varies between 1000 and 1200 °C depending on the type and the amount of MPD elements as well as the presence of alloying elements in interlayer [9]. On the basis of standard TLP models, joining process includes three

* Corresponding author.
E-mail addresses: khakian_meysam@yahoo.com (M. Khakian), snategh@yahoo.com (S. Nategh).

http://dx.doi.org/10.1016/j.jallcom.2015.09.044
0925-8388/

consecutive stages: base metal dissolution, isothermal solidification and homogenization of bonding zone [10–12]. At bonding temperature, interlayer melts and wets the base metals surfaces. At this time, complete contact between solid and liquid is established and base metal dissolution commences. By MPD diffusion from interlayer to base metal and also diffusion of alloying elements from base metal to interlayer, volume of liquid increases. The increment of liquid volume continues up to create a local equilibrium between solid and liquid. The dissolution stage continues until liquidus temperature of molten interlayer reaches to bonding temperature, and then isothermal solidification starts from solid/liquid interface to the joint centerline. After completion of isothermal solidification, there would be a single phase in the bond line. If no sufficient time devotes to completion of solidification, remained liquid subjects to athermal solidification processes during cooling from joining temperature to lower temperatures and transforms to brittle eutectic intermetallic phases. So, one of the most important parameters in TLP joining, is the time required for isothermal solidification completion which prevents the formation of undesirable eutectic phases. This parameter depends on coefficient of diffusion and solubility of MPD into the base metal and substantially affected by process variables like interlayer thickness and bonding temperature [5].

In this study, completion of isothermal solidification process in TLP bonding of IN738LC and Nimonic 75 by use of MBF-80 interlayer at temperature of 1080–1180 °C was investigated. Also, the effect of bonding time on microstructure development of bond and diffusion affected zone was surveyed. Finally, using established analytical models, the time of isothermal solidification is calculated and compared with experimental results.

2. Materials and experiments

In this study, IN738LC and Nimonic 75 superalloys in solution treatment condition were used as the base metals. An interlayer with composition of Ni–15Cr-3.5B and trade name of MBF-80 in amorphous form and thickness of 75 μm was used as interlayer. Chemical composition of the base metals and the interlayer is shown in Table 1.

Test specimens and interlayer first were cut in dimension of 10 × 10 × 5 mm and 11 × 6 mm, respectively. Then, they were put in a fixture to prevent any excess moving. No external pressure was applied at the bond surface. Also, green stop-off was used to prevent the flow of molten interlayer at the bonding temperature. Solidus and liquidus temperatures of interlayer are 1050 °C and 1090 °C, respectively. So, bonding temperature was selected at temperatures above 1050 °C. Experiments were performed in a an electrical furnace with a vacuum of 10^{-5}mbar and at temperatures of 1080 °C, 1120 °C, 1150 °C and 1180 °C. Also, bonding time varied from 5 to 180 min. Bonding heat treatment cycle is shown schematically in Fig. 1. Heating rate from 950 °C to the joining temperature was arranged on 20 °C/min.

Samples then were prepared for final metallographic and SEM studies, using Kalling's etchant (5 gr $CuCl_2$ + 100 cc HCl +100 cc Ethyl alcohol), to evaluate the effect of bonding time and temperature on microstructure of TLP bonding. In order to evaluate the

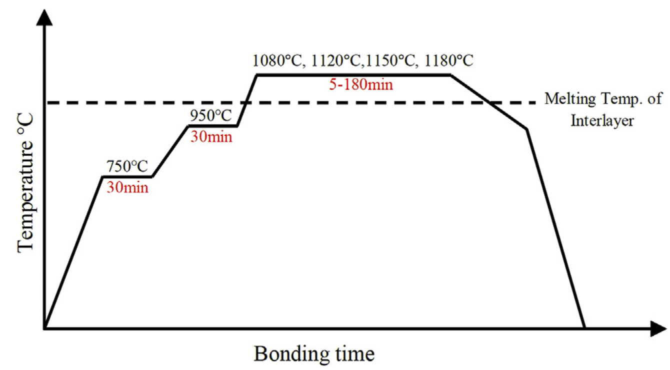

Fig. 1. Schematic illustration of heat treatment cycle.

mechanical strength of the bond, room temperature shear test was performed by use of a fixture which applies a pure shear stress at the bond surface. Instron tensile machine with the strain rate of 10^{-4} s^{-1} employed to perform the shear test.

3. Results and discussion

3.1. Overall microstructure of the joint

Fig. 2 shows the SEM microstructure of TLP bonded sample that is performed at 1120 °C in 5 min. As can be seen, bonding area contains eight individual microstructural zones.

- Base metal – Nimonic 75
- Diffusion Affected Zone – Nimonic 75 Side (DAZ- Nimonic Side)
- Isothermally Solidified Zone – Nimonic 75 Side (ISZ- Nimonic Side)
- Athermally Solidified Zone (ASZ)
- Secondary phases
- Isothermally Solidified Zone – Inconel 738 Side (ISZ- Inconel Side)
- Diffusion Affected Zone – Inconel 738 Side (DAZ- Inconel Side)
- Base metal - IN738LC

Chemical analyses of the mentioned zones are listed in Table 2.

3.2. Phases formed in solidified zone

Duval [10] and Gale [13] divided the TLP bonding process into three separate stages. First, at joining temperature interlayer, containing MPDs like boron, melts and then reacts with base metal. Boron, due to its high coefficient of diffusion, diffuses to base metal very rapidly. This process leads to dissolution of base metal and an increment of liquid phase volume. Because of very thin thickness of molten interlayer and also high coefficient of boron diffusion at molten interlayer, its concentration in liquid would be constant [12].

Analyses of ISZ zones (E and D in Fig. 1) which are presented in Table 2, showed that elements like Mo, Co, W, Nb, Al and Ti, that were not present in the interlayer, have diffused into the bonding

Table 1
Chemical composition of base metals and interlayer used in this study (wt.%).

Alloys	Cr	Co	Al	Ti	W	Mo	Ta	Nb	Fe	C	B	Ni
IN738LC	16.23	8.56	3.41	3.45	3.05	1.73	1.57	0.67	0.08	0.09	0.0063	Bal.
Nimonic 75	20.50	–	0.29	0.55	–	–	–	–	4.78	0.10	–	Bal.
MBF-80	14.89	–	–	–	–	–	–	–	–	–	3.72	Bal.