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An investigation on diffusion bonding of TZM alloy and Nb-Zr alloy using Ni foil as an interlayer

J.M. Lin [a], Z.W. Yang [a, *], H.H. Wei [b], Y. Wang [a], Z.Q. Ma [a], D.P. Wang [a]

[a] Tianjin Key Lab of Advanced Joining Technology, School of Materials Science and Engineering, Tianjin University, Tianjin 300350, China
[b] Tianjin Aviation Electro-Mechanical Co., Ltd., Tianjin 300308, China

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ABSTRACT

Diffusion bonding of TZM alloy and Nb-Zr alloy without and with Ni interlayer was carried out at the temperature ranging from 1000 °C to 1100 °C for 30min under a pressure of 10 MPa. The effects of bonding temperature and the thickness of Ni interlayer on the microstructure and mechanical properties of the diffusion bonded joints were investigated systematically. Compared with the direct diffusion bonding method, sound TZM/Nb-Zr joints were obtained with Ni interlayer at a low bonding temperature of 1000 °C. When the bonding temperature was 1100 °C, sound joints could be achieved for both methods. But the joint shear strength with 30 μm Ni interlayer reached 228 MPa, which was 60% higher than that bonded without Ni interlayer. The diffusion-induced reaction layers were determined to be NiMo, $Ni_3Mo + Ni_4Mo$, Ni_8Nb, Ni_3Nb and Ni_6Nb_7, whose thickness and micro-hardness were measured at different bonding conditions to establish a correlation between the interfacial microstructure and joint properties. It was found that the thickness of Ni_3Nb layer and the remained Ni foil were beneficial to the joint shear strength. By changing Ni foil from 0 to 45 μm, the shear strength was improved obviously, and then kept at around 250 MPa with further increasing Ni foil to 120 μm. The maximum shear strength was 264 MPa when the joint was bonded at 1100 °C for 30min with 45 μm Ni foil. Cracks were initiated from NiMo and Ni_6Nb_7 diffusion layers, and then propagated across the central diffusion layers.

1. Introduction

Titanium-zirconium-molybdenum (TZM) alloy is one of the most widely used refractory molybdenum alloys due to its characteristics of high melting-point, high elastic modulus, strong corrosion resistance, low coefficient of thermal expansion, high thermal conductivity and excellent high temperature mechanical properties [1–4]. It has been widely used in aerospace, power generation, nuclear reactor, military, and other fields. However, its application is limited by its poor toughness [5,6]. On the contrast, Nb-Zr alloy exhibits excellent performance in terms of toughness [7]. Niobium is a leading candidate material for aerospace power systems based primarily on its good high temperature strength, compatibility with liquid alkali metals and lower density compared with other refractory metals and alloys [8]. However, at temperatures above 1000 °C, the strength of Nb decreases substantially, which would limit its application in aerospace. To improve its high temperature strength, many kinds of techniques were utilized, including solid solution strengthening, precipitation strengthening and composite strengthening [9–11]. Among them, solid solution strengthening is an effective and easy method to realize. Furthermore, the previous work demonstrated that the addition of Zr to the Nb benefited to prevent oxygen from gathering towards grain boundaries and increase high temperature strength. Besides, the maximum solid solubility of the Zr element in the Nb element is 100 at. % when the temperature is higher than 500 °C [12–14]. Thus, Nb-Zr alloy is regarded as one of the most suitable materials for aerospace application. The development of TZM and Nb-Zr bonding technique would be meaningful to widen the scope of application of the two alloys.

According to the known literatures, conventional welding processes had been successfully used to join TZM alloy with other materials, including electron beam welding, friction welding, and brazing [15–18]. Compared with these bonding techniques, diffusion bonding in vacuum, as a solid state welding, is demonstrated to be a feasible technique to overcome the oxidation of TZM alloy [19].

* Corresponding author.
E-mail addresses: tjuyangzhenwen@163.com, yangzw@tju.edu.cn (Z.W. Yang).

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However, there are two problems for the direct diffusion bonding of TZM and Nb-Zr alloys. According to the Mo-Nb binary phase diagram, Mo and Nb can't be completely miscible until the temperature is higher than 2400 °C [20]. Besides, there would be residual stress in the joints produced by coefficient of thermal expansion (CTE) mismatch between TZM and Nb-Zr alloy [21,22]. Consequently, effective joints are difficult to obtain by direct diffusion bonding at a relatively low temperature. The addition of an appropriate interlayer has been successfully demonstrated to reduce the diffusion bonding temperature as well as to relieve the detrimental residual stress. Among various kinds of interlayers, Ni is widely selected because of its chemical compatibility with other alloys and good plasticity which can relief the residual stress [23,24]. Zhang W. J. [25] used Ni as an interlayer to diffusion bond TZM alloy to itself, and the results showed that an obvious diffusion layer formed at the interface between TZM and Ni. The maximum joint shear strength was 294 MPa, which was higher than that of the joints bonded with both Ti interlayer (225 MPa) and Nb interlayer (25 MPa). Yang W. Q. et al. made full use of the plasticity of Ni and successfully diffusion bonded ZrB_2-SiC ceramic and Nb. The result showed that the joint shear strength was improved obviously from 108 MPa to 156 MPa because of the addition of Ni interlayer [26]. However, for the diffusion bonding between TZM and Nb-Zr alloy, the properties of each diffusion layer formed between Ni and Nb was not clear enough, especially for the joining of Nb-Zr alloy with high Zr content.

In this work, diffusion bonding of TZM alloy and Nb-Zr alloy without and with Ni interlayer was carried out. The mechanical properties of each diffusion-induced reaction layer formed between Ni and the parent alloys were discussed in detail. Besides, the effects of bonding temperature and the thickness of Ni interlayer on the interfacial microstructure and mechanical properties were investigated. The correlation among the microstructure, micro-hardness, shear strength and fracture path of the diffusion bonded joints was established.

2. Materials and experimental procedures

The microstructure and XRD patterns of parent alloys used in the experiments were shown in Fig. 1. The nominal composition of TZM alloy was 1.63 at. % Ti, 1.02 at. % Zr, and 97.35 at. % Mo. The microstructure of TZM alloy was etched in the corrosive liquid mixed of commercial concentrated HNO_3, concentrated H_2SO_4 and H_2O with the ratio of 5:3:2 for 5s. As seen in Fig. 1(a), three characteristic areas could be observed. The magnification of the characteristic areas (marked as A-C) was shown in Fig. 1(b). The EDS results inserted in Fig. 1(b) indicated that both light grey phase A and grey phase B consisted of 97.37 at. % Mo, but the content of Zr in phase A was a little higher than that of phase B. Under secondary electron (SE) mode of SEM, different contrasts represented different feature details on the sample surface such as bosses, pits and so on. As can be seen in Fig. 1(b), there was a small boss at the junction of phase A and B (In other words, phase A was slightly higher than phase B), indicating the addition of Zr into Mo alloy benefited to its corrosion resistance. The phenomenon was also reported by other research [27]. The chemical composition of Nb-Zr alloy was 16.69 at. % Zr and balance Nb. As seen in Fig. 1(c), after etched in Kroll reagent for 2 min, Nb-Zr alloy presented the microstructure with the average grain size of 213 μm. From the composition measurement of the magnified microstructure inserted in Fig. 1(c), it could be concluded that Zr was primarily accumulated at the grain boundaries. The XRD results in Fig. 1(d) showed that the parent alloys of TZM and Nb-Zr were mainly comprised of Mo and Nb solid solutions. The TZM sample size used in the experiment was 10 mm × 15 mm × 3 mm and Nb-Zr alloy was cut in cube with the size of 5 mm. All the sample surfaces to be bonded were polished with SiC papers from 100 to 2000#, and then cleaned in acetone using an ultrasonic bath before diffusion bonding process. Pure Ni foils with the thickness of 30, 45, 60 and 120 μm were used to diffusion bond TZM and Nb-Zr. The Ni foils were sandwiched between cubic Nb-Zr alloy and TZM slice with the assembly structure of TZM/Ni/Nb-Zr.

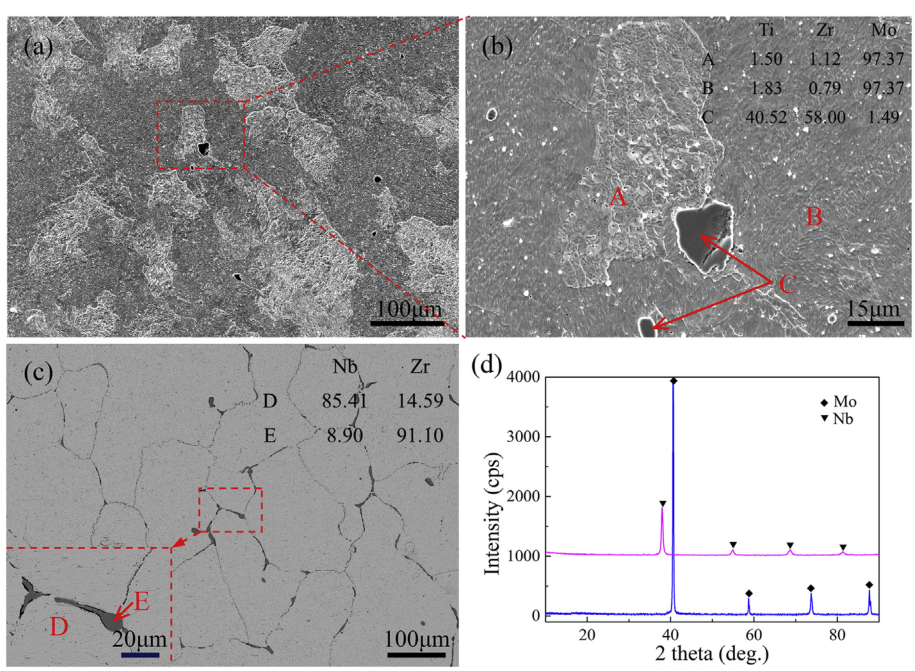

Fig. 1. Microstructure and XRD analysis of the parent alloys: (a–b) microstructure of TZM; (c) microstructure of Nb-Zr alloy, and (d) XRD patterns of TZM and Nb-Zr alloy.