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TEM study of microstructural characteristic and evaluation of mechanical performance for the hastelloy N/Ti/Hastelloy N superalloy joint brazed for diverse soaking time

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A B S T R A C T

The purpose of this work was to describe and discuss the fundamental issues involved in brazing of Hastelloy N to Hastelloy N superalloy using pure Ti foil at 1333 K for different soaking time (1 ~ 90 min). A detailed electron microscopy examination (transmission electron microscopy and high-resolution transmission electron microscopy) was performed to study the microstructure of the joint. The mechanical performance of the joint was evaluated by a shear test. Results show that the brazed joint obtained could be described as Hastelloy N/Zone 1/Zone 2/Zone 1/Hastelloy N. The Zone 1 whose constitution was hardly affected through modifying the soaking time was produced because of the eutectic melting of $Cr_9Mo_{21}Ni_{20}$ and Ni_3Ti intermetallics. The constitution of Zone 2, however, was very sensitive to the joining condition. Among the soaking time under investigation, the highest joint average shear strength obtained was 350.4 MPa. The strength of the joint, as revealed, was closely related with the microstructure in the Zone 2. When the Hastelloy N superalloy was brazed for different soaking time, the microstructural evolution in the joint was clarified and its relationship with mechanical performance was built. The work will contribute to understand the brazeability of the Hastelloy series alloys and then broaden their applications.

1. Introduction

Ni-based superalloys are widely used in industrial fields due to their superior performances in aggressive environments. There are many types of Ni-based superalloys, such as Inconel, Incoloy and Hastelloy. The Ni-Mo based Hastelloy alloys, manufactured by Haynes International, Inc, belong to a typical group of Ni-based superalloys [1]. The series alloys exhibit excellent high-temperature mechanical properties and outstanding corrosion and wear resistance in reducing or oxidizing environments, having wide applications in nuclear industries, aerospace, chemical processing, oil and gas industries [2]. Many Hastelloy series alloys, i.e., Hastelloy B [3], Hastelloy C22 [4], Hastelloy C276 [5], Hastelloy C2000 [6], Hastelloy N [7] and Hastelloy X (HX) [8], have been fabricated until now. In order to produce large or structure-complicated components, it is necessary to weld the Hastelloy alloys. Many welding techniques, i.e., gas tungsten arc welding [9], laser welding [10], electron beam welding [11] and explosive welding [12], have been reported. The techniques of vacuum brazing, induction brazing or transient liquid phase bonding of the Hastelloy may have a role to play in some cases, such as in the production of heat exchangers [13–15]. For the Ni-based superalloys, the commonly used brazing filler alloys are the Ni-Si, Ni-Cr-P, Ni-Cr-Si, Ni-Cr-Si-B alloys with the form of powder, paste and amorphous foil. Y. Luo et al. [16] reported that the microstructure, mechanical property and fracture behavior of Hastelloy C276 alloy joint brazed with BNi2 filler alloy. In general, silicon and boron in various concentrations are usually incorporated in the fillers as the melting-point depressants (MPDs) [17]. During joining, the MPDs can react with Ni, Fe or Cr to produce brittle compounds. Their presence may decrease the microstructural stability and decline the structural strength [18]. Considering this, it is necessary to develop a

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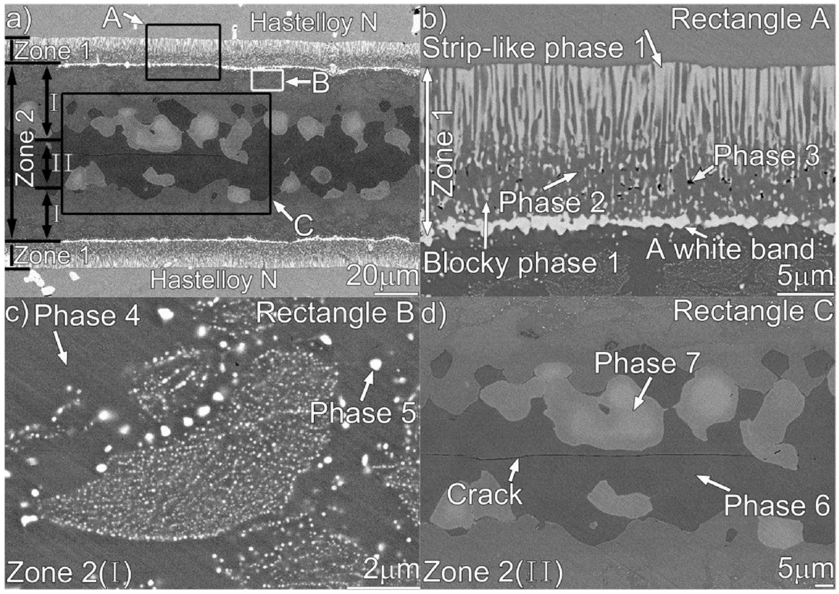

Fig. 1. SEM back-scattered electron (BSE) micrographs of the Hastelloy N alloy joint brazed with pure Ti foil at 1333 K for 1 min: a) overall morphology, b) magnified rectangle A in a), c) magnified rectangle B in a), and d) magnified rectangle C in a).

new filler to join the Ni-based alloys. The new filler should not contain the MPD elements, and can also be compatible with the Ni-based alloys. In addition, the Ni-based alloys brazed with such new filler should be used at moderate temperatures. In this work pure Ti foil was introduced to join the Hastelloy N alloy (a typical type of Hastelloy series alloy), and effect of soaking time on the microstructure and mechanical properties was investigated. Ti will react with Ni within the Hastelloy N through a contact reaction, producing Ti-Ni liquid during joining. The lowest temperature that the liquid occurs at is merely 1215 K in the Ni-Ti binary system [19]. Such a low temperature will ensure the joining process cost-effective and easy-controlled. Besides that, three stable compounds, i.e., NiTi, Ni_3Ti and Ti_2Ni, are found to appear in the Ti-Ni system. The NiTi are ductile while the Ni_3Ti and Ti_2Ni are brittle [20]. By adjusting the joining parameters, it can be expected that the braze zone will be predominated by the ductile NiTi. It should be mentioned that the Ni-Ti intermetallics can withstand a moderate temperature, which means the Hastelloy N alloy brazed with Ti can be used at elevated temperatures. Primarily three aspects were emphasized in the work: a) to precisely identify phases in the joints through the state-of-the art TEM and HRTEM analysis, b) to clarify the microstructural evolution in the joints brazed for different soaking time, and c) to correlate the microstructure with mechanical properties. Based on this, brazeability of Hastelloy N superalloys was clarified. The data obtained will not only be applicable to the Hastelloy N alloy, but also to other Ni-based alloys.

2. Materials and methods

In this work, the Hastelloy N alloy used, basically consisting of Ni-17Mo-7Cr-4Fe-0.6Mn-0.5Si-0.05C (wt.%), was a commercial material. Ti foil with a thickness of 127 μm was used as the filler. The Hastelloy N was cut into two dimensions of 4 mm × 4 mm × 4 mm and 10 mm × 8 mm × 4 mm (bonding surface: 4 mm × 4 mm). The procedure for sample preparation was described in detail elsewhere [21]. Ti foil (4 mm × 4 mm) was placed between two pieces of Hastelloy N, and a normal load of 0.01 MPa was applied on the top of the assembly to make them contact closely. Brazing temperature and soaking time, as is well known, are two significant parameters, which can critically influence the microstructure in the joint during brazing, and then determine the joint bond strength. It is shown from Ti-Ni phase diagram [19] that Ti-rich liquid appears in the joint when the heating temperature reaches 1215 K. In that case the microstructure in the joint can be described as: Hastelloy N/Ni_3Ti/NiTi/Ti_2Ni/Ti-rich liquid/residual β-Ti/Ti-rich liquid/Ti_2Ni/NiTi/ Ni_3Ti/Hastelloy N. As above mentioned, the Ni_3Ti and Ti_2Ni are brittle while the NiTi are ductile [20]. From this we should remove the Ni_3Ti and Ti_2Ni layers from the brazed joint as much as possible. Removing Ni_3Ti should need a lowest eutectic temperature of 1391 K [20]. For the Ti_2Ni, it is seen from Ti-Ni phase diagram that they will be completely dissolved when the temperature is over 1257 K. That is, the lowest liquidus temperature to eliminate Ti_2Ni should be over 1257 K. In general, brazing temperature used should be 50–100 K over the liquidus temperature. Therefore, brazing temperature used should be set in the temperature range of 1307–1357 K. Based on this, we set the brazing temperature to 1333 K. The braze seam, as mentioned, should be predominated by the ductile NiTi through adjusting the brazing parameters. Note that the NiTi intermetallics, as has been demonstrated in Ti-Ni phase diagram, can be precipitated from Ti-rich liquid at 1333 K. Considering this, different soaking time at 1333 K were investigated to clarify the formation process of NiTi. That is, effect of soaking time on the microstructure and mechanical properties of the joints was studied. Therefore, the assembly was heated to 1333 K under vacuum (~10^{-3} Pa) during brazing, and isothermally held for 1 min, 30 min, 60 min and 90 min, respectively. After that, the joints obtained were prepared and examined using scanning electron microscopy (SEM, FEI Quanta 200 F) together with an energy dispersive spectroscopy (EDS). TEM samples were also prepared by a focused ion beam technique (FEI, Helios NanoLab 600i). TEM and HRTEM analyses were conducted to characterize the microstructure in the joints. Finally, bonding strength of the lap joints was measured by a shear test (MTS, CMT4204).

3. Results

3.1. Microstructural characterization

Fig. 1 shows the SEM BSE micrographs of the Hastelloy N-Hastelloy N alloy joint brazed with pure Ti foil at 1333 K for 1 min. Two reaction zones (Zone 1 and 2), as shown, appear in the joint, with the Zone 1 being contact with the Hastelloy N. A white band can be clearly inspected between the Zone 1 and 2, see Fig. 1a and b. For the Zone 1, it can be seen from Fig. 1b that three phases, labeled 1, 2 and 3, are included. For the Zone 2, its structure can be expressed as layer I-layer