Microstructural response at the interface and its effect on the fatigue fracture behavior of rotary friction welded dissimilar titanium alloys: Ti–5Al–2Sn–2Zr–4Mo–4Cr (Ti17) and Ti–6Al–2Sn–4Zr–2Mo (Ti6242)

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Abstract

Ti17 and Ti6242 tubes were subjected to rotary friction welding to fully understand the microstructural response and its effect on the fatigue fracture behavior of the dissimilar joint. Experiment was conducted using friction linear speed 1 m s\(^{-1}\), friction pressure 80 MPa, burn-off length 5 mm and forging pressure 120 MPa as welding parameters. Electron backscattered diffraction was utilized to systematically examine the microstructures and microtextures across the Ti17/Ti6242 friction welded interface. Thereafter, two fatigue tests were conducted to characterize the fatigue performance of Ti17/Ti6242 joint, one of which is used to identify the fatigue fracture location of the joint and another one to analyze the fatigue fracture behavior. Results clinched that the formation of joint exhibited 600 \(\mu\)m thick weld interface comprises of thermal-mechanical affected zone (TMAZ), heat affected zone (HAZ) and welding zone (WZ) with varying thicknesses (i.e. 100 \(\mu\)m to 200 \(\mu\)m). It was also observed that Ti17 WZ is occupied by equiaxed \(\beta\) grains (mean size of 10 \(\mu\)m) with only one texture which was closely similar to 

\[
\{110\} \prec <111>.
\]

Whereas, Ti6242 WZ contained acicular \(\alpha'\) laths (1 \(\mu\)m) with two types of \(\alpha\) texture. Ti17 HAZ + TMAZ were consisted of acicular \(\alpha'\) laths within refined equiaxed \(\beta\) grains and three types of texture of \(\alpha\) and \(\beta\), were respectively found in Ti17 HAZ + TMAZ zone. Whereas, Ti6242 HAZ + TMAZ zone was developed by elongated equiaxed \(\alpha\), acicular \(\alpha'\) laths and few \(\beta\) phases and only two types of texture of \(\alpha\) and one type texture of \(\beta\) were found in this zone. The microstructural response across the joint concentrates plastic deformation in Ti6242 HAZ + TMAZ during fatigue cycle, which causes the fatigue fracture occurs at a radial distance of 150\(\mu\)m from the boundary between the Ti6242 TMAZ + HAZ and Ti6242 base metal.

1. Introduction

Assembling dissimilar Ti-alloys within the aerospace industry has constantly risen the interest for the past decades, which utilizes the properties of different titanium alloys [1–3]. Recent studies involving the successful welding assembly of dissimilar titanium alloys have demonstrated viable configurations which exhibited satisfying mechanical strength for practical applications [4–7]. Compared with mechanical assemblies, welding technique shows strong advantages in reducing weight and enhancing strength. Among which, friction welding of Ti–5Al–2Sn–2Zr–4Mo–4Cr (Ti17) and Ti–6Al–2Sn–4Zr–2Mo (Ti6242) is highly appreciated in the aircraft industry for producing the reliable coalescence of low and high temperature parts of titanium alloy. Specifically, Ti17 is always employed to manufacture cryogenic compressor rotor whereas Ti6242 of high temperature
compressor rotor [8–11]. When joining these rotational Ti17/Ti6242 components, such as the disk–disk assemblies, rotary friction welding (RFW) is the most ideal choice for its outstanding features such as excellent properties (i.e., fatigue properties), low cost, and high reliability [12–15].

Rotary friction welding produces combination of materials under compressive force, where workpieces are rotated relative to one another to produce frictional heat [16, 17]. Once enough heat has been generated, the softened (plasticized) material at the friction interface will be extruded to form the flash under the maintained friction pressure until the preset burn-off length is achieved. The forging action is followed, where the forging pressure forces the joint to promote the solid-state bond. Therefore, materials at the friction interface suffer high temperature and severe plastic deformation. As a result, across the welded interface, the welding zone (WZ), thermal-mechanical affected zone (TMAZ) and heat affected zone (HAZ) are formed, where the microstructure varies to different zones. In particular, the microstructure has more variations when friction welding dissimilar materials. For example, at least four zones (Ti17 TMZ + HAZ, Ti17 WZ, Ti6242 WZ, Ti6242 TMAZ + HAZ) will be formed across the welded interface when Ti17/Ti6242 joint is fabricated by rotary friction welding. However, few efforts have been made to understand the microstructure evolution.

Early literatures have reported microstructure evolution of titanium alloys joints fabricated by friction welding in aspects of grains [9, 10, 18–20], phase distribution [9], macrotexture [9] and microtexture evolution [18], and local strain in the grains [20], where electron backscattered diffraction (EBSD) was always employed as the main analysis method to obtain the detailed microstructural information. Wang [18] reported the grains and microtexture evolution at the interface of Ti11 joint welded by linear friction welding, which thought to be the two main factors that may affect the properties of similar titanium joints. Su [19, 20] further discussed and analyzed the effect of local strain in the grains on the properties of Ti–4Al–0.005B friction stir welded titanium joint. When it comes to the dissimilar titanium alloys joints, phase distribution [9] and macrotexture [9] are additional factors. For example, Xavier Boyat characterized Ti17/Ti6242 joint fabricated by linear friction welding in the aspects of microstructure evolution, phase distribution and macrotexture evolution of welding zone, i.e., Ti17 WZ and Ti6242 WZ [9]. However, a comprehensive analysis of the (Ti17 TMZ + HAZ, Ti17 WZ, Ti6242 WZ, Ti6242 TMAZ + HAZ) is still lacking, which may eventually affect the properties.

When it comes to the properties of aviation parts, fatigue performance is more sensitive to the microstructural response at the interface of the joint rather than the tensile properties. Wen [2] evaluated the fatigue properties of linear friction welded dissimilar joints between Ti–6Al–4V and Ti17. Yang [21] attributed the fatigue properties of the joint to the distribution of α phase when investigating the linear friction welding of Ti11 and Ti17. García’s study [22] further discussed the effect of depletion of α precipitates on the fatigue strength when fabricating linear friction welded Ti17/Ti6242 joint. These studies show that the fatigue properties of dissimilar titanium joint may be related to the microstructural response at the interface (i.e., distribution of α phase), but no further studies were conducted to investigate the its effect on the fatigue fracture behavior, which is the key data of aviation parts.

The present study, therefore, focuses on the microstructural response at the interface and its effect on the fatigue fracture behavior of rotary friction welded Ti17 and Ti6242. Ti17 alloy is consider as a near-β titanium alloy, whereas Ti6242 as a near-α. RFW experiment was conducted and then the microstructures and microtextures across the Ti17/Ti6242 friction welded interface were systematically examined and characterized using electron backscattered diffraction (EBSD). Thereafter, two fatigue tests were conducted to characterize the fatigue performance of Ti17/Ti6242 joint, one of which is used to identify the fatigue fracture location of the joint and another one to analyze the fatigue fracture behavior. This provides a comprehensive understanding of microstructural response and its effect on the fatigue fracture behavior of Ti17/Ti6242 joint fabricated by rotary friction welding.

2. Materials and experimental procedures

2.1. Base metals

Tubes of commercial standard forging state titanium alloy grades: Ti17 and Ti6242 were used as base metals, chemical compositions (wt%) of which are 5.12 Al, 2.03 Sn, 2.10 Zr, 4.04 Mo, 3.94 Cr, 0.10 Fe, 0.012 C, 0.007 N, 0.007 H, 0.12 O, Ti balance (Ti17) and 6.00 Al, 2.12 Sn, 4.17 Zr, 2.02 Mo, 0.086 Si, 0.02 Fe, 0.12 O, 0.001 H, 0.004 N, Ti balance (Ti6242) respectively. Ti17 alloy is consider as a near-β titanium alloy with a tensile strength of 1050 MPa, whereas Ti6242 as a near-α with a tensile strength of 925 MPa. The outer diameter and inner diameter of the tubes is 30 and 20 mm, respectively. Before welding, the surfaces of the specimens were polished by sandpapers and diamond grinding paste, ultrasonically cleaned in alcohol and dried in air. The microstructure of the base metals used in this study is shown in figure 1, where typical bimodal $\alpha + \beta$ microstructure consisting of equiaxed prior-α (white phase) and intergranular transformed β (black phase) microstructure, where the lamellar $\alpha$ and $\beta$ phases are alternate.
2.2. Friction welding

The RFW experiment was then conducted on a continuous-drive rotary friction welding machine, where the welding parameters were set as follows: friction linear speed 1 m s$^{-1}$, friction pressure 80 MPa, burn-off length 5 mm, forging pressure 120 MPa. The tube specimens rotated and rubbed against each other for seconds under the friction pressure until the preset burn-off length (5 mm) was achieved. Forging stage then took place to promote the solid phase bond under 120 MPa for 5 s.

2.3. Microstructure characterization

After welding, the joint cross-section was cut by electrical discharge machining to conduct EBSD examination. The observation scheme and EBSD scanning region was shown in figure 2, where the coordination system employed for microstructure and microtexture analysis was defined as well. Rolling direction (RD) is parallel to the welded interface, the direction that plasticized metal being extruded. Normal direction (ND) is parallel to the welding direction and transverse direction (TD) is parallel to the shear friction direction. The EBSD sample was mechanically polished and then were electropolished in a solution (30%C4H9OH + 64%CH3OH + 6% HClO4) with a voltage of 20 V for 40 s at 15 °C and cleaned with alcohol. EBSD structural observations were performed on the sections parallel to the rolling axis using a Tescan-VEGA scanning electron microscope equipped with an electron backscattering diffraction (EBSD) system, operating at an accelerating 20 kV with an inclination angle of 70°. The whole cross-section (shown in figure 5) was scanned at a step length of 0.3 μm, whereas 0.1 μm for more details when gradually characterizing the featured four zones (Ti17 TMAZ + HAZ, Ti17 WZ, Ti6242 WZ, Ti6242 TMAZ + HAZ, shown in figures 7–14). The oxford HKLChannel5 software was then used for EBSD data acquisition and further analysis. Inverse pole figures with grain boundaries are used to characterize the microstructure, where the orientation difference of 15 degrees was defined as large angle grain boundary. Recrystallized distribution map was used to analysis the recrystallization behavior of the grains, where blue ones represent recrystallized grains, yellow substructured and red deformed grains. The Pole figures were further employed to analyze the microtextures.

![Figure 1. Microstructure of base metals: (a) Ti 17; (b) Ti6242.](image)

![Figure 2. Schematic illustration of a Ti17/Ti6242 rotary friction welded assembly, the sampling strategy and the EBSD examination region with coordination system.](image)
2.4. Fatigue fracture behavior analysis

Thereafter, fatigue tests were conducted to understand the fatigue fracture behavior of the joint, where figure 3(a) shows the sliced fatigue test samples from the joint and figure 3(b) shows the detailed dimensions. The fatigue test samples were designed according to GB/T3075-2008, where gauge length was designed as 39.064 mm with a radius of 80 mm compared with the thickness of <1 mm affected by the welding cycle. The samples were removed from the joint by wire cutting and mechanically polished to obtain a smooth surface before fatigue testing. The stress-controlled fatigue test was conducted using a computerized fatigue testing system of Instron 8801 with a frequency of 120 Hz. Sine wave form loading with a maximum stress of 500 MPa (55% of the joint tensile strength 907 MPa reported in [10, 22]) and stress ratio of 0.1 was applied at a constant displacement rate of 1 mm min$^{-1}$ during testing. Finally, the fatigue life and the fracture location of the joint can be obtained. Based on this, another fatigue test loaded with $3/4$ joint fatigue life was conducted to analyze the fatigue fracture behavior during the test. $3/4$ joint fatigue life was designed to make the phenomenon more remarkable and to prevent the joint fatigue fracture. EBSD was then conducted to characterize the fracture location and analyze the fatigue fracture behavior. The EBSD tests were conducted at the same way as mentioned above. In addition, the Kernel Average Misorientation (KAM) figure was employed to analyze the fatigue fracture behavior here.

3. Results and discussions

3.1. Appearance of the joint and overview of the microstructure

Appearance of Ti17/Ti6242 joint manufactured by rotary friction welding is shown in figure 4, which presents excellent welding effect without obvious defects. The morphology presents almost a flat interface and the flash bends towards two sides, which indicates similar properties of these two dissimilar titanium alloys at the welding temperature. The interface was then subjected to EBSD examination. Figure 5 shows the EBSD results, where figure 5(a) summarizes the microstructure of Ti17/Ti6242 joint. Figure 5(b) further shows the phase distribution across the joint, where $\alpha$ phase is marked in green whereas $\beta$ phase yellow. Figures 5(c) and (d) respectively present HCP ($\alpha$ phase) indexed data with $\beta$ grain boundaries and BCC ($\beta$ phase) indexed data with $\alpha$ grain boundaries, which is used to support the analysis of microstructural evolution and phase distribution across the joint. Generally, four main areas (Ti17 TMAZ + HAZ, Ti17 WZ, Ti6242 WZ, Ti6242 TMAZ + HAZ) with a thickness of 600 $\mu$m affected by the welding cycle show noteworthy differences in microstructure. Starting from the welded line (WL) and to the left side (i.e. Ti17 side), a thick band...
about 100 μm of refined equiaxed β grains can be observed, which is defined as Ti17 WZ here and detailed analyzed in figure 6. Ti17 HAZ + TMAZ, which is between the Ti17 WZ and Ti17 BM with a thickness of 200 μm, consists of acicular α’ laths interspersed in seemingly refined equiaxed β grains and further characterized in figures 8–10. Whereas, to the right side (i.e. Ti6242 side), Ti6242 WZ is characterized by a 100 μm thick zone of HCP indexed microstructure. A detailed examination of this zone is carried out in figure 7. Ti6242 HAZ + TMAZ (thickness of 200 μm) consists of elongated equiaxed α, acicular α’ laths and few β phases, which is further analyzed in figures 11–13.

3.2. Microstructure and microtexture evolution across the joint

3.2.1. Ti17 WZ

Microstructure and microtexture of Ti17 WZ in shown in figure 6, where figure 6(a) shows the equiaxed β grains governing this zone. Accounting for this, an adequate α→β phase transformation in this zone occurred during RFW. The β grains then recrystallized to form equiaxed grains, which stabilized by the elements (Mo, Cr) in the material at a high cooling rate to room temperature. Figures 6(b) and (c) further analyze the microtexture of Ti17 WZ with a density of 7.52. There is only one type of β texture, the purple one, whose <100> axis is closely in parallel with RD and <110> parallel to the ND. Meanwhile, when rotated 45 degrees counterclockwise
along the TD axis, it’s closely similar to the \{110\} <111> texture, the commonly form in hot deformation process of \(\beta\) titanium [23, 24]. Severe plastic flow during rotary friction welding may account for this.

### 3.2.2. Ti6242 WZ

Microstructure and microtexture of Ti6242 WZ in figure 7, where figure 7(a) presents the microstructure consisted of acicular \(\alpha'\) laths with a thickness of approximately 1 \(\mu\)m. Accounting for this, different form Ti17, Ti6242 is a near \(\alpha\) titanium without so much \(\beta\) stabilizing elements to stabilize the equiaxed recrystallized \(\beta\) grains to the room temperature. Therefore, refined \(\beta\) grains transferred to a band of \(\alpha'\) laths during the cooling process. Figures 7(b) and (c) present the microtexture of Ti6242 WZ with a strength of 9.47, which consists of two main types of \(\alpha\) texture. The green one, of which <0001> axis is closely in parallel with ND and <10_10> parallel to RD; The red one, whose <11_20> is closely in parallel with RD and <10_10> parallel to ND.

![Figure 7. Microstructure and microtexture of Ti6242 WZ: (a) Inverse pole figures (band contrast); (b) \{0001\}, \{11_20\} and \{10_10\} pole figures of \(\alpha\) (hcp) phase and (c) separated texture components and the corresponding 3D orientation diagrams of (b).](image7)

### 3.2.3. Ti17 HAZ + TMAZ

Microstructure of Ti17 HAZ + TMAZ in figure 8, where acicular \(\alpha'\) laths interspersed in seemingly refined equiaxed \(\beta\) grains govern this region. Since the HAZ of rotary friction welded joint is hard and meaningless to differ from TMAZ, they are discussed together here. Ti17 HAZ + TMAZ, as has been introduced in section 3.1, is just about 100 \(\mu\)m from the WL, so it has suffered the welding cycle (thermal-mechanical effect) as well.

![Figure 8. Microstructure of Ti17 HAZ + TMAZ: (a) Inverse pole figures (band contrast) with \(\beta\) grain boundaries; (b) recrystallized distribution map of acicular \(\alpha'\) laths within \(\beta\) grains.](image8)
Figure 9. Texture of β phase distribution in Ti17 HAZ + TMAZ: (a) Inverse pole figures with β grain boundaries, (b) pole figures of β (bcc) phase and (c) separated texture components and the corresponding 3D orientation diagrams of (b).

Figure 10. Texture of α phase distribution in Ti17 HAZ + TMAZ: (a) Inverse pole figures, (b) {0001}, {11_20} and {10_10} pole figures of α (hcp) phase and (c) separated texture components and the corresponding 3D orientation diagrams of (b).

Figure 11. Inverse pole figures (band contrast) of Ti6242 HAZ + TMAZ.
According to the microstructure obtained in Ti17 HAZ + TMAZ, it can be inferred that the temperature of this zone during the welding process is little lower than that of Ti17 WZ so that an incomplete \( \alpha \rightarrow \beta \) phase transformation took place. After the acicular \( \alpha' \) phase and part of equiaxed \( \alpha \) in the base metal transitioning to the equiaxed \( \beta \) grains, the residual equiaxed \( \alpha \) and the newly generated equiaxed \( \beta \) grains deformed under the action of shear force transmitted from the welding interface. As a result, the residual equiaxed \( \alpha \) is elongated and broken, as is shown in figure 8(a). Figure 8(b) further shows the recrystallized distribution map of acicular \( \alpha' \) laths within \( \beta \) grains to confirm this result, which presents the acicular \( \alpha' \) laths mainly composed of fragmented deformed grains. Moreover, texture of Ti17 HAZ + TMAZ is quite different from that of WZ, which consisted of texture of \( \alpha \) phase and \( \beta \) phase.

Figure 9 shows the microtexture of \( \beta \) phase distributed in Ti17 HAZ + TMAZ with a density of 5.15. As is shown in figure 9(b), there are several points with high density in pole figures, indicating that several textures in this region are expected. Therefore, the texture components were divided into three individual pole figures and the corresponding 3D crystal orientation were created in figure 9(c). For \( \beta \) phase, there are generally three types of texture: the red one, of which \(< 100 > \) axis is closely in parallel with RD; the green one, of which \(< 100 > \) axis is closely in parallel with RD as well; the purple one, of which \(< 111 > \) is in parallel with TD.

Figure 10 shows the microtexture of \( \alpha \) phase distribution in Ti17 HAZ + TMAZ with a density of 4.96. Similar to the \( \beta \) phase, three types of texture of \( \alpha \) are found: the red one, of which \(< 0001 > \) axis is in parallel with TD; the green one, of which \(< 0001 > \) and \(< 10_{-10} > \) axis is closely in parallel with RD; and the purple one, of which \(< 11_{-20} > \) and \(< 10_{-10} > \) axis is closely in parallel with RD as well.
3.2.4 Ti6242 TMAZ + HAZ

Microstructure of Ti6242 HAZ + TMAZ in figure 11, which consisted of elongated equiaxed $\alpha$, acicular $\alpha'$ laths and few $\beta$ phases. Similar to the HAZ + TMAZ of Ti17 side, Ti6242 HAZ + TMAZ is also affected by the thermal-mechanical process of the friction process. During the welding process, the incomplete $\alpha \rightarrow \beta$ phase transformation took place and the residual equiaxed $\alpha$ and the newly generated equiaxed $\beta$ grains deformed. However, different from Ti17, the deformed equiaxed $\beta$ grains transitioned from the $\alpha$ phase under the welding process will transition into acicular $\alpha'$ laths during the cooling process after welding. Therefore, equiaxed $\alpha$, acicular $\alpha'$ laths and few $\beta$ phases make up this zone.

Figures 12 and 13 shows the microtexture of $\alpha$ phase and $\beta$ phase distribution in Ti6242 HAZ + TMAZ, the maximum densities of which are about 5.33 and 6.60, respectively. Different from the Ti17 HAZ + TMAZ, there are only two types of texture of $\alpha$ and one type texture of $\beta$. For $\alpha$ phase, the two types are: the green one, whose $<0001>$ is in parallel with ND and $<10\overline{1}0>$ axis is in parallel with RD; the red one, whose $<0001>$ axis is closely in parallel with TD. For $\beta$ phase, the purple texture's $<111>$ axis is in parallel with TD.

3.3. Fatigue fracture behavior

Fatigue tests were conducted to understand the fatigue fracture behavior of the joint. Figure 14 shows the results with EBSD examination regions marked. Figure 15 shows the fractured Ti17 / Ti6242 joint (with a fatigue life of $8 \times 10^6$), where figure 15(a) presents the microstructure and figure 15(b) further shows the corresponding phase distribution across the joint ($\alpha$ phase is marked in green whereas $\beta$ phase yellow). According to the presented results, the fatigue fracture occurs at a radial distance of 150 $\mu$m from the boundary between the Ti6242 TMAZ + HAZ and Ti6242 BM. As one may noticed, some points (areas) in the figure are not calibrated (in black), which results from the stress on the sample surface after fatigue.

EBSD results of the sample loaded with 3/4 fatigue life ($\sim 6 \times 10^6$) in shown in figure 16, where figure 16(a) presents the microstructure and figure 16(b) the corresponding phase distribution. Figure 16(c) further shows the kernel average misorientation figures of the joint, where the blue or green area indicates the area with weak plastic deformation and the yellow or red areas with severe plastic deformation. Across the joint, the plastic deformation is concentrated in Ti6242 side, more significantly, in Ti6242 TMAZ + HAZ, during fatigue cycle. Accounting for this, $\alpha$ phase with hcp isn't easy to deform. Moreover, drastic changes of grain size between the Ti6242 TMAZ + HAZ and Ti6242 BM concentrate the stress at the boundary of Ti6242 TMAZ + HAZ and
4. Conclusions

In this study, the microstructural response at the interface and its effect on the fatigue fracture behavior of rotary friction welded Ti17 and Ti6242 has been focused. Microstructures and microtextures across the Ti17/Ti6242 rotary friction welded joint were systematically examined and characterized. Furthermore, the microstructural effect on the fatigue fracture behavior was analyzed. The following conclusions can be drawn:

1. The joint zone affected by the welding cycle is a region with a thickness of about 600 μm, consisted of four main areas, Ti17 TMAZ + HAZ (200 μm), Ti17 WZ (100 μm), Ti6242 WZ (100 μm), Ti6242 TMAZ + HAZ (200 μm).

2. The welding zone is made up of Ti17 WZ and Ti6242 WZ. Ti17 WZ is occupied by the equiaxed β grains, the microtexture of which has only one type and is closely similar to the {110} < 111 > texture. Whereas, Ti6242 WZ is governed by a band of acicular α’ laths with a thickness of about 1 μm, microtexture of which consists of two types of α texture.

3. Structural response at the HAZ + TMAZ zone is more complex. Ti17 HAZ + TMAZ is consisted of acicular α’ laths within refined equiaxed β grains. There are three types of texture of α and β respectively are found in Ti17 HAZ + TMAZ zone. Whereas, Ti6242 HAZ + TMAZ zone is composed by elongated equiaxed α, acicular α’ laths and few β phases. Different from the Ti17 HAZ + TMAZ, there are only two types of texture of α and one type texture of β in Ti6242 HAZ + TMAZ zone.

4. Ti17/Ti6242 joint has a fatigue life of 8 × 10^6 (sine wave form loading, maximum stress 500MPa, stress ratio 0.1) and the fatigue fracture occurs at a radial distance of 150 μm from the boundary between the Ti6242 TMAZ + HAZ and Ti6242 BM. Concentration of plastic deformation in Ti6242 HAZ + TMAZ during fatigue cycle caused by the microstructural response across the joint is responsible for this.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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