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ARTICLE

Microstructure Evolution and Super-Diffusion Mechanism of Weld Zone of Dissimilar Titanium Alloys After Linear Friction Welding

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Abstract: The microstructure evolution and super-diffusion mechanism of weld zone of TC11 and TC17 dissimilar titanium alloys after linear friction welding under different frictional pressures (22–47 MPa) were investigated. The joint microstructure was analyzed by scanning electron microscope, and the atomic concentration near the joint interface was analyzed by electron probe. Results show that the temperature in the weld zone exceeds the β-phase transition temperature, the temperature of the joint drops rapidly after welding, and the weld microstructure changes to a fully recrystallized microstructure. Super-diffusion of atoms occurs at the joint interface, and the diffusion coefficient of typical atoms is about 100 times higher than that of diffusion welding atoms. Within the experiment parameter range, increasing the frictional pressure can extend the diffusion distance of typical atoms.

Key words: linear friction welding; dissimilar Ti alloys; microstructure; interface; super-diffusion

Integral bladed-disks (blisks), as a complex and critical part of gas turbine engine, are usually made of titanium or nickel alloys. Because the blades and disks need to suffer different loads under service conditions, they are usually made of different metal materials for the optimal performance. The blade usually suffers high cycle fatigue and high temperature and the disk suffers low cycle fatigue[1]. Joining dissimilar Ti alloys has been widely applied in industrial applications, particularly in the manufacture of integral blisks by linear friction welding (LFW). The structural strength of integral blisks prepared by LFW increases and the mass reduces. However, the connection mechanism at LFW interface of dissimilar titanium alloys is still obscure. LFW is a solid phase welding process to join dissimilar alloys. The friction between the two base metals (BMs) results in sufficient heat to soften the materials at the friction interface. The friction interface produces a thermoplastic area, where the atoms are fully activated and can diffuse rapidly across the interface. Besides, the dynamic recrystallization usually occurs in a narrower region near the interface[2–5].

Wanjara et al[6] investigated the LFW joint microstructure of Ti-6Al-4V (TC4) alloy and concluded that the welding temperature exceeds the β-transus temperature, thus forming martensitic/acicular α phase at the weld line (WL). Daymond[7] and Preuss[8] et al observed the LFW joints of TC4 and IMI550 alloys, respectively. Large residual tensile stresses with a significant hydrostatic tensile stress exist in the weld zone (WZ), which can be released after the optimized post weld heat treatments. Daymond et al[7] also indicated the presence of textured zones through the grain reorientation during welding. Ma et al[9] investigated the formation mechanism of LFW joint of TC4 alloys and concluded that the dynamic recovery and recrystallization resulting from the severe plastic deformation and fast heating/cooling processes during LFW lead to the superfine $\alpha+\beta$ grains in the weld center. Romero et al[10] studied the effect of forging pressure on the microstructure of LFW joint of TC4 alloy and found that a strong α-Ti texture is generated in WL and it can be reduced by increasing the weld pressure.

TC11 and TC17 titanium alloys are widely used in gas

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turbine compressors due to their good mechanical properties, high specific strength, and excellent corrosion resistance in the medium temperature range. Through the investigations about the effect of heat treatment on the microstructure and impact toughness as well as the thermal deformation mechanism of TC11/TC17 LFW joint[11–14], it is found that the microhardness difference on each side of the joint narrows significantly, and the impact toughness of the joint is improved sharply by 200%. The low angle grain boundaries and the mean density of geometrically necessary dislocations are increased with increasing the compression strain.

In this research, the diffusion behavior of interfacial elements and the effect of frictional pressure on the diffusion behavior were investigated, providing research basis for the joint formation mechanism of LFW.

1 Experiment

The base materials were TC11 and TC17 titanium alloys with composition of Ti-6.5Al-3.5Mo-1.5Zr-0.3Si (wt%) and Ti-5Al-2Sn-2Zr-4Mo-4Cr (wt%), respectively. The nominal β-transus temperature of TC11 and TC17 alloys was 1000 and 890 °C, respectively. Fig.1 shows the microstructures of TC11 and TC17 BMs observed by scanning electron microscope (SEM). As shown in Fig.1a, the microstructure of TC11 BM consists of equiaxed lamellar prior-α and intergranular transformed β phases. The binary-state microstructure of TC17 BM consists of equiaxed secondary α and lamellar β transformation structures, as shown in Fig.1b. The friction surface of the specimens was machined into rectangular shape with 75 mm in length and 20 mm in width. Before LFW, the specimen surfaces were polished by grinding machine and cleaned by acetone to remove the greasy dirt. The friction pressures were set as 20, 33, and 47 MPa, the oscillation frequency was 30 Hz, the friction time was 5 s, and the friction amplitude was 3 mm.

In order to study the element diffusion behavior at the joint interface, the cross-sections of weld joints were cut for observation, and the electron probe microanalysis (EPMA) was used to detect the element concentrations at the joint interface and both sides of BMs. SEM and optical microscope (OM) were used for microstructure observation.

2 Results and Discussion

2.1 WZ microstructure

Fig.2 shows the appearance of the joints at different friction pressures. As shown in Fig.2, obvious flash can be observed on both sides of the joints, and the flash length is decreased with decreasing the friction pressure. The friction with different pressures generates different amounts of heat at the joint interface, thereby influencing the LFW joints. The average power input (w) can be used to characterize the process parameters[15], as follows:

$$w = \frac{afP}{2\pi A} \tag{1}$$

where a, f, P, and A are the oscillation amplitude, oscillation frequency, friction pressure, and cross-section area of the weld joint, respectively. According to Eq.(1), the higher the friction pressure, the larger the power input and the more the high thermoplastic metal generated and expelled at the weld interface (Fig.2).

Fig. 3 shows SEM microstructures of LFW joints under different friction pressures. It can be seen that the microstructure of LFW joints can be divided into several distinct regions[5]: BM, thermo-mechanically affected zone (TMAZ), and WZ. The WZ width of LFW joints under different friction pressures is shown in Fig.4. With decreasing the friction pressure from 47 MPa to 20 MPa, the WZ width is increased from 380 μm to 700 μm, which is similar to the simulation and experiment results in Ref.[16]. The reduced WZ width at high friction pressure can be ascribed to the less plastic metal extruded by higher friction pressure.

Fig.5 shows the typical WZ microstructures of LFW joint interface between TC11 and TC17 BMs under different friction pressures. It can be seen that they all consist of

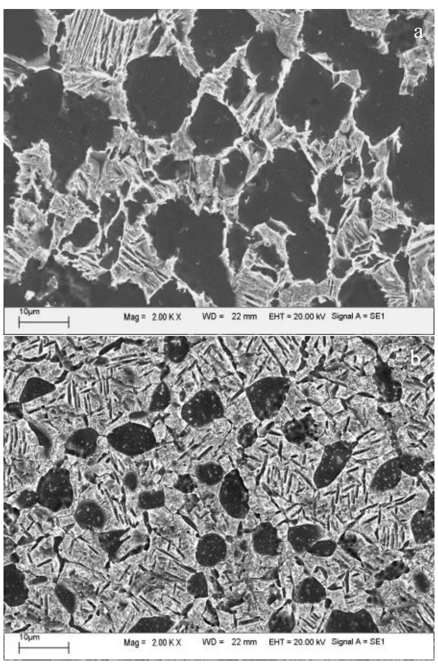

Fig.1 SEM microstructures of TC11 (a) and TC17 (b) BMs

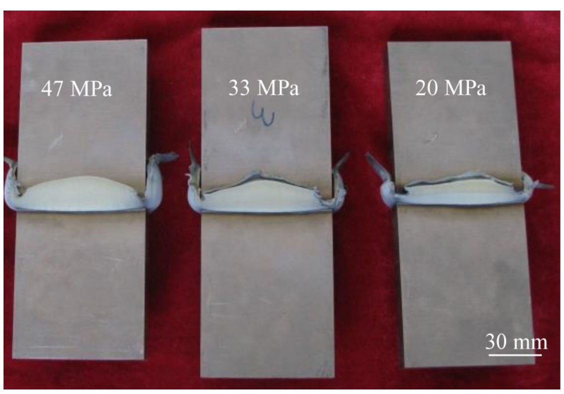

Fig.2 Appearance of LFW joints under different friction pressures

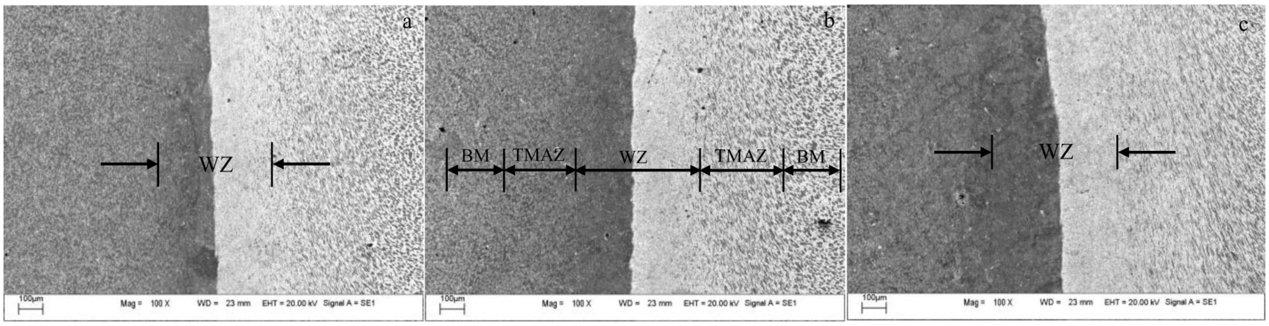

Fig.3 SEM microstructures of LFW joints under different friction pressures: (a) 47 MPa, (b) 33 MPa, and (c) 20 MPa

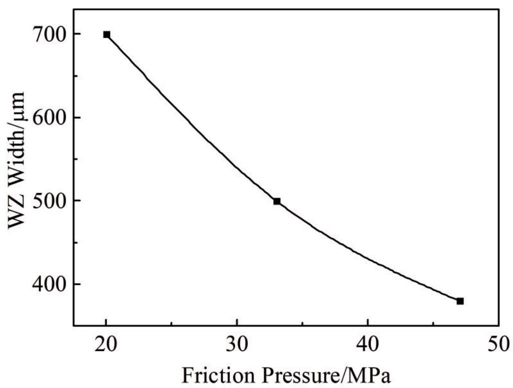

Fig.4 Effect of friction pressure on WZ width

recrystallized grains and intergrowth grains. The WZ microstructure near TC11 BM is mainly composed of acicular martensite phase with Widmanstaten structure, and that near TC17 BM consists of metastable β grains. The fully recrystallized microstructure in all joints indicates that the WZ temperature exceeds the β-transition temperature during LFW.

2.2 Super-diffusion behavior of LFW joint

EPMA quantitative analysis of elements at the weld interface under different friction pressures is shown in Fig.6. All joint interfaces exhibit obvious element interdiffusion transition zones. The LFW joint under friction pressure of 47 MPa has the largest width of interdiffusion zone as 8−10 μm. The width of the weld interdiffusion zone under friction pressure of 33 and 20 MPa is 6−8 and 4−6 μm, respectively. According to Eq.(1), the increasing friction pressure results in increasing power input, which leads to higher temperature at the joint interface. The higher the temperature, the larger the thermal activation energy of the elements. Therefore, the elements migrate more easily and the diffusion coefficient of atoms is larger. The element diffusion lengths in LFW joints under friction pressure of 47, 33, and 20 MPa are about 10, 8, and 6 μm, respectively.

Thermocouples were used to measure the temperature at characteristic points of joints during LFW process. The characteristic points are located at the width side of the specimen. With LFW process proceeding, the measurement points slowly approach the friction interface. After LFW, the temperature measurement point is located at the friction interface, and the relationship between the maximum temperature of the interface and the temperature after welding can be obtained, as shown in Fig.7. It is known that there are three different stages of temperature change in LFW process. At the rising stage, the temperature of joint interface increases rapidly from room temperature to peak temperature of about 1160 °C. At the equilibrium stage, the temperature reaches to the maximum and remains constant. During this stage, the weld interface changes continuously and the material of high-temperature-plasticized layer is extruded, forming flash. At the third stage, the weld temperature begins to decline and the interface does not change anymore. The temperature decreases from peak temperature to 300 °C within only 10 s, which indicates the effective diffusion time.

The average diffusion coefficient $\overline{D}$ of elements at weld joint can be estimated. The physical model of element diffusion is shown in Fig.8, and the boundary conditions are as follows:

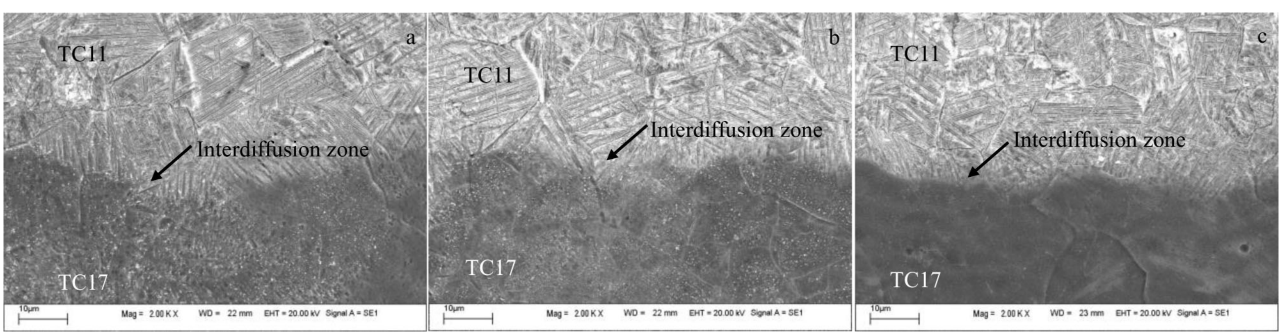

Fig.5 SEM microstructures of LFW joint interface under different friction pressures: (a) 47 MPa, (b) 33 MPa, and (c) 20 MPa

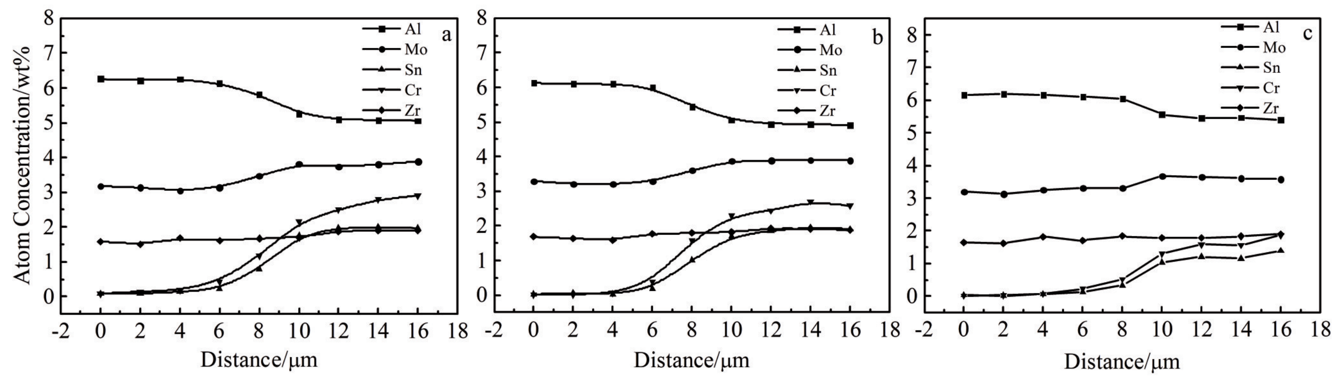

Fig.6 Atom concentrations across LFW joint interface from TC11 BM to TC17 BM under different friction pressures: (a) 47 MPa, (b) 33 MPa, and (c) 20 MPa

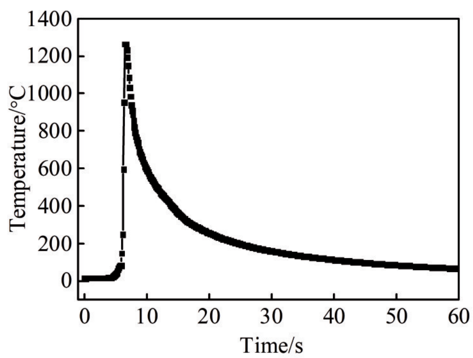

Fig.7 Temperature variation of joints during LFW process

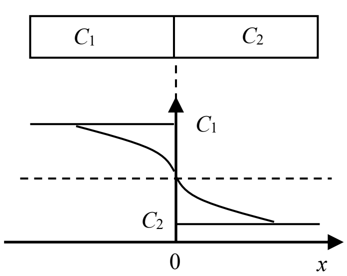

Fig.8 Schematic diagram of physical model of element diffusion

$$C(x, t=0) = \begin{cases} C_1 & (x<0) \\ C_2 & (x>0) \end{cases} \quad (2)$$

where $C(x,t)$ is the atom concentration; C_1 is the upper limit of atom concentration; C_2 is the lower limit of atom concentration; x is the distance to the interface; t is the diffusion time. Thus, Eq.(3) can be obtained, as follows:

$$C(x,t) = A + B\mathrm{erf}\left(\frac{x}{\sqrt{4\overline{D}t}}\right) \quad (3)$$

where A and B are constants; $\mathrm{erf}\left(\frac{x}{\sqrt{4\overline{D}t}}\right)$ is Gaussian error function.

The initial conditions are as follows:

$$\begin{cases} C_1 = A - B \\ C_2 = A + B \end{cases} \text{with } A = \frac{C_1 + C_2}{2}, B = -\frac{C_1 - C_2}{2} \quad (4)$$

Then, the atom concentration can be transformed into Eq.(5), as follows:

$$C(x,t) = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{2}\mathrm{erf}\left(\frac{x}{\sqrt{4\overline{D}t}}\right) \quad (5)$$

Eq.(2−5) were used to analyze the element diffusion. Take the diffusion coefficient of Al element for example. By substituting the quantitative EPMA data, the average diffusion coefficient of Al in weld joints after LFW under friction pressure of 47, 33, and 20 MPa is 2.70×10^{-9}, 2.37×10^{-9}, and 1.86×10^{-9} cm^2/s, respectively. It is also found that the diffusion coefficient of Al is increased with increasing the power input at the interface. Arrhenius equation of diffusion coefficient of atoms is expressed by Eq.(6), as follows:

$$D = D_0 \exp\left(-\frac{Q}{kT}\right) \quad (6)$$

where D_0 is diffusion constant, Q is activation energy, k is a constant, and T is the temperature. Combining Eq. (6) with Eq. (1), within the parameters of this research, the peak temperature of the friction surface is increased with increasing the friction pressure. According to Eq. (6), the diffusion coefficient is increased with increasing the temperature. During diffusion welding, the diffusion coefficient of Al in Ti alloys is about 10^{-11} cm^2/s. Therefore, the diffusion coefficient of Al in LFW is about 100 times higher than that in diffusion welding, which indicates that the super-diffusion occurs at the interface during LFW. The major driving force for atomic super-diffusion is the imposed forging compressive stress, which produces a strain gradient in the work pieces. The dissimilar Ti alloys are joined due to the temperature variation from WZ to TMAZ until BM. The relationship between diffusion coefficients with strain (D_{strain}) and without strain (D_{relax}) is shown in Ref.[17], as follows:

$$D_{\mathrm{strain}} = D_{\mathrm{relax}} \exp\left(-\frac{Q's}{kT}\right) \quad (7)$$

where s is the strain (positive for tension and negative for compression) and Q' is activation energy per unit strain. Thus, Eq.(8) can be obtained, as follows:

$$D_{\mathrm{relax}} = D_0 \exp\left(-\frac{Q}{kT}\right) \quad (8)$$

Combining Eq. (6) with Eq. (7), D_{strain} can be obtained, as follows:

$$D_{\text{strain}} = D_{\text{relax}} \exp\left(-\frac{Q's}{kT}\right) = D_0 \exp\left(-\frac{Q + Q's}{kT}\right) \quad (9)$$

During LFW, the joint undergoes compressive strain, and therefore Eq.(10) can be obtained, as follows:

$$D_{\text{strain}} = D_0 \exp\left(-\frac{Q - Q'|s|}{kT}\right) = D_0 \exp\left(-\frac{Q_{\text{LFW}}}{kT}\right) = D_{\text{LFW}} \quad (10)$$

where Q_{LFW} is activation energy for LFW diffusion and D_{LFW} is diffusion coefficient of LFW. According to Eq. (10), during LFW, the activation energy for diffusion is reduced by compressive strain, which increases the driving force for atomic diffusion. The diffusion coefficient depends on the activation energy of diffusion. Nevertheless, besides the compressive strain, other parameters can also influence atomic diffusion rates.

(1) Interface

During friction welding, the interface atoms are fully activated and can rapidly achieve close contacts. At high temperatures, the atoms can cross over the interface with lower activation energy, which is the necessary condition for super-diffusion.

(2) Temperature

Temperature is one of the most important factors affecting the atom diffusion rate. The temperature of weld interface may exceed 1100 °C. The higher the temperature, the greater the thermal activation energy of the atoms. Thus, the atoms can diffuse more easily and quickly at high temperatures.

(3) Big deformation

Severe plastic deformation occurs in WZ. The deformation activation energy of atoms is greatly increased, resulting in the increased diffusion driving force. Thus, the diffusion rate of atoms increases rapidly.

(4) Crystal defects

Dynamic recrystallization occurs in WZ during LFW, the microstructure is refined, and the volume fractions of grains and phase boundaries are increased. The width of α plate in WZ is only 300 – 400 nm. The activation energy of atoms diffusing through grain boundaries and phase boundaries is lower than that through intracrystalline. Dislocation, vacancy, grain boundary, and phase boundary all provide the paths of high diffusivity for atoms, namely the short circuit diffusion. The friction interface provides the favorable conditions for atom diffusion and super-diffusion at the interface, thereby resulting in the high-quality LFW joint.

3 Conclusions

1) The weld zone (WZ) temperature exceeds the nominal β-transus temperature, which results in the formation of complete transformation microstructure. WZs prepared under different friction pressures all consist of recrystallized grains and intergrowth grains. The WZ microstructure near TC11 base metal is mainly composed of acicular martensite α' phase with Widmanstaten structure, and that near TC17 base metal consists of single metastable β grains.

2) Super-diffusion occurs at the interface and the diffusion coefficient of Al atoms is about 100 times higher than that in diffusion welding. During linear friction welding, the activation energy for diffusion is reduced by compressive strain, which increases the driving force for atomic diffusion. The diffusion length is increased with increasing the friction pressure.

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异种钛合金线性摩擦焊组织演变及超扩散机理

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摘 要：研究了TC11和TC17异种钛合金在不同摩擦压力（22~47 MPa）下的线性摩擦焊组织演变和超扩散机理。通过扫描电子显微镜分析接头的微观结构，并通过电子探针分析了接头界面近域的原子浓度。结果表明，焊缝区域温度超过β相变温度，焊接后接头温度迅速下降，焊缝组织转变为完全再结晶组织。焊缝界面处原子发生了超扩散现象，典型原子的扩散系数约为扩散焊接处原子的100倍。在试验参数范围内，增加摩擦压力会增加典型原子扩散距离。

关键词：线性摩擦焊；异种钛合金；显微组织；界面；超扩散

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