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Vacuum brazing of GH99 superalloy using graphene reinforced BNi-2 composite filler

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ABSTRACT

A novel graphene reinforced BNi-2 composite filler was developed for brazing GH99 superalloy. The interfacial microstructure of brazed joints was analyzed by field emission scanning electron microscope and a transmission electron microscope. The effects of graphene addition on the microstructure evolution and mechanical properties of brazed joints were investigated, and the strengthening mechanism of graphene was analyzed. The results revealed that due to the addition of graphene, $M_{23}(C,B)_6$ compounds were synthesized in the γ solid solution and brittle boride precipitates near the brazing seam decreased. Graphene was effective in retarding solute atoms diffusion thus impeding the precipitation of borides. Furthermore, the low coefficient of thermal expansion (CTE) of graphene was conducive to relieve stress concentration of the brazed joints during the cooling process. The shear strengths of brazed joints were significantly improved by exerting the strengthening effect of graphene. The maximum shear strengths of the brazed joints were 410.4 MPa and 329.7 MPa at room temperature and 800 °C, respectively.

1. Introduction

As a kind of high-temperature structure material, GH99 superalloy has been widely utilized for advanced aeronautic and industrial turbine blades and combustor components due to its excellent high-temperature strength, corrosion and oxidation resistance [1–3]. Corrosion crack, deformation pits and other defects appeared in the aeroengine blade since it was subject to wear, impact, hot gas and thermal fatigue in corrosive or oxidizing environment, causing the damage of a large number of blades. Repairing the blade with cracks could improve utilization rate of blades. However, GH99 superalloy with high alloying contained certain amount of γ' promoting elements (Ti and Al), which was highly susceptible to heat-affected zone cracking during welding and the post-weld heat treatment [4,5]. Therefore, the development of reliable bonding of GH99 superalloy is essential to the engineering applications.

Various kinds of joining methods have been carried out to achieve reliable bonding of nickel based superalloys, such as friction welding [6–8], laser welding [9,10] and diffusion bonding [11,12]. Brazing, as one of the cost-effective joining techniques, was often used to join nickel based superalloy [13]. Typical high temperature brazing with nickel based filler alloys, containing melting point depressant (MPD) elements such as boron and silicon, evolved as an effective way to join these superalloys [14,15]. However, the low melting point element of the braze alloy reacted with nickel based superalloys substrate to form the brittle intermetallic compounds, resulting in the low strength of the brazed joints in high temperature [16,17]. Currently, composite fillers, which are prepared by introducing tiny ceramic particles or fibers into traditional active brazing fillers, have been successfully applied retarding or avoiding the growth of the brittle compounds [18,19]. The use of silicon nanoparticles diminished the size of eutectic structure and promoted a uniform distribution in the bonding area [20]. The composite filler which was incorporated with 0.5 wt% TiO_2 nanoparticles could be effective in retarding the growth of the overall intermetallic compounds (IMC) layer in the brazed joints [21]. Shen et al. added ZrO_2 nanoparticles into a Sn-Ag filler by mechanically stirring. ZrO_2 nanoparticles suppressed the formation of IMC particles during solidification, and IMC particles distributed uniformly in the interface [22].

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Table 1
Chemical compositions of GH99 superalloy and BNi-2 (wt%).

	Cr	Co	W	Mo	Si	B	Fe	Al	Ti	Ni
GH99 superalloy	18.21	6.67	8.03	2.86	–	–	0.32	1.15	1.43	Bal.
BNi-2	7.06	–	–	–	4.54	2.85	3.04	–	–	Bal.

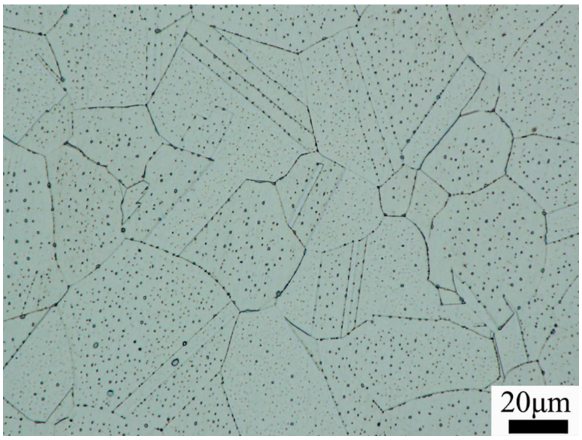

Fig. 1. Microstructure of GH99 superalloy.

Graphene, owing to its excellent properties such as high surface area, fracture strength and low density, has become a promising candidate in improving material properties [23,24]. Song et al. [25] reported the interfacial residual stress was effectively alleviated by exerting the extreme low coefficient of thermal expansion (CTE) of graphene. Wang et al. [26] and Qi et al. [27] reported that graphene showed chemical inertness for a variety of metal atoms as well as retarded the diffusion of metal atoms. Due to the inhibition for atoms diffusion, graphene suppressed the growth of brittle IMC layer, and reliable bonding interface was obtained [28]. Graphene strengthened Ag-based filler alloy [29], Cu-based filler alloy [30] and Ti-based filler alloy [25] have been studied in past years. Adding graphene into Ni-based alloy for brazing Ni-based alloy has not been investigated yet. In this work, graphene strengthened BNi-2 composite filler (BNi-2_G) was used to join GH99 superalloy. The interfacial microstructure of brazed joints was analyzed. The effects of graphene on the microstructure and mechanical properties of the joints was investigated. The formation mechanism of brazed joints was studied in detail.

2. Experimental

Materials used in this work were GH99 superalloy and commercially obtained BNi-2 filler. The chemical compositions of GH99 superalloy and BNi-2 filler were listed in Table 1. GH99 superalloy was cut into specimens with sizes of 10 mm × 10 mm × 2 mm and 5 mm × 2 mm × 2 mm, respectively. The microstructure of GH99 superalloy was shown in Fig. 1. BNi-2_G composite filler was prepared by adding 0.5 wt% graphene (with the thickness of 0.53–0.74 nm) into BNi-2 powder filler. The graphene was first ultrasonicated in acetone for 30 min before the BNi-2 powder was added into the well-dispersed graphene acetone solution. Then the mixture was ultrasonic stirred for 30 min with a speed of 500 r/min. The morphology of the composite filler was shown in Fig. 2. Furthermore, the surface to be bonded was sanded with 1000 grit SiC papers, and then ultrasonically cleaned in acetone for 15 min.

Brazing experiment was performed in a vacuum furnace under the vacuum of 1.5×10^{-3} Pa. The sample assembly was first heated to 900 °C at a rate of 20 °C/min and held for 10 min. Then the temperature was increased to specified temperature (1090 °C–1200 °C) at a rate of 10 °C/min and held for 30 min. Finally, the assembly was cooled down to 600 °C at a rate of 10 °C/min and then furnace-cooled down to the room temperature.

Interfacial microstructure and fracture surface of GH99 superalloy brazed joints were characterized by field emission scanning electron microscopy (FE-SEM) equipped with an energy dispersive spectrometer (EDS). Grain morphology of base material was studied by an electron backscatter diffraction (EBSD) coupled with SEM. The reaction products formed in the brazing seam were identified by a transmission electron microscope (TEM) and selected area electron diffraction (SAED). Shear tests were performed by universal material testing machine to obtain the shear strength of the brazed joints. The brazed specimens were loaded by the testing machine with a constant displacement rate of 0.5 mm/min. At least five specimens brazed at the same brazing parameters were tested and the average value of the shear strength was obtained.

3. Results and discussion

3.1. Microstructure of brazed joints

The typical microstructure of the GH99 superalloy joints using BNi-2 filler, brazed at 1170 °C for 30 min is shown in Fig. 3(a). The satisfactory wettability of BNi-2 filler promoted a good metallurgical bonding for the base metal. The interfacial microstructure of joints was obviously divided into two distinct zones: brazing seam (BS) and diffusion zone (DZ).

The chemical compositions of every zone marked by A, B and C were measured by EDS in Table 2. It can be found that the nickel con-

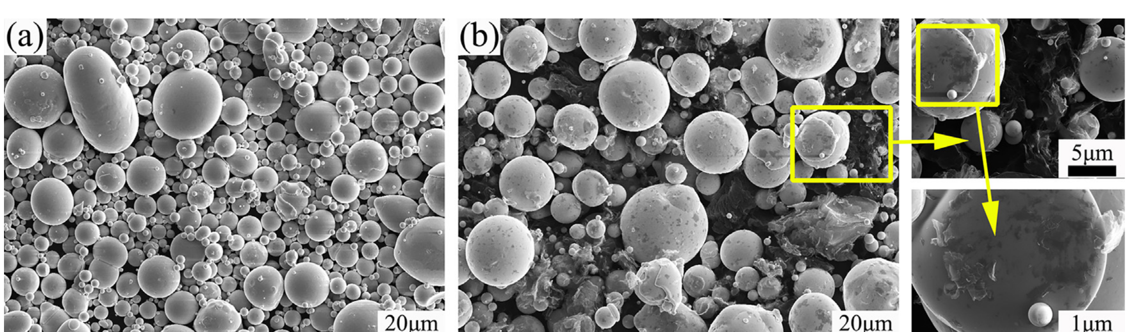

Fig. 2. Morphologies of BNi-2 filler (a) and BNi-2G filler (b).

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