

Interface Characterization of Friction-Welded Single Crystal DD3 and Fine-Grained GH4169 Superalloys Postprint

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Abstract

The friction welding interface of single-crystal DD3 and fine-grained GH4169 superalloys used in manufacturing welded integral turbine blisks was investigated using SEM, TEM, and EDS. The results show that a friction deformation band primarily composed of GH4169 alloy exists in the welded zone, and dynamically recrystallized grains were formed in the thermomechanically affected zones of both the single-crystal and fine-grained alloys on either side; the bonding interface is located between the dynamically recrystallized grains of the two alloys, and the connection of the two alloys was achieved through shared grains and shared grain boundaries on the bonding interface; compositional transition mainly occurred within the shared grains and at the shared grain boundaries at the bonding interface. The shared grain (C2) at the TEM analysis location has a special orientation relationship with the adjacent GH4169 dynamically recrystallized grain (C3): $[1\ 14]C2\ [1\ 10]C3$ and $(220)C2\ (220)C3$; under the action of the friction welding thermal cycle and post-weld heat treatment, g' phase precipitation occurred in the shared grains and the dynamically recrystallized grains on both sides; the g' phase exhibited a fine spherical distribution and was coherent with the g matrix, but no g" phase precipitation was observed.

Full Text

Characterization of the Friction Welding Interface Between Single Crystal DD3 and Fine-Grained GH4169 Superalloys

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Abstract

The friction welding interface between single crystal DD3 and fine-grained GH4169 superalloys, used for manufacturing welded turbine blisks, was investigated using SEM, TEM, and EDS. The results show that a friction deformation band dominated by GH4169 alloy exists in the weld zone. Dynamic recrystallization grains formed in the thermo-mechanically affected zones of both the single crystal and fine-grained alloys. The bonding interface is located between the dynamic recrystallization grains of the two alloys, and connection is achieved through common grains and common grain boundaries at the interface. Composition transition occurs primarily within the common grains and at the common grain boundaries. The common grain (C2) at the TEM analysis position and the adjacent GH4169 dynamic recrystallization grain (C3) exhibit a special orientation relationship: $[1\ 14]_{C2} \parallel [1\ 10]_{C3}$ and $(220)_{C2} \perp (220)_{C3}$. Under the friction welding thermal cycle and post-weld heat treatment, γ' phase precipitates in both the common grains and the dynamic recrystallization grains on both sides, distributed as fine spherical particles coherent with the γ matrix. However, no γ'' phase precipitation was observed.

KEY WORDS: single crystal superalloy, superalloy, friction welding, bonding mechanism, common grain

Introduction

Single crystal superalloys and fine-grained superalloys are the optimal choices for manufacturing blades and disks, respectively, in new aero-engine welded turbine blisks. Welded blisks comprehensively utilize the excellent high-temperature creep performance of single crystal superalloys and the high fatigue performance of fine-grained superalloys [1~4]. Fusion welding of these precipitation-strengthened superalloys tends to produce cracks, making it difficult to obtain satisfactory joints, whereas solid-state welding methods are more suitable [5~10]. Research on welding of dissimilar single crystal and fine-grained superalloys started relatively late [11,12]. Liu et al. [13] studied the transient liquid phase (TLP) diffusion bonding behavior between single crystal DD98 and polycrystalline M963 nickel-based superalloys, noting that isothermal solidification in dissimilar alloy TLP diffusion bonding is a diffusion-controlled process. After isothermal solidification at 1190 °C for 4 h, the joint's high-temperature rupture performance was comparable to that of the M963 alloy. Steuer and

Singer [14] added B as a melting point depressant in TLP diffusion bonding of columnar-grained nickel-based superalloy and PWA1483 single crystal nickel-based superalloy, finding that B addition had no effect on joint performance at higher bonding temperatures. Liu et al. [15] investigated TLP diffusion bonding between single crystal DD3 and polycrystalline GH4169 nickel-based superalloys, reporting a diffusion zone width of approximately 35 μm and hardness higher than that of the DD3 single crystal alloy.

Regarding friction welding of single crystal and fine-grained superalloys, Karadge et al. [16] studied the effect of single crystal orientation on the linear friction welding performance between CMSX-4 single crystal superalloy and RR1000 fine-grained superalloy, concluding that the angle between the vibration direction and the [110] direction of the single crystal alloy significantly affects welding performance. Du et al. [17~19] conducted preliminary studies on the microstructure, properties, and friction interface behavior of friction-welded joints between single crystal and fine-grained superalloys, deriving an equation for friction coefficient variation with temperature. The results showed that the high-temperature rupture performance of friction-welded joints was superior to that of the single crystal base material.

Currently, research on welding of single crystal and fine-grained superalloys has focused primarily on TLP diffusion bonding, while the friction welding mechanism remains unclear. This work presents an in-depth investigation of the bonding mechanism and interface characteristics of friction-welded joints between DD3 single crystal superalloy (blade material) and GH4169 fine-grained superalloy (disk material).

1. Experimental Methods

The materials used were DD3 nickel-based single crystal superalloy and fine-grained GH4169 nickel-iron-based superalloy. The chemical compositions of both alloys are listed in Table 1. Welding specimens were rods with a diameter of 15 mm, with the [001] direction of the DD3 alloy parallel to the rod axis. Welding was performed using a C25 continuous drive friction welding machine equipped with an industrial computer for closed-loop control and data acquisition, enabling real-time monitoring and control of welding parameters. The main process parameters were: friction pressure 90 MPa, upset pressure 150 MPa, welding time 9 s, and spindle speed 1250 r/min. Post-weld heat treatment was conducted at $(600 \pm 2)^\circ\text{C}$ for 8 h followed by furnace cooling.

The metallographic etchant for welded joints consisted of 20 mL HCl + 20 mL C₂H₅OH + 4 g CuSO₄, with an etching time of 30–45 s. TEM foil specimens were prepared by ion milling. Microstructure, phase identification, grain orientation, and composition of the weld zone were examined using a Quanta 400 field emission scanning electron microscope (SEM) equipped with an Oxford

INCA EDS system and a Tecnai G2 F30 field emission transmission electron microscope (TEM) equipped with an EDAX EDS system.

2.1 SEM Analysis of the Weld Zone

Figure 1 [Figure 1: see original paper] shows SEM images of the friction welding zone between DD3 and GH4169 alloys. A readily etched zone approximately 6 mm wide can be observed near the axis of the welding plane (Figs. 1a and 1b), containing numerous white particles distributed along grain boundaries and within grains (Fig. 1c), primarily on the GH4169 alloy side. The specific composition and structure of these particles require further analysis. The DD3 and GH4169 alloys lie on either side of this zone. During welding, severe plastic deformation occurred in this region, with plastic deformation and dynamic recrystallization (DRX) proceeding simultaneously to form fine DRX grains. Due to high deformation energy, this region is more susceptible to etching than fully recrystallized coarse-grained structures, suggesting it is a friction deformation band. Because the degree of torsional and shear plastic deformation and the temperature vary along the radial direction during rotary friction welding, the friction deformation band exhibits different morphologies. Figures 1a and 1b show the region near the workpiece axis, while Figs. 1c and 1d show the region near the cylindrical surface.

SEM/EDS line scan results indicate that the friction deformation band consists mainly of GH4169 alloy. During friction welding, the interface temperature reaches approximately 1200 °C, at which DD3 alloy has higher strength than GH4169 alloy [20]. Consequently, relative shear deformation between the two alloys during welding concentrates primarily in the GH4169-dominated friction deformation band, resulting in severe plastic deformation and the formation of fine DRX grains.

Nickel-based single crystal superalloys undergo dissolution of the γ' phase when certain deformation levels and temperatures are reached, which facilitates DRX nucleation [21~23]. During friction welding, the combined thermal and mechanical effects cause severe plastic deformation in the DD3 alloy region near the friction deformation band, leading to a rapid temperature increase and dissolution of the γ' phase, which generates dynamic recrystallization. The recrystallized region is approximately 30 mm wide with curved grain boundaries and non-uniform grain sizes.

The GH4169 alloy on the right side of the friction band formed a typical DRX structure. Because the region near the friction band experienced large plastic deformation and high temperatures, grain growth was more complete, resulting in relatively straight, well-defined grain boundaries with polygonal grains of uniform size approximately 3 μm in diameter.

A distinct boundary (bonding interface) exists between the DD3 DRX zone and

the GH4169 friction deformation band. During friction heating, upset deformation, dynamic recrystallization, and subsequent static recrystallization during pressure holding and cooling, recrystallized grains on both sides grew toward each other, forming common grains in some regions and overlapping grain boundaries with the bonding interface to create common grain boundaries in others. As shown in Fig. 1d, a clear boundary (bonding interface) remains within a common grain at the interface, with the left side belonging to the DD3 alloy and the right side to the GH4169 alloy.

Composition line scan analysis of common grains and common grain boundaries at the bonding interface reveals steep composition gradients of alloying elements at the interface, whether the interface is located at a common grain boundary or within a common grain (Figs. 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper]). Within common grains, two regions with significantly different compositions can form, separated by the bonding interface, with compositions on each side essentially matching the respective base materials. The similarity of crystal structures across the bonding interface within common grains requires further investigation.

2.2.1 TEM/EDS Analysis of the Weld Zone

Figure 4a [Figure 4: see original paper] shows a TEM image of the weld zone in a DD3/GH4169 friction-welded joint, with DD3 alloy on the left and GH4169 alloy on the right. Composition line scans were performed across grains C1–C4 in Fig. 4a over a length of 4.065 mm at 100 points, with results shown in Fig. 4b. GH4169 is a Ni–Cr–Fe-based superalloy, while DD3 is a nickel-based superalloy. GH4169 has lower Ni content but higher Cr content, and contains Fe and Nb. Figure 4b shows that alloying element content changes continuously primarily within grain C2, while remaining essentially constant within grains C1, C3, and C4. Within grain C2, Ni content gradually decreases while Fe, Cr, and Nb contents increase. This indicates that C2 is a common grain of both alloys, grain C1 is a DD3 recrystallized grain, and grains C3 and C4 are GH4169 recrystallized grains. The mutual diffusion range of alloying elements from both sides is mainly confined within the common grain.

2.2.2 TEM/SAED Analysis of the Weld Zone

Further TEM/selected area electron diffraction (SAED) analysis was performed on grains C1, C2, and C3 in the weld zone of the DD3/GH4169 friction-welded joint, with results shown in Fig. 5 [Figure 5: see original paper]. The selected area electron diffraction patterns indicate that all three grains consist of $\gamma + \gamma'$ phases (Figs. 5b, 5c, and 5d). The center dark-field image of the γ' phase in grain C2 is shown in Fig. 5f. The γ' γ' -Ni₃(Al, Ti, Nb) phase has an fcc-L12 structure, with Al atoms at the fcc lattice vertices and Ni atoms at face-centered

positions, with a lattice constant $a = 0.3590$ nm. The lattice constant of the γ' phase is similar to that of the γ matrix, generally differing by no more than 1%. The γ' phase precipitates along the $\{100\}$ planes of the matrix and is coherent with it [24]. The γ' phase appears as small spherical particles dispersed in the matrix. In the direct aged (DA) condition, GH4169 alloy has a γ matrix with γ' -Ni₃Nb as the main strengthening phase and a certain amount of γ' -Ni₃(Al, Ti, Nb) for secondary strengthening [25]. Grain C3 belongs to the GH4169 alloy, but no γ' phase diffraction spots were observed (Fig. 5d), indicating that the γ' phase dissolved during the friction welding thermal cycle and did not re-precipitate during post-weld cooling and heat treatment.

2.3 Orientation Relationship Analysis

To determine the orientation relationships between the common grain and the recrystallized grains of DD3 and GH4169 alloys, bicrystal diffraction tests were performed on C2-C1 and C2-C3 grain pairs using selected area electron diffraction. Analysis of the diffraction patterns revealed no special orientation relationship between grains C1 and C2, but a special orientation relationship was found between grains C2 and C3 (Fig. 5e). During testing, SAED was first performed on grain C2, then on the C2-C3 interface region, with the electron beam direction and specimen orientation remaining unchanged. After indexing and calculation, one set of spots corresponded to grain C2 (compared with the individual diffraction pattern of C2 in Fig. 5c) with zone axis $[uvw]_{C2} = [1\ 14]$, while the other set corresponded to grain C3 (compared with the individual diffraction pattern of C3 in Fig. 5d) with zone axis $[uvw]_{C3} = [1\ 10]$. This indicates the two grains have a crystallographic direction parallelism relationship: $[1\ 14]_{C2} \parallel [1\ 10]_{C3}$. Simultaneously, R vectors in the same direction show overlapping diffraction spots $(220)_{C2}$ and $(220)_{C3}$, indicating a crystallographic plane parallelism relationship: $(220)_{C2} \parallel (220)_{C3}$. Therefore, the orientation relationship between the C2 and C3 grain matrices can be expressed as:

$$[1\ 14]_{C2} \parallel [1\ 10]_{C3}, (220)_{C2} \parallel (220)_{C3} \quad (1)$$

Conclusions

1. A friction deformation band dominated by GH4169 alloy exists in the weld zone of single crystal DD3 and fine-grained GH4169 superalloy friction-welded joints. Dynamic recrystallization occurred in the thermo-mechanically affected zones of both the single crystal and fine-grained superalloys.
2. The bonding interface between single crystal DD3 and fine-grained GH4169 superalloys is located between the dynamic recrystallization grains on both sides. Connection is achieved through common grains and

common grain boundaries, with steep composition gradients of alloying elements across the bonding interface.

3. The common grain at the analyzed location exhibits a special orientation relationship with the GH4169 alloy dynamic recrystallization grain: $[1\ 14]C2$ $[1\ 10]C3$ and $(220)C2$ $(220)C3$.
4. After the friction welding thermal cycle and post-weld heat treatment, γ' phase precipitates in both the common grains and the dynamic recrystallization grains on both sides, distributed as fine spherical particles coherent with the γ matrix. However, no γ'' phase precipitation was observed.

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