Rare Metal Materials and Engineering
Volume 53, Issue 5, May 2024
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Li Huizhao, Liang Kaiming, Pan Rui, et al. Effects of Holding Temperature and Heat Treatment on Microstructure and Properties of TC4 Titanium Alloy Thermal Self-Compressing Bonding Joint[J]. Rare Metal Materials and Engineering, 2024, 53(05): 1287-1295. DOI: 10.12442/j.issn.1002-185X.E20230026.

ARTICLE

Effects of Holding Temperature and Heat Treatment on Microstructure and Properties of TC4 Titanium Alloy Thermal Self-Compressing Bonding Joint

Li Huizhao[1], Liang Kaiming[2], Pan Rui[1], Zhu Xiaoteng[1], Jiang Bingxin[1], Tao Huwei[1], Li Zhihang[1], Hu Zhenggen[2], Zhang Hua[1]

[1] School of Mechanical Engineering, Beijing Institute of Petrochemical Technology, Beijing 102617, China; [2] Beijing Institute of Astronautical Systems and Engineering, Beijing 100076, China

Abstract: Self-designed induction coils, rigid restraint kits, and the existing laboratory induction heating apparatus were combined to conduct a local induction heating-based rigid restraint thermal self-compressing bonding (TSCB) treatment on a 5 mm-thick TC4 titanium alloy plate (the base metal), and the influence of holding temperature and heat treatment on the microstructure and mechanical properties of the joint was investigated. The results demonstrate that excessively low holding temperature (900 °C) results in insufficient atomic diffusion, while excessively high holding temperature (990 °C), exceeding the $\beta\rightarrow\alpha$ phase-transition temperature, leads to the formation of coarse Widmanstatten microstructures, both of which contribute to the decrease in the mechanical properties of the joint. As the temperature increases, the pressure applied to the joint by the thermal constraint stress field initially rises and subsequently declines, so does the quality of the joint connection. Optimal mechanical properties are achieved only when the holding temperature is slightly below the $\beta\rightarrow\alpha$ phase-transition temperature, specifically 950 °C, at which the microstructure distribution exhibits the highest level of uniformity, characterized by a significant presence of equiaxed α-phase grains. Additionally, the atomic diffusion is sufficiently enhanced, coupled with the highest pressure of the joint exerted by the stress field, resulting in the attainment of optimal mechanical performance. Upon annealing heat treatment at 650 °C for 3 h, the $\alpha\rightarrow\beta$ phase-transition is observed, accompanied by a reduction in the degree of lattice distortion and grain refinement. The residual stress state of the TSCB joint transitions from tensile stress to compressive stress. The residual stress is significantly reduced, leading to stress relief. Consequently, the mechanical properties of the TSCB joint are improved, addressing the problem of low plasticity of the TSCB joint.

Key words: TC4 titanium alloy; thermal self-compressing diffusion bonding; heat treatment; microstructure; mechanical properties

With advancements in civil and military sectors, aircraft equipment demands greater energy efficiency, performance, reliability, and durability. Consequently, materials with high structural properties are essential, leading to the development and extensive utilization of titanium alloys due to their low density and exceptional resistance to corrosion, high temperatures, and fatigue[1–3]. Titanium alloys have been widely used in aerospace, ships, weapons, equipment, and biomedical fields[4–6]. Fusion welding is a commonly used technique for the welding of titanium alloys. However, this welding process is prone to the occurrence of defects, such as porosity and cracks[7].

Diffusion welding is a solid-state joining technique that possesses several advantages over conventional fusion welding methods by effectively preventing defects such as porosity and cracks in the weld joint[8–9]. However, traditional diffusion welding relies on high temperature and external pressure to induce plastic deformation for bonding[10], which can lead to lower welding quality of joints due to insufficient external pressure. For addressing this problem, a novel method called as local induction heating-based rigid restraint thermal self-compressing bonding (TSCB) is proposed in this

Received date: August 26, 2023
Foundation item: Cross-Disciplinary Science Foundation from Beijing Institute of Petrochemical Technology (BIPTCSF-013); Classified Development Projects of Beijing Municipal Institutions (11000023T000002199202)
Corresponding author: Zhang Hua, Ph. D., Professor, School of Mechanical Engineering, Beijing Institute of Petrochemical Technology, Beijing 102617, P. R. China, Tel: 0086-10-81292220, E-mail: huazhang@bipt.edu.cn

study. In this method, the joint is subjected to localized non-melting heating, leading to the generation of a temperature gradient within the joint under rigid constraint, and thereby forming a stress field. Compared with traditional diffusion welding, this method significantly enhances the pressure applied to the joint due to the formation of the stress field, thereby achieving enhanced efficiency and quality in diffusion welding. Currently, research on TSCB primarily focuses on the following aspects: demonstrating its feasibility, investigating the effects of different holding time on the microstructure and properties of joints, assessing joint fatigue performance, analyzing the thermal stress-strain process, and exploring optimal electron beam power settings[8–15]. Pan et al[9] conducted thermal self-compressing diffusion bonding on a TC4 titanium alloy plate, revealed the thermal stress-strain cycle occurring during TSCB bonding, and confirmed the feasibility of TSCB bonding. Deng et al[8] investigated the influence of holding time on the microstructure and properties of TSCB joints. The findings reveal that holding time exceeding 5 min results in TSCB joints with high quality, uniform microstructure, and favorable mechanical properties. However, it is observed that when held for the same time of 2 min, TSCB joints exhibit a significant decrease in elongation compared with the base material. Furthermore, it is found that the influence of different holding temperatures on the microstructure and properties of TSCB joints has not been thoroughly analyzed, despite extensive research on the effects of varying holding time.

Therefore, self-designed induction coils, rigid restraint kits, and the existing laboratory induction heating apparatus were employed to conduct a local induction heating-based rigid restraint TSCB on a 5 mm-thick TC4 titanium alloy plate (the base metal). By investigating the influence of different holding temperature conditions on the microstructure and properties of the joints, this research provides valuable guidance for attaining high-performance TSCB joints. To address the problem of reduced elongation of TSCB joints compared with that of the base material, 650 °C/3 h annealing heat treatment was applied to the TSCB joints under the optimal holding temperature conditions. This treatment aims to establish a foundation for the further application and development of TSCB technique.

1 Experiment

In this test, a 5 mm-thick TC4 titanium alloy plate (measuring 60 mm (L)×50 mm (W)×5 mm (H)) was used as the welding material, and the chemical composition details are provided in Table 1. Prior to welding, the surface of the test plate intended for bonding underwent grinding by a grinding machine to achieve a roughness of R_a=0.8 and to facilitate diffusion bonding. Subsequently, the plate was immersed in an acid solution to eliminate impurities such as grease and oxidation film.

Fig. 1 illustrates a device used for local induction heating-based rigid restraint TSCB. The operating principle[16–17] of this device involves the use of an electromagnetic induction heat source for non-melting localized heating on a rigid restraint interface that needs to be bonded. By subjecting the interface zone to high-temperature heating, the metal in that region experienced extrusion and expansion within a thermal restraint stress-strain field. This field is formed due to the surrounding cold metal material and rigid restraint. As a result, atomic diffusion occurs on both sides of the interface, leading to solid-state bonding. The test plates were subjected to local heating by the induction heating apparatus with temperatures controlled by an infrared camera and temperature-regulating device in tandem.

Table 1 Chemical composition of TC4 titanium alloy (wt%)

Al	V	Fe	C	N	H	O	Other
5.5–6.8	3.5–4.5	≤0.3	≤0.1	≤0.05	≤0.015	≤0.2	≤0.4

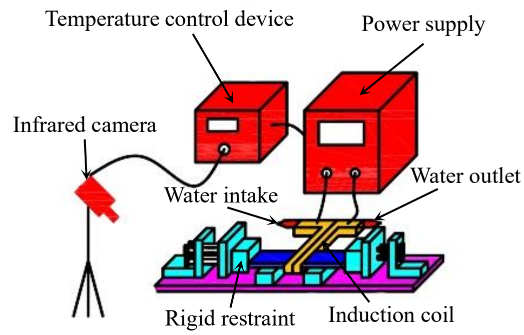

Fig.1 Schematic diagram of the whole TSCB device

Upon completion of the diffusion bonding process, the test plate was sectioned by wire-cut electrical discharge machining in a direction perpendicular to the bonding interface. Subsequently, epoxy resin was poured onto the cut section, resulting in the formation of a metallographic specimen. The specimen was ground by abrasive paper, and then polished with a polishing machine. Additionally, it was subjected to corrosion in a corrosive liquid (HF: HNO_3: H_2O=3: 10: 100). The metallographic structure of the specimen was then examined by a Leica DMi8C metalloscope. In order to investigate the reasons behind the performance improvement resulting from post-weld heat treatment, the TSCB joints were subjected to heat treatment under the optimal parameters: holding temperature of 950 °C for a duration of 7.5 min. The heat treatment parameters included the holding temperature of 650 °C, holding time of 3 h, and subsequent furnace cooling. The residual stress distribution along the transverse cross-section at the wide center position of the TC4 titanium alloy plate was evaluated before and after heat treatment. The residual stress measurement was conducted by X-ray diffraction residual stress testing method. A Cu target was employed with the diffraction plane of (213). Tensile specimens were obtained by wire cutting equipment to extract specimens perpendicular to the joint interface direction. These specimens were then subjected to tensile testing to evaluate the mechanical properties of TSCB joints at different holding temperatures before/after heat treatment. The dimensions of the tensile specimens are as shown in Fig. 2. Three tensile specimens were prepared for each experimental group. Tensile testing was performed on a CMT-7304 electronic universal testing machine.

2 Results and Discussion

2.1 Effects of different holding temperatures on microstructure

Fig.3 depicts optical microscope (OM) images of the TSCB joint interface held at varying temperatures for 7.5 min. At a holding temperature of 900 °C, the joint interface exhibits unwelded areas (Fig. 3a). However, when the holding temperature is elevated to 950 °C, the butt joint interface is nearly indistinguishable without unwelded areas (Fig. 3b). When the holding temperature further increases to 990 °C, the butt joint interface reappears, accompanied by a few unwelded areas (Fig.3c). At holding temperatures of 900 or 950 °C, the microstructure of the joint interface exhibits equiaxed α and β grains. However, when held at 990 °C, the microstructure surrounding the joint interface exhibits Widmanstatten patterns. The final structure of the joint is determined by the thermal cycle during the diffusion bonding process. When the holding temperature is set at 900 or 950 °C, the joint does not undergo significant structural changes during the TSCB process. This is because both holding temperatures are lower than the $\beta \rightarrow \alpha$ phase-transition temperature of the TC4 titanium alloy, and the heating time is relatively short. Consequently, after TSCB, the heated areas of the joint exhibits uniform structures. The diffusion of alloying elements within the α phase and the suppression of the boundary phase contribute to slow grain growth during the heating process, ultimately resulting in the formation of equiaxed structures. At a holding temperature of 990 °C, which exceeds the $\beta \rightarrow \alpha$ phase-transition temperature of the TC4 titanium alloy, the original $\alpha+\beta$ phase structure of the material is completely transformed into β phase structure. Due to the poor thermal conductivity and high thermal capacity of the TC4 alloy[18], the diffusion coefficient of atoms within the β phase increases, leading to the formation of coarse β grains. During the slow cooling stage, a diffusion-type structural transformation occurs, wherein the β phase is transformed into flake-like or needle-like α phase. The β phase grain boundaries are transformed, resulting in the formation of α phase structure along the grain boundaries while retaining the original shape of the β grains. During the rapid cooling stage, it is challenging to separate the α phase from the β phase due to the difficulty in inhibiting the crystal structure formation of the β phase through cooling. The crystal structure of the original β phase changes, resulting in a supersaturated solid solution where the original components remain unchanged, but the crystal structure resembles martensite, forming a needle-like martensitic α' structure due to edge trimming[19]. When heated to 990 °C, the structures surrounding the interface are completely transformed into coarse β phase grains. During the cooling process, the cooling rate is relatively slow, but still higher than the furnace cooling rate. As a result, a non-diffusion-type structural transformation occurs, wherein the β phase is transformed into a needle-like α phase coexisting with the coarse β grains. Ultimately, a coarse Widmanstatten structure is formed.

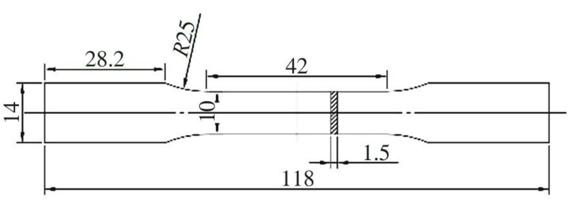

Fig.2 Schematic diagram of TSCB joint tensile specimen

2.2 Effects of different holding temperatures on mechanical properties

Fig. 4 depicts the tensile properties of the rigid restraint TSCB joint held at various temperatures for 7.5 min. When the holding temperature is set at 900 °C, the restricted plastic deformation can be attributed to the low holding temperature. Additionally, the presence of a small temperature gradient near the interface contributes to a reduced extrusion effect on the thermoplastic state metal. Consequently, the insufficient atomic diffusion at the joint interface of the TSCB joint adversely affects the interface bonding quality. Moreover, the joint exhibits comparatively diminished tensile strength, yield strength, and elongation. With the elevation of the holding temperature to 950 °C, a notable plastic deformation occurs at the interface due to the influence of tensile stress, thereby

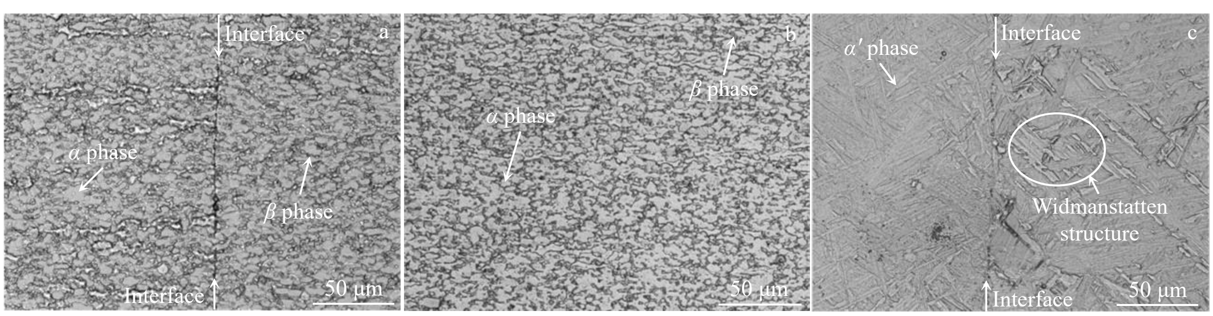

Fig.3 OM images of TSCB joints held at different temperatures for 7.5 min : (a) 900 °C, (b) 950 °C, and (c) 990 °C

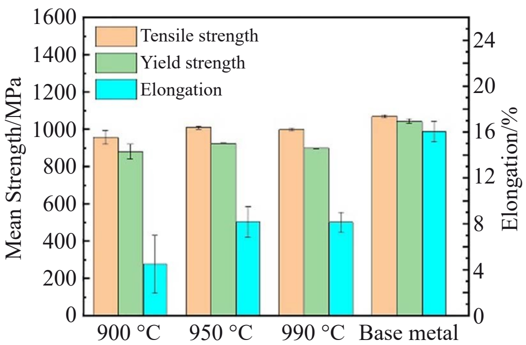

Fig.4 Comparison of mechanical properties between TSCB joints and base material[9]

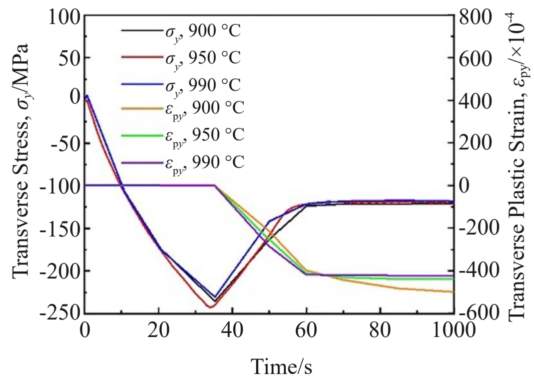

Fig.5 Transverse stress and transverse plastic strain evolution at the interface center point during TSCB jointing process

enhancing the thermocompression effect. The thermal elastic-plastic stress-strain field within the TSCB interface is reinforced due to the heightened thermocompression effect, resulting in an augmented diffusion depth of the interfacial elements. The equiaxed transformation of the α phase particles becomes more pronounced, accompanied by improved atomic diffusion and a more uniform distribution of β phase and α phase particles. Consequently, the joint experiences enhancements in its tensile strength, yield strength, and elongation. When the holding temperature reaches 990 °C, several effects are observed. Firstly, a non-diffusion-type transformation occurs, causing the β phase to transform into a needle-like α' phase. This transformation weakens the interaction of intergranular β phase at the nail dislocation site within the joint. Secondly, the joint undergoes a transformation into a coarse Widmanstatten structure, leading to grain coarsening and a subsequent reduction in mechanical properties. Consequently, compared with that at the temperature of 950 °C, the joint exhibits decreased tensile strength, yield strength, and elongation. The tensile experiments on TC4 titanium alloy base metal were conducted by Pan et al[9] using specimens with the same dimensions. The average tensile strength, yield strength, and elongation of the TC4 titanium alloy base metal were measured to be 1069.8 MPa[9], 1042.9 MPa[9], and 16.1%[9], respectively, as shown in Fig.4. Under three different holding temperature conditions, it can be observed that the tensile strength and yield strength of TSCB joints are comparable to those of the base material. However, the elongation of TSCB joints decreases by 72%, 49%, and 49.7% compared with that of the base material at 900, 950, and 990 °C, respectively. These results indicate that though TSCB joints exhibit higher strength, there is a notable decrease in plasticity.

2.3 Impact of pressure on jointing quality in TSCB process

The trend of the transverse stress-strain at the center point of the TSCB joint bonding interface is shown in Fig.5.

The calculation method for the stress-strain field remains consistent with the approach proposed by Pan et al[9]. Traditional diffusion bonding relies on external pressure to induce plastic deformation into the materials. However, due to the limitations of external pressure, the applied pressure typically ranges within 10−20 MPa[20–22]. In this experiment, a self-constrained method was employed to generate a stress field. The stress field is formed as a result of temperature gradients near the heated materials, leading to significantly higher pressure compared with traditional diffusion bonding methods. From Fig.5, it can be observed that the peak values of transverse compressive stress (σ_y) at 900, 950, and 990 °C are 235.6, 242.9, and 230.6 MPa, respectively. These values are significantly higher than the external pressure applied during traditional diffusion bonding. The time required to reach peak σ_y at 900, 950, and 990 °C is 35.3, 34.0, and 35.3 s, respectively. The occurrence of transverse plastic strain (ε_{py}) takes place at 50 s for all three temperatures, indicating a delay of approximately 15 s in the onset of plastic deformation in TSCB joints. This delay can be attributed to the non-melting heating temperature difference effect, which generates a thermally constrained stress field. It causes the plastic deformation to initiate only after a certain heating duration, when the transverse compressive stress approaches its peak and exceeds the yield strength of the material. As the temperature increases, σ_y initially rises and then decreases, indicating a corresponding trend in the applied pressure on the joint. This suggests that the influence of pressure on the jointing connection quality follows an trend of initial increasing and then decreasing. When the holding temperature is 900 °C, the effect of the thermally constrained stress field on the joint is relatively small, resulting in a comparatively low applied pressure on the joint. As the holding temperature increases to 950 °C, the impact of the thermally constrained stress field on the joint intensifies, enhancing the joint connection and increasing its yield strength. Consequently, the applied pressure on the joint increases. However, if the temperature rises to 990 °C, a phase transformation occurs near the bond interface, resulting in the formation of coarse β-phase structures that are subsequently transformed into Widmanstatten structures upon cooling[23]. The volume change caused by this phase transformation affects the plastic deformation of the joint structure. Due to the smaller volume of β-phase crystals compared to α-phase, the formation of β-phase structures leads to volume contraction and decrease in transverse compressive stress[24]. In conclusion, temperature is the main influencing factor on the pressure of TSCB joints. Heating temperature difference generates a thermally constrained stress field, which applies pressure to the joint. As a result, the pressure on TSCB joints is primarily determined by the holding temperature. The optimal joint connection is achieved when the holding temperature is slightly below the $\beta \rightarrow \alpha$ phase-transition temperature of TC4 titanium alloy, as it maximizes the applied pressure on the joint and ensures the best bond quality.

2.4 Influence of post-weld heat treatment on residual stress of TSCB joints

Under the optimal process parameters of a holding temperature of 950 °C and a holding time of 7.5 min, the residual stress distribution of the TSCB joint before and after annealing at 650 °C for 3 h is shown in Fig. 6. It can be observed that the range of stress distribution is reduced from 25 mm away from the weld interface to 8 mm after the heat treatment. Before heat treatment, the longitudinal stress within 26 mm from the joint interface is tensile stress, and the maximum tensile stress is located at 6 mm from the joint interface, measuring 105.43 MPa. The transverse stress within approximately 18 mm from the joint interface is tensile stress, and the maximum tensile stress is located at 2 mm from the joint interface, measuring 111.2 MPa. Compressive stress is observed away from the joint interface, with the maximum compressive stress of 14.6 MPa located at a distance of 20 mm from the joint interface. After heat treatment, the transverse stress within approximately 8 mm from the joining interface is predominantly compressive, with a maximum

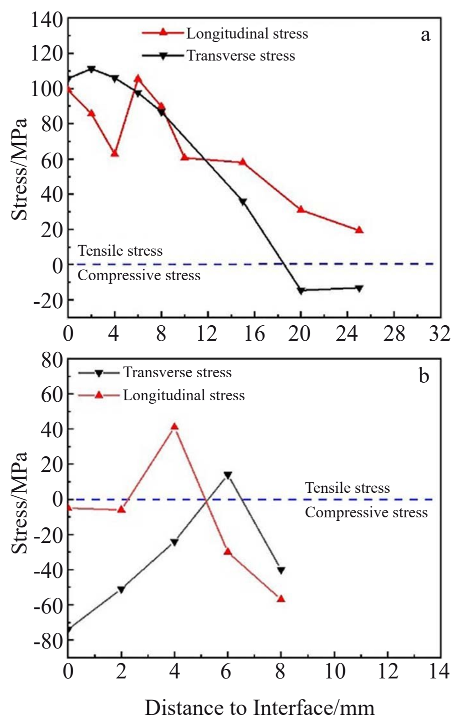

Fig.6 Residual stress distribution of joint before (a) and after (b) heat treatment

compressive stress of 74 MPa. The longitudinal stress exhibits tensile stress within 2 – 5 mm from the bonding interface, while the rest of the region exhibits compressive stress, with a maximum tensile stress of 41 MPa and a maximum compressive stress of 57 MPa. In TC4 titanium alloy, the α phase and β phase have hexagonal close-packed (hcp) and body-centered cubic (bcc) structures, respectively[25]. After heat treatment, $\alpha \rightarrow \beta$ phase transformation occurs, which improves the matching degree between the lattices of the α and β phases. This leads to a reduction in residual stress within the joint, and the residual stress state changes from tensile stress to compressive stress.

2.5 Influence of post-weld heat treatment on microstructure of TSCB joints

The grain orientation distribution maps, inverse pole figure (IPF), and phase distribution (PD) maps of the joint before and after heat treatment are presented in Fig. 7. Minimal changes in the microstructure of the TSCB joint can be observed before and after heat treatment, as depicted in Fig.7a and 7b. The microstructure of the joint primarily consists of equiaxed α grains and intergranular β grains, both before and after heat treatment. The IPF analysis of the β phase, as presented in Fig.7c, reveals a prominent preferred orientation of β grains along the $<10\bar{1}0>$ crystallographic direction prior to heat treatment, characterized by a high maximum uniform density (MUD) value exceeding 10. Nonetheless, after heat treatment, as illustrated in Fig. 7d, the MUD value of the β grains decreases below 10, indicating a diminished degree of preferred orientation along the $<10\bar{1}0>$ crystallographic direction. The phase content distribution before and after heat treatment is illustrated in Fig. 7e and 7f, respectively. After heat treatment, the content of the β phase increases from the initial 1.0% to 2.1%. This can be attributed to the transformation of the stress state within the joint from tensile stress to compressive stress during heat treatment. The change in stress leads to a decrease in the $\alpha \rightarrow \beta$ phase-transition temperature of the joint, facilitating the redistribution of solute elements between the two phases. This leads to an increase in the free energy of the α phase and a decrease in the free energy of the β phase, promoting the partial transformation of α phase into β phase.

Fig. 8 presents the microstructures of the TSCB joint obtained by electron backscatter diffraction (EBSD) before and after heat treatment. Fig.8a and 8b correspond to the grain orientation spread (GOS) maps before and after heat treatment, respectively. It is generally believed that grains with a GOS smaller than 2° undergo recrystallization, while grains with a GOS larger than 2° undergo deformation[26]. After the heat treatment, the proportion of deformed grains with a GOS larger than 2° decreases from 15.6% to 14.8%. Additionally, the average GOS value of the grains decreases from 0.65° to 0.6°, indicating a reduction in the degree of deformation within the grains[27]. After heat treatment, there is a slight increase in the proportion of recrystallized grains within the joint, from 78.0% to 80.3%. Fig.8c and 8d depict

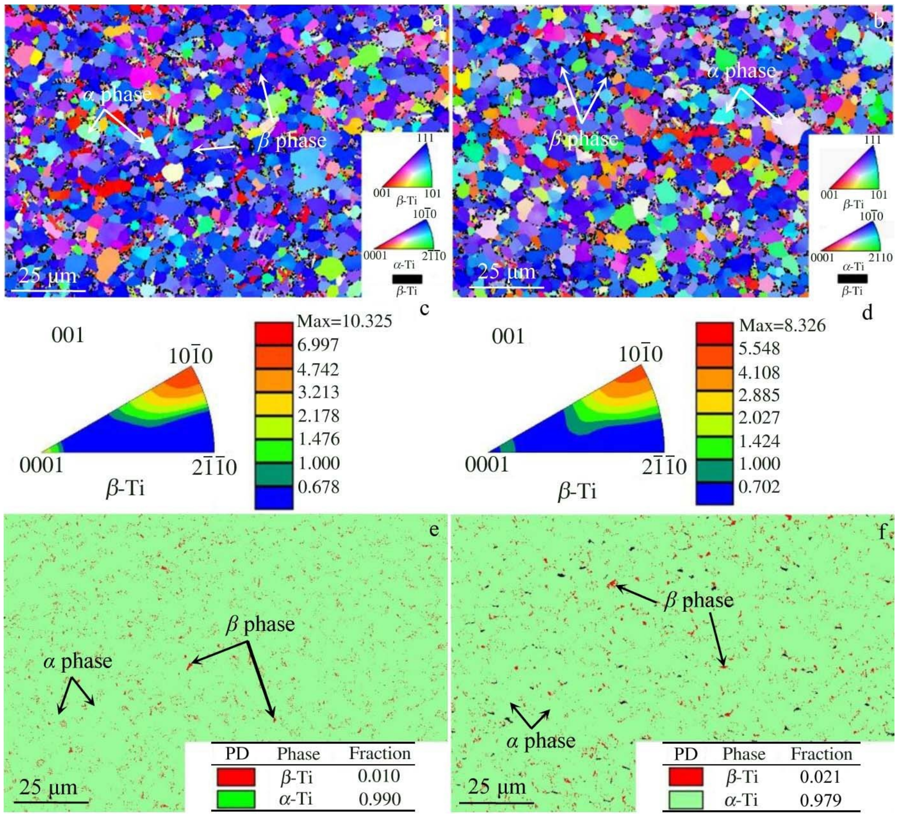

Fig.7 Grain orientation distribution maps (a–b), IPFs (c–d), and PD maps (e–f) of TSCB joint before (a, c, e) and after (b, d, f) heat treatment

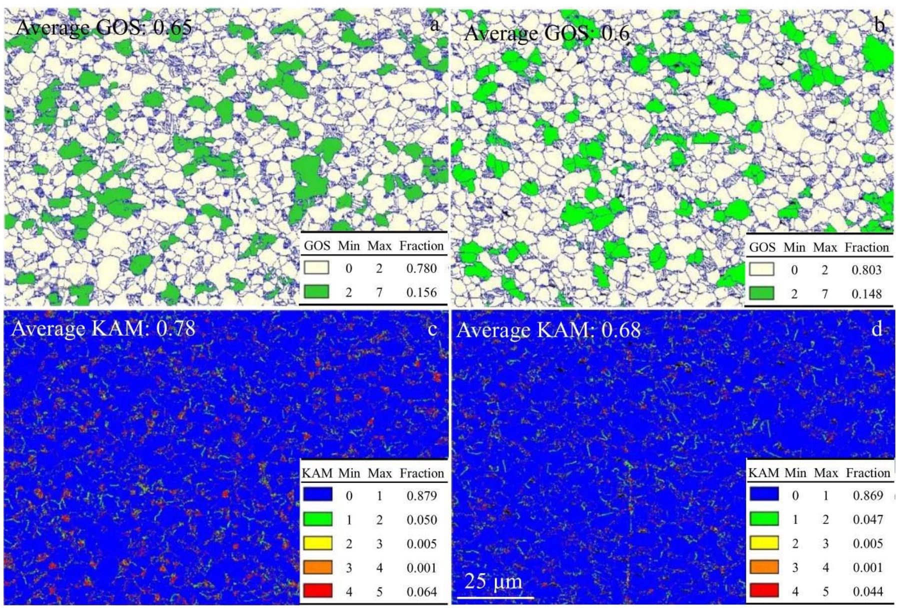

Fig.8 EBSD microstructures before (a, c) and after (b, d) heat treatment: (a–b) GOS maps and (c–d) KAM maps

the kernel average misorientation (KAM) maps before and after heat treatment of the joint. The KAM distribution within the joint interface primarily ranges from 0° to 1°, accounting for 87.9% and 86.9% before and after heat treatment, respectively. After the heat treatment, the average KAM value decreases from its original value of 0.78 to 0.68, indicating a reduction in lattice distortion within the joint. And the local strain and geometrically necessary dislocation density are reduced[27]. Consequently, the mechanical properties are improved.

Fig. 9a presents a comparison of grain size distribution before and after heat treatment. The grain size distribution within the joint, both before and after heat treatment, predominantly ranges from 0.3 μm to 2 μm. The proportion of grains with average grain size smaller than 2 μm within the joint before and after heat treatment is 50.7% and 56.6%, respectively. The reduction in average grain size after heat treatment indicates grain refinement. EBSD observations demonstrate that the grain refinement in TSCB joints after heat treatment is a synergistic outcome of three mechanisms. The first mechanism involves the segmentation of grains due to dislocation interfaces during the heat treatment process. Due to the presence of numerous low angle grain boundaries (LAGBs) in the original TSCB joint, a large number of dislocation interfaces are also present. These dislocation interfaces continuously fragment the grains during the heat treatment process, resulting in grain refinement[28]. The second mechanism involves the stress concentration formed by the motion and accumulation of dislocations, leading to the segmentation and refinement of deformed grains. As depicted in Fig. 8, a larger number of deformed grains are observed prior to heat treatment. During the heat treatment process, the joint experiences plastic deformation, leading to the proliferation of dislocations within the deformed grains.

Additionally, the change in stress during heat treatment causes the proliferated dislocations within the deformed grains to migrate and to accumulate at grain boundaries, creating stress concentrations that drive the initiation and propagation of cracks. Consequently, the deformed grains undergo segmentation, resulting in a reduction in their quantity and the development of a finer grain size. The third mechanism involves grain refinement through dynamic recrystallization. As depicted in Fig.8, an increased proportion of recrystallized grains within the joint after heat treatment indicates the occurrence of dynamic recrystallization during the heat treatment process, leading to grain refinement[29]. Fig. 9b presents the distribution of grain orientation differences before and after heat treatment. It can be observed that both before and after heat treatment, the TSCB joint is predominantly composed of LAGBs ranging from 2° to 10°. The proportion of LAGBs in the joint before heat treatment is 82.6%. After heat treatment, the proportion of LAGBs in the joint increases to 84.7%, increased by 2.9% compared to the pre-heat treatment condition. This phenomenon can be attributed to the presence of intergranular β-phase grains in the joint microstructure. The joint already contains a large number of LAGBs before heat treatment, which store a higher amount of dislocation energy compared with high angle grain boundaries (HAGBs). During the heat treatment process, the LAGBs, influenced by the pinning effect of the intergranular β-phase grains, undergo a more limited release of stored energy compared to HAGBs. Consequently, the heat treatment facilitates atomic mobility and reduces the energy stored in HAGBs, thereby facilitating their transformation into LAGBs.

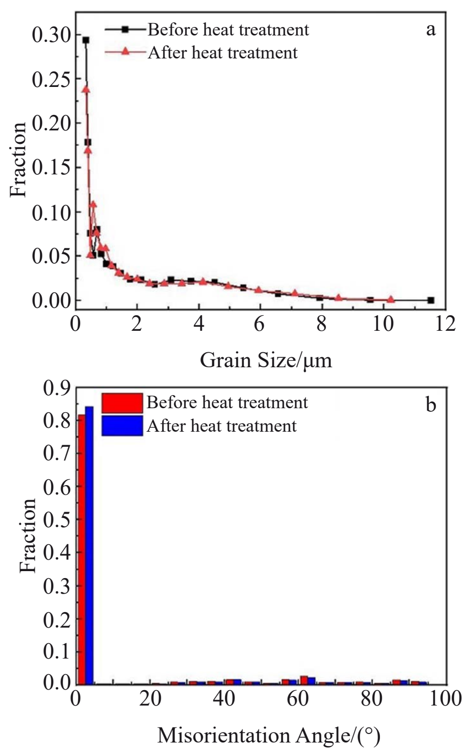

Fig.9 Comparison of grain size (a) and orientation difference distributions (b) before and after heat treatment

2.6 Influence of post-weld heat treatment on mechanical properties of TSCB joints

The tensile mechanical properties of the TSCB joint before and after heat treatment are presented in Fig. 10. The average tensile strength, yield strength, and elongation of the original TSCB joint are determined to be 1008.4 MPa, 924.9 MPa, and 8.2%, respectively. After heat treatment, the average tensile strength, yield strength, and elongation of the TSCB joint are measured as 1026.8 MPa, 969.6 MPa, and 15.5%, respectively. The average tensile strength, yield strength, and elongation of TC4 titanium alloy base material are consistent with those shown in Fig. 4, as depicted in Fig. 10[9]. After annealing heat treatment at 650 °C for 3 h, the TSCB joint exhibits notable increase in its tensile strength, yield strength, and elongation by 1.8%, 4.8%, and 89.3%, respectively. The significantly increased elongation problem in the TSCB joint after heat treatment is evident from the comparison shown in Fig. 10. After heat treatment, a decrease in grain deformation and a reduction in local strain are observed. On the one hand, the pinning effect of intergranular β phase dislocations is significantly enhanced by the heat treatment-induced transformation of the microstructure from α phase to β phase. This results in an improved lattice matching between the α and β phases, leading to a transition of the residual stress state in the joint from tensile stress to compressive stress. And there is a decrease in residual stress and stress relief. On the other hand, grain refinement not only strengthens the grain boundaries but also facilitates the interaction of dislocations, thereby effectively enhancing the tensile strength of the joint. After heat treatment, an increase in the number of LAGBs and a concurrent grain refinement result in a higher interfacial area at the grain boundaries. This hinders the motion of dislocations and leads to an improvement in the yield strength of the joint. The plasticity of the joint is enhanced due to increased content of β phase after heat treatment, as β phase exhibits higher plasticity compared with α phase[30]. The grain

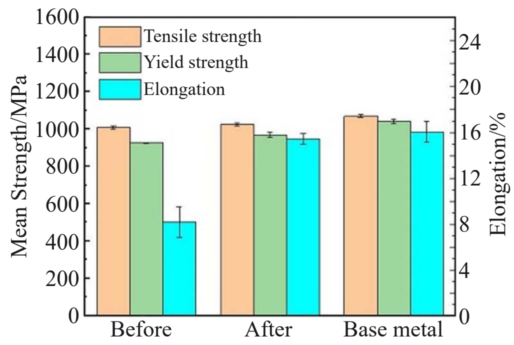

Fig.10 Comparative analysis of mechanical properties of TSCB joints before and after heat treatment[9]

refinement and reduction in lattice distortion lead to a decrease in dislocation density within the grains of the joint. Additionally, the increased LAGBs facilitate dislocation slip, resulting in a significant enhancement of the joint's plasticity[26].

3 Conclusions

1) Under the same holding time, different scenarios emerge. Specifically, at a holding temperature of 900 or 950 °C, the interface microstructure of the joint is composed of equiaxed α and β grains. However, when the holding temperature reaches 990 °C, the joint microstructure is transformed into Widmanstatten patterns.

2) At a holding temperature of 900 °C, which is relatively low, insufficient atomic diffusion occurs, resulting in relatively poorer mechanical performance. When the holding temperature is set at 950 °C, slightly below the $\beta \rightarrow \alpha$ phase-transition temperature, the presence of equiaxed α-phase grains becomes more prominent. The grain distribution becomes more uniform, and there is an increased depth of element diffusion, indicating sufficient atomic diffusion. This temperature results in the best tensile strength, yield strength, and elongation, making it the optimal holding temperature. However, if the holding temperature exceeds the $\beta \rightarrow \alpha$ phase-transition temperature of the titanium alloy (990 °C), the transformation of the joint microstructure leads to a reduction in mechanical properties.

3) As the temperature increases, σ_y initially rises and then decreases, indicating a corresponding trend in the applied pressure on the joint. This suggests that the influence of pressure on the joint bonding quality follows an trend of initial increasing and then decreasing. The pressure on TSCB joints is primarily determined by the holding temperature. Optimal joint connection is achieved when the holding temperature is slightly below the $\beta \rightarrow \alpha$ phase-transition temperature of TC4 titanium alloy, because it can maximize the applied pressure on the joint and thus ensure the best bond quality.

4) After annealing at 650 °C for 3 h, no significant changes can be observed in the microstructure, which consists of equiaxed α grains and intergranular β grains. Heat treatment has the capability to refine the grain structure of TSCB joints, to promote the transformation of α phase into β phase, to reduce lattice distortion, and to increase the quantity of LAGBs. Consequently, a significant improvement in plasticity can be achieved, effectively addressing the problem of low plasticity of TSCB joints.

5) The microstructural changes, phase content distribution, degree of deformation within grains, and distribution of grain misorientation exhibit minimal variations after heat treatment, indicating that they are not the primary factors influencing the mechanical properties. However, significant changes are observed in the residual stress distribution, KAM distribution, and grain size before and after heat treatment. This suggests that the main factors contributing to the improved mechanical properties after heat treatment are: (1) reduction in lattice distortion within the joint, (2) transition and relief of residual stress state, and (3) grain refinement.

References

1 Liu Yanming, Jia Xinlu, Zhang Yikai *et al. Materials China*[J], 2023, 42(9): 699 (in Chinese)

2 Su Huabing, Yin Lin, Jiang Hongjun *et al. Heat Treatment*[J], 2023, 38(4): 36

3 Fang Naiwen, Huang Ruisheng, Long Weimin *et al. Rare Metal Materials and Engineering*[J], 2023, 52(5): 1725

4 Li Xifeng, Li Tianle, An Dayong *et al. Acta Metallurgica Sinica*[J], 2022, 58(4): 473 (in Chinese)

5 Zhang Mingyu, Yun Xinbing, Fu Hongwang. *Rare Metal Materials and Engineering*[J], 2023, 52(9): 3106

6 Pan Ting, Li Dongya, Cheng Ming *et al. Hot Working Technology*[J], 2023, 52(8): 12 (in Chinese)

7 Su Yu, Li Wenya, Wang Xinyu *et al. Materials China*[J], 2017, 36(11): 852 (in Chinese)

8 Deng Yunhua, Guan Qiao, Tao Jun *et al. Rare Metal Materials and Engineering*[J], 2017, 46(6): 1620

9 Pan Rui, Deng Yunhua, Zhang Hua. *Rare Metal Materials and Engineering*[J], 2021, 50(2): 373

10 Deng Yunhua, Guan Qiao, Tao Jun. *Transactions of Nonferrous Metals Society of China*[J], 2018, 28(4): 662

11 Deng Yunhua, Guan Qiao, Tao Jun *et al. Acta Metallurgica Sinica*[J], 2015, 51(9): 1111 (in Chinese)

12 Deng Yunhua, Guan Qiao, Wu Bing *et al. Rare Metal Materials and Engineering*[J], 2016, 45(3): 788

13 Deng Yunhua, Guan Qiao, Tao Jun *et al. Chinese Journal of Mechanical Engineering*[J], 2018, 31(4): 140

14 Deng Yunhua, Guan Qiao. *Materials Letters*[J], 2015, 146: 1

15 Deng Yunhua, Guan Qiao, Wu Bing *et al. Materials Letters*[J], 2014, 129: 43

16 Li H, Liu H B, Yu W X *et al. Materials Letters*[J], 2013, 108: 212

17 Yang Xingyuan, Jiang Muchi, Ren Dechun *et al. Rare Metal Materials and Engineering*[J], 2023, 52(12): 4125

18 Li Ting, Du Yu, Zhao Liang *et al*. *Materials China*[J], 2017, 36(10): 765 (in Chinese)

19 Peng Peiwen, Ou Kengliang, Chao Chihyeh *et al. Journal of Alloys and Compounds*[J], 2010, 490(1–2): 661

20 Liu Yingzong, Li Yuanxing, Zheng Xiangbo *et al. Rare Metal Materials and Engineering*[J], 2022, 51(12): 4757 (in Chinese)

21 Wang Jie, Zhang Yiwei, Xiong Yanlin *et al. Rare Metal Materials and Engineering*[J], 2022, 51(12): 4446

22 Zhou Fangming, Zhang Fuqiang, Song Feiyuan *et al. Rare Metal Materials and Engineering*[J], 2013, 42(9): 1785

23 Deng Yunhua, Yue Xishan, Tao Jun *et al. Transactions of the China Welding Institution*[J], 2019, 40(11): 139

24 Chen Song, Huang Sensen, Ma Yingjie *et al. Rare Metal Materials and Engineering*[J], 2024, 53(2): 435 (in Chinese)

25 Song Wei, Li Wanjia, Yu Shurong *et al. Rare Metal Materials and Engineering*[J], 2023, 52(5): 1791 (in Chinese)

26 Raturi M, Bhattacharya A. *Materials Science & Engineering A*[J], 2021, 825: 141891

27 Lu Bing, Wang Haiyao, Wang Yin *et al. The Chinese Journal of Nonferrous Metals*[J], 2023, 33(4): 1024 (in Chinese)

28 Xu Shenghang, Shen Kaijie, Zhang Huibin *et al. The Chinese Journal of Nonferrous Metals*[J], 2021, 31(11): 3141 (in Chinese)

29 Zhang Rongjun, Zhang Jin, Ji Pengfei *et al. Rare Metal Materials and Engineering*[J], 2023, 52(4): 1352 (in Chinese)

30 Yan Taiqi, Chen Bingqing, Liang Jiayu *et al. Laser & Optoelectronics Progress*[J], 2022, 59(17): 327

加热温度和热处理对TC4钛合金热自压连接接头组织和性能的影响

李会朝[1]，梁凯铭[2]，潘　睿[1]，朱晓腾[1]，姜炳鑫[1]，陶虎威[1]，李志航[1]，胡正根[2]，张　华[1]

(1. 北京石油化工学院 机械工程学院，北京 102617)

(2. 北京宇航系统工程研究所，北京 100076)

摘　要：采用自行设计的感应线圈、刚性拘束工装与实验室现有感应加热装置结合，以5 mm厚TC4钛合金为母材进行局部感应加热刚性拘束热自压扩散连接（TSCB），探究了不同加热温度和热处理对接头微观组织和力学性能的影响。结果表明，加热温度过低（900 ℃）会导致原子扩散不充分，加热温度过高（990 ℃，超过$\beta\rightarrow\alpha$相变温度）会形成的粗大魏氏体组织，导致接头力学性能降低。随着温度的升高，热拘束应力场对接头施加的压力先升高后降低，接头的连接质量也先升高后降低。只有加热温度为950 ℃即稍低于$\beta\rightarrow\alpha$相变温度时，组织分布最均匀，等轴α相晶粒最明显，且原子扩散更充分，应力场对接头施加的压力最高，接头力学性能最好。经650 ℃/3 h退火热处理后，发生了$\alpha\rightarrow\beta$相变，晶格的畸变程度降低，晶粒细化。TSCB接头残余应力状态由拉应力转变为压应力。残余应力显著降低，应力得到释放，从而提高了TSCB接头的力学性能，解决了TSCB接头塑性较低的问题。

关键词：TC4钛合金；热自压扩散连接；热处理；显微组织；力学性能

作者简介：李会朝，男，1999年生，硕士，北京石油化工学院机械工程学院，北京 102617，E-mail：lihuizhao123@foxmail.com