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The Fracture Behavior of Diffusion-Bonded Duplex Gamma TiAl

G. Çam, K.-H. Bohm, J. Müllauer, and M. Koçak

Solid-state diffusion bonding in conjunction with superplastic forming is a potential candidate for producing complex structural components from gamma-based titanium aluminides for aerospace applications. Solid-state diffusion bonding of TiAl was carried out with different bonding parameters within the superplastic temperature range. Defect-free sound bonds were achieved within the temperature range of 925–1,100°C and the pressure range of 20–40 MPa. Microtensile tests were carried out to evaluate room-temperature tensile properties of the bonds for comparison of the bonding parameters.
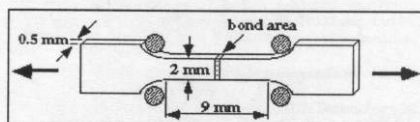
Figure 1. The geometry of microtensile specimens tested by loading at the shoulders of the specimens.
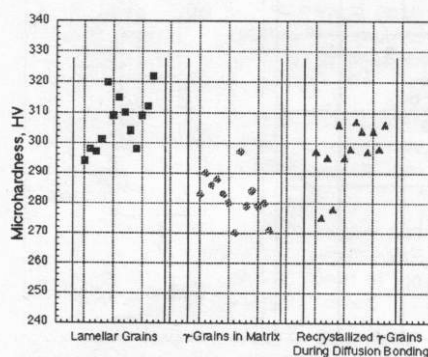

Figure 2. Microhardness values of the lamellar grains and γ grains present in the base metal and the γ grains formed during bonding.

INTRODUCTION

The need for the development of high-temperature materials with superior strength-to-weight ratios has stimulated a great deal of interest in the ordered intermetallic compound TiAl. Remarkable developments in the high-temperature creep properties and processing technology of gamma-based titanium aluminides during recent years have made them potential engineering alloys for high-temperature structural applications in the aerospace industry.[1] This compound exhibits a desirable combination of high modulus retention, creep, and oxidation resistance at elevated temperatures as well as low density.[2-4] However, the limited ductility of this compound at room temperature is the main drawback, which may limit its wider use in structural applications. Thus, appropriate joining techniques are indispensable for the practical utilization of this material in elevated-temperature structural applications.

Although there have been remarkable developments in the understanding of alloy development, processing, microstructural control, and microstructure-mechanical property relationships,[5-8] there are a few reports[9] aimed at the establishment of fabrication/processing techniques for these materials, particularly on joining techniques.[10-16] Electron-beam welding was studied by Patterson et al.,[10] who reported that welding cracks cannot be easily avoided. Nakao et al.[11] investigated the diffusion bonding of Ti-52Al, which almost consists of single-phase γ TiAl. Although they succeeded in obtaining solid bonds, the process involved heat treatment at 1,300°C with some bonding pressure, which may not be useful for the practical applications. Yan and Wallach[12,13] studied the solid-state diffusion bonding and transient-liquid-phase (TLP) bonding of Ti-48Al. They reported that it was possible to obtain solid bonds by autogenous diffusion bonding. However, post-bond heat treatments (PBHT) at high temperatures are required in the case of TLP bonding in order to improve the strength of the bonds. Very recently, Uenishi et al.[14,15] also investigated the bonding of TiAl by using aluminum-filler metal and self-propagating high-temperature synthesis (SHS); again, PBHT is required in both methods to improve joint strength. Recently, superplasticity in TiAl was reported by Mitao et al.[16] and Kaibyshev.[17] They reported maximum strains of greater than 100% at 1,100°C and ~250% at 925°C, respectively. Maeda et al.[18] and Ameyama et al.[19] also observed superplastic behavior in TiAl. These reports were reviewed in detail in Reference 20.

The best fracture toughness and creep properties are usually exhibited by the fully lamellar structure of this alloy system. However, they generally show poor ductility and lower room-temperature strength, although it is possible to improve these properties by reducing lamellae grain size. A fully duplex structure, on the other hand, displays the best ductility (i.e., up to 3.5%) with reduced fracture toughness and creep
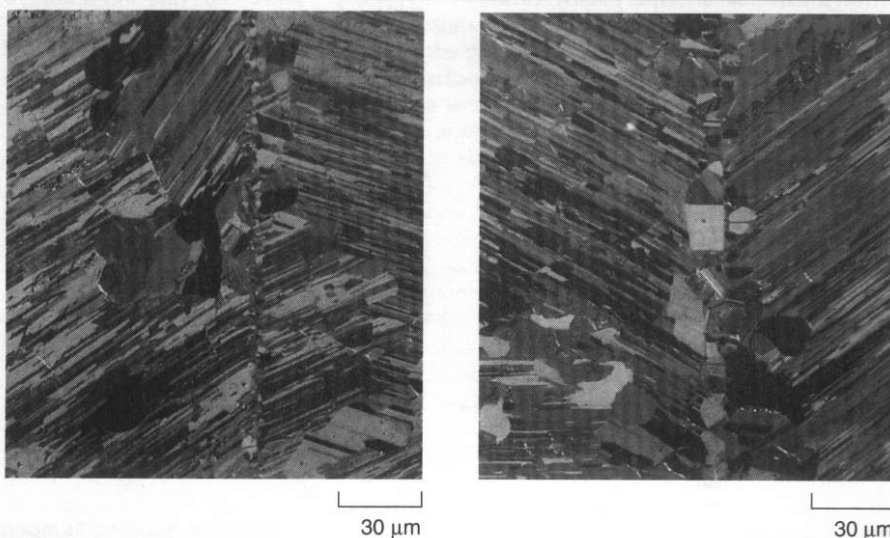

30 μm   30 μm

Figure 3. Polarized light micrographs of the specimens bonded at (a) 925°C and (b) 1,100°C.

a   20 μm   b   20 μm
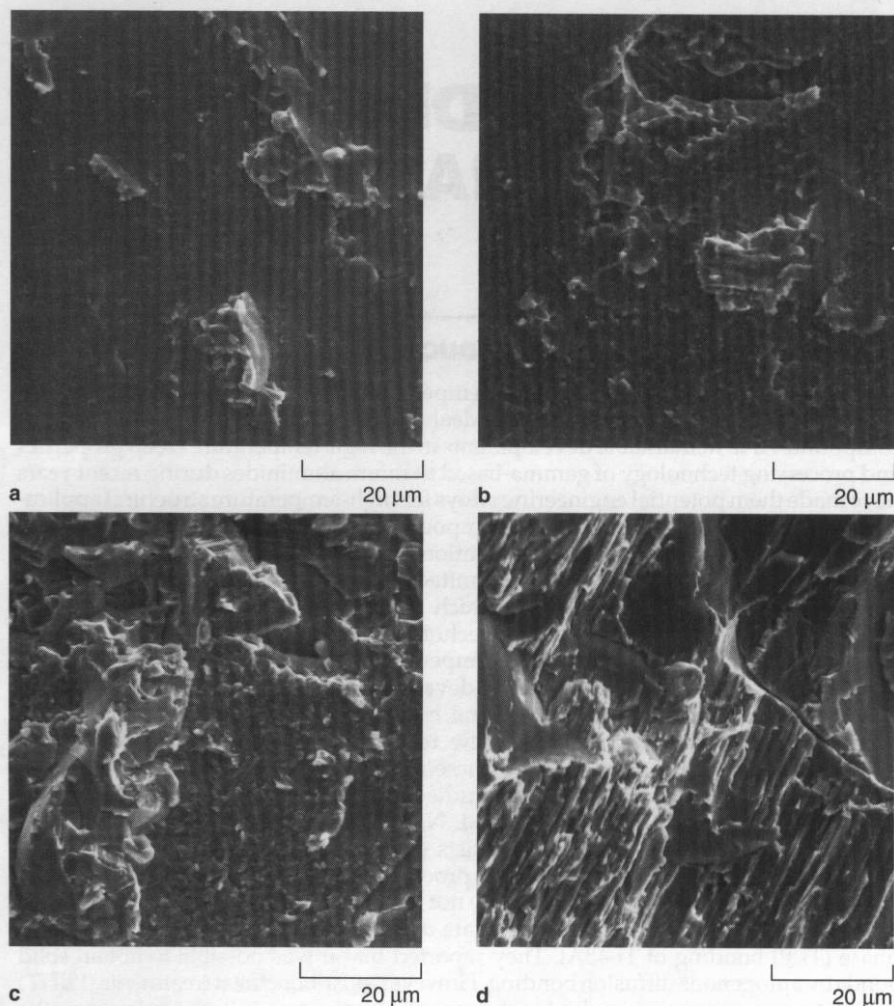
c   20 μm   d   20 μm

Figure 4. Fracture surfaces of the bonds made at (a) 925°C, (b) 1,000°C and (c) 1,100°C with failure at the bond line, and (d) 1,100°C with failure in the base metal, a typical fracture of lamellar and globular γ grains.

50 μm

Figure 5. Schematic of a specimen (bonded at 1,100°C) fractured away from the bond line and respective light micrographs showing the intact bond line and the fracture location in the base metal.

resistance. This leads to an inverse relation between tensile ductility and fracture toughness in relation to the microstructure.

Based on experience at the GKSS Research Center in Germany on the development of γ-TiAl alloys and creep/fracture mechanisms, studies on diffusion bonding and laser welding this alloy have started. This article reports the preliminary results of this project on diffusion bonding. The γ-TiAl alloy used is in the as-cast condition, having a nearly lamellar duplex structure consisting of γ/α₂ lamellae and equiaxed γ grains, which is considered to offer the best combination of mechanical properties. The aim of this study is to establish an appropriate solid-state diffusion bonding procedure within the industrial superplastic forming temperature range of titanium alloys to apply to γ-TAB alloy.

EXPERIMENTAL PROCEDURES

A series of diffusion bonds with different bonding parameters were made using γ-TAB (47Al + Cr-Mn-Nb-Si-B) specimens of approximately 11 mm × 15 mm × 21 mm. The material used was vacuum arc-melted, investment cast, and hot isostatically pressed at 1,185°C and 140 MPa for four hours. The starting microstructure of the material was composed of a nearly lamellar duplex structure consisting of γ/α₂ lamellae and equiaxed γ grains. Bonding temperatures within the industrial superplastic forming temperature range of gamma alloys (i.e., 925–1,100°C) and bonding pressures ranging from 20–40 MPa were used. The surfaces were machined and ground with
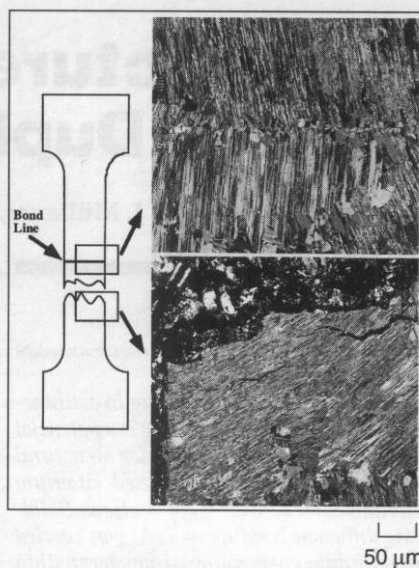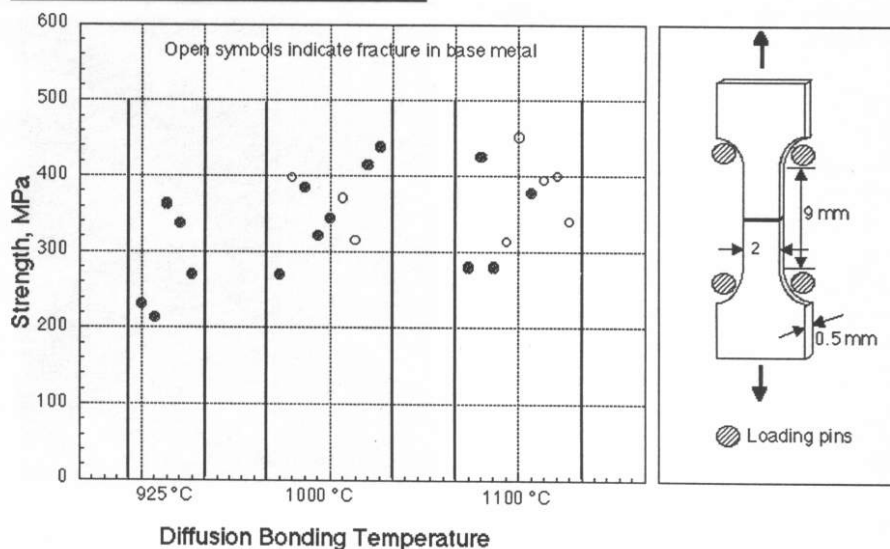

Figure 6. Tensile strengths of the bonds presenting the effect of bonding temperature.
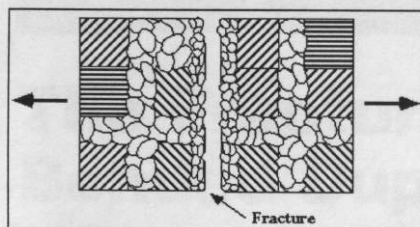
Figure 7. Schematic presentation of the fracture mechanism of the microtensile specimens fracturing at the bond area. Flat regions represent fracture along the bond line; rough regions indicate fracture of the recrystallized γ grains.

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1,200 grid emery paper, followed by rinsing with alcohol prior to bonding. The vacuum was better than 4.5×10^{-5} torr for all bonds.

Optical metallography and scanning electron microscopy were employed to investigate the microstructural development during diffusion bonding and to assess the quality of the bonds made at various bonding conditions. Microtensile specimens 21 mm long, 2 mm wide, and 0.5 mm thick with a 9 mm gauge length were machined using spark-erosion cutting. The tensile tests (conducted by loading the specimens on shoulders as shown in Figure 1) were carried out at room temperature.

RESULTS AND DISCUSSION

The formation of equiaxed γ grains at the bond line during bonding (due to dynamic recrystallization induced by asperity deformation on mating surfaces under the applied bonding pressure) was observed at all of the bonding conditions studied. The actual bond lines almost disappeared following nucleation and growth of fine recrystallized grains in the bonds made at higher temperatures (i.e., 1,100°C). This dynamic recrystallization is expected to improve bond strength by removing planar boundaries at the original interface. The microstructural development sequence at the diffusion bond line is reported in detail elsewhere.[21] The hardness value of the recrystallized γ grains formed at the bond line lies between the hardness of lamellar grains and γ grains present in the original γ-TAB matrix (Figure 2).

Cross-sectional microstructures of bonds produced using different bonding conditions are shown in Figure 3. As seen, the size of the recrystallized γ grains increase with increasing bonding temperature. Thus, the strength of the bonds made at higher temperatures are expected to be higher. The bonds made at even higher temperature (i.e., 1,200°C) or PBHT should produce an almost indiscernible bond line.

The bonds made at 925°C displayed poor tensile elongation and strength, as expected. As seen from Figure 3a, the original bond line is clearly visible after diffusion bonding. The presence of this planar boundary presents a preferable crack path in a transverse-tensile test. It can be seen in Figure 4a that flat and some rough regions are present at the fracture surface of the tensile specimen bonded at 925°C. The rough regions correspond to the fracture in the recrystallized γ grains formed at the bond line during bonding; whereas, the flat regions, which predominate the fracture surface, correspond to the fracture along the bond line. Brittle fracture was observed to take place along the bond line with some fracture of recrystallized γ grains.[21]

The bonds made at 1,000°C displayed better tensile ductility and strength values than those made at 925°C; however, most of the specimens failed again along the bond line. Fracture surfaces of the bonds made at 1,000°C contain more rough regions (Figure 4b) than the 925°C specimen. This confirms the better tensile strength of the bonds made at 1,000°C.

The best tensile properties were displayed by the bonds made at 1,100°C, in which half of the specimens failed away from the bond line. This was expected as the bond line after bonding at 1,100°C was almost indistinguishable (Figure 3b). The 1,100°C specimens that failed at the bond line displayed relatively higher tensile properties than those bonded at 925°C and 1,000°C. Figure 4c shows the fracture surface of a specimen bonded at 1,100°C and failed at the bond line, illustrating a much rougher fracture surface (direct evidence of the fracture of the newly formed γ grains) than the bonds made at lower temperatures. Flat regions of the fracture surface also have a much rougher morphology. Figure 4d shows the fracture surface of a specimen bonded at 1,100°C that failed in the base metal—a typical fracture of lamellar and globular γ grains. Figure 5 is a bond fractured away from the bond line, showing that the bond line stayed intact and fracture took place away from the bond line.

The bond strengths and tensile elongations measured for the samples are shown in Figure 6. Relatively lower tensile strengths of the bonds are due to the nonpolished surfaces of the microtensile specimens (surface microcracks can be present after spark-erosion cutting of the microtensile specimens). There is a distinct tendency for increasing cross-tensile strength with increasing bonding temperature. This may be due to the increase in grain size of the recrystallized γ grains forming at the bond line during bonding since the planar boundary across the bond line disappears as the newly formed γ grains grow larger with increasing temperature. This is demonstrated by a decreasing proportion of flat regions at the fracture surfaces by increasing bonding temperature, in turn, increasing recrystallized γ grain size.

Figure 7 shows a schematic representation of the failure mechanism of the specimens fracturing at the bond line. When the grain size of the recrystallized γ grains increase, more energy may be needed to break these grains along the grain boundaries, which leads to a higher tensile strength and a relatively nonplanar crack propagation (rough fracture surface) as shown in Figure 4c.

Work is in progress to determine the fracture toughness properties of the bond region and the effect of microstructural/mechanical heterogeneity (mismatch) of the bond area on the micromechanism of the fracture/deformation process. Furthermore, the effects of PBHT and the use of thin interlayer material on deformation and the fracture process at the diffusion-bonded interface as well as bonding at higher temperatures (i.e., 1,200 °C) will also be studied.