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Characterization of the interfacial-microstructure evolution and void shrinkage of Ti-22Al-25Nb orthorhombic alloy with different surface roughness during diffusion bonding

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ABSTRACT

Ti-22Al-25Nb alloy specimens with different surface roughness were joined, through diffusion bonding at 975 °C at 12.5 MPa. The interfacial-microstructure evolution during this process was characterized via scanning electron microscopy combined with electron probe microanalysis and electron backscatter diffraction analysis. Further, the interfacial void-shrinkage mechanism and the quality of the bonded joints were determined through atomic force microscopy, which revealed the three-dimensional morphologies of the surfaces, and shear strength testing of the joints. The results revealed that fine equiaxed α_2 grains are precipitated in the bonding interface of specimens with ground surfaces. These interfacial α_2 grains were formed via phase transformation and recrystallization processes, which were triggered by asperity deformation at the contact plane and unavoidable oxygen contamination. Two types of fracture occurred during the shear strength tests, where the bonds generated from (i) polished surfaces failed predominantly along the bond line, and (ii) ground surfaces failed predominantly in the base material away from the bond line. This indicated that the mechanism controlling the void-shrinkage process associated with the contact between two rough surfaces during diffusion bonding varied with the surface roughness: the void-shrinkage process of specimens with (i) polished surfaces is controlled by diffusion, and (ii) ground surfaces was controlled by both diffusion and plastic deformation.

1. Introduction

Ti_3Al intermetallic alloys have excellent potential for use as advanced aerospace and elevated-temperature structural materials, due to their high specific strength, high oxidation resistance, good creep resistance, and high-temperature strength, compared with those of Ti alloys [1,2]. However, these alloys have relatively low fracture toughness and are brittle at room temperature. The addition of Nb is considered an effective method for improving the room-temperature ductility and fracture toughness [3]. Since Banerjee [4] discovered the ordered orthorhombic Ti_2AlNb (O) phase, titanium aluminides with compositions based on the stoichiometry of Ti_2AlNb have received considerable attention [4,5]. Ti_2AlNb-based alloys exhibit improved room-temperature ductility, tensile strength, and fracture toughness compared with those of conventional intermetallic alloys, such as TiAl-based and Ti_3Al-based alloys [6]. The development of joining processes for high-quality joined structures plays a crucial role in the use of Ti_2AlNb alloy in high-temperature applications of the aerospace industry [7]. To date, a few studies have been published on fusion welding techniques (laser or electron beam welding) of this alloy [8,9]. However, the microstructure and corresponding properties of welded structures are difficult to control during fusion welding and defects, such as voids and hot cracking, always occur in the joint.

Diffusion bonding, a solid-state welding process, is highly effective in realizing low-defect joining of Ti_2AlNb alloys with each other or with other materials, since the microstructure in the heat affected zone remains unchanged after bonding [10,11]. Further, this bonding may be combined with superplastic forming [12,13]. Diffusion bonding of Ti_2AlNb alloys has been extensively investigated [14,15], and most of these studies have focused on the technical aspects and mechanical properties of the joints. However, the microstructural evolution at the diffusion-bonding interface, which is critical to the performance of the joints and the subsequent superplastic forming process, has rarely been considered.

Therefore, in the present work, the process zone developed during the diffusion bonding of Ti_2AlNb-alloy specimens with different surface

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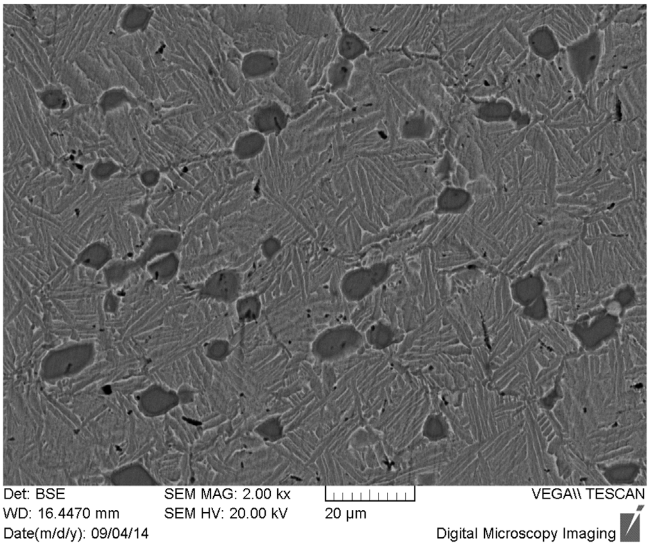

Fig. 1. Initial microstructure.

roughness was investigated, and the shear strength characteristics and fracture behavior were revealed.

2. Experimental procedure

A Ti2AlNb orthorhombic alloy, Ti-22 at.% Al-25 at.%Nb, was selected as the bonding material in the present work. This material was hot-roll annealed. The starting microstructure consisted of equiaxed α_2 grains, lath O grains, and an intergranular B2 phase (ordered β phase), as shown in Fig. 1. For the diffusion bonding trials, four different surface qualities were prepared: (i) polished with 1 μm diamond abrading agent; (ii) ground successively with 80, 240, 400, 600, 800, 1000, and 1500 grade SiC paper; (iii) ground successively with 80, 240, 400, 600, and 800 grade SiC paper; (iv) finish ground with a grinding machine. Bonding temperatures of 900 °C, 950 °C, 975 °C, and 1000 °C were applied at a fixed pressure level and bonding time of 12.5 MPa and 90 min, respectively. All bonds were produced under a vacuum lower than 1×10^{-2} Pa. Fig. 2a shows a schematic of the cross-section of the overlap joints (total length: 40 mm), which were prepared for microstructural observation via standard metallographic techniques. Microstructural development during bonding and the quality of the bonds

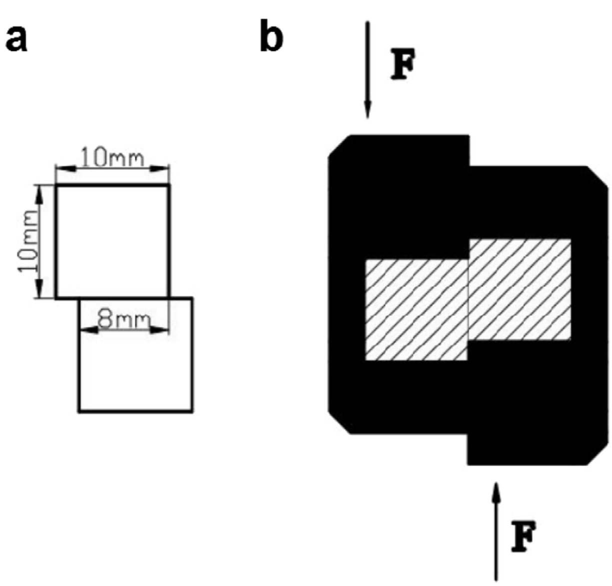

Fig. 2. Schematic of the (a) cross-section of the overlap joints and (b) shear strength tests.

produced using different bonding parameters were evaluated via scanning electron microscopy (SEM) examination of the interfaces. In addition, the orientation of the precipitated phase at the bonding interface (fine equiaxed α_2 phase) and its relationship with the initial phase were determined via electron backscatter diffraction (EBSD; Channel 5™, HKL®) in SEM. A small step size (0.2 μm) was used to ensure resolution of very fine orientation details. To determine the shear strengths of the bonds, non-standard (length: 20 mm, width (bond area): 8 mm, thickness: 2.5 mm) shear specimens cut from the overlap joints were tested at room temperature and a loading rate of 0.2 mm/min, as shown in Fig. 2b. After this test, the fracture surfaces of the joints were examined via SEM.

3. Results and discussion

3.1. Surface characterization

The surface of each specimen was characterized prior to diffusion bonding. Fig. 3 shows the three dimensional (3D) surface morphologies obtained via atomic force microscopy (AFM) of the specimens (see Table 1 for the roughness values of the surfaces). Ra, Rq, and Rmax are used to characterize the surfaces and are defined as the (i) arithmetic mean deviation of the absolute value of the distances from each point of the profile to the mean line, (ii) root mean square deviation of the distances from each point of the profile to the mean line, and (iii) maximum distance from the peak to the valley of the profile, respectively. As shown in Fig. 3 and Table 1, the polished surface of each specimen is quite flat, and consists of only a few residual shallow scratches. In contrast, the ground surfaces of the specimens are quite rough, and consist of long triangular ridges. The surfaces finally ground by 1500# SiC paper, 800# SiC paper, and a grinding machine, respectively, exhibit gradually increasing roughness values. However, grinding with different-number SiC papers yields an undulating ridges consisting of peaks and valleys. The specimen surfaces were further characterized by extracting contour lines of surfaces with different roughness values (see Fig. 4). As the figure shows, the contour lines exhibit the same trend as the 3D surface topographies, i.e., ground surfaces are considerably rougher than polished ones. Furthermore, the undulating contour lines of the ground surfaces have complex shapes, where the larger peaks and valleys comprising these lines are composed of a few smaller peaks and valleys. Further characterization of these specimens included determining the key relationship between the (i) morphology characteristics of the specimen surfaces and the interfacial microstructures of the diffusion-bonded zones, and (ii) fracture behavior of the diffusion-bonded joints during shear strength tests and the control mechanisms of the void-shrinkage process during diffusion bonding.

3.2. Interfacial microstructure of the diffusion-bonded zones

Although the bond line was clearly visible (see Fig. 5a–b) unbonded regions were absent from the polished surfaces used to produce bonds at 12.5 MPa/90 min and bonding temperatures of 900 °C and 950 °C. This indicates that the bonding temperature was too low and, hence, insufficient diffusion and asperity plastic deformation occurred across the bond interface on the mating surfaces. Defect-free bonds with an almost invisible bond line were produced at 12.5 MPa/90 min and bonding temperatures of 975 °C and 1000 °C. As Fig. 5c and d shows, a few β and O phase grains grew across the bond interface. The diffusion coefficient increased with increasing bond temperature, whereas the flow stress decreased, thereby promoting movement of the atoms across the mating surfaces, and the formation of high-quality diffusion bonds. Further investigations were performed at 975 °C as this temperature is adequate for the required bonding qualities, and lies within the range where most Ti_2AlNb-based alloys exhibit excellent superplasticity [13,16].