Effect of Electron Beam Power on Rigid-Constraint Thermo-Self-Pressure Joining, Joint Microstructure, and Mechanical Properties of TC4 Alloy (Postprint)

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Abstract

Using an electron beam as the heat source, rigid constraint thermal self-pressure bonding of TC4 titanium alloy was performed with different beam powers. The interface bonding quality, microstructure, and mechanical properties of the joints were tested and analyzed. Simultaneously, based on experimental results, finite element numerical analysis of the thermal stress and strain process during rigid constraint thermal self-pressure bonding was conducted. The influence of beam power on the interface bonding quality, microstructure, and properties of the joints was analyzed through a combination of experimental research and numerical simulation. The results show that as beam power increases, the heating temperature, dwell time in the high-temperature zone, volume of the high-temperature zone, and compressive plastic deformation of the interface metal increase accordingly, which promotes atomic diffusion across the interface and improves interface bonding quality. Beam power significantly affects the microstructure of the joints. When heated with low beam power, joints with uniform microstructure can be obtained. When heated with high beam power, acicular α phase forms in the interface heat-affected zone, and the misorientation of α/α phase boundaries is primarily located near 59.85°, exhibiting characteristics of formation within the same β phase grain. The mechanical properties of the joints are jointly influenced by the interface bonding ratio and the microstructure of the heat-affected zone. At low beam power, numerous unbonded defects exist at the interface, resulting in low bonding strength. At high beam power, significant microstructural transformation occurs in the heat-affected zone, with coarse grains, leading to poor joint ductility. When the beam power is 330 W, the joint exhibits uniform microstructure and good interface bonding quality, obtaining a joint with excellent comprehensive mechanical properties.

Full Text

Effect of Electron Beam Power on Rigid Restraint Thermal Self-Compressing Bonding, Microstructure, and Mechanical Properties of TC4 Alloy Joints

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Abstract

Rigid restraint thermal self-compressing bonding is a new solid-state bonding process. During the process, localized non-melted heating method is employed to heat the butted interface of the rigid restrained plates to be bonded. Under the localized heating, materials close to the butted interface are expanded. However, due to the existence of surrounding cool metals and rigid restraints, the expansion of the high temperature materials is restrained and thus, a compressive pressure is developed which compresses the high temperature metals near the bond interface and facilitates the atom diffusion between butt-weld specimens to produce a permanent solid-state joint. Utilizing the localized stress-strain field to accomplish atomic bonding, this process can avoid the use of external forces on which diffusion bonding and other solid-state bonding methods rely. Previous study has proven the feasibility of this process to join titanium alloys.

In present work, the effect of beam power on bond interface, microstructure, and mechanical properties of the TC4 joints bonded at different beam powers were analyzed through OM observation, EBSD analysis, mechanical property test, and fracture morphology analysis. Meanwhile, in order to reveal the mechanism about the effect of beam power on bond interface, the experimental study on microstructure and mechanical property and finite element analysis on present bonding were conducted to investigate the effect of beam power on the thermal stress-strain process during bonding. The results show that with the increase of beam power, the heating temperature, dwell time over high temperature, volume of materials with high temperature, and the compressive plastic strain increase, which promote the atom diffusion and thus bond quality of the interface is improved. At low beam power, the microstructure of the joints is homogeneous, while coarse grain with acicular α-phase forms in the joint when the beam power is high. Mechanical properties of the joint are dependent on bond rate and microstructure. When the beam power is lower or higher, the compressive mechanical properties of the joints are poor because of the poor bonding quality of the interface or the coarse microstructure developed in the joint. Good comprehensive mechanical properties are obtained at the beam power of 330 W.

KEY WORDS thermal self-compressing bonding, thermal stress-strain process, beam power, microstructure, mechanical property

Introduction

In conventional fusion welding with concentrated heat sources, the high-temperature thermal cycle causes melting and solidification, leading to cast microstructures and defects such as pores and cracks in the joints. These defects result in non-uniform microstructure and mechanical properties, adversely affecting the comprehensive mechanical performance of the joints [1–4]. To address this issue, our research group previously proposed a solid-state joining method—rigid restraint thermal self-compressing bonding—which transforms concentrated heat source melting heating into non-melting heating to achieve solid-state joining of materials, thereby avoiding the formation of cast microstructures and defects [5]. The fundamental principle of rigid restraint thermal self-compressing bonding utilizes concentrated heat source non-melting local heating on the interface of rigidly restrained materials. Due to the presence of surrounding cool metal and rigid restraints, the expansion of high-temperature metal at the interface is constrained, generating thermal compressive stress that extrudes the metal in the thermoplastic state at the interface and promotes atomic diffusion across the interface, thereby achieving solid-state bonding [5]. During the joining process, no external force is required; instead, the thermal restraint stress-strain field formed by non-melting local heating produces self-extrusion on the thermoplastic metal at the bonding zone.

Previous research [5] used an electron beam as the heat source to perform rigid restraint thermal self-compressing bonding on TC4 titanium alloy, obtaining joints with uniform microstructure and excellent comprehensive mechanical properties, thereby verifying the feasibility of the principle. Additionally, studies on element distribution in TA2/TC4 dissimilar material joints proved the existence of atomic diffusion effects during the bonding process [6].

As the principle indicates, the realization of rigid restraint thermal self-compressing bonding depends on the thermal extrusion effect of the thermal restraint stress-strain field generated by non-melting local heating on the bonding interface. When using an electron beam heat source for non-melting heating, changes in beam power inevitably alter the thermal restraint stress-strain field during bonding and the thermal extrusion effect at the interface, thereby affecting the interface bonding quality, microstructure, and properties of the joint. This work selected different beam powers to conduct rigid restraint thermal self-compressing bonding experiments on TC4 titanium alloy. Through optical microscope observation of the bonding interface, electron backscatter diffraction (EBSD) analysis of joint microstructure, and tensile mechanical property testing, the effects of beam power on bonding quality, microstructure, and properties were analyzed. Meanwhile, based on experimental results, finite element numerical analysis was employed to investigate the influence of beam power on the thermal stress-strain process during rigid restraint thermal self-compressing bonding, elucidating the reasons for the effect of beam power on the bonding process and joint properties.

1. Experimental Methods

The experimental material was 5 mm thick TC4 alloy with a nominal chemical composition (mass fraction) of 5.5%–6.8% Al (α-phase stabilizing element), 3.5%–4.5% V (β-phase stabilizing element), impurity elements Fe $ $0.3%, N $ $0.05%, C $ $0.1%, H $ $0.015%, and Ti balance [7]. The bonding specimen dimensions were 59 mm × 50 mm. Based on research on titanium alloy diffusion bonding, smoother bonding interfaces facilitate the diffusion bonding process [8,9]. Therefore, before rigid restraint thermal self-compressing bonding, the bonding surfaces of specimens were precision machined and acid-cleaned to remove surface grease and oxide contaminants. The acid solution composition was $HF:HNO_3:H_2O = 5:20:75$ (volume ratio). The specimens were then butt-assembled and clamped as shown in Figure 1 [Figure 1: see original paper].

The fundamental principle of rigid restraint thermal self-compressing bonding is illustrated in Figure 1. During the experiment, an electron beam heat source was used for heating, and a ZD150-15MH CV3M vacuum electron beam welding machine was employed for TC4 titanium alloy rigid restraint thermal self-compressing bonding experiments. To achieve sufficient thermal extrusion effect, the electron beam multi-beam control system was utilized to scan and heat along the butt interface. The scanning length was equal to the plate width of 50 mm, and the scanning frequency was 100 Hz.

The heat source power P is the product of electron beam voltage U and beam current I . In the experiments, U was fixed at 150 kV while I was varied to analyze the effect of P on rigid restraint thermal self-compressing bonding. The experimental parameters are listed in Table 1 .

2. Results

2.1 Bonding Interface After completing the rigid restraint thermal self-compressing bonding, cross-sectional specimens of the bonding interface were cut by machining and subjected to grinding, polishing, and etching. The etching solution composition was HF:HNO_3:H_2O = 5:10:85 (volume ratio). Metallographic specimens were prepared and examined using a DM6000M optical microscope (OM) to observe unbonded defects and joint microstructure at the bonding interface, while EBSD analysis was also performed on the joint microstructure.

According to GB2651-2008, three tensile test specimens each for base metal and bonded joints were prepared with dimensions shown in Figure 2 [Figure 2: see original paper]. A Zwick Z100 electronic universal material testing machine was used to test the mechanical properties of the base metal and joints, with results taken as the average of three specimens. A 250FEG scanning electron microscope (SEM) was used to analyze the fracture surfaces of tensile specimens from the base metal and joints.

A Proto iXRD stress analyzer was used to measure the transverse and longitudinal residual stresses in the TC4 alloy rigid restraint thermal self-compressing bonding joints. Measurement points were located on the upper surface along the centerline perpendicular to the butt interface. The thermal cycle during bonding at the center point of the butt line on the lower surface was measured using the thermocouple method with a B-type thermocouple.

The TC4 alloy rigid restraint thermal self-compressing bonding interfaces obtained at different beam powers are shown in Figure 3 [Figure 3: see original paper]. When the beam power was 270 W (Figure 3a), numerous unbonded defects existed at the interface, resulting in poor interface bonding quality. When the beam power increased to 330 W (Figure 3b), the original butt line disappeared with only a few small unbonded holes remaining, indicating good interface bonding quality. When the beam power further increased to 780 W (Figure 3c), the original butt line completely disappeared, new grains formed at the interface that traversed the original butt line, and no obvious unbonded defects were observed, demonstrating excellent interface bonding quality. Evidently, beam power significantly affects interface bonding quality; as beam power increases, unbonded holes at the interface decrease and bonding quality improves.

2.2 Joint Microstructure The microstructure of TC4 alloy base metal is shown in Figure 4 [Figure 4: see original paper], revealing that the base metal consists of equiaxed α-phase and transformed β-phase microstructure.

The microstructures of the interface heating zone in rigid restraint thermal self-compressing bonding joints at different beam powers are shown in Figure 3. As seen in Figures 3a and 3b, when beam powers were 270 W and 330 W, the interface zone microstructure consisted of equiaxed α-phase and β-phase transformed structure, similar to the base metal without significant transformation. When the beam power was 780 W, the joint heating zone microstructure consisted of acicular α-phase and grain boundary α-phase with coarse grains, significantly different from the base metal microstructure. Thus, beam power significantly affects the microstructure of rigid restraint thermal self-compressing bonding joints during the joining process.

To further determine the effect of beam power on joint microstructure characteristics, EBSD analysis was performed on the base metal and joint interface zones at beam powers of 330 W and 780 W. The grain orientation distribution maps are shown in Figure 5 [Figure 5: see original paper]. The results show that at a heating power of 330 W, the grain orientation distribution in the joint bonding zone was similar to that of the original base metal without significant change. At a beam power of 780 W, coarse grains existed near the joint interface bonding zone, and the coarse grains exhibited orientation features of parallel or cross distribution inside the grains, which were distinctly different from the base metal grain orientation characteristics, indicating significant changes in grain orientation distribution.

The statistical results of α-phase misorientation angle distributions in the TC4 alloy base metal and joint interface bonding zones at beam powers of 330 W and 780 W are shown in Figure 6 [Figure 6: see original paper]. As shown in Figure 6a, the base metal grain misorientation distribution was mainly concentrated near 6.45°, 59.85°, and 86.55°. At a beam power of 330 W, the misorientation distribution in the joint interface zone was similar to that of the base metal, with only slight changes in proportions. At a beam power of 780 W, the misorientation distribution in the joint interface zone was mainly located near 59.85°, with a significantly increased proportion compared to the base metal. Meanwhile, the proportions near 6.45° and 77.65° decreased, and misorientations near 33.15°, 42.05°, and 86.55° disappeared.

According to literature [10], when β-phase transforms to α-phase, the formation of α/α boundaries occurs in three cases: α/α boundaries generated within the same α-phase grain, α/α boundaries generated within the same β-phase grain, and α/α boundaries generated from two different β-phase grains. The corresponding misorientation angles differ for each case: when α/α boundaries are generated within the same α-phase grain, misorientation angles are mainly in the range of 2.00°–8.03°; when generated within the same β-phase grain, misorientation angles are mainly in the ranges of 8.03°–13.03°, 57.50°–65.76°, and 87.50°–92.50°; and when generated from two different β-phase grains, misorientation angles are mainly in the ranges of 13.03°–57.50°, 65.76°–87.50°, and 92.50°–94.00°.

Therefore, based on the misorientation distribution results, compared with the base metal, when the beam power was 330 W, no obvious change occurred in TC4 alloy grain orientation before and after rigid restraint thermal self-compressing bonding, indicating minimal effect on the original microstructure at this power. When the beam power was 780 W, the formation mechanism of α/α boundaries in the joint interface heating zone changed significantly, showing a marked reduction in boundaries generated from the same α-phase grain and from two different β-phase grains, with most boundaries being generated from within the same β-phase grain.

2.3 Joint Mechanical Properties The mechanical property test results of TC4 alloy rigid restraint thermal self-compressing bonding joints at different beam powers are listed in Table 2 . At a low beam power of 270 W, the tensile strength was 405.1 MPa, only 40.5% of the base metal tensile strength, indicating low joint strength. The tensile specimen fractured at the bonding interface, and the fracture morphology is shown in Figure 7a [Figure 7: see original paper]. The fracture surface was flat, with numerous unbonded hole defects and parallel groove-like unbonded defects (continuous unbonded defects) on the interface. When the beam power increased to 330 W, both the tensile strength and elongation of the joint improved to levels comparable with the base metal. The tensile specimen fractured in the base metal (Figure 7b), exhibiting numerous dimples and characteristic ductile fracture features. When the beam power further increased to 780 W, the joint tensile strength remained comparable to the base metal, but the elongation decreased significantly compared to the base metal. The tensile specimen fractured in the heated zone near the interface (Figure 7c), showing mixed fracture characteristics of cleavage fracture with few dimples and tearing features.

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3. Finite Element Numerical Analysis

The thermal self-compressing effect that enables atomic diffusion bonding during rigid restraint thermal self-compressing bonding varies with process parameters. This work employed a thermal elastoplastic finite element model to analyze the thermal stress-strain process of rigid restraint thermal self-compressing bonding under different beam powers. Considering the symmetry of the problem (Figure 1), one-half of the geometry was used for three-dimensional numerical simulation analysis. The mesh near the butt interface is shown in Figure 8 [Figure 8: see original paper], with a minimum element size of 1 mm × 1 mm × 0.5 mm. Sparse mesh was used in regions farther from the interface to balance solution accuracy and computational efficiency.

In the temperature field analysis, the material was assumed to be isotropic, and the entire thermal process was simulated using heat conduction. Temperature-dependent thermophysical properties were selected, with relevant values taken from reference [11]. Regarding heat source model selection, although conical heat source models [12], rotating Gaussian body heat sources [13,14], and combined heat sources [15,16] have been developed for electron beam deep penetration welding to account for the keyhole effect, the electron beam heat source in rigid restraint thermal self-compressing bonding is non-melting heating where heat transfers from the workpiece upper surface throughout the specimen. Therefore, the Gaussian heat source model better reflects the actual heat transfer characteristics. Considering the electron beam scanning heating effect, an elongated Gaussian surface heat source was selected in the model, as illustrated in Figure 9 [Figure 9: see original paper]. The heat source expression is:

$$q = \frac{\eta P}{l\sqrt{\pi}R} \exp\left(-\frac{y^2}{R^2}\right)$$

where q is the heat flux density, is the heat source efficiency, l is the length of the elongated Gaussian surface heat source (i.e., scanning length), R is the effective action radius of the Gaussian heat source, and y is the distance from different positions on the heat source heating surface to the butt interface.

A thermo-mechanical sequential coupling method was used to calculate the rigid restraint thermal self-compressing thermal stress-strain process. The material yielding in the calculation followed the von Mises criterion. The material was assumed to be isotropic, with temperature-dependent thermomechanical property parameters selected from references [7,17].

For a beam power of 330 W, the experimentally measured and finite element numerically analyzed results of the thermal cycle and joint residual stress during TC4 alloy rigid restraint thermal self-compressing bonding are shown in Figure 10 [Figure 10: see original paper]. Compared with experimental measurements, the numerical simulation results of thermal cycles and residual stress distributions show the same distribution trends, though with slight numerical differences, mainly due to experimental measurement errors and assumptions about material properties and heat source form in the numerical model that differ from actual conditions.

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4. Discussion

4.1 Effect of Beam Power on Thermal Stress-Strain Process The thermal cycles at different positions on the butt surface during TC4 alloy rigid restraint thermal self-compressing bonding at different beam powers are shown in Figure 11 [Figure 11: see original paper]. As shown in Figure 11a, when the beam power was 270 W, the peak temperature at point P1 (midpoint of the butt line on the upper surface) was 932.4°C. At 330 W, the peak temperature at P1 was 1029.5°C, near the β-phase transformation temperature of TC4 alloy. When the beam power increased to 780 W, the peak temperature at P1 was 1603.5°C, approaching the melting point of TC4 material. Evidently, beam power significantly affects the peak temperature during rigid restraint thermal self-compressing bonding; higher beam power results in higher peak temperature, primarily because increased beam power delivers more heat into the workpiece. Points P2 (midpoint of the bond interface) and P3 (midpoint of the butt line on the lower surface) exhibited the same trend.

Additionally, Figure 11 shows that as beam power increases, the high-temperature dwell time (>800°C) of interface metal increases. Taking the central point of the bonding interface P2 as an example, the high-temperature dwell times were approximately 30.8 s and 84.0 s at beam powers of 270 W and 330 W, respectively. When the beam power increased to 780 W, the high-temperature zone dwell time increased to 137.5 s.

The temperature distributions on the cross-section perpendicular to the butt interface (x=0 plane) at a heating time of 150 s under different beam powers are shown in Figure 12 [Figure 12: see original paper]. The results show that under non-melting scanning heating by the electron beam heat source, the temperature distribution along the butt plate length is non-uniform with obvious temperature gradients. Meanwhile, as beam power increases, the volume of high-temperature zone (>800°C) metal significantly increases due to more heat input into the workpiece. When beam power increased to 780 W, metal within 20 mm of the butt interface was in the high-temperature zone favorable for atomic diffusion.

The evolution of transverse stress and strain at the central point of the TC4 alloy butt interface (P2) during non-melting heating at different beam powers is shown in Figure 13 [Figure 13: see original paper]. As shown in Figure 13a, at a beam power of 270 W, the transverse stress remained in a compressive state during heating because significant temperature gradients existed during the bonding process (Figure 12). Metal near the interface had high temperature, and its expansion was constrained by surrounding cool metal, resulting in corresponding transverse compression that generated compressive elastic and subsequent compressive plastic strain, making the transverse stress compressive. Additionally, in the early heating stage, the thermal extrusion effect increased significantly with temperature, causing the transverse compressive stress to increase correspondingly. At 54.7 s, the transverse compressive stress reached its peak value of -246.7 MPa. Subsequently, as material strength decreased with increasing temperature, the transverse compressive stress gradually decreased, reaching -91.5 MPa at the end of heating. However, the transverse compressive plastic strain continued to increase during heating due to the thermal extrusion effect on high-temperature metal at the interface, reaching -0.089 at the end of heating. During cooling, the contraction of high-temperature metal at the interface was constrained by surrounding metal, causing deformation incompatibility and tensile action on the interface metal. The compressive elastic strain gradually transformed into tensile elastic strain, and the transverse stress changed from compressive to tensile gradually, ending as residual tensile stress at the completion of bonding. During cooling, the transverse compressive plastic strain remained essentially unchanged, mainly because titanium alloy material has a small “limit plastic deformation ratio,” making it difficult to yield during cooling, and only elastic unloading occurs in the later cooling stage, leaving the plastic deformation unchanged to room temperature [18,19].

At beam powers of 330 W and 780 W (Figures 13b and 13c), the evolution of thermal stress and strain during bonding showed the same pattern as at 270 W, but with obvious differences in the time and magnitude of peak compressive stress during heating. At 330 W, the compressive stress reached its peak of

-235.7 MPa at 36.7 s of heating, while at 780 W, the peak compressive stress of -155.1 MPa occurred at 9.6 s of heating. The results show that as beam power increases, the time required to reach peak compressive stress decreases and the peak compressive stress magnitude also decreases, mainly due to two factors: material strength variation with temperature and the thermal extrusion effect changing with beam power. The thermal extrusion effect strength is influenced by two aspects: temperature gradient and heated metal volume. At a heating time of about 10.1 s, the transverse temperature distributions along the TC4 alloy butt interface center point under non-melting heating at different beam powers are shown in Figure 14 [Figure 14: see original paper]. At 780 W, due to the high beam power, metal at the butt interface heated rapidly, creating obvious temperature gradients along the transverse direction. Under this temperature gradient, the interface metal experienced strong thermal extrusion. As shown in Figure 13c, the transverse thermal self-compressing stress on the interface at this moment was about -155 MPa, reaching the material yield strength at the corresponding temperature. As temperature continued to rise, material yield strength decreased, causing the compressive stress to decrease accordingly, but compressive plastic deformation began to appear and gradually increased. At beam powers of 270 W and 330 W, as shown in Figure 14, the temperature gradients at this moment (about 10 s heating time) were significantly smaller than at 780 W, resulting in insufficient thermal extrusion effect. The compressive stresses were -53.6 MPa and -65.7 MPa, respectively (Figures 13b and 13c), which were lower than the material tensile strength at the corresponding temperatures. As heating continued for both beam powers, the temperature gradients and heated metal range increased further. For the 330 W case, although the temperature gradient was slightly lower than at 780 W at the time when compressive stress reached its peak (36.7 s, temperature distribution shown in Figure 15 [Figure 15: see original paper]), the heated metal volume was larger, making the thermal extrusion effect sufficient to cause interface metal yielding. Because the beam power was smaller, the temperature at this moment was about 651.8°C, lower than the temperature corresponding to the maximum stress moment at 780 W (733.2°C). At lower temperatures, material yield strength is higher, so the maximum peak compressive stress at 330 W was greater than at 780 W. At 270 W, because the beam power was even smaller, it took about 54.7 s of heating to achieve thermal extrusion sufficient to cause material yielding, with the corresponding interface temperature also being lower, resulting in an even greater peak compressive stress.

4.2 Effect of Beam Power on Interface Bonding Quality According to diffusion bonding void closure theory, the diffusion bonding process can be regarded as a void closure process, where increases in diffusion bonding temperature, pressure, and time all promote void closure [20–23]. Rigid restraint thermal self-compressing bonding also relies on atomic diffusion effects to achieve atomic-level bonding across the interface and realize solid-state joining. Based on numerical analysis results at the bonding interface center point (P2), at 270

W, although the interface metal experienced relatively high compressive stress favorable for atomic diffusion across the interface, the high-temperature dwell time was short, with only about 30 s above 800°C. Consequently, atomic diffusion across the interface was limited during heating, resulting in numerous unbonded defects at the interface. When beam power increased from 270 W to 330 W, the overall transverse compressive stress decreased slightly, but heating temperature, high-temperature dwell time, high-temperature zone range, and compressive plastic strain at the interface all increased significantly, correspondingly promoting atomic diffusion across the butt interface and accelerating void closure, thereby improving interface bonding quality. When beam power increased from 330 W to 780 W, the transverse compressive stress decreased more noticeably, but heating temperature, high-temperature dwell time, and high-temperature zone range all increased substantially. Particularly, the heating temperature exceeded the β-phase transformation temperature of TC4 alloy, where alloy element diffusion speed in the β-phase is much greater than in the α-phase [24]. Therefore, void closure speed increased, and voids completely disappeared after bonding, further improving interface bonding quality.

4.3 Effect of Beam Power on Joint Microstructure The microstructure of TC4 alloy welded joints 主要取决于连接过程中热循环. During heating, when temperature exceeds the β-phase transformation temperature (995$±$15°C), the original $\alpha+\beta$ phase in the base metal completely transforms to β-phase microstructure. Due to the poor thermal conductivity and large heat capacity of titanium alloy, the fully β-phase temperature zone has fast atomic diffusion speeds, and β-phase microstructure easily grows rapidly above the transformation temperature, forming coarse β grains. During subsequent cooling, when cooling speed is slow, the β-phase transforms to α-phase through atomic diffusion, generating lamellar or acicular α-phase, and β grain boundaries transform to grain boundary α-phase microstructure, preserving the original β grain morphology to room temperature. When cooling speed is fast, the β-phase transforms to acicular martensitic α' microstructure through shear transformation [25].

At a beam power of 270 W, the peak temperature of the bonding process was 932.4°C, below the $\alpha+\beta\rightarrow\beta$ transformation temperature. Because alloy element diffusion speed in the α-phase is slow and boundary phases have an inhibiting effect, grain growth was slow during heating, and the short heating time in rigid restraint bonding prevented obvious microstructural transformation. Consequently, the joint heating zone microstructure at room temperature was similar to the base metal microstructure, yielding a relatively uniform joint microstructure.

At a beam power of 330 W, the heating peak temperature was 1029.5°C, slightly above the $\alpha+\beta\rightarrow\beta$ transformation temperature, but the entire joint remained below the β transformation temperature. The microstructure did not completely transform to β-phase during heating, and the cooled microstructure was similar to the base metal, with no significant changes in grain orientation distribution or misorientation angles.

At a beam power of 780 W, the peak temperature approached the material melting point, and the temperature at the butt interface center on the lower specimen surface reached 1340.6°C, with long dwell time above the β-phase temperature. The heating zone near the interface completely transformed to coarse β-phase grains. During subsequent cooling, according to the thermal cycle curves, the cooling rate was slower than furnace cooling but faster than air cooling. The β-phase transformed to α-phase through atomic diffusion, generating acicular α-phase. Because the β grains were coarse, numerous α-phase variants with different orientations formed within the same β-phase grain during the $\beta \rightarrow \alpha$ transformation. Therefore, at room temperature, the α/α phase misorientation distribution showed concentration near 59.85°, exhibiting the characteristic of α/α interfaces generated within the same β grain.

4.4 Effect of Beam Power on Joint Mechanical Properties The mechanical properties of rigid restraint thermal self-compressing bonding joints depend on both joint microstructure and unbonded defects. At 270 W, although the joint microstructure was uniform, numerous unbonded defects existed at the interface. During tensile loading, these unbonded defects reduced the effective bearing area, causing the actual stress at the interface to be high. When this exceeded the bonding strength, fracture occurred with little plastic deformation before failure, resulting in low strength and poor elongation. At 330 W, the joint not only had uniform microstructure but also significantly improved interface bonding quality with only tiny unbonded holes, leading to excellent mechanical properties. At 780 W, although interface bonding quality was good, the grains near the interface heating zone were coarse and the joint microstructure was non-uniform. During tensile testing, this caused severe deformation incompatibility compared with the base metal, leading to non-uniform stress-strain fields. When the stress peak reached the fracture strength level, local fracture occurred, followed by unstable crack propagation until final fracture. No obvious necking occurred during the fracture process, resulting in small elongation.

Conclusions

1. During rigid restraint thermal self-compressing bonding of titanium alloy, as electron beam power increases, the heating temperature of interface metal, high-temperature dwell time, high-temperature zone volume, and transverse compressive plastic deformation all increase, thereby promoting atomic diffusion across the interface, reducing unbonded defects, and improving interface bonding quality.
2. Electron beam power variation significantly affects joint microstructure. At low beam power, the heating peak temperature is below the β-phase

transformation temperature, the interface zone microstructure is similar to the base metal, and the joint microstructure is relatively uniform. At high beam power, the interface zone metal temperature exceeds the β-phase transformation temperature, generating acicular α-phase microstructure in the interface zone with coarse grains. The α/α interfaces are generated within the same β-phase grain, resulting in non-uniform joint microstructure.

3. Due to the combined influence of interface bonding quality and heating zone microstructure, the comprehensive mechanical properties of thermal self-compressing bonding joints first increase and then decrease with increasing beam power. At low beam power, although the joint microstructure is uniform, numerous unbonded defects at the interface result in low bonding strength. At a beam power of 330 W, the joint has uniform microstructure and good interface bonding quality, yielding excellent comprehensive mechanical properties. At higher beam power, although interface bonding quality is good, significant microstructural transformation occurs in the heating zone with coarse grains, resulting in poor joint ductility.

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