Effects of Surface Plastic Deformation on Diffusion Bonding of High-Nb TiAl Alloys: Postprint

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Abstract

High-energy shot peening was employed to introduce plastic deformation on the surface of high Nb-TiAl alloys, and its influence on the diffusion bonding of high Nb-TiAl alloys was investigated. The results indicate that: after shot peening, a deformation-affected zone with a thickness of approximately 150 m was generated on the surfaces to be bonded. The surface deformation zone did not undergo significant recrystallization during the diffusion bonding process; however, intense recrystallization occurred at the bonding interface after subsequent heat treatment, with the γ phase occupying the originally flat interface. Room-temperature shear strength testing results demonstrate that surface plastic deformation can effectively reduce the diffusion bonding temperature of high Nb-TiAl alloys, with the shear strength of the bonded joints reaching a maximum of 420 MPa.

Full Text

Influence of Surface Plastic Deformation on Diffusion Bonding of High Nb Containing TiAl Alloy

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Abstract

Surface plastic deformation was applied to a high Nb containing TiAl alloy by means of high energy shot peening (HESP) to investigate its influence on diffusion bonding. The results show that a deformed region with a depth of approximately 150 m was produced on the treated surface. No significant recrystallization occurred in the deformed region during the bonding process itself; however, intense recrystallization took place at the bonding interface after post-bonding heat treatment, with the γ phase occupying the originally flat interface. Room-temperature shear testing revealed that surface plastic deformation effectively reduced the diffusion bonding temperature of high Nb-TiAl alloys, achieving a maximum shear strength of 420 MPa for the bonded joints.

Keywords: metallic materials, high Nb containing TiAl alloy, diffusion bonding, surface plastic deformation, shear strength

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Introduction

TiAl alloys are promising candidates for weight reduction in the temperature range between the upper service limit of high-temperature titanium alloys and the lower service limit of superalloys, offering low density, high specific strength, high specific stiffness, excellent burn resistance, and good high-temperature mechanical properties and oxidation resistance [1, 2]. High Nb-TiAl alloys containing 5-10% Nb exhibit even superior high-temperature oxidation resistance and mechanical properties compared to conventional TiAl alloys [3-5]. However, their intrinsic brittleness and poor workability [6, 7] have limited widespread application. Joining technology represents a critical forming method for complex structural components, and developing effective joining techniques for TiAl alloys is essential for promoting their practical application.

Current joining technologies for TiAl alloys primarily include fusion welding methods such as tungsten inert gas welding [8] and electron beam welding [9, 10], as well as solid-state joining techniques like diffusion bonding. Fusion welding suffers from rapid cooling after welding, which tends to form hot cracks or metastable phases in the joint region [11], degrading mechanical properties and high-temperature microstructural stability. In contrast, diffusion bonding [12-14] involves no liquid phase during welding, with the entire component heated uniformly and cooled slowly in the furnace, thereby avoiding defects such as hot cracks, metastable phases, and microstructural changes in the joint. Consequently, diffusion bonding is considered a viable technique for fabricating TiAl alloy components.

Nevertheless, TiAl alloys exhibit high flow stress and stable high-temperature microstructures, requiring high bonding temperatures, pressures, and long holding times to achieve high-quality joints, which restricts the practical application of diffusion bonding technology. To optimize the diffusion bonding process, numerous studies have been conducted. He et al. [15, 16] investigated the use of hydrogenated TC4 as an interlayer for TiAl alloy diffusion bonding, finding that it promoted elemental diffusion and reduced the required bonding temperature and pressure. Duarte et al. [12, 17] employed nanoscale Ti/Al composite interlayers to lower the bonding temperature to 800-1000°C. Additionally, nanoscale Ni/Al and Ti/Ni [13, 14, 18, 19] composite interlayers have also been shown to reduce bonding parameters. However, adding interlayers increases costs and limits the size and geometry of components, hindering practical application. Han et al. [20] discovered that surface plastic deformation could promote atomic diffusion and improve diffusion bonding quality, yet research on its effects on TiAl alloy diffusion bonding remains limited and the underlying mechanisms are not fully understood. Therefore, this study employs high energy shot peening to introduce surface plastic deformation in high Nb-TiAl alloys and investigates the effects of surface plastic deformation and post-weld heat treatment on diffusion bonding behavior.

1 Experimental Methods

The experimental high Nb-TiAl alloy with a nominal composition of Ti-45Al-8.5Nb-0.2W-0.1B-0.1Y was prepared by vacuum arc melting. After melting, the alloy underwent hot isostatic pressing at 1280°C/140 MPa, followed by canned forging at 1200°C, and finally annealing at 1380°C/90 min. The resulting microstructure is shown in [Figure 1: see original paper]. The alloy exhibited a near-lamellar structure with lamellar colony sizes of approximately 250 m and interlamellar spacing of about 1.5 m, with small amounts of equiaxed γ and β phases distributed at colony boundaries.

Rectangular specimens measuring 35 mm × 8 mm × 5 mm were cut by wire electrical discharge machining for diffusion bonding. Prior to bonding, high energy shot peening was applied to the faying surfaces at 0.4 MPa for 15 min to introduce surface plastic deformation. The specimens were polished before shot peening. After treatment, the peened surfaces were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), and microhardness testing.

Surface roughness increased significantly after shot peening, from Ra 0.027 to Ra 2.765. To meet diffusion bonding requirements, the shot-peened surfaces were ground with 800# and 1500# wet abrasive paper, then polished with 1.5 m diamond paste. Diffusion bonding was performed in a vacuum diffusion bonding furnace under two conditions: 1000°C-30 MPa-45 min and 1100°C-30 MPa-45 min, with a minimum vacuum level of 3$×10^{-3}$ Pa. After bonding, specimens were subjected to recrystallization annealing in a tube furnace at 1150°C for 300 min.

The microstructure and composition of the joints before and after annealing were characterized by optical microscopy (OM), SEM, and energy-dispersive spectroscopy (EDS). The mechanical properties of the bonded joints were evaluated by room-temperature shear testing.

2 Results and Discussion

2.1 Microstructure of the Deformed Surface

[Figure 2: see original paper] shows the cross-sectional microstructure and X-ray diffraction pattern of the surface after 0.4 MPa-15 min shot peening. As seen in [Figure 2a: see original paper], the lamellae were significantly bent to a depth of approximately 50 m, though no grain refinement occurred at the surface. Although high Nb-TiAl alloys have poor room-temperature deformability, the shot peening process involves adiabatic heating, causing the surface temperature to rise gradually and enhancing deformability, ultimately resulting in plastic deformation and lamellar bending [20]. XRD analysis of the surface ([Figure 2b: see original paper]) revealed decreased diffraction peak intensity and significant broadening, indicating the generation of numerous crystal defects and residual compressive stresses. Since no grain refinement was observed, the peak broadening was attributed to lattice microstrain. Using the appropriate equations for calculation, the surface microstrain increased from 0.1701% (\$±0.01084)*to*0.5689±\$0.00705).

[Figure 3: see original paper] presents the microhardness variation along the thickness direction of the deformed surface. Microhardness increased significantly after surface plastic deformation, reaching a maximum of 630 HV at the surface, demonstrating work hardening of the TiAl alloy. The hardness profile from surface to core can be divided into three regions: a heavily deformed region with high hardness (~50 m thick), a deformation-affected zone with slightly higher hardness than the substrate (~100 m thick), and the unaffected substrate region.

2.2 Effect of Surface Plastic Deformation on Bonding Interface Evolution

[Figure 4: see original paper] shows the diffusion bonding interface microstructures obtained without surface plastic deformation under different conditions. After bonding at 1000°C-30 MPa-45 min ([Figure 4a: see original paper]), a joint free of unclosed voids was achieved, but the interface remained flat and distinct, with the lamellar structure unchanged. At 1100°C-30 MPa-45 min ([Figure 4b: see original paper]), equiaxed grains approximately 5 m in size formed at the interface. EDS analysis identified these as γ grains (composition shown in). Since the eutectoid temperature of high Nb-TiAl alloys is near 1160°C, no phase transformation occurs at 1100°C, indicating that the equiaxed grains formed through recrystallization. This recrystallization at the interface arises from microscopic plastic deformation occurring in localized regions due to surface roughness during bonding, with the resulting strain energy providing the driving force for recrystallization.

[Figure 5: see original paper] shows the interface microstructures after diffusion bonding with shot-peened surfaces under the same conditions. Compared to untreated specimens, the bonding interfaces were significantly less distinct in both cases, due to two primary factors: (1) the high density of crystal defects introduced by surface deformation served as fast diffusion channels, accelerating interdiffusion across the interface and promoting interface evolution; and (2) the γ lamellae adjacent to the interface underwent torsional rotation during bonding, reducing the orientation mismatch across the interface and making it less visible. Imayev et al. [22] reported that deformation during shot peening occurs primarily in the γ phase, which accumulates high strain energy, increasing the Gibbs free energy of the deformed surface. To reduce this energy, dislocations in the highly deformed γ lamellae rearranged to form dislocation walls during bonding. With increasing bonding time, these walls absorbed more defects to form low-angle boundaries, which then migrated and rotated to produce lamellar rotation, as schematically illustrated in [Figure 6: see original paper]. Additionally, recrystallization also occurred at the interface during bonding at 1100°C-30 MPa-45 min, but the recrystallized grains were smaller (~2 m) due to the higher strain energy from shot peening providing greater nucleation driving force. Notably, the bent lamellae did not completely disappear after bonding, indicating that not all strain energy from shot peening was released during the process.

2.3 Effect of Post-Bonding Heat Treatment on Interface Evolution

[Figure 7: see original paper] shows the interface microstructure after post-bonding heat treatment (PBHT) at 1150°C for 5 h. Significant recrystallization and spheroidization occurred near the interface, with γ grains forming through recrystallization. Nucleation and growth of these grains promoted migration of the bonding interface, with the original flat interface being replaced by γ grains. Since the deformability of TiAl alloys depends on lamellar orientation [23], different lamellae experienced varying degrees of deformation during shot peening, providing conditions for boundary bulging nucleation. To reduce system free energy, less-deformed lamellae near the interface protruded into more highly deformed regions, forming recrystallization nuclei that grew under the driving force of strain energy, causing grain boundaries to cross and eliminate the original interface.

2.4 Shear Properties of Bonded Joints

[Figure 8: see original paper] presents the shear strengths of joints bonded under different conditions. Shot peening effectively improved shear strength, increasing it from 305 MPa to 340 MPa at 1000°C-30 MPa-45 min, and from 345 MPa to 365 MPa at 1100°C-30 MPa-45 min—substantially more effective than PBHT alone. When shot-peened specimens underwent PBHT at 1150°C, the shear strength further increased to 420 MPa. The enhanced properties result from lamellar rotation reducing orientation mismatch across the interface, thereby improving deformation compatibility and joint quality.

Conclusions

1. High energy shot peening produces a deformation-affected zone approximately 150 m deep on the bonding surface, with microhardness gradually decreasing from the surface (630 HV) to the core.
2. Surface plastic deformation promotes elemental diffusion near the bonding interface and accelerates interface evolution. Post-bonding heat treatment at 1150°C induces recrystallization of γ-phase grains near the interface.
3. Introducing surface plastic deformation on the faying surfaces can reduce diffusion bonding parameters while maintaining joint strength. Post-bonding heat treatment can further increase the shear strength to 420 MPa.

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