Original Article

Abnormal fracture of 7085 high strength aluminum alloy thick plate joint via friction stir welding

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A R T I C L E   I N F O

Article history:
Received 19 February 2019
Accepted 30 September 2019
Available online 16 October 2019

Keywords:
Friction stir welding
7085-T7452 aluminum alloy thick plate
Microstructure
Fracture behavior

A B S T R A C T

7xxx series high-strength aluminum alloy joints by friction stir welding (FSW) generally fracture in the heat affected zone (HAZ), i.e. the lowest hardness zone (LHZ) during tensile test. However, the experiment results of this study indicate that defect-free FSW joints of 7085-T7452 aluminum alloy thick plate fracture in the weld nugget zone (WNZ) instead of the HAZ for the whole joint or the top slice exhibits very low strength and elongation when using a high rotational rate of 600rpm. Both the microstructure characteristics and the microhardness distribution are not main reasons for the abnormal fracture in WNZ for the whole joint and the top slice. WNZ-top presents both the lowest average Taylor factor and the largest area fraction of grains with high strain. Moreover, the significant strain is concentrated in WNZ-top, showing the inhomogeneous deformation, for the whole joint or the top slice with the increase of nominal stress. But no strain concentration is presented in WNZ-middle and WNZ-bottom and the strain increases uniformly in HAZ for the middle and bottom slices. Combined actions of the above three factors lead to the characteristic of preferential intergranular fracture in WNZ for the whole joint and the top slice.

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1. Introduction

7xxx series high-strength aluminum alloy thick plates are widely used in aerospace due to their advantages, such as high strength to weight ratio and corrosion resistance. At the same time, the preparation of complex structural parts by high strength aluminum alloy is inseparable with the corresponding welding technology. The joints are prone to form melting/solidification defects by the fusion welding, resulting in significant reduction in both of strength and ductility [1,2]. Therefore, there is a need for a high quality welded aluminum alloy technology. The invention of solid-phase welding technology, i.e., friction stir welding (FSW), has brought a revolutionary leap to the joining of aluminum alloy [1–3]. Many defects are avoided, such as voids, hot cracks and large residual stress, since the aluminum alloy is in a plastic state during FSW process [4–8]. So the strength and toughness of FSW aluminum alloy joints have been greatly improved, and have received a lot of attention.

The existing literature reports that the defect-free FSW joints of precipitation-hardened aluminum alloys mostly frac-
ture in the lowest hardness zone (LHZ), i.e. the heat affected zone (HAZ) or thermo-mechanical affected zone (TMAZ) [6–9]. Tensile fracture in TMAZ of FSW 2219 aluminum alloy joints was reported by Mastanaiah et al. [9], which is attributed to the presence of coarsening and agglomerated second phase particles resulting in a higher degree of softening in TMAZ by using the hybrid tool. Khan et al. [10] found that all similar and dissimilar AA2219-O and AA7475-T761 aluminum alloys joints made by FSW fracture in TMAZ or HAZ due to the thermal softening caused by the coarsen and dissolution of the precipitates. Niu et al. [11] investigated the effect of offset of the centre of a tensile specimen to the weld line on global tensile properties of FSW AA2024 joints. The fracture location of joints was in HAZ of the retreating side (RS) and 45° to the loading axis. Deng et al. [12] found most fatigue cracks initiated at TMAZ and HAZ on the advancing side (AS) of the FSW 7050-T7451 aluminum alloy butt welds, which is primarily due to the metallurgical heterogeneity.

Recently, some research results demonstrate that the FSW Al-Li alloy joint fractures in a defect-free weld nugget zone (WNZ) in place of the LHZ [13,14]. Tao et al. [13] reported that 3.2 mm thick FSW 2198-T8 Al-Li alloy joints fractured in the defect-free WNZ instead of the LHZ. The experimental results indicate that lazy S was no longer a determinant of abnormal fracture. A combination of two factors, which were the lowest average Taylor factor of the transition zone between the shoulder-affected zone and the pin-affected zone in the WNZ as well as obvious lithium segregation at grain boundaries, eventually leaded to fracture in the WNZ. Meanwhile, Liu et al. [14] demonstrated that all FSW 2060-T8 Al-Li alloy joints fractured in the WNZ due to only small amount of T1, β’ and α’ resulting in lower microhardness and stress concentration caused by the inhomogeneous microstructure in comparison with the BM. Some research reports on the fracture of FSWed dissimilar materials in WNZ were also investigated. Derazkola et al. [15] showed that dissimilar FSW of AA5083 aluminum alloy and A441 AISI steel failed at the interface of WNZ between aluminum and steel because of the appearance of intermetallic compounds in brittle aluminum steel. Welding parameters, especially the rotational rate, affect the final microstructure and mechanical properties of FSW aluminum alloy thick plate joints [2,9,14]. However, few studies have reported that FSW high-strength aluminum alloy thick plate joints without defect fracture in the WNZ when the rotational rate is increased. So far, it is unclear whether both the global and local FSW thick plate joints have the same fracture locations.

This paper aims to confirm what happens to the mechanical properties including the fracture position of the defect-free whole joint and local slices of FSW high-strength aluminum alloy thick plate under high rotational rate. By the way, microstructure characteristics of different zones are observed using electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM). The contour maps of principal strain at different stages for the whole joint and different slices are collected by the digital image correlation (DIC).

2. Experimental procedure

12 mm thick 7085-T7452 aluminum alloy plates having the dimensions of 400 mm (length) × 150 mm (width) were used in this study and its chemical composition is given in Table 1. A welding tool with a 24 mm shoulder diameter and a 10.5 mm in root diameter and 6 mm in tip diameter conical threaded pin was used to prepare for the butt joints. Meanwhile, a rotational rate of 600 rpm and a welding speed of 60 mm/min were adopted.

The specimens for EBSD observation were cut perpendicular to the welding direction (WD, the same as rolling direction), ground by water sandpaper, and then electro-polished using 10% HClO4 and 90% C2H5OH solution operated at 30 V for 40 s, at last they were characterized using a TESCAN field-emission scanning electron microscopy (FE-SEM) equipped with an EBSD detector and an HKL Channel 5 system. Thin foils cut from the corresponding zones in the weld were polished to 80 μm using water sandpaper, punched into a disk diameter of 3 mm, then electro-polished by jet electro-polishing using 30% nitric acid and 70% methanol solution at -30 °C, and finally the grain morphology and precipitates were characterized by TEM (FEI Talos F200X) operated at 200 kV. Detection locations undergone EBSD and TEM examination are the same as the reference [16].

Both the whole and equal three slices of joints were cut into dog bone shape tensile specimens with a gauge length of 25 mm, a width of 6 mm and a thickness of 12 mm (whole) and 4 mm (slice) according to ASTM E8. The room temperature tensile properties were evaluated with three tensile specimens cut from the same joint. Tensile properties were tested using an electron universal testing machine (Instron-3382) at a strain rate of 10⁻³ s⁻¹, and the local strain fields were determined by DIC. The region size for the DIC software setting was 32 mm long and 12 mm (whole joint) or 4 mm (slices) width, corresponding to the length and thickness of the parallel section of the tensile specimen. Each mesh was 10 x 10 pixels in size for the DIC analysis. Typical fracture was observed by the TESCAN FE-SEM. Meanwhile, a microhardness of the entire weld cross section with 0.5 mm spacing between adjacent indentations was detected by a THV-1D Vickers hardness tester with a testing load of 200 g and a dwell time of 20 s.

3. Results and discussion

3.1. Tensile properties

Fig. 1 shows typical engineering stress-strain curves of the whole and different slices of 7085 aluminum alloy BM and their FSW joints made at a rotational rate of 600 rpm and welding speed of 60 mm/min. It can be seen from Fig. 1 that both the strength and the elongation to failure of the whole joint and slices reduce compared with the BM. In particular, the whole joint and the top slice even fracture just after the yielding point and without yielding, respectively (Fig 1b).
Table 1 – Chemical composition (wt%) of 7085-T7452 aluminum alloy.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Al</th>
<th>Zn</th>
<th>Mg</th>
<th>Cu</th>
<th>Fe</th>
<th>Si</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>Balance</td>
<td>7.0–8.0</td>
<td>1.2–1.8</td>
<td>1.5–2.0</td>
<td>0.08</td>
<td>0.06</td>
<td>0.08–0.15</td>
</tr>
</tbody>
</table>

Fig. 1 – Engineering stress vs. strain curves (a) and high magnification view (b) of the whole and slices of 7085 aluminum alloy BM and FSW joints.

Fig. 2 – Mechanical properties of the whole and slices of 7085 aluminum alloy BM and FSW joints.

From Fig. 2 and Table 2, the yield strength (YS), ultimate tensile strength (UTS) and elongation to failure of the whole joint under the high rotational rate of 600 rpm decrease to 301 ± 9.9 MPa, 332 ± 14.1 MPa and 1.55 ± 0.4% compared with that of BM (442 ± 14 MPa, 500 ± 11.3 MPa and 18.4 ± 0.5%), respectively. For the different slices, the minimum YS, UTS and elongation to failure appear in the top slice and the values are respectively only 176 ± N/A MPa, 237 ± 31.1 MPa and 0.7 ± 0.4%, and reaches only 37, 47, 7% of the same size BM slice, respectively. The corresponding values of middle and bottom slices are 310 ± 7.8 MPa, 393 ± 0.7 MPa, 3.82 ± 0.3% and 292 ± 3.5 MPa, 387 ± 0.7 MPa, 4.51 ± 0.5%, respectively. The ratio of these values to the corresponding BM slices is 66, 78, 39% and 63, 76, 42%, respectively. Therefore, it can be confirmed that the decrease in the toughness of the whole joint made at 600 rpm depends on the deterioration of the top slice.

3.2. Fracture characteristics

It should be noted that the zig-zag fracture feature is observed in the whole joint and the top slice. Both middle and bottom slices are 45° shear fractures with the tensile direction. However, for the high rotational rate of 600 rpm, the whole joint and the top slice fracture in WNZ. Middle and bottom slices present the same fracture position as the low rotational rate of 300 rpm [17] and the fracture occurred at the traditional ‘weakest link’ of the HAZ, as shown in Fig. 3. Similar result was found by Lin et al. [18] on FSW 7055 aluminum alloy joints. This phenomenon is related to material flow and intermingling during the FSW process. The different mixture and even unmixed part caused by the uneven material flow and pull forces on both sides of weld lead to the forming sharp zig-zag shape interface [18,19]. There is a large non-uniform mixing of material along the thickness direction of the plate, especially in WNZ when selecting inappropriate welding parameters. The reason is uneven thermo-mechanical coupling for FSW thick plate joints. The macroscopic fracture sections of the whole joint and the top slice present zig-zag features.

The typical fracture surfaces were observed by SEM to analyze the fracture mechanism of the whole joint and slices. Fig. 4 shows the SEM micrographs of the fracture surface of the whole joint and slices obtained at the rotational rate of 600 rpm. It is interesting to note that a stratified fracture feature as well as rough and wavelike surface is observed in the whole joint and top slice from the low magnification SEM micrographs (see Fig. 4a and 4b). However, relatively flat 45° shear fracture surfaces are visible in middle and bottom slices, as shown in Fig. 4c and d.

From the high magnification view of corresponding zones, the characteristic of intergranular fracture is obvious for the whole joint and top slice. It is difficult to observe the dimples representing transgranular ductile features, except for the high magnification images of zones B in Fig. 4a and E in Fig. 4b exhibit a number of small and shallow dimples. As a
Table 2 – Mechanical properties and ratio of these values to the corresponding BM of the 7085-T7452 aluminum alloy and FSW joints.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Mechanical properties</th>
<th>Ratio to the corresponding BM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YS (MPa)</td>
<td>UTS (MPa)</td>
</tr>
<tr>
<td>Whole joint</td>
<td>301 ± 9.9</td>
<td>332 ± 14.1</td>
</tr>
<tr>
<td>Top slice</td>
<td>176 ± N/A</td>
<td>237 ± 31.1</td>
</tr>
<tr>
<td>Middle slice</td>
<td>310 ± 7.8</td>
<td>393 ± 0.7</td>
</tr>
<tr>
<td>Bottom slice</td>
<td>292 ± 3.5</td>
<td>387 ± 0.7</td>
</tr>
</tbody>
</table>

Fig. 3 – Macroscopic fracture of whole (a) and slices (b) of 7085 aluminum alloy FSW joints.

Fig. 4 – SEM micrographs of typical fracture surface and high magnification view of the whole joint (a), top (b), middle (c) and bottom (d) slices.
result, some regions did not undergo full plastic deformation and fractured in the early stage of deformation, resulting in relatively low elongation. For the middle and bottom slices, the number of dimples increases significantly. That is to say, both middle and bottom slices present a significant plastic deformation during the tensile test. It is consistent with the fact that both of them have high elongation, as shown in Figs. 1 and 2.

3.3. Microhardness

Fig. 5 shows the map and profiles of microhardness distribution in the whole cross section and five different regions along the thickness direction of the joint (top surface, top slice, middle slice, bottom slice and bottom surface), respectively. It is worth noting that the microhardness value of WNZ is close to the BM and the width of LHZ at HAZ increases significantly in comparison to the joint obtained at a low rotational rate of 300 rpm [17]. Microhardness decrease in HAZ can only be attributed to the coarsening or the dissolution of precipitates, which is reported by Ahmed et al. [20] and Carlone et al. [21]. Furthermore, the width of LHZ on RS is relatively larger than that on AS and the hardness level has no obvious difference on both sides. It also can be observed that a significant hardness reduction to 130 HV is exhibited in WNZ for the top slice. It is well known that the LHZ is usually consistent with the fracture location. However, both the whole joint and the top slice tend to fracture in WNZ and the result is contrary to the previous reports made at low rotational rate of 300 rpm [17].

3.4. Effect of microstructure on fracture behavior

In order to describe the microstructure characteristic in detail, the quantified characteristics of grain boundary, i.e. the misorientation angle across grain boundaries, is investigated using EBSD. Generally, grain boundaries are divided into low angle grain boundaries (LAGBs), where the misorientation is in a certain range, typically from 2° to 15° and high angle grain boundaries (HAGBs) where the misorientation is over 15°. In this study, LAGBs and HAGBs are marked with a red line and blue line, respectively. Fig. 6 shows the grain orientation maps in the WNZ-top, WNZ-middle, WNZ-bottom and HAZ. The corresponding misorientation angle distributions and grain size distributions are shown in Fig. 7. The proportions of HAGBs are 19.81%, 59.51%, 65.85%, 59.71% and 35.78% separately for the above five zones. The corresponding values of LAGBs are 39.76%, 23.18%, 18.43%, 23.87% and 40.08%.

Compared with FSW joint made at a low rotational rate of 300 rpm [16], the average grain size of joint obtained at high rotational rate of 600 rpm presents significant coarsening. The values of grain size are 4.74, 6.24, 6.36 and 12.19 μm for WNZ-top, WNZ-middle, WNZ-bottom and HAZ, respectively. It can be seen from Fig. 7b that the main distribution range of grain size expands and the number fraction of peak grain size reduces in the corresponding zones compared with the previous reports of microstructure evolution made at a low rotational rate of 300 rpm [16]. Meanwhile, WNZ is mainly characterized by fine equiaxed recrystallized grains and the fraction of small grains is obviously higher than that of HAZ. It can be concluded that microstructure characteristic such as the misorientation angle distributions, grain size and its distribution obtained by EBSD are not the main reasons for the fracture of the whole joint and the top slice in WNZ.

When the rotational rate changes from 300 rpm to 600 rpm, the weld experiences a higher temperature, which makes all grains grow. At this moment, the increased dissipate heat between the bottom surface of the weld and the backing plate is smaller than the increased dissipate heat from the upper weld. However, the strain rate of mechanical action along the thickness direction presents the decreasing trend. It is well known that there are two thermal-mechanical parameters in FSW, namely frictional heat and mechanical stirring action of the welding tool, they can be held to be responsible for the change in the grain structure. During FSW process, the effect of strain rate on the grain refinement dominates over the effect of frictional heat [16,22]. The bottom of WNZ which experiences the relatively higher temperature as well as the longer dwelling time and the lower strain rate. Thus, the average grain size should be larger than that in the top and middle of WNZ. And the grain size presents an increasing trend along the thickness direction in WNZ made at a high rotational rate of 600 rpm. Such microstructural characteristics are inconsistent with Hall-Petch relationship. So this is unable to explain the cause of fracture in WNZ for the whole joint and the top slice.

3.5. Effect of Taylor factors on fracture behavior

Grain-specific Taylor factors (M) for three different zones of WNZ (top, middle and bottom) and HAZ are calculated in
Fig. 6 – EBSD misorientation color maps of the BM (a), top (b), middle (c) and bottom (d) of WNZ, HAZ (e) of joint.

Fig. 7 – Misorientation angle distributions (a) and grain size distributions (b) of BM and different WNZ and HAZ of joint.

terms of the corresponding of EBSD results to evaluate the deformation ability and the tendency of crack initiation in the above four zones. The uniaxial tensile deformation of M can be expressed as: \( M = \sigma / \tau_c \) [13,23], where \( \sigma \) represents the flow stress of material during the single axial loading and \( \tau_c \) denotes the resolved shear stress applied to the easy-to-open slip system. So the value of M depends on the imposed stress and the crystal orientations. The larger the value of M, the smaller the resolved shear stress, i.e., the crystal material with larger M is more difficult to deform.

Taylor factor M distribution maps of BM and four different weld zones are shown in Fig. 8. The larger M value of grains are, the heavier shade of black is shaded. WNZ-top has a smaller area fraction of grains with a large M value than other zones which including WNZ-middle, WNZ-bottom, HAZ and BM. Calculated average M values in the above four zones are 2.98, 3.28, 3.24 and 3.13, respectively. This indicates that WNZ-top has the smallest M value in comparison with other zones, and that is to say, the largest resolved shear stress acts on the easy-to-open slip system under the same uniaxial tensile stress in the WNZ-top. However, the M values in WNZ-middle and WNZ-bottom are larger than that in HAZ. For the top slice and the whole joint, the plastic deformation should easily occur in WNZ relative to other zones, which results in preferential cracking in WNZ during tensile test. Meanwhile, this also reveals the cause of the fracture in HAZ for middle and bottom slices.

Strain contouring component, measuring the maximum misorientation between any two points in a grain, provides an estimate of the extent of deformation or strain, in an individual grain in a map. A larger area fraction of grains with high strain can be observed in WNZ-top compared with other zones, as shown in Fig. 9. Meanwhile, from the above Taylor factor results, the larger deformation can be obtained for the whole joint and the top slice when applying the same uniaxial tensile stress. The critical strain fracture value of the material is easier to achieve because of the accumulation of two strains. Compared with WNZ-middle and WNZ-bottom, the larger area fraction of grains with high strain presents in HAZ as well as has a relatively small Taylor factor. Consequently, the tendency to fracture in WNZ has been enhanced for the whole joint and the top slice or HAZ for the middle and bottom slices, respectively.

3.6. Effect of precipitates on fracture behavior

The grain structure and the distribution of precipitates in different positions of WNZ and HAZ are further observed by TEM, as illustrated in Fig. 10. It is noted that the increasing trend of grain size in WNZ appears from top to bottom
along the thickness direction of the plate, same as the previous EBSD test results (Fig. 6 and Fig. 7b). It is consistent with the previous literature results that the rate of plastic deformation has a greater effect on the change of grain size than that of experiencing temperature [16,22]. Moreover, the grain of WNZ-bottom growing significantly is attributed to the larger heat conduction from WNZ-top, which is in agreement with the above results of the grain size obtained by EBSD (Fig. 6 and Fig. 7b).

The main strengthening precipitates of 7085-T7452 are η’ and η phases [24]. Precipitates in different weld zones present various behaviors such as dissolution, reprecipitation and coarsening due to suffering from different thermal cycling and varying plastic deformation [25]. The WNZ experiences the most severe thermo-mechanical coupling. The change of the precipitates is an extremely complicated process, and considering the influence of plastic deformation will further complicate the problem. So we have considered the influence of the welding thermal cycle on the precipitates separately. During the temperature increasing, η’ and η phases dissolve into the matrix at high temperature to form a supersaturated solid solution, and the uniform fine η phase is formed during the subsequent cooling. Uniform and fine η phase is the reason for the high strength and hardness of WNZ. Compared with WNZ, the larger aggregated particles exhibit in HAZ, as shown in Fig. 10d. The peak temperature of HAZ is much lower than the peak temperature of WNZ. So the precipitates only partially dissolve in HAZ during the heating process. The remaining part of precipitates, acting as an initial nucleus, grows by absorbing the surrounding solute during the cooling process. A large-scale precipitate phase at the grain boundary and segregating in the grains is formed in the end. The disappearance of the HAZ fine precipitate phase and the formation of a coarse precipitate phase are the reasons for the low hardness and strength of the region.

Moreover, the dwelling time for high temperature increases while the degree of plastic deformation decreases along the thickness direction in WNZ. Some rod-shaped precipitates
spheroidize into a spherical shape and the highest degree of spheroidization exhibits in WNZ-bottom compared with other zones. On the other hand, precipitates on the grain boundary in HAZ are coarser than those in WNZ-top and there is no significant difference in different WNZ. Therefore, both the shape and distribution of precipitates are not determined factors for lower mechanical properties in WNZ-top. Grain size and distribution of precipitates are not the main reasons for determining the deterioration of ductility in WNZ-top.

3.7. **Effect of plastic strain on fracture behavior**

In order to obtain more information about plastic strain behavior of FSW joints, the strain during tensile is tested using the DIC system. **Fig. 11** shows cross-sectional tensile strain contour maps of FSW joints under different stages during tensile test. It can be clearly seen from **Fig. 11a** and 11b that the strain concentration occurs from the upper surface of WNZ for the whole joint and top slice when the tensile stress is under or lower than the YS. The strain of top slice in WNZ increases to
14.1%, which is significantly higher than that in other zones. And then with the increase of tensile stress, local strain concentration increases rapidly until the limit of fracture strain is reached, while no complete plastic deformation occurs in other zones. Nevertheless, the plastic deformation of WNZ is uniform for the middle and bottom slices at this moment. Strain concentration of both of them presents in HAZ (i.e. LHZ) instead when tensile stress is over their respective YS, as shown in Fig. 11c and 11d. Therefore, WNZ for the top slice and whole joint and HAZ for both middle and bottom slices become the weakest zones of the specimens. These obvious differences are mainly due to the fact that various grain sizes and precipitates have a significant impact on the microhardness that determines the deformation resistance capacity. It can be clearly seen from Fig. 6 that different microstructures exist in WNZ, HAZ and BM, resulting in uneven strength and hardness distribution. Different aspect ratios and yield strength result in large differences in stress states in different regions. The triaxial stress in the weak zone can be more than doubled [26], so the local strain accelerating the fracture of the joint is concentrated in the WNZ or HAZ of the corresponding sample.

Fig. 11 – Experimental DIC contour maps of principal strain at different stages (a) whole joint, (b) top slice, (c) middle slice and (d) bottom slice.
Fig. 12 – Tensile strain distribution in the middle cross-section of whole joint delamination (a) and local slices (b) for different nominal stresses.

Tensile strain distribution in the cross-section of whole joint delamination and local slices in different nominal stresses is shown in Fig. 12. The tensile strain of slices is significantly higher than that of the whole joint delamination. Both the top part of the whole joint and the top slice present relatively higher strain values in WNZ, but the peak strain value locates in HAZ and the smaller uniform strain distribution presents in WNZ for other parts or slices with the increase of nominal stress. These are mainly attributed to the lower elongation to failure and deformation resistance capacity of the top part or slice. On the contrary, the middle and bottom parts or slices have a higher elongation to failure and the
strain concentration as well as a better stress relaxation. For the middle and bottom parts or slices, the WNZ has higher deformation resistance capacity and better elongation relative to the softer HAZ. So the higher peak strain presents in HAZ with the increase of tensile nominal stress. The increase of tensile nominal stress remains unchanged when the cross-head speed is constant. The load-bearing section of whole joint is approximately three times more than that of the slices. It takes a long time to reach the critical fracture strain across the entire section. Meanwhile, the uniform strain distribution in the cross-section of the whole joint is obtained by a longer stress relaxation. Hence, the lower peak strain can be acquired for the whole joint in comparison with the slices. It also can be concluded from Figs. 11 and 12 that once tensile specimens formed crack in top of WNZ, no complete plastic deformation occurs in the middle and bottom parts of the whole joint before the failure.

4. Conclusions

All whole joints and top slices fracture abnormally in WNZ rather than HAZ for middle and bottom slices of FSW thick plate defect-free joint when using a high rotational rate of 600 rpm. Both strength and elongation of the whole joint and the top slice have deteriorated severely and show the zig-zag fracture feature. Both middle and bottom slices are 45° shear fractures with the tensile direction and mainly based on the ductile fracture characterized by dimples.

Both the microhardness distribution and the microstructure characteristics including grain size, misorientation, precipitates morphology and distribution are not main reasons for the abnormal fracture in WNZ for the whole joint and the top slice.

The smallest Taylor factor appears in the top of WNZ, indicating that the plastic deformation is most likely to occur in this zone during tension, which results in the preferential crack initiation in WNZ-top. Moreover, the smaller Taylor factor presents in HAZ as compared with WNZ-middle and WNZ-bottom. By the way, the significant strain is concentrated in WNZ-top which contains the larger area fraction of grains with high strain during tension for the whole joint or the top slice. For middle and bottom slices, no strain concentration can be found in WNZ-middle and WNZ-bottom and the strain increases uniformly in HAZ with the increase of nominal stress. The combined action of the above three factors are conducive to crack initiation in WNZ for the whole joint and top slice and in HAZ for middle and bottom slices during tension and eventually causing fracture in the corresponding zone.

Conflict of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, Abnormal fracture of 7085 high strength aluminum alloy thick plate joint via friction stir welding.

Acknowledgements

This work was financially supported by National Natural Science Foundation of China (Grant No. 51405392), China Post-doctoral Science Foundation (Grant No. 2019T120954) and Shaanxi Province Postdoctoral Science Foundation (Grant No. 2018BSH0YXMZZ231). Also, we would like to thank the funding support by the Fundamental Research Funds for the Central Universities (Grant No. 3102019MS0404).

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