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Pulsed electric current bonding between Ni-based single crystal and powder metallurgy superalloys

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ABSTRACT

Pulsed electric current bonding (PECB) between Ni-based single crystal (SC) and powder metallurgy (PM) superalloys was first carried out to investigate the influence of PECB conditions on the interface microstructure and element diffusion. ANSYS simulation was employed to obtain temperature distribution during PECB process. Non-uniformity of temperature gradient occurred in the bonding interface, leading to non-uniform interface microstructure. Irregular γ′ precipitates developed in DD6 diffusion zone, and uniform spherical γ′ precipitates reprecipitated in FGH96 diffusion zone. Interface microstructure under 1100 °C/35 MPa/10 min was more desirable due to few large irregular γ′ precipitates formed. Average tensile strength at 750 °C was evaluated to be 978 MPa for PECB joints with the highest tensile strength of 1010 MPa under 1100 °C/35 MPa/10 min.

1. Introduction

With the development of dual-property turbine rotor, there is a great demand for bonding Ni-based SC superalloy blades and PM superalloy turbine disks. Traditional fusion welding employed in the bonding of two superalloys is extremely susceptible to cracking due to high γ′ volume fraction [1,2]. Several bonding methods without melting such as transient liquid bonding, diffusion bonding, and so forth have been put forward in recent years [3,4]. However, these processes often require long holding times at high temperature and high pressure, which is not only uneconomical, but also detrimental to parent metals/alloys and joints.

PECB, a rapid densification process considered successful in producing PM compacts at lower temperature with shorter exposure [5,6], is now applied in the joining of metals. Much work has been made on the application of PECB in aluminums, titanium, steels, etc. [7–9]. PECB method in bonding Ni-based superalloys was first used and microstructure variation and elements diffusion of joints were studied.

2. Experimental procedure

The DD6 alloy used in this study is a second generation Ni-based SC superalloy with excellent high-temperature properties, produced in the [001] direction by screw selection crystal method in a directionally solidified furnace. The FGH96 PM superalloy is procured by hot deformation following hot isostatic pressing. FGH96 powder is obtained by plasma rotating electrode process. Chemical compositions of the materials used are listed in Table 1.

Different heat treatments were conducted for as-received alloys prior to PECB. DD6 alloy was subjected to 1290 °C/1 h/AC (air cool) + 1300 °C/2 h/AC + 1315 °C/4 h/AC + 1120 °C/4 h/AC + 870 °C/32 h/AC. Heat treatment for FGH96 alloy involves 1150 °C/2 h/WQ (water quench) and 760 °C/8 h/AC. SEM microstructures of DD6 and FGH96 alloys in heat treated conditons are shown in Fig. 1(a). Cubic γ′ precipitates were orderly distributed in the core area of DD6 alloy, whereas irregular γ′ precipitates arrayed disorderly in the interdendritic area. Bi-modal distribution of spherical γ′ precipitates was uniformly exhibited in FGH96 alloy.

Specimens with $\varnothing 15 \times 35\ mm^2$ were machined from both heat treated alloys. The specimens were polished, and then were ultrasonically cleaned in a solution of acetone. The specimens were placed between two graphite punches as depicted in Fig. 1 (b). Direct current pulse of rectangular waves was discharged from the upper electrode to the lower one. The pulse current was employed to heat specimens at a certain temperature. When the fixed temperature was reached, the pulse current was adjusted to keep this temperature for several minutes. The specimens were compressed under an applied uniaxial punch pressure during the whole process. The pressure and electric current were simultaneously transmitted and discharged. In this study, the specimens were heated to fixed temperatures of 1080 °C, 1100 °C and 1120 °C under 35 MPa for 10 min in a vacuum ($< 10^{-2}$ Pa) condition.

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The coupled thermo-electric model in ANSYS software was employed to simulate temperature field of PECB interface. The material constants of DD6 and FGH96 alloys were incorporated. A resistance model of resistance welding was used for PECB characterization. And the resistance can be determined by the number of escaped electrons, N, as follows:

$$N = 4\pi \frac{m_e (k_B T)^2}{h^3} e^{-W/k_B T} \quad (1)$$

where m_e is the electron mass, h is the planck constant, K_B is the boltzmann constant, T is the absolute temperature, and W is the the power.

Fig. 1(c) illustrates non-uniform temperature gradient through PECB interface, where the heat concentrated on the interface and the temperature decreased with the distance from the interface center. Microstructure evolution and element distribution would be studied in DD6 diffusion zone and FGH96 diffusion zone.

3. Results and discussion

3.1. Interface morphology

The micrographs of DD6/FGH96 PECB interfaces at different temperatures are shown in Fig. 2. The width of interface zones increases with temperature and no voids were observed as shown in Fig. 2(a1)–(a3). Large irregular γ′ precipitates developed in the interface zones were considered to be detrimental to the properties of joints. The coalescence of γ′ precipitates is accompanied with γ′ dissolution during PECB process. The rate of γ′ coalescence locally is higher than that of γ′ dissolution, which may be responsible for the formation of irregular γ′ precipitates. Otherwise no obvious irregular γ′ precipitates formed in PECB interface.

More sufficient deformation and interface contact occurred with temperature at a constant pressure, leading to few smaller voids left in the interface zone. The concurrent element diffusion also promoted the decrease of voids. Aluminum oxides identified by energy dispersive spectrometer (EDS) were accompanied with voids due to the interaction of the air in the voids with Al element.

Table 1
Chemical compositions of the materials used (mass%).

Alloys	Al	Ti	Cr	Co	Mo	Nb	Ta	Re	W	Hf	C	Ni
DD6	5.7	0.0	4.3	9.0	2.0	0.6	7.2	2.0	8.0	0.1	0.003	Bal.
FGH96	2.1	3.7	16	13	4.0	0.7	0.0	0.0	4.0	0.0	0.035	Bal.

Lower temperature in the interface edge than in the interface center was observed in Fig. 1(c), which is unfavorable to the decrease of voids in the interface edge in Fig. 2(c1) and (c2), illustrating that closer bonding occurred in the interface center than in the interface edge. The voids in the interface edge were considerably decreased with temperature rising to 1100 °C. And voids almost disappeared and only oxides were left at 1120 °C.

3.2. Element diffusion across interfaces

Element diffusion plays a dominant role in the final morphology of interfaces, especially γ′ element such as Al, Ti and Ta. Therefore, the variations in the concentrations of Al, Ti and Ta in interface zones were measured by EDS and plotted in Fig. 3. An element inter-diffusion zone was observed in interface zones, which led to the difference of γ′ morphologies in between the interface zone and the mother alloys. Besides, a more dramatic change of element concentration in DD6 diffusion zone than in FGH96 diffusion zone occurred as shown in Fig. 3(a2), (b2) and (c2). Small spherical γ′ precipitates around standard cubic γ′ ones and large irregular γ′ precipitates were present in DD6 diffusion zone, which coincided with high concentrations of γ′ forming elements. The dissolution of bi-modal spherical γ′ precipitates occurred in FGH96 diffusion zone and uniform spherical γ′ precipitates reprecipitated. In comparison of microstructures in Fig. 3(a1), (b1) and (c1), interface microstructure at 1100 °C is more desirable due to few large irregular γ′ precipitates formed.

3.3. PECB process

Interface temperature varied with time during PECB process is shown in Fig. 4, which was calculated by ANSYS software. The PECB process was divided into two periods. The first period is defined as interface contacting period within 60 s. Fig. 4(a) and (b) shows temperature distribution of PECB interfaces after 10 s and 20 s, respectively. Interface temperature increased with time and high-temperature interface zone broadened more quickly. That is because lots of contact regions were formed on the interface and it subsequently led to the decrease of resistance and the increase of current in this period.

The second period is in which interface temperature was almost kept constant after 60 s as shown in Fig. 4. Since interface contact was ceased in this period, the resistance and current were kept constant. Figs. 4(c) and (d) show temperature distribution of PECB interfaces after 60 s and 600 s. No broadening of high-temperature interface zone was observed in the second period due to the fact that nickel-based superalloys have very low heat exchange coefficient.

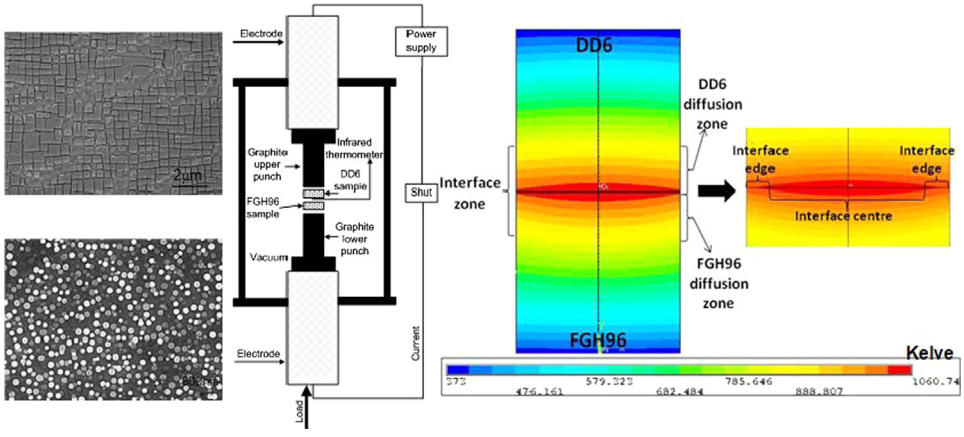

Fig. 1. Schematic illustration of PECB (a) SEM microstructures of DD6 and FGH96 alloys prior to PECB; (b) the schematic of PECB equipment; and (c) temperature distribution of bonding samples.