J Mater Sci (2010) 45:6218–6224
DOI 10.1007/s10853-010-4716-9

Microstructural evolution of a TC11 titanium alloy during linear friction welding

B. Lang · T. C. Zhang · X. H. Li · D. L. Guo

Received: 31 January 2010 / Accepted: 14 June 2010 / Published online: 25 June 2010

Abstract Linear friction welded titanium alloy microstructures were investigated to understand the microstructural evolution in the joints. The results show that extrusion of material at the rubbing interface occurred after complete transformation of alpha to beta phase. Finer prior-beta grains were obtained in the flash as compared to the parent material due to dynamic recrystallization. Metallographic examination revealed that two different structures were existed in the joints, i.e., thermomechanically affected zone developing at the edge of joint and weld appearing in the central portion of joint. Although no dynamic recrystallization was observed in the thermomechanically affected zone, the phase transformation would occur concurrently with material deformation during welding. In contrast, dynamic recrystallization had occurred in the weld. Effect of welding parameter on the microstructure was investigated by changing amplitude of oscillation (1.56–2.03 mm). Some defects such as kiss bonding and porosity occurred in the joint at relatively low amplitude of oscillation. Therefore, relatively high amplitude of oscillation is more preferable for obtaining a fully bonded joint.

Introduction

Titanium alloys have attracted great attention in academic research and aerospace industrial application owing to their unique properties such as low density, good mechanical properties, and high corrosion-resistant ability [1]. These materials are particularly suitable for service temperature below 600 °C and high dynamic load applied to the component. Typical applications are gas turbine components such as disks, vans, and blades of compressor. In recent years, newly developed joining technologies such as friction stir welding (FSW) and linear friction welding (LFW) have created a new impetus for the use of titanium alloys, which can be used for the manufacture and repair of a wide range of aerospace components. Friction stir welded titanium alloys and aluminum alloys had been investigated [2–6]. Of particular interest for aircraft engine applications is the LFW technique, which has the potential use to produce highly efficient joints on new components as well as in repair applications, thereby increasing significantly component's life cycle [7]. In fact, enormous research works have concentrated on the LFW technique in recent years. Various materials, principally titanium alloy [8–14], steel [15, 16], and nickel-based superalloys [17], were utilized in the investigations and many useful insights and data have been obtained about the microstructure and mechanical properties of linear friction welded joint.

Use of titanium alloy blisks (integrally bladed disks) instead of blades and disks is one of the recent developments in manufacturing aeroengines. The first approach was to forge a disk with a sufficient large (oversized) diameter and then form the blades at the rim by machining. However, no repair method would be available for the damaged or broken blades if a large volume of material is wasted. This non-economically production procedure stimulated the development and improvement of a friction welding method in which the blades are attached to the disk by LFW process. To date, most of the LFW development has been driven by the aeroengine industry's desire to fabricate titanium alloy blisks, giving lower weight and improved performance over existing slotted blade/disk assemblies. LFW can also be used to join dissimilar alloys

B. Lang (✉) · T. C. Zhang · X. H. Li · D. L. Guo
Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China
e-mail: langbo198009@163.com

to employ the optimum alloys for the blade (exposed to high cycle fatigue and high temperature) and disk (exposed to low cycle fatigue) [18]. However, inspection of the published literature showed that limited prior works have focused on dealing with the microstructural evolution of titanium alloys during LFW. Therefore, further research and development efforts are necessary to utilize the full potential of these materials.

In recent years, TC11 titanium alloys were used widely for gas turbine components such as disks and blades of compressor owing to good mechanical properties in the middle temperature range, high specific strength, and corrosion-resistant ability. Therefore, it is very important for investigation of linear friction welded TC11 titanium alloy. Microstructure plays a very important role in the mechanical properties of alloys, such as strength, ductility, creep resistance, fracture toughness, and crack propagation resistance. It depends primarily on the chemical composition, processing history, and thermal treatment procedures. By investigating the microstructures of linear friction welded TC11 titanium alloy joints, the present work aims to deepen our understanding of the linear friction weldability of the TC11 titanium alloys.

Experimental

Table 1 listed the nominal chemical composition of the bimodal alpha–beta structure TC11 titanium alloy block used in this contribution. The nominal beta-transus temperature of this material is approximately 1009 °C. As shown in Fig. 1, the microstructure consists of equiaxed prior-alpha and intergranular transformed beta microstructure (mixture of lamellar alpha and beta phases). The volume fraction of transformed beta microstructure is around 47.4%. The average size of prior-beta grain consisting of the equiaxed prior-alpha phase and transformed beta microstructure is around 32 μm in the parent material. Specimen can be mistaken for finished weld. To exclude such ambiguity, pieces used for joining may be designated as blocks and the resulting configuration as the joint. LFW specimens with dimensions of 11.8-mm width (*W*), 26-mm height (*H*), and 60-mm length (*L*) were cut from TC11 titanium alloy block. Prior to welding, the specimen surfaces were polished with 1200 grade emery paper and cleaned in an acetone bath for obtaining uniform surface state, and then two specimens were installed as a butt joint, as shown in Fig. 2. The welding test was carried out by a LFW machine with 200-kN force capacity. In the investigation, forge force was absent during LFW. Effect of welding parameter was investigated by changing amplitude of oscillation (1.56–2.03 mm) under the conditions of 2 s friction time (which it takes to rub at the interface under the

Table 1 Chemical composition of titanium alloy (wt%)

Al	Mo	Zr	Si	Fe	O	C	Ti
6.29	3.38	1.68	0.24	0.053	0.0317	0.012	Balance

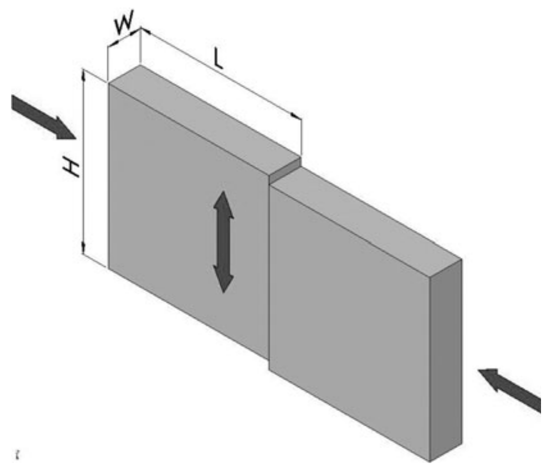

Fig. 2 Schematic of the linear friction welding process

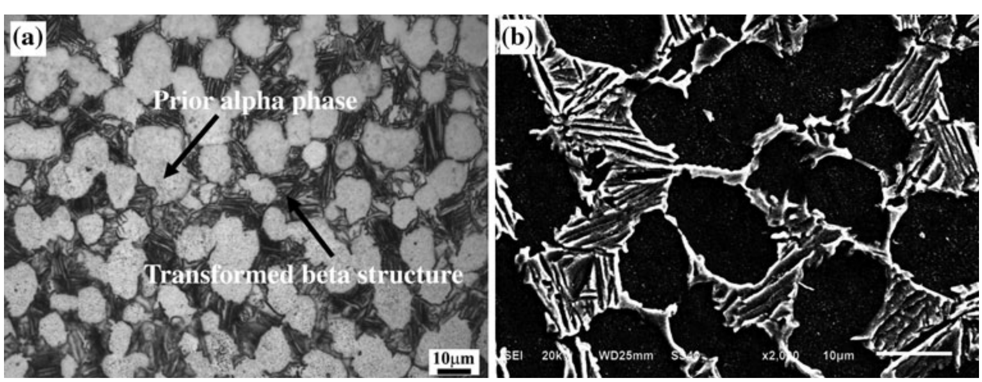

Fig. 1 Microstructure of parent metal **a** OPM and **b** SEM

uniform friction pressure and amplitude of oscillation), 40-Hz frequency of oscillation and 146.7-MPa friction pressure. After welding, the sectioning of joints and flash was performed transverse to the weld interface, perpendicular to the plane of reciprocating linear motion. The cross-sections were grounded, polished, and etched using Kroll's reagent (100 mL H_2O + 2 mL HF + 5 mL HNO_3) for metallographic examination.

The microstructures of joints and flash were examined using optical microscopy (OPM) and scanning electron microscopy (SEM). The grain size and alpha lath width measurements were made using linear-intercept method from the resulting optical micrographs [19], based on the average of three measurements per condition. The volume percentage of the beta phase at high temperatures can be estimated from the volume of the transformed beta microstructure, because all the high-temperature beta grains will be transformed into transformed beta microstructure during cooling from high temperature to room temperature. The examination of phase volume percentage was carried out by Scion Image software from the resulting micrographs.

Results and discussion

Flash characteristics

Figure 3 shows that an appreciable flash from all sides of joints can be observed at relatively high amplitude of oscillation. The flash length increased with amplitude of oscillation rising, which is consistent with the larger axial sample shortening (that is double the difference between specimen length before LFW and that after LFW), see Fig. 4. The average power input can be used to characterize the process parameters as follows [20]:

$$\mathrm{PI} = 4\mu fap \quad (1)$$

where μ, f, p, and a are the average coefficient of friction, frequency of oscillation, friction pressure, and amplitude of oscillation, respectively. According to Eq. 1, high amplitude of oscillation will render high power input and hence more material to yield at the interface. In this case, sufficient heat generation led to a big flash formed and a fully bonded joint made, as seen in Fig. 3d. The flash layer was composed of plastically deformed material that was extruded during LFW. The flash length was larger in the direction of the reciprocal motion, i.e., parallel to the specimen height, as compared to that along the specimen width. Figure 3e shows that the flash appeared in the form of ridges along the specimen height, and the number of ridges was associated with that of oscillation, which are generated as a result of the periodical oscillating extrusion of plastically deformed material during reciprocal motion. A ridge in the flash was formed in a period of oscillation. In the investigation, it could be concluded that a period of oscillation (1/f) is 0.025 s, according to 40 Hz frequency of oscillation (f). As shown in Fig. 5, the number of ridges in the flash is around 70. These results suggest that it took around 1.75 s to extrude the flash during LFW. However, the flash along the specimen width generally showed little evidence of ridges, see Fig. 3e. Consequently, it may be concluded that axial sample shortening proceeded in a stepwise fashion. The pumping action was associated with material yielding and extruding in pulses.

Figure 5 shows that the flash did not have a uniform thickness along the specimen height. At the beginning stage of friction, temperature at the rubbing interface was not very uniform. As material at the rubbing interface

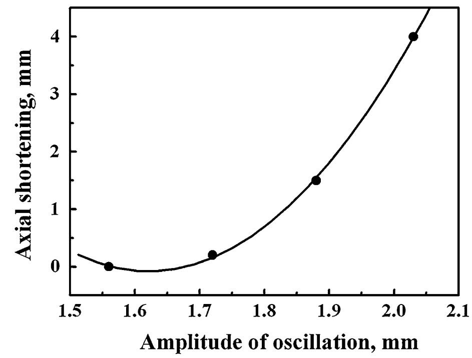

Fig. 4 Effect of amplitude of oscillation on the axial sample shortening

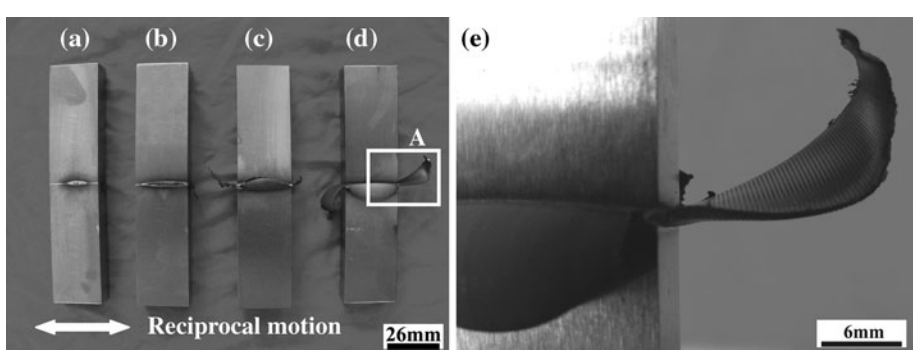

Fig. 3 Optical micrographs of joints at different amplitude of oscillation (*a*) 1.56 mm, (*b*) 1.72 mm, (*c*) 1.88 mm, (*d*) 2.03 mm, (*e*) morphology of A zone at high magnification

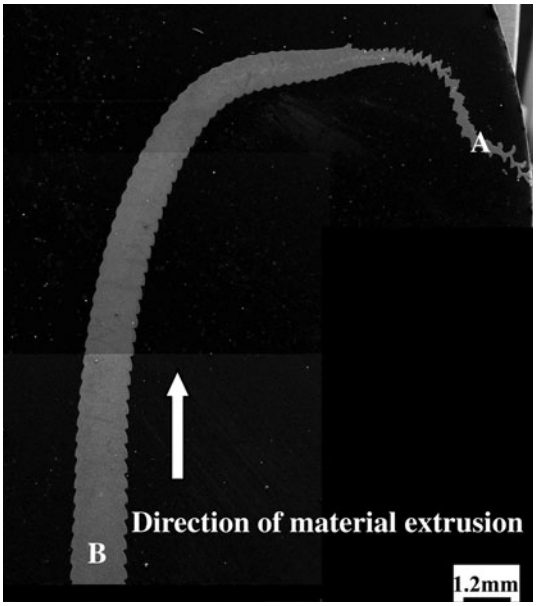

Fig. 5 A flash layer composed of ridges along the specimen height

heated up to high temperature due to friction, the yield stress of materials dropped below the applied friction pressure, resulting in the deformation and extrusion of materials. Continued friction and deformation of specimens increased temperature at the interface instantaneously causing more material to yield, and hence the extrusion rate of material enhanced to increase the thickness of flash cross-section under the applied friction pressure. Subsequently, the extrusion rate of material was slightly changed, which was associated mainly with the balance between the heat input rate and the heat extraction rate at the interface. This feature is required to obtain a uniform material flow during the equilibrium phase of the friction welding process, developing a fully bonded joint.

Microstructure in the flash was considerably different from that in the parent material. Figure 6 shows the microstructure of the material at the tip of flash (where the material was extruded firstly from the rubbing interface, marked as zone A in Fig. 5). Initial bimodal alpha–beta structure was transformed to a structure with equiaxed prior-beta grains and lamellar transformed alpha phase. For alpha–beta TC11 alloy, this evolution in the microstructure can be reasoned by considering the nominal beta-transus temperature of 1009 °C, which represents the condition of the transformation of the microstructure to the single-beta phase field. Hence, the heat input during LFW, which raised temperature in the proximity of the weld interface, resulted in a progressive transformation of alpha to beta phase. The presence of a microstructure consisting of prior-beta grains at the tip of flash suggested that complete transformation of the alpha phase had occurred as the material at the rubbing interface was extruded first, which results from temperature at the interface exceeding the beta transus. These results show that extrusion of materials took place after complete transformation of alpha phase. A closer examination of the microstructure in the flash reveals that the prior-beta grain size was refined and the grain boundaries were curved as compared to those in the parent material. These evidences indicate that beta phase in the extrusion material underwent dynamic recrystallization (DRX) at high strain rate and strain. DRX process at the interface is favorable to obtain plasticized interface conditions for a fully bonded joint. From Fig. 7, prior-beta grain size analysis complemented by microstructure examination at the end of flash (where the material was extruded finally from the rubbing interface, marked as zone B in Fig. 5) revealed larger grains than those at the tip of flash. Average grain size of prior-beta grain reached to around 12.8 μm at the end of flash, while around 7.7 μm average grain size at the tip of flash. This phenomenon can be reasonably attributed to the grain growth since the interface temperature was evaluated during LFW. According to previous analyses of flash, temperature at the interface increased with friction time prolonging owing to continued friction and deformation of specimens. In addition, average alpha plate width in the flash increased slightly from 0.14 to 0.22 μm as volume of extrusion material increased, which was related to the low cooling rate due to the increase of heat input. To some extent, the microstructure of flash reflects the microstructural evolution in the joint.

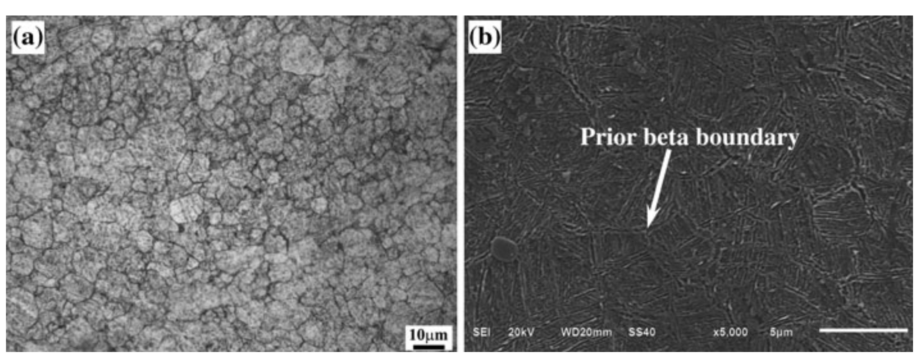

Fig. 6 Microstructure at the tip of flash (A zone in Fig. 5) **a** OPM and **b** SEM

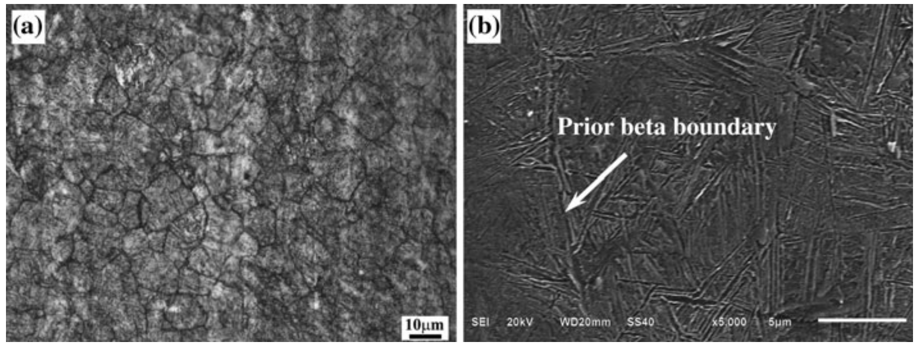

Fig. 7 Microstructure at the end of flash (B zone in Fig. 5) **a** OPM and **b** SEM

Joint characteristics

Generally, metallographic examination revealed that linear friction welded joints contain two different structures, which are the thermomechanically affected zone (TMAZ) developed at the edge of joint and weld appeared in the central portion of joint, as depicted in Fig. 8. In addition, the specimen was heated locally near weld zone due to the low thermal conductivity of titanium alloy during LFW. The microstructure of material near the weld zone was related mostly to temperature and stress. The zone affected exclusively by temperature was absent in the joint. The heat-affected zone (HAZ) was overshadowed through the TMAZ. This can be used to explain the reason why the HAZ was much limited and could not be detected in this investigation.

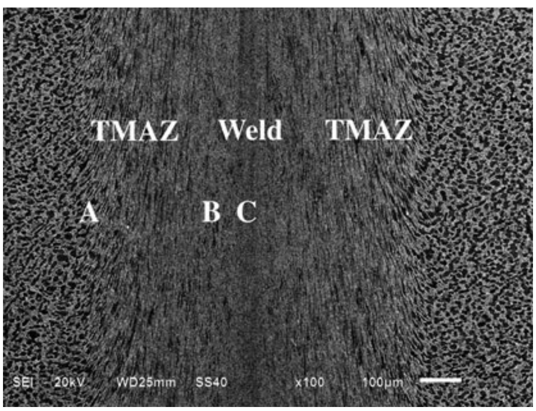

Fig. 8 Microstructure of joints at 2.03-mm amplitude of oscillation

To quantify the microstructural evolution in the joint, grain morphology analyses were carried out for relatively high amplitude of oscillation (Fig. 9). It can be observed that morphology of matrix grain was changed significantly in the TMAZ, which consisted of a highly deformed alpha–beta microstructure. The original grains in the parent material were reoriented during LFW. The elongated alpha

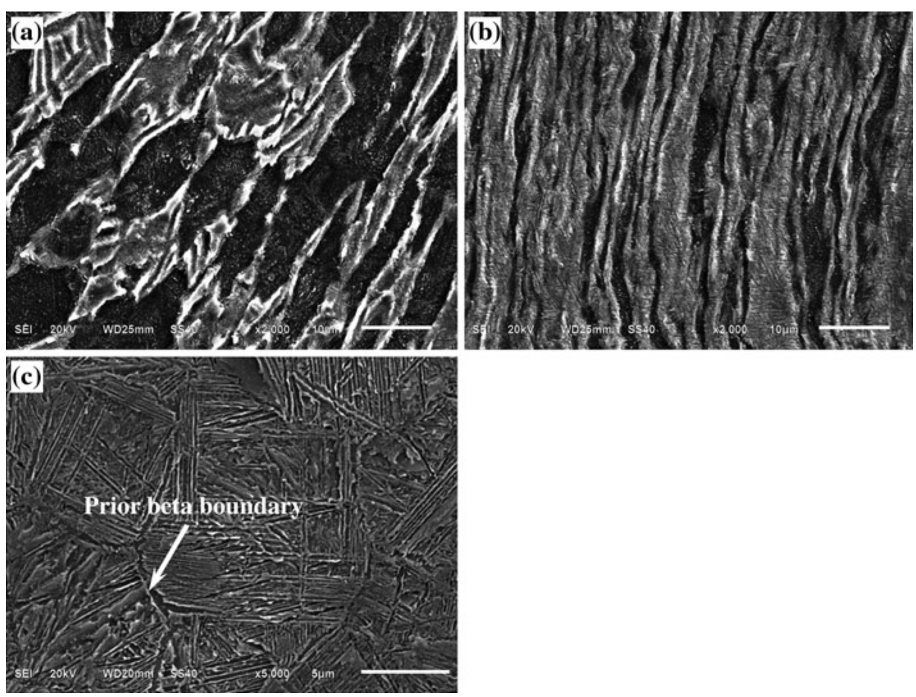

Fig. 9 Microstructure in **a** TMAZ in the region close to parent material, **b** TMAZ in the region close to weld, **c** weld

with intergranular beta phase could be observed in the TMAZ. It is noteworthy that the existence of bimodal microstructure suggests the temperature in the TMAZ not exceeding the beta-transus temperature of 1009 °C. The maximum strain rate at the rubbing interface can be calculated by the following relation [21]:

$$\dot{\varepsilon}_{\max} = \frac{\alpha f}{H} \quad (2)$$

where α, f, and H are amplitude of oscillation, frequency of oscillation, and the height of specimen, respectively. The material in the TMAZ could be considered to experience a hot working process below 3.1 s^{-1} strain rate and below beta-transus temperature. For most metallic materials, the required driving force for phase transformation is much higher than that for DRX, which implies that the occurrence of phase transformation is harder than DRX during hot working process [22]. In fact, the phase transformation occurred concurrently with material deformation during LFW. In this investigation, there was no DRX occurring in the TMAZ, since the beta-transus temperature was not reached in the TMAZ, the original microstructure was retained, as shown in Fig. 9a and b.

The temperature was not uniform in the TMAZ, and hence could be affected by transformation from alpha to beta phase of material at the interface. The transformed beta microstructure volume fraction in the region close to parent material (labeled A region in Fig. 8) is around 51.2%, which is higher slightly than that in the parent material, see Fig. 9a. The result shows that only small prior-alpha phase in the TMAZ was transformed to beta phase due to the relatively low temperature. In comparison with parent material, equiaxed prior-alpha phase in the TMAZ was twisted and elongated by reciprocal motion during LFW. Figure 9b shows the microstructure of TMAZ in the region close to weld (labeled B region in Fig. 8). A relative increase in the volume fraction of transformed beta microstructure was observed, which indicates that temperature in the region was close to the beta transus, and transformation of prior-alpha phase in part. The morphology of retained prior-alpha phase was changed from globosity to strip. The transformed beta microstructure volume fraction increased rapidly from around 51.2% in the region close to parent material to around 70.5% in the region close to weld. Therefore, the transformed beta microstructure volume fraction increased markedly with increasing temperature in the TMAZ.

A lamellar microstructure with evidence of prior-beta grain boundaries could be observed in the weld, which is different evidently from that of parent material, as shown in Fig. 9c (region C labeled in Fig. 8). It shows that complete phase transformation of alpha to beta phase had occurred because of the temperature at the interface exceeding the nominal beta-transus temperature during LFW. Finer prior-beta grain as compared to that in parent material indicates that DRX had taken place during the welding process, which is consistent with previous analyses of the microstructure of flash. According to the results of the TMAZ, it could be considered that DRX should take place after complete phase transformation of alpha to beta phase during LFW, namely, in the single-beta phase field. In fact, DRX of bimodal alpha–beta structure titanium alloys usually appears by deformation in single-beta phase field, because recovery occurs slowly in low stacking fault energy body-centered cubic beta phase, which elevates driving force for recrystallization of beta phase [22]. There is a dependence of prior-beta DRX grain size on the Zener–Holloman parameter according to [23]:

$$D_{\mathrm{DRX}} = kZ^{-c} \quad (3)$$

where $Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right)$, Q is the activation energy, $\dot{\varepsilon}$ is strain rate at the interface, R is the gas constant, k and c are constants. If flash was once formed during reciprocal motion, strain rate of material at the interface would have small changes. However, temperature at the interface increased markedly due to continued friction and deformation of specimens. Therefore, the following relation can be obtained by simplifying relation (3):

$$D_{\mathrm{DRX}} = \exp\left(m - c\frac{Q}{RT}\right) \quad (4)$$

where m is a constant. In terms of Eq. 4, the DRX grain size in the weld would be greater with friction time rising due to higher temperature, which is consistent with the previous results that average prior-beta grain size at the end of flash was greater than that at the tip of flash. During cooling from single-beta phase field to room temperature, a fine lamellar microstructure consisting of multioriented alpha platelets with an inter-platelet beta phase was formed in the weld.

Some defects such as kiss bonding and elliptic porosity existed at the edge of joint along the direction of height at relatively low amplitude of oscillation, see Fig. 10. The width of joint decreased with increasing the distance from the central zone (region A labeled in Fig. 10a), which suggests that the temperature at the edge of the joint is lower than that in the center of the joint during LFW owning to relatively good heat dissipation. Therefore, temperature at the interface was not very uniform during LFW. In particular, temperature in the center of the joint was elevated rapidly as compared to that at the edge of the joint, and hence parent material yielded. However, heat was dissipated so rapidly by the parent material in the vicinity of joint that there was no adequate time to heat the material at the edge of joint, as shown in Fig. 3a. The material that had become plastic during LFW could not

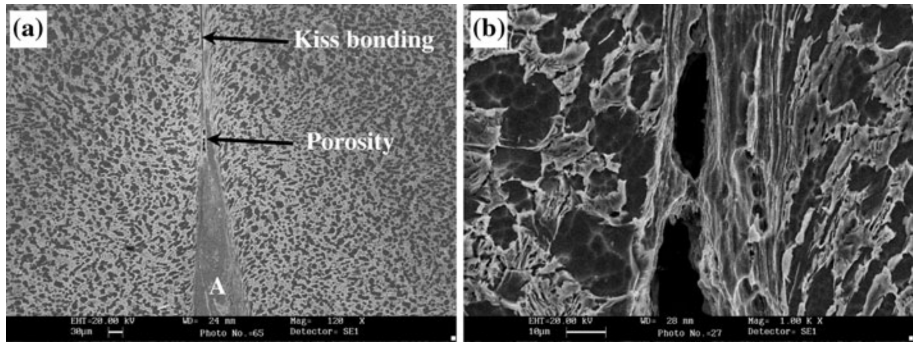

Fig. 10 Microstructure of joints at 1.56-mm amplitude of oscillation **a** at relatively low magnification and **b** at relatively high magnification

spread uniformly at the entire interface. In this case, the true area of weld is smaller than the cross-sectional area of specimens. Consequently, an incomplete joint with some defects was obtained. In contrast, for relatively high amplitude of oscillation, no defect was observed in the joint due to sufficient heat input, as shown in Fig. 8.

The welded joint consisted of a highly deformed alpha–beta microstructure at relatively low amplitude of oscillation, and DRX was not detected in the joint, as shown in Fig. 10b. The results show that the temperature in the joint did not exceed the beta-transus temperature due to relatively low heat input. The material at the interface could be considered to experience a hot working process below 2.4 s^{-1} strain rate and below beta-transus temperature. The phase transformation of alpha to beta phase in the joint had taken place during LFW. As a result, a relative increase in the volume fraction of transformed beta microstructure in the joint was observed as compared to that in the parent material.

Conclusions

(1) The extrusion of material occurred after a complete transformation of alpha to beta phase. Finer prior-beta grains were obtained in the flash as compared to the parent material. The average grain size of prior-beta grain reached to around 12.8 μm at the end of flash, while around 7.7 μm average grain size at the tip of flash.

(2) The TMAZ consisted of a highly deformed alpha–beta microstructure, which implies that the temperature in the TMAZ did not exceed the beta-transus temperature. The phase transformation of alpha to beta phase would occur concurrently with material deformation during LFW. The transformed beta microstructure volume fraction increased as far from the parent material zone.

(3) Temperature at the interface exceeded the nominal beta transus, which rendered complete transformation of alpha to beta phase in the weld during LFW. The prior-beta grain size in the weld would be greater with friction time rising due to higher temperature.

(4) Some defects such as kiss bonding and porosity appeared in the joint at relatively low amplitude of oscillation. Relatively high amplitude of oscillation is more favorable for obtaining a fully bonded joint.

References

1. Daymonda MR, Bonner NW (2003) Physica B 325:130
2. Zhou L, Liu HJ, Liu QW (2010) J Mater Sci 45(1):39. doi:10.1007/s10853-009-3881-1
3. Woo W, Choo H, Withers PJ, Feng Z (2009) J Mater Sci 44(23):6302. doi:10.1007/s10853-009-3868-y
4. Safarkhanian MA, Goodarzi M, Boutorabi SMA (2009) J Mater Sci 44(20):5452. doi:10.1007/s10853-009-3735-x
5. Venkateswaran P, Xu ZH, Li XD, Reynolds AP (2009) J Mater Sci 44(15):4140. doi:10.1007/s10853-009-3607-4
6. Chen T (2009) J Mater Sci 44(10):2573. doi:10.1007/s10853-009-3336-8
7. Mary C, Jahazi M (2008) Adv Eng Mater 10(6):573
8. Romero J, Attallah MM, Preuss M, Karadge M, Bray SE (2009) Acta Mater 57:5582
9. Corzo M, Torres Y, Anglada M, Mateo A (2007) An Mec Fract 1:75
10. Vairis A, Frost M (1999) Mater Sci Eng A 271:477
11. Vairis A (2008) J Eng Sci Technol Rev 1:28
12. Ma TJ, Li WY, Yang SY (2009) Mater Des 30:2128
13. Preuss M, Quinta Da Fonseca J, Steuwer A, Wang L, Withers PJ, Bray S (2004) J Neutron Res 12(1–3):165
14. Karadge M, Preuss M, Lovell C, Withers PJ, Bray S (2007) Mater Sci Eng A 459:182
15. Ginn BJ, Gooch TG (1998) Weld Res Suppl 8:341s
16. Li WY, Ma TJ, Yang SQ, Xu QZ, Zhang Y, Li JL, Liao HL (2008) Mater Lett 62:293
17. Karadge M, Preuss M, Withers PJ, Bray S (2008) Mater Sci Eng A 491:446
18. Ma TJ, Shi DG, Zhang Y, Yang SQ (2009) J Aeronaut Mater 29(4):33
19. Callister WD (2004) Fundamental of materials science and engineering, 5th edn. Chemical Industry Press, Beijing, p 119
20. Li WY, Ma TJ, Zhang Y, Xu QZ, Li JL, Yang SQ, Liao HL (2008) Adv Eng Mater 10(1–2):89
21. Vairis A, Frost M (1998) Wear 217:117
22. Ding R, Guo ZX, Wilson A (2002) Mater Sci Eng A 327:233
23. Vairis A, Frost M (2000) Mater Sci Eng A 292:8