Through-Thickness Microstructure of Friction Stir Welded TC4 Titanium Alloy (Postprint)

Authors: Ji Shude, hot spring, Ma Lin, Li Jizhong, Zhang Li

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Abstract

Friction stir welding (FSW) was employed to join 2 mm thick TC4 titanium alloy, and the influence of temperature distribution on the through-thickness microstructural characteristics and joint mechanical properties was investigated in conjunction with numerical simulation results. The results indicate that when the welding speed is 50 mm/min and the rotation speed is 300 r/min, the peak material temperature near the weld surface exceeds the β transus temperature. With increasing distance from the weld surface, the peak temperature gradually decreases, and the material near the weld bottom does not exceed the β transus temperature. In the weld region where the peak temperature exceeds the β transus, the microstructure consists of primary α phase, lamellar α phase, and retained transformed β phase, with the lamellar α phase in the weld interior being larger in size than that in the near-surface region. The weld bottom undergoes dynamic recrystallization, exhibiting a fine α and β dual-phase microstructure with a more uniform distribution of β phase in the α phase matrix. When the rotation speed is increased to 350 r/min, the region exceeding the β transus temperature along the weld thickness direction becomes wider, the area fraction and size of the lamellar α phase increase, and clusters of lamellar α phase appear in the microstructure. Lamellar α phases with different orientations are randomly distributed in the microstructure, hindering crack propagation and benefiting the tensile strength of the joint.

Full Text

Preamble

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Title

Microstructure Along Thickness Direction of Friction Stir Welded TC4 Titanium Alloy Joint

JI Shude[1], **WEN Quan**[1], **MA Lin**[1], **LI Jizhong**[2], **ZHANG Li**[1]
[1] Faculty of Aerospace Engineering, Shenyang Aerospace University, Shenyang 110136
[2] Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024

Correspondent: JI Shude, associate professor, Tel: (024)87923472, E-mail: superjsd@163.com

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Abstract

Friction stir welding (FSW), as a solid-state joining technology, has been employed to weld titanium alloys to avoid defects associated with fusion welding. While numerous studies have investigated microstructural characteristics and evolution during FSW of titanium alloys, few have addressed the mechanism of microstructural transformation along the joint thickness direction. To address this gap, 2 mm thick TC4 titanium alloy plates were successfully welded by FSW in this work. Based on numerical simulation results, the influence of temperature distribution on microstructure along the weld thickness direction and joint mechanical properties was investigated. The results demonstrate that under a rotational speed of 300 r/min and welding speed of 50 mm/min, the peak temperature of material near the weld surface exceeds the β phase transus temperature. The peak temperature gradually decreases with increasing distance from the weld surface, and the material near the weld bottom does not exceed the β transus temperature. In regions where the peak temperature surpasses the β transus, the microstructure consists of primary α phase, lath-shaped α phase, and retained transformed β phase, with lath-shaped α grains inside the weld being larger than those near the surface. Dynamic recrystallization occurs near the weld bottom, producing a fine $\alpha+\beta$ duplex microstructure with more uniform β phase distribution in the α matrix. When the rotational speed increases to 350 r/min, the region exceeding the β transus temperature widens along the thickness direction, leading to increased size and area fraction of lath-shaped α phase and the formation of lath-shaped α colonies. Lath-shaped α phase with different orientations, scattered throughout the microstructure, impedes crack propagation and benefits the tensile strength of the FSW joint.

KEY WORDS friction stir welding, TC4 titanium alloy, peak temperature, microstructure, tensile strength

Introduction

Titanium alloys, as important lightweight materials, offer high specific strength, excellent high-temperature resistance, corrosion resistance, and superior cryogenic properties, leading to their widespread and increasing applications in shipbuilding, medical devices, aerospace, and other industries [1~4]. Currently, fusion welding is the primary joining method for titanium alloys; however, defects such as porosity and cracking in the weld metal degrade joint performance [5,6].

Friction stir welding (FSW) is a novel solid-state joining technology that has successfully achieved high-quality joining of Cu, Mg, and Ag alloys [7,8]. For titanium alloys, FSW has become a research focus in recent years because the relatively low thermal cycle during the process avoids defects associated with melting [9,10].

Microstructure is well known to be the primary factor controlling FSW joint performance. Consequently, numerous studies have investigated microstructural evolution and formation mechanisms in FSW joints of titanium alloys [11~13]. Wang et al. [11] examined microstructural transformation characteristics in FSW joints of TC4 titanium alloy, revealing that the stir zone primarily consists of lamellar α+β phases transformed from β phase, while the heat-affected zone (HAZ) exhibits equiaxed α grains and lamellar α+β phases. Zhou et al. [12] investigated the effect of rotational speed on microstructure of TC4 FSW joints, finding that the stir zone transforms from a bimodal microstructure to a fully lamellar α+β structure with increasing rotational speed. Wang et al. [13] reported that the weld nugget consists of fine equiaxed grains, with numerous α/β interface phases present in the transition zone between the HAZ and base metal. Owing to the influence of temperature, cooling conditions, and other factors, microstructural transformations in FSW of titanium alloys exhibit complexity and diversity. The extremely low thermal conductivity of titanium alloys inevitably leads to significant temperature distribution differences along the joint thickness direction, resulting in different microstructural transformation mechanisms through the thickness. However, direct temperature measurement in the thickness direction of the weld zone during FSW is difficult, leaving this area underexplored. Therefore, this study investigates the influence of temperature distribution along the weld thickness direction on microstructure and mechanical properties, based on numerical simulation of the temperature field during FSW of TC4 titanium alloy using ABAQUS/Standard finite element software.

Experimental

Rolled TC4 titanium alloy plates with dimensions of 200 mm × 100 mm × 2 mm were used for butt welding experiments. The main alloying element composition (mass fraction, %) was: Al 6.17, V 4.08, Fe 0.30, C 0.1, O 0.2, and Ti balance. FSW experiments were conducted on an FSW-3LM-4012 friction stir welding machine. Welding parameters were as follows: rotational speeds of 300 and 350 r/min, and a welding speed of 50 mm/min. The tool material was high-strength W-La alloy, with a shoulder diameter of 12 mm, pin root diameter of 6 mm, pin tip diameter of 4 mm, and pin length of 1.8 mm. To prevent the formation of brittle compounds through reaction between titanium alloy and H_2, O_2, and N_2 during welding, Ar shielding gas was applied to the welding zone. After welding, workpieces were sectioned transversely using wire electrical discharge machining to prepare metallographic specimens. Specimens were ground and polished, then etched with Kroll's reagent (13 mL HF + 26 mL HNO_3 + 100 mL H_2O). Tensile properties of the welded joints were tested using an Instron testing machine at a crosshead speed of 5 mm/min.

Mechanical property tests of welded joints were conducted according to GB/T 2651-2008. Tensile specimen dimensions are shown in Figure 1 [Figure 1: see original paper]. A GX71 optical microscope (OM) and SU3500 scanning electron microscope (SEM) were used to observe and analyze weld microstructure and fracture surfaces.

2.1 Model Meshing

The temperature field during FSW was simulated using ABAQUS/Standard finite element software. The workpiece dimensions in the simulation were identical to those used in experiments. The mesh generation is shown in Figure 2 [Figure 2: see original paper].

FSW is a non-uniform heating process with drastic temperature variations in the weld zone and gradual changes far from the weld. To balance high computational accuracy with reasonable computation time, a non-uniform meshing method was employed. Fine meshes with element size of 0.25 mm were used to refine the weld region. Mesh density decreased with increasing distance from the weld (Figure 2). The model consisted of 250,880 DC3D8 elements—eight-node hexahedral elements capable of three-dimensional steady-state or transient thermal analysis.

2.2 Heat Source Model

Heat during FSW is primarily generated by friction between the tool shoulder and pin against the workpiece. This study adopted the heat source model proposed by Li et al. [14]. The tapered pin was simplified as a cylindrical shape in the model, and plastic deformation heat, which constitutes only a small fraction, was neglected.

The expression for shoulder heat generation is given by Equation (1), and the expression for pin heat generation is given by Equation (2). In these equations, Q represents heat input, R is the shoulder outer radius, r is the pin radius, ω is the rotational speed, τ is the material yield strength, and n is the tool rotational speed.

In the simulation, the shoulder heat source was treated as a circular surface heat source with a diameter of 12 mm, while the pin heat source was modeled as a cylindrical heat source with a diameter of 6 mm and length of 1.8 mm. Heat flux density was calculated using equations (1) and (2), then applied to the temperature field analysis model through the DFLUX subroutine in ABAQUS to obtain the welding temperature field.

2.3 Material Parameters and Heat Dissipation Boundary Conditions

In the simulation, the initial temperature of the workpiece and ambient temperature were both set to 20 °C. For the 2 mm thin plates used in this work, considering the influence of fixtures on temperature in the actual welding process was particularly important in the simulation. Heat dissipation boundary conditions were established based on actual welding conditions, with the model fully accounting for heat conduction between the workpiece and steel backing plates and clamps. Based on temperature measurement experiments, the model was iteratively refined, and the contact heat transfer coefficient between the workpiece and fixtures was finally set to 100 $W/(m^2 \cdot °C)$. Meanwhile, the convection heat transfer coefficient for all free surfaces exposed to air was set to 50 $W/(m^2 \cdot °C)$, with an emissivity of 0.7. To describe the strong convection caused by shielding gas for titanium alloy, the convection coefficient in the weld region was set to 90 $W/(m^2 \cdot °C)$. Figure 5 [Figure 5: see original paper] shows a schematic of the heat dissipation boundary conditions used in the simulation.

Since FSW temperature field simulation involves nonlinear transient thermal analysis, temperature-dependent material physical properties significantly influence simulation accuracy. As the density of titanium alloy varies little with temperature, a constant value of 4450 kg/m^3 was used. Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper] show the temperature-dependent thermal conductivity, specific heat capacity, and yield strength of TC4 titanium alloy.

Results and Discussion

3.1 Temperature Field Analysis and Experimental Validation

To validate the numerical temperature field simulation results, NiCr-NiSi thermocouple temperature measurement experiments were conducted during actual welding. A comparison between experimental temperature curves and numerically simulated thermal cycles at rotational speeds of 300 and 350 r/min is presented in Figure 6 [Figure 6: see original paper], where l represents the distance from the measurement point to the weld center. Analysis reveals that the measured and simulated curves exhibit identical trends, both experiencing rapid heating followed by rapid cooling in the initial stage and slow cooling in the later stage. During experiments, the strong convection from Ar shielding gas moving synchronously with the tool only rapidly cooled the region adjacent to the tool.

In the simulation, the heat transfer coefficient for the entire weld region was set to the strong convection value to simplify calculations (Figure 5 [Figure 5: see original paper]). Consequently, discrepancies between measured and simulated curves become larger during the later cooling stage. At rotational speeds of 300 and 350 r/min, the maximum temperatures measured in experiments were 476.139 °C and 368.589 °C, respectively, while the simulated maximum temperatures were 487.887 °C and 375.279 °C, corresponding to errors of 2.467% and 1.815%. The good agreement between experimental and simulated results validates the rationality and accuracy of the finite element model established in this study, confirming its capability to accurately describe the welding temperature field.

Temperature distributions along the thickness direction of TC4 titanium alloy FSW joints at different rotational speeds are shown in Figure 7 [Figure 7: see original paper]. Temperature peaks were extracted at four points along the weld thickness direction at 0.5 mm intervals. The results show that at rotational speeds of 300 and 350 r/min, the temperature varies from 1080~983 °C and 1100~1000 °C, respectively, from the weld surface to the bottom. During FSW, frictional heat increases with rotational speed at a constant welding speed, enlarging the high-temperature zone around the tool. Therefore, the high-temperature area at 300 r/min is smaller than that at 350 r/min. Additionally, the shoulder generates more heat and has a larger diameter than the pin, resulting in a wider high-temperature region at the workpiece top surface than at the bottom. The temperature distribution on the cross-section exhibits a bowl-shaped pattern, with peak temperature gradually decreasing with distance from the workpiece top surface.

3.2 Weld Morphology

Macroscopic and cross-sectional morphologies of TC4 titanium alloy FSW joints obtained at different rotational speeds are shown in Figure 8 [Figure 8: see original paper]. At both rotational speeds, the welds exhibited good formation with smooth surfaces and minimal flash. Ar shielding gas was used during welding, preventing oxidation on the weld surface. Cross-sectional morphology reveals that the weld interior is continuous and dense without welding defects. Due to the low thermal conductivity of titanium alloy and the temperature field distribution (Figure 7 [Figure 7: see original paper]), the cross-sectional morphology exhibits a typical “bowl-shaped” structure. The joint can be divided into four regions: stir zone (SZ), shoulder-affected zone (SAZ), heat-affected zone (HAZ), and base metal (BM).

3.3 Microstructure Analysis

The phase transformation temperature of TC4 titanium alloy is crucial for alloy processing and serves as the basis for selecting thermomechanical processing parameters [15]. Studies [16~18] have found that the content and type of alloying elements in titanium alloys affect the phase transformation temperature, though the magnitude of this effect is small. Experiments measuring the phase transformation temperature of titanium alloys (under rapid cooling conditions) and other research [19~21] have shown it to be essentially constant. In this study, the V content in TC4 titanium alloy is 4.08%. According to the TC4 titanium alloy phase diagram in reference [22], the primary phases are $\alpha+\beta$ in the range of 500~1003 °C, and β phase above 1003 °C. Thus, the $(\alpha+\beta)/\beta$ transformation temperature (β transus temperature) is 1003 °C, which is consistent with the β transus temperature of 1005 °C reported by Qazi et al. [23].

The hot-rolled and annealed TC4 titanium alloy base material exhibits a duplex microstructure consisting of elongated primary α phase and a small amount of transformed β phase, with the transformed β phase uniformly distributed in the α matrix. The microstructure is shown in Figure 9 [Figure 9: see original paper], where the gray and white regions correspond to primary α phase and transformed β phase, respectively.

Different regions along the joint thickness direction experience distinct thermal cycles, resulting in varied microstructural characteristics. Figure 10 [Figure 10: see original paper] shows the microstructure of TC4 titanium alloy welded joints at various locations through the thickness direction at a rotational speed of 350 r/min, where d represents the distance from the weld surface. Significant microstructural differences are evident along the thickness direction. The microstructure near the weld surface consists of primary α phase, lath-shaped α phase, and retained transformed β phase (Figure 10a). Compared with the base material, the primary α phase near the surface is smaller in size because the microstructure in this region is fragmented by the squeezing and stirring action of the shoulder during FSW, while the short high-temperature dwell time near the surface inhibits grain growth. Based on temperature field simulation results (Figure 7b), the peak temperature near the weld surface is 1080 °C, exceeding the β transus temperature, which indicates that this region was in the high-temperature stable β phase during FSW.

In the post-weld region, the weld continuously cools from the β phase temperature. However, since the cooling condition in this study was air cooling with a relatively slow cooling rate, the α phase precipitated from β phase after welding nucleated on β grain boundaries, i.e., the hcp$\rightarrow\beta$ transformation occurred. The generated α nuclei grew from the grain boundaries into the β grains (bcc$\rightarrow\beta$), forming lath-shaped α structures. As the lath-shaped α phase grew, it compressed the remaining β phase into a linear distribution, ultimately forming a lamellar $\alpha+\beta$ structure composed of lath-shaped α phase and retained transformed β phase.

Based on theoretical analysis, when the temperature of TC4 titanium alloy exceeds the β transus temperature, all primary α phase should transform to β phase, and the microstructure should consist entirely of β phase without any α phase. However, Figures 10a and b show the presence of primary α phase, which contradicts this theory. Analysis suggests that the theoretical premise requires the material to remain above the β transus temperature for sufficient time to allow complete transformation of α phase to β phase. In FSW, however, the frictional heat from the tool heats the material instantaneously, causing some primary α phase to enter the post-weld cooling stage before complete transformation can occur. Therefore, some primary α phase remains in the microstructure. A schematic illustration of the actual microstructural transformation mechanism during FSW of TC4 titanium alloy is shown in Figure 11 [Figure 11: see original paper].

Figure 7b shows that although the peak temperature decreases along the thickness direction, the temperature peaks within 1.5 mm from the weld surface all exceed the β transus temperature, resulting in similar microstructural constituents in this region (Figures 10a~c). The lath-shaped α structure transformed from β phase near the weld surface did not have sufficient time to grow due to cooling by the Ar shielding gas moving synchronously with the tool. With increasing distance from the workpiece top surface, the cooling effect of the shielding gas diminishes, increasing the high-temperature dwell time for the formed lath-shaped α phase and promoting significant growth in both quantity and size of lath-shaped α phase, as shown in Figure 10b. At the location shown in Figure 10c, the peak temperature is slightly above the β transus but much lower than near the weld surface, resulting in reduced quantity and size of lath-shaped α phase.

Figure 10d shows the microstructure near the weld bottom. No lath-shaped α phase is observed, similar to the base material, but both primary α and β grains are finer and the β phase is more uniformly distributed in the α matrix. Temperature field simulation results indicate that the peak temperature at the weld bottom is below the β transus temperature but within the $\alpha+\beta$ phase temperature range. In this temperature range, both $\alpha \rightarrow \beta$ and $\beta \rightarrow \alpha$ transformations occur simultaneously, maintaining dynamic equilibrium and generating small amounts of lath-shaped α phase. Under the intense stirring action of the pin, the small amount of generated lath-shaped α phase is fragmented, while β and α phases become more uniformly distributed. According to reference [12], the recrystallization temperature of TC4 titanium alloy is 700 °C. The peak temperature at the weld bottom exceeds the recrystallization temperature, and combined with the stirring action of the pin, dynamic recrystallization occurs in this region. Consequently, the primary α and β grains are finer than those in the base material.

Microstructures of TC4 titanium alloy welded joints at various thickness locations at a rotational speed of 300 r/min are shown in Figure 12 [Figure 12: see original paper]. Within 0.75 mm from the weld surface, the peak temperature exceeds the β transus temperature, and the microstructure consists of primary α, lath-shaped α, and small amounts of linear transformed β phase (Figures 12a and b). The shielding gas enhances convective heat dissipation between the weld surface and air, reducing the growth time for α nuclei precipitated at β grain boundaries. Along the thickness direction, the cooling rate decreases, increasing the high-temperature dwell time for α nuclei and promoting growth of lath-shaped α phase in Figure 12b, with some α phases interconnecting to form lath-shaped α colonies. With decreasing peak temperature along the thickness direction, the temperature falls below the β transus at locations below the weld center and near the bottom (Figure 7a). Consequently, the microstructure resembles the base material without lath-shaped α phase (Figures 12c and d), while the stirring action of the tool refines both primary α and transformed β phases compared to the base material.

Comparison between Figures 12 and 10 reveals that increasing rotational speed increases both the quantity and size of lath-shaped α phase in the microstructure, with grown lath-shaped α phases interconnecting to form lath-shaped α colonies (Figures 10b and c). This occurs because the overall peak temperature of the joint increases with rotational speed (Figure 7). The increased peak temperature promotes more α phase transformation during FSW. During post-weld air cooling, more α phase nuclei precipitate at β grain boundaries. Although experiencing the same cooling conditions as the lower rotational speed, the higher peak temperature at increased rotational speed effectively increases the total time the material spends at high temperature, promoting growth of α phase nuclei. Moreover, the increased rotational speed enlarges the area where the peak temperature exceeds the β transus through the thickness direction, which manifests in the microstructure as the appearance of lamellar α+β structure composed of lath-shaped α phase and retained transformed β phase at the location shown in Figure 10c, whereas no such structure appears at the corresponding location at lower rotational speed (Figure 12c).

3.4 Mechanical Properties Analysis

The tensile strengths of titanium alloy welded joints at rotational speeds of 300 and 350 r/min were 790.93 MPa and 896.67 MPa, respectively, indicating that joint tensile strength increases with rotational speed. As is well known, the microstructure of FSW joints determines their mechanical properties [24~27]. Microstructural analysis reveals that with increasing rotational speed, more α nuclei precipitate at β grain boundaries during continuous cooling of the weld from β phase temperature. The increased rotational speed also extends the high-temperature dwell time for α nuclei, ultimately increasing the quantity, size, and area fraction of lath-shaped α phase generated in the joint cross-section. During tensile fracture, cracks typically propagate along α/β phase interfaces. Lath-shaped α phase transformed from β phase is scattered throughout the microstructure with different orientations, impeding crack propagation and thereby increasing joint tensile strength. Fracture locations of welded joints at different rotational speeds are shown in Figure 13 [Figure 13: see original paper]. During FSW of titanium alloys, the advancing side (AS) experiences higher thermal cycles and temperatures compared to the retreating side (RS), while the HAZ microstructure, influenced only by frictional heat, has larger grain sizes than other regions [28,29]. Consequently, both parameter sets exhibit the same fracture tendency, with failure occurring in the AS heat-affected zone. Larger grain sizes near the shoulder-affected zone (Figures 10b and 12b) cause the fracture direction to propagate at a 45° angle from the bottom surface toward the shoulder-affected zone, with final fracture occurring in this region.

Figures 14 [Figure 14: see original paper] and 15 [Figure 15: see original paper] show fracture morphologies of TC4 titanium alloy welded joints at rotational speeds of 300 and 350 r/min, respectively. Dimples of various shapes, sizes, and depths are distributed across fracture surfaces at different locations along the joint thickness direction under both rotational speeds, indicating ductile fracture mode. During tensile testing, interlaced α phases are torn to form dimples. The size and quantity of lath-shaped α phase in the microstructure increase then decrease from the weld surface to the bottom (Figures 10 and 12), resulting in relatively flat fracture surfaces with small, shallow dimples near the weld surface. With increasing distance from the bottom, fracture surfaces become progressively rougher, with larger and deeper dimples (Figures 14b and 15b). Compared with the surface, the smaller amount of lath-shaped α phase near the weld bottom produces smaller, shallower dimples and flatter fracture surfaces (Figure 14c). With increasing rotational speed, higher peak temperatures cause more regions through the thickness to exceed the β transus temperature, increasing the quantity of lath-shaped α phase in the microstructure. Consequently, compared with Figure 14, the corresponding locations in Figure 15 exhibit greater surface roughness, larger dimples, and deeper dimples.

Conclusions

(1) With increasing distance from the workpiece top surface, the peak temperature of material in TC4 titanium alloy friction stir welds decreases, making it likely for the region near the weld bottom to experience peak temperatures below the β transus temperature. Increasing rotational speed reduces the area where temperature remains below the β transus.

(2) Different regions along the weld thickness direction experience varying thermal cycles, resulting in distinct microstructural characteristics. Lath-shaped α phase appears in regions where the peak temperature exceeds the transus temperature, with smaller quantities and sizes near the surface. The weld bottom undergoes dynamic recrystallization, exhibiting fine $\alpha+\beta$ duplex microstructure with more uniform β phase distribution in the α matrix.

(3) Welding peak temperature increases with rotational speed, promoting the formation of larger lath-shaped α phase and facilitating the development of lath-shaped α colonies. Lath-shaped α phase with different orientations in the microstructure contributes to increased joint tensile strength.

(4) All welded joints fracture in the advancing side heat-affected zone. The fracture mode is ductile for all joints, with dimple size and depth through the thickness direction first increasing then decreasing. Increasing rotational speed increases dimple size and depth.

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Note: Figure translations are in progress. See original paper for figures.