Structural response of A286 superalloy to rotary friction welding at different rotation speed

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Abstract

Rotary friction welding was conducted on A286 with a diameter of \( \phi 25 \) mm under 300, 900 and 2100 rpm to understand the structural response of the joint welded at different rotation speeds. Joint morphologies, grain structures inside the morphologies and the corresponding mechanism that governs its formation were characterized and investigated using electron backscattered diffraction (EBSD), which focused on three featured zones located at the center, 1/2R and periphery of the joint. The influence of structural response on joint properties was also investigated. Results show that the morphology of the joint evolves from ‘disk shape’ to ‘near-line shape’ and ‘scissors shape’ as the rotation speed increases from 300 rpm to 2100 rpm. At low rotation speed, refined and recrystallized grains were formed inside disk shape morphologies. Whereas, sub-grains and deformed grains were evolved at the middle (900 rpm) and high (2100 rpm) rotation speed. The recrystallized grains surrounded by the ‘disk shape’ morphology have a positive effect on the joint strength compared with the sub-grains and deformed grains confined by the ‘near-line shape’ and ‘scissors shape’ morphologies.

1. Introduction

A286 is an austenitic superalloy which is widely used in manufacturing disks and shafts in the gas turbine industry due to its good thermal resistance and superior mechanical properties [1, 2]. When joining these rotational components (i.e., rods and tubes) with high qualities, rotary friction welding (RFW) is the best choice for its outstanding characteristics such as high reliability, low cost, and excellent properties [3–6].

RFW produces coalescences of materials under compressive forces through the contact of workpieces, rotating relative to one another to produce heat which softens the materials at friction interface. Then recrystallized grains take over the interface, which is the key that ensures the high qualities of the joints. Therefore, early literature has focused the RFW process on the aspect of microstructure evolution with parameters at the axial direction, which is widely known as welding zone (WZ), thermal–mechanical affected zone (TMAZ) and heat-affected zone (HAZ) [3, 6, 7]. This topic has been systematically investigated and the microstructure at axial direction has been characterized in detail, which has been proved to be the main factor of the joint qualities when the diameter of the rod type component is small either the tube-structure [8, 9]. For instance, diameter of rod-structure specimens used in [8] and [9] was just \( \phi 13 \) mm and wall thickness of pipe-structure specimens used in [7], was 5.1 mm with a diameter of \( \phi 25.4 \) mm, under such circumstances it can safely abstract the joint as a ‘near-line’ shape morphology, thus, the axial microstructure plays main role in determining the joint properties.

It should be pointed, however, when joining larger-sized cylindrical structures, strain, strain rate, and temperature varies at different locations during the RFW process. Consequently, different morphologies are formed under different parameters, which is more closely related to the rotation speed. Characteristics of the
2. Materials and experiments

Rods of commercially available A286 superalloy in diameter of \( \phi 25 \text{ mm} \) were used as base metals, with chemical composition (wt\%) is 24.72 Ni, 14.17 Cr, 1.82 Ti, 1.25 Mn, 1.09 Mo, 0.53 Si, 0.24 V, 0.16 Al, 0.03 Cu, 0.03 C, 0.007 P, 0.005 B, and Fe balance. Before welding, the faying surfaces of the specimens were polished to eliminate the effect of surface roughness and ultrasonically cleaned in alcohol and dried in air.

To obtain the morphologies of A286 joint welded at different rotation speeds, RFW experiments were conducted on a continuous-drive rotary friction welding machine (C320, Hanzhong Shuangji Friction Welding Techniques Co. Ltd, China). Then, stop actions were taken to freeze the morphologies during the RFW process to reveal the formation mechanism during different morphologies. Welding parameters were set as follows: welding pressure 125 MPa, burn-off length 5 mm. Yet, the rotation speeds were designed as 300 rpm, 900 rpm, and 2100 rpm, which denotes low, middle and high rotation speeds. Different joint section morphologies were obtained first, the formation mechanism of which was revealed by taking stop actions to analyze the morphology evolution during the RFW process.

Electron backscattered diffraction (EBSD) was then employed to further characterize the features of grains inside different morphologies, which focused on three featured zones located at the center, \( 1/2R \) (R demonstrates the specimen radius) and periphery of the joint. Tensile properties of the joints sampled from the location of interest (i.e., center, \( 1/2R \) and periphery) were analyzed with structural response behavior. This work would provide a comprehensive understanding of welding the A286 joint by rotary friction welding process.

3. Results and discussion

3.1. Morphology evolution

Figure 3 shows the morphologies of A286 joint welded at 300, 900 and 2100 rpm (pressure was set at 125 MPa and burn-off length 5 mm), which have been closed by red contours in figures 3(a)–(c) according to the axial structure evolution shown in figure 3(d). Generally, morphology of the A286 joint evolves from ‘disk shape’ to ‘near-line shape’ and ‘scissors shape’ as the rotation speed increases from 300 rpm to 900 rpm and 2100 rpm. To further analyze the formation mechanism of the different morphologies, stop actions were taken to freeze the
Figure 1. The initial microstructure of base metal A286 superalloy before welding.

Figure 2. Dimensions and configuration of (a) the joint and (b) sampled location of (c) sliced samples for tensile test (in mm).

Figure 3. Morphologies of A286 joint welded at (a) 300 rpm, (b) 900 rpm (c) 2100 rpm and (d) the axial structure evolution.
morphologies during the RFW process. Figure 4 shows the results. At low rotation speed (300 rpm) as shown by figure 4(a), enough plasticized metal initiates under almost 0.4 m s$^{-1}$ at 0.50 R and then spreads in both directions, which grows inward to store enough metal at the center and outside to form the zones structures inside morphologies of the joint welded at different rotation speeds, corresponding to the marked three featured zones.

To promote a comprehensive characterization of the features of grain structures inside different morphologies, 3.2. Evolution of grain structures

To further investigate the structural response of A286 superalloy to RFW at different rotation speed, a recrystallized distribution map and the pole figures of the grains were employed to reveal the corresponding mechanism that governs grain structures. Figure 6 shows the recrystallized distribution map of the grains inside different morphologies. At low rotation speed (300 rpm) as shown by figures 6(a)–(c), sufficient recrystallized grains govern the microstructure. Whereas, at the middle (900 rpm) and high (2100 rpm) rotation speed, as shown by figures 6(d)–(f) and (g)–(i), variously-sized deformed grains with incomplete grain boundaries and sub-boundaries (white line) are formed.

3.2.2. Mechanism governing grain structures

To further investigate the structural response of A286 superalloy to RFW at different rotation speed, a recrystallized distribution map and the pole figures of the grains were employed to reveal the corresponding mechanism that governs grain structures. Figure 6 shows the recrystallized distribution map of the grains inside different morphologies. At low rotation speed (300 rpm) as shown by figures 6(a)–(c), sufficient recrystallized grains govern the microstructure. Whereas, at the middle (900 rpm) and high (2100 rpm) rotation speed, as shown by figures 6(d)–(f) and (g)–(i), variously-sized deformed grains with incomplete grain boundaries and sub-boundaries (white line) are formed.

Figure 7 shows the pole figures of the grains. Generally, at low rotation speed (300 rpm) as shown by figures 7(a)–(c), texture patterns as {112}, {115} and {110} are formed. Figure 7(a) presents the {112} texture pattern with a strength of 8.22, which is thought that the weak recrystallization texture is affected by the material flow of the stored plasticized metal at the center of the morphology, welded at 300 rpm. Weak {115} and {110} texture patterns formed at 1/2R and periphery confirms that recrystallization governs the microstructure of the joint welded at 300 rpm. Whereas, at the middle (900 rpm) and high (2100 rpm) rotation speed, as shown by figures 7(d)–(f) and (g)–(i), typical cube texture pattern {100} is formed. The cube texture is thought to characterize the recrystallization of fcc metal. However, strength of the texture formed at middle and high rotation speed is high, which is thought to be affected by the heavy deformation. It confirms the acquired sub-grains and deformed grains inside the morphologies welded at middle (900 rpm) and high (2100 rpm) rotation speed.

In summary, refined recrystallized grains govern the microstructure of the joint welded at a low rotation speed (300 rpm). Whereas, sub-grains and deformed grains govern the microstructure of the joint welded at the middle (900 rpm) and high (2100 rpm) rotation speed. Therefore, it can be interpreted that the thick ‘disk shape’ morphology formed at low (300 rpm) rotation speed provides an enclosed contour for the inside grains to undergo a full recrystallization process. Whereas, the thin ‘near-line shape’ and ‘scissors shape’ morphologies formed at the middle (900 rpm) and high (2100 rpm) rotation speed cause heavy deformation within the grains inside these morphologies.
Figure 5. Grain structures inside morphologies of the joint welded at (a)–(c) 300 rpm, (d)–(f) 900 rpm and (g)–(i) 2100 rpm.

Figure 6. Recrystallized distribution map of the grains inside morphologies of the joint welded at (a)–(c) 300 rpm, (d)–(f) 900 rpm and (g)–(i) 2100 rpm.
3.3. Tensile properties
To investigate the influence of structural response on the joint properties, tensile tests sampled at the corresponding locations (i.e., center, 1/2R and periphery) were conducted. Figure 8 shows the local tensile properties of A286 joint welded at different rotation speeds, where strength of the joint welded at low rotation speed (300 rpm) is generally higher than the joint welded at the middle (900 rpm) and high (2100 rpm) rotation speed. Therefore, it can be inferred that the recrystallized grains surrounded by the ‘disk shape’ morphology have a positive effect on the joint strength compared with the sub-grains and deformed grains confined by the ‘near-line shape’ and ‘scissors shape’ morphologies.

4. Conclusions
The present study has examined the structural response of A286 superalloy to RFW at different rotation speeds. RFW experiments were conducted on A286 with a diameter of 25 mm under 300, 900 and 2100 rpm, which denotes low, middle and high rotation speeds respectively. Morphologies of the joint were characterized first, formation mechanism of which was studied according to the morphology evolution during the RFW process. Then, a comprehensive characterization of the features of grains inside different morphologies and the corresponding mechanism governing its formation was conducted using EBSD, which focused on three featured zones located at the center, 1/2R and periphery of the joint. Furthermore, the influence of structural response on the joint properties was investigated as well. The following conclusions were drawn:

(1) Morphology of the joint evolves from ‘disk shape’ to ‘near-line shape’ and ‘scissors shape’ as the rotation speed increases from 300 rpm to 900 rpm and 2100 rpm, the formation mechanism of which was attributed
to the initiation location of the plasticized metal under different rotation speeds. At low rotation speed (300 rpm), enough plasticized metal initiates at 0.50 R and then spreads in both directions. Much metal is stored at the center to form a thick ‘disk shape’ morphology. Whereas, at the middle (900 rpm) and high (2100 rpm) rotation speed, plasticized metal initiates in axis zone and later spreads outside with growing area to fill out so that the thin ‘near-line shape’ and ‘scissors shape’ morphologies are formed.

(2) Refined recrystallized grains govern the microstructure of the joint welded at a low rotation speed (300 rpm). Whereas, sub-grains and deformed grains govern the microstructure of the joint welded at middle (900 rpm) and high (2100 rpm) rotation speed. The thick ‘disk shape’ morphology formed at low (300 rpm) rotation speed provides an enclosed contour for the inside grains to undergo a full recrystallization process. Whereas, the thin ‘near-line shape’ and ‘scissors shape’ morphologies formed at the middle (900 rpm) and high (2100 rpm) rotation speed cause heavy deformation within the grains inside these morphologies.

(3) The recrystallized grains surrounded by the ‘disk shape’ morphology have a positive effect on the joint strength compared with the sub-grains and deformed grains confined by the ‘near-line shape’ and ‘scissors shape’ morphologies.

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References

[1] Mustafa A H et al 2008 Investigation into thermal stresses in gas turbine transition-piece: influence of material properties on stress levels J. Mater. Process. Technol. 201 369–73
[2] Oscar M, Tiedra P D and San-Juan M 2015 Study of influence of gamma prime and eta phases on corrosion behaviour of A286 superalloy by using electrochemical potentiokinetic techniques Mater. Des. 87 266–71
[3] Li W Y et al 2016 Linear and rotary friction welding review Int. Mater. Rev. 61 71–100
[4] Li P et al 2017 Metallurgical and mechanical properties of continuous drive friction welded copper/alumina dissimilar joints Mater. Des. 127 311–9
[5] Li P et al 2018 Inhomogeneous interface structure and mechanical properties of rotary friction welded TC4 titanium alloy/316L stainless steel joints J. Manuf. Processes 33 54–63
[6] Maalekian M 2007 Friction welding—critical assessment of literature Sci. Technol. Weld. Joining 12 738–59
[7] Liu F C and Nelson T W 2018 Grain structure evolution, grain boundary sliding and material flow resistance in friction welding of alloy 718 Materials Science and Engineering: A 710 280–8
[8] Damodaram R, Ramana S G S and Rao K P 2013 Microstructure and mechanical properties of friction welded alloy 718 Materials Science and Engineering: A 560 781–6
[9] Damodaram R, Ramana S G S and Rao K P 2014 Effect of post-weld heat treatments on microstructure and mechanical properties of friction welded alloy 718 joints Mater. Des. 53 954–61
[10] Satyanarayana V V, Reddy G M and Mohandas T 2004 Continuous drive friction welding studies on AISI 304 austenitic stainless steel welds Mater. Manuf. Processes 3 487–505
[11] Hasegawa M and Ieda T 1999 Effects of friction welding conditions on initial joining phenomenon Weld. Int. 13 701–11
[12] Kimura M et al 2003 Observation of joining phenomena in friction stage and improving friction welding method JSME International Journal Series A 46 364–90
[13] Kimura M et al 2002 Observation of joining phenomena in first phase of friction welding, study of joining mechanism of friction welding (Report 1) Quarterly Journal of the Japan Welding Society 20 425–31
[14] Kimura M et al 2002 Effect of various conditions on friction torque in the first phase of friction welding, study of joining mechanism of friction welding (Report 2) Quarterly Journal of the Japan Welding Society 20 432–8
[15] Kimura M et al 2013 Effect of friction welding conditions and aging treatment on mechanical properties of A7075–T6 aluminium alloy friction joints Science & Technology of Welding & Joining 10 606–12
[16] Ajith P M, Sathiya P and Aravindan S 2014 Experimental investigation on friction welding of UNS S32205 duplex stainless steel Acta Metallurgica Sinica (English Letters) 27 993–1007
[17] Udayakumar T et al 2013 Experimental investigation on mechanical and metallurgical properties of super duplex stainless steel joints using friction welding process J. Manuf. Processes 15 538–71