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Effect of initial butt surface on tensile properties and fracture behavior of friction stir welded Al–Zn–Mg–Cu alloy

S.R. Ren [a], Z.Y. Ma [a,*], L.Q. Chen [b]

[a] *Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China*
[b] *The State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110004, China*

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Abstract

A new experimental procedure—stir-in-plate welding was adopted to eliminate the initial butt surface of two plates to be joined and examine the effect of the initial butt surface on the formation of the zigzag line and the tensile properties of the welds. The comparison between the butt and stir-in-plate welds indicated that under as-welded condition the zigzag line did not show up in the welds, and two welds exhibited similar tensile properties and fracture characteristics. After post-weld T6-treatment, the zigzag line appeared on the butt weld as zigzag micro-crack at the root tip and discontinuously-distributed cavities of 50–200 μm throughout the weld, which were verified to be associated with the oxide particles. This resulted in the reduced tensile strength and significantly deteriorated ductility with the fracture initiating and propagating along the zigzag line. No zigzag line was discernible on the T6-treated stir-in-plate weld.

Keywords: Friction stir welding; Aluminum; Property; Fracture; Heat treatment

1. Introduction

Since its invention as a solid-state joining process by The Welding Institute (TWI) of the UK, friction stir welding (FSW) has been proved to be one of the most significant achievements in the field of joining aluminum alloys, and has been widely used in the aerospace industry for joining high-strength 7xxx aluminum alloys that are difficult to weld using conventional fusion techniques [1–3]. The FSW offers several advantages such as better mechanical properties, less distortion, weight savings, and fewer weld defects [3].

Recently, two microstructural features, which could negatively influence the mechanical properties of the FSW aluminum joints, have attracted great scientific interests. The first feature was the existence of faint line patterns in the stirred zone (SZ) called as “lazy S”, “zigzag line” or “kissing bond” [4–7]. The zigzag line, which runs through the whole SZ from the bottom to the top or appears only at the root of the SZ, was usually generated under lower heat-input welding condition and showed up after the weld was etched [5–7]. The second feature was the intrinsic instability of the fine-grained microstructure of the weld. For FSW aerospace aluminum alloys, the heat-affected zone (HAZ) is the weakest region of the weld due to the dissolution and coarsening of the precipitates. In order to restore the loss of strength in the HAZ, one option is to conduct a post-weld T6-treatment (PW-T6) [8,9]. However, abnormal grain growth (AGG) was observed in the SZ during high temperature post-weld heat treatment (PWHT) for several FSW aluminum alloys [10–12].

Okamura et al. [5] reported that the zigzag line remained as a vestige of the oxide layer and it did not affect the mechanical properties of the FSW 6xxx alloy weld. Sato et al. [6] observed the microstructure at the root tip of the zigzag line of FSW 5052Al alloy by FIB-assisted TEM. They suggested that the zigzag line originated from the oxide layer of the initial butt surface that was fragmented during FSW and the distribution of Al_2O_3 oxide particles in a local region did not affect the root-bend property of the weld. Recently, Zhou et al. [7] reported that the fatigue lives of the FSW 5083Al and 2024Al joints with the oxide array were much shorter than those of the sound welds.

It is noted that the studies mentioned above were all conducted on the as-welded condition. The study on the effect of the PW-T6 on the formation of the zigzag line is lacking. Recently, the effect of the zigzag line on the mechanical properties of

* Corresponding author. Tel.: +86 24 83978908; fax: +86 24 83978908.
E-mail address: zyma@imr.ac.cn (Z.Y. Ma).

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FSW 2219Al-O joints under both as-welded and PW-T6 conditions was investigated by Liu et al. [13]. They used two kinds of FSW samples: one was directly welded without any clearing of the surface oxide layer and the other was cleared to remove the surface oxide layer prior to FSW. Under the PW-T6 condition, a zigzag line was distinctly visible as continuous micro-cracks throughout the weld thickness for the weld without clearing, whereas no zigzag line was detected for the weld with clearing. Furthermore, the AGG occurred in both welds during the PW-T6 [13]. However, they did not show if the zigzag line showed up under the as-FSW condition. They reported that while the zigzag line exerted no effect on the mechanical properties of the as-welded joint, the properties of the PW-T6 weld were seriously deteriorated due to the formation of micro-cracks along the zigzag line.

It is well known that the aluminum alloy is very prone to be oxidized and the compact Al_2O_3 layer will persist firmly on the surface to prevent the further corruption [14]. Even if the Al_2O_3 layer is removed, it will grow immediately. For the FSW process, the aluminum workpieces ahead of the traveling tool will experience the thermal exposure to a certain extent. In this case, it is unavoidable for the workpieces to be oxidized. Therefore, the experimental procedure of examining the effect of the zigzag line by clearing the surface oxide layer prior to FSW is highly subjected to doubt.

In this study, a new experimental procedure was used to examine the effect of the zigzag line on the mechanical properties of FSW aluminum joints. Considering the fact that the zigzag line is mainly resulted from the oxide layer of the initial butt surface, we eliminate the zigzag line by using stir-in-plate welding, i.e., a welding without the initial butt surface. Further, a PW-T6 was conducted to examine the effect of the PW-T6 on the formation of the zigzag line. By comparing the experimental results of the butt weld to those of the stir-in-plate one, the effect of the initial butt surface on the mechanical properties and fracture behavior of FSW aluminum joints can be unambiguously established.

2. Experimental

Eight millimeters thick 7075Al-T651 rolled plates with different widths were used in this study. The nominal chemical composition and tensile properties of the plates were listed in Table 1. Eighty millimeters wide plates were longitudinally butt welded (hereafter referred to as butt weld), whereas 160 mm wide plate was stir-in-plate welded (hereafter referred to as stir-in-plate weld) with the FSW running along the centerline of the plate. Thus, both butt and stir-in-plate FSW operations had similar heat dissipation condition. A tool with a shoulder of 20 mm in diameter and a threaded cone-shaped pin of 8 mm in bottom diameter was used. Prior to the welding, the top surfaces of all the plates were cleared by the abrasive papers, and further, the butt surfaces for the butt FSW were cleared by milling. Considering the fact that the zigzag line is apt to form under lower heat-input [5–7], a little hot welding parameter (tool rotation rate ω: 600 rpm and traverse speed v: 100 mm/min) was used for both FSW processes to weaken the formation of the zigzag line. Parts of FSW samples were subjected to a T6-treatment (solutionized at 470 °C for 1 h, water quenched, and then aged at 120 °C for 24 h).

The FSW samples were cross-sectioned perpendicular to the welding direction. After successive steps of grinding and polishing, the samples were etched using Keller's reagent and examined using optical microscopy (OM) and scanning electron microscopy (SEM, HITACHI S-3400 N). Grain sizes were estimated by the linear intercept method. Hardness measurement was conducted along the mid-thickness of the transverse cross-section of the welds using an automatic testing machine (Leco, LM-247AT) under a load of 300 g for 15 s. Transverse tensile specimens with a gage length of 40 mm and a width of 10 mm were machined perpendicular to the welding direction. Room-temperature tensile tests were carried out at a strain rate of 4×10^{-4} s^{-1} and the property data for each condition was obtained by averaging three test results. The fracture surfaces of tensile specimens were examined using SEM.

3. Results and discussion

Fig. 1 shows the typical cross-sectional macrographs of FSW 7075Al-T651 joints etched using Keller's reagent. Under the as-welded condition, no welding defect and zigzag line were detected on both butt and stir-in-plate welds, and the onion rings were visible in the SZ (Fig. 1a and c). In the previous studies, it was reported that for lower heat-input, the zigzag line was distinctly visible on the welds after etching [5–7,15]. However, for higher heat-input, the zigzag line was not observed on the etched welds due to enhanced stirring effect [15]. The present observation in FSW 7075Al-T651 is consistent with that in FSW 1050Al-H24 by Sato et al. [15]. The microstructure of the SZ was characterized by fine and equiaxed grains with the average grain size being 5.2 and 5.9 μm for the butt and stir-in-plate welds, respectively (Fig. 2a and c).

The PW-T6 did not result in an AGG and only caused slight grain coarsening in the SZ of both butt and stir-in-plate welds (Figs. 1b and d, 2b and d), indicating that the fine-grained microstructure of the FSW 7075Al-T651 was stable for the solution treatment (ST) of 470 °C/1 h. The mean grain size increased to 7.3 and 7.6 μm for the butt and stir-in-plate welds, respectively. This can be explained by the effective pinning effect of

Table 1
Nominal chemical compositions and tensile properties of 7075Al-T651 rolled plate

Nominal chemical composition (wt.%)								Tensile properties		
Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti	UTS (MPa)	YS (MPa)	El. (%)
5.6	2.5	1.6	0.23	Maximum 0.5	Maximum 0.4	Maximum 0.3	Maximum 0.2	574	502	12.6

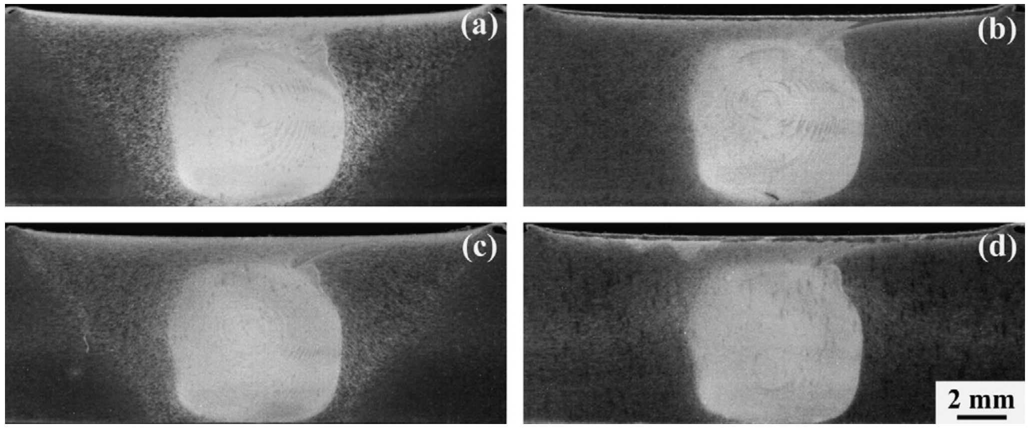

Fig. 1. Cross-sectional macrographs of FSW 7075Al-T651: (a) as-welded butt weld, (b) PW-T6 butt weld, (c) as-welded stir-in-plate weld, and (d) PW-T6 stir-in-plate weld (the advancing side is on the right).

the dispersoids on the grain boundaries. In a previous study [16], it was reported that the fine-grained microstructure of 3.8 μm in FSP 7075Al-T651 was relatively stable without AGG for a heat treatment of 490 °C/1 h, which was attributed to effective pinning by Cr-bearing dispersoids at the grain boundaries [16,17]. However, AGG has been observed in FSW 6061Al-O and 2219Al-O during ST [9,10,13].

After the PW-T6, while no trace of the zigzag line was detected in the stir-in-plate weld, a zigzag micro-crack was macroscopically visible at the root tip of the butt weld (Fig. 1b and d). At a higher magnification, except for the zigzag micro-crack, numerous cavities were detected throughout the SZ (Fig. 3a), and these cavities formed a discontinuous zigzag line. Some cavities appear to be associated with the onion rings as shown by point C in Fig. 3a. By comparison, no flaw was detected in as-FSW butt weld (Fig. 3b). This indicates that for this FSW 7075Al-T651 butt weld produced with a little hot welding parameter, the zigzag line showed up only after high temperature heat treatment, i.e., the zigzag line could not be completely eliminated even with clearing the surface oxide layer prior to FSW. This result is quite different from that obtained by Liu et al. [13] in FSW 2219Al-O joints. Liu et al. reported that under PW-T6 condition, for the weld without any clearing of the surface oxide layer, a zigzag line was distinctly visible as con-

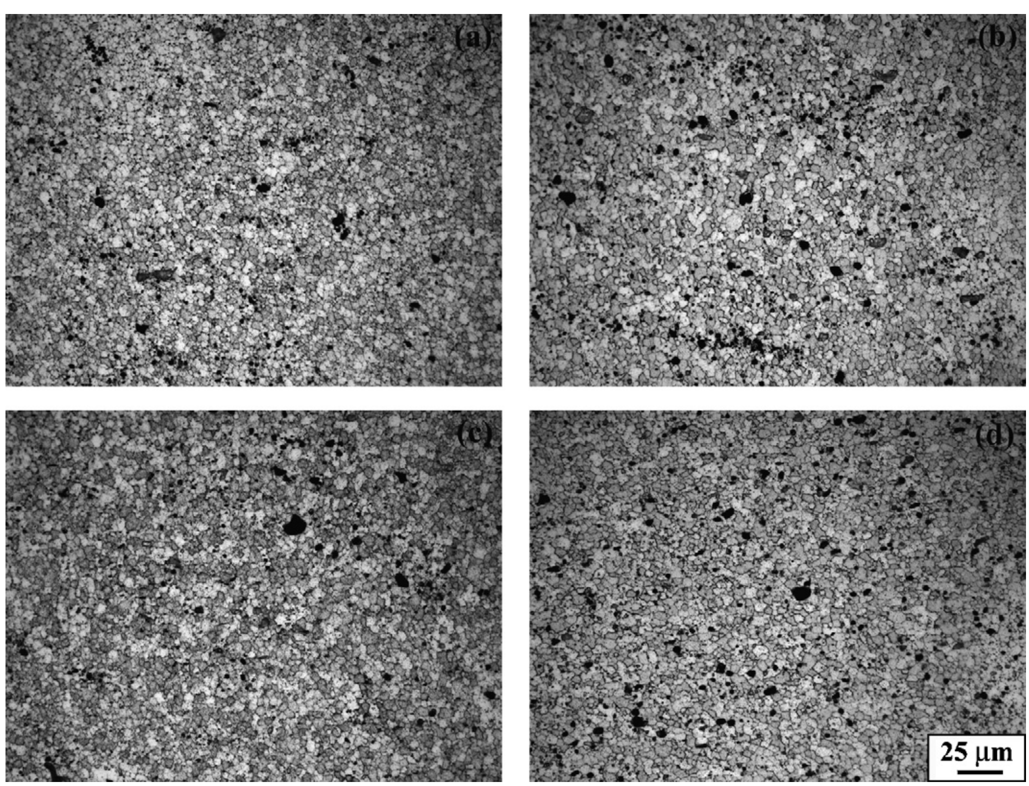

Fig. 2. Optical micrographs showing grain structure of the SZ in FSW 7075Al-T651: (a) as-welded butt weld, (b) PW-T6 butt weld, (c) as-welded stir-in-plate weld, and (d) PW-T6 stir-in-plate weld.

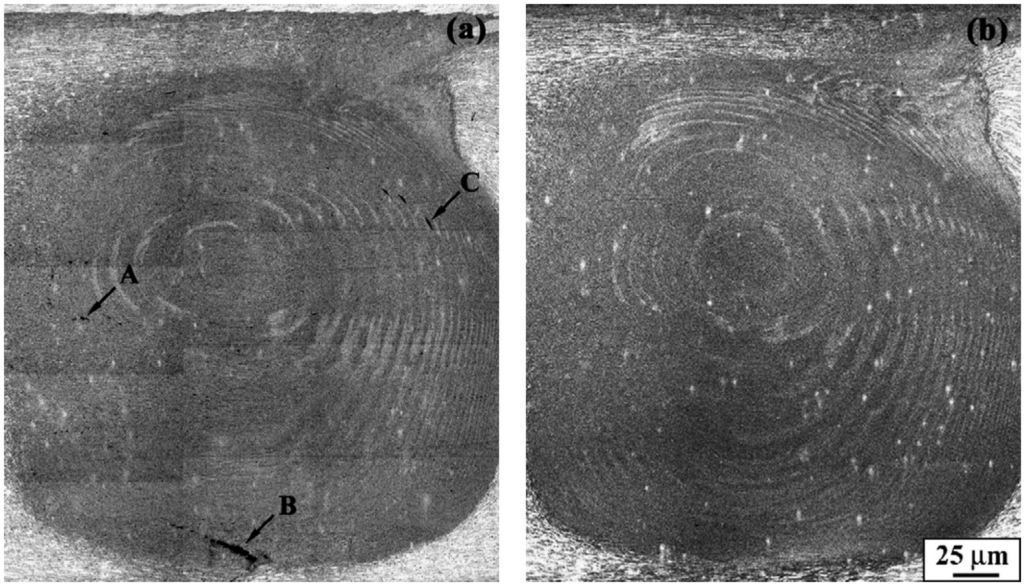

Fig. 3. Optical micrographs showing (a) zigzag micro-crack and discontinuous cavities on PW-T6 butt weld and (b) defect-free as-welded butt weld.

tinuous micro-cracks throughout the weld thickness, whereas the zigzag line disappeared in the weld with clearing the surface oxide layer before the FSW. Based on the present observations, it is suggested that the zigzag line might be weakened, but could not be completely eliminated by clearing the surface oxide layer prior to FSW because the oxide layer will form immediately after clearing, in particular under high temperature thermal exposure ahead of the traveling tool.

SEM observations indicated that the small cavities had a size of 50–200 μm with some inclusions inside (Fig. 4a and c), and the cavities distributed along the onion rings exhibited an elongated shape (Fig. 4c). A high oxygen content (24 at.%) was detected on these inclusions by EDS analyses (point A in Fig. 4a). This indicates that these inclusions were associated with the oxide layer of the initial butt surface. Furthermore, at the tip of the zigzag micro-crack, some smaller cavities were

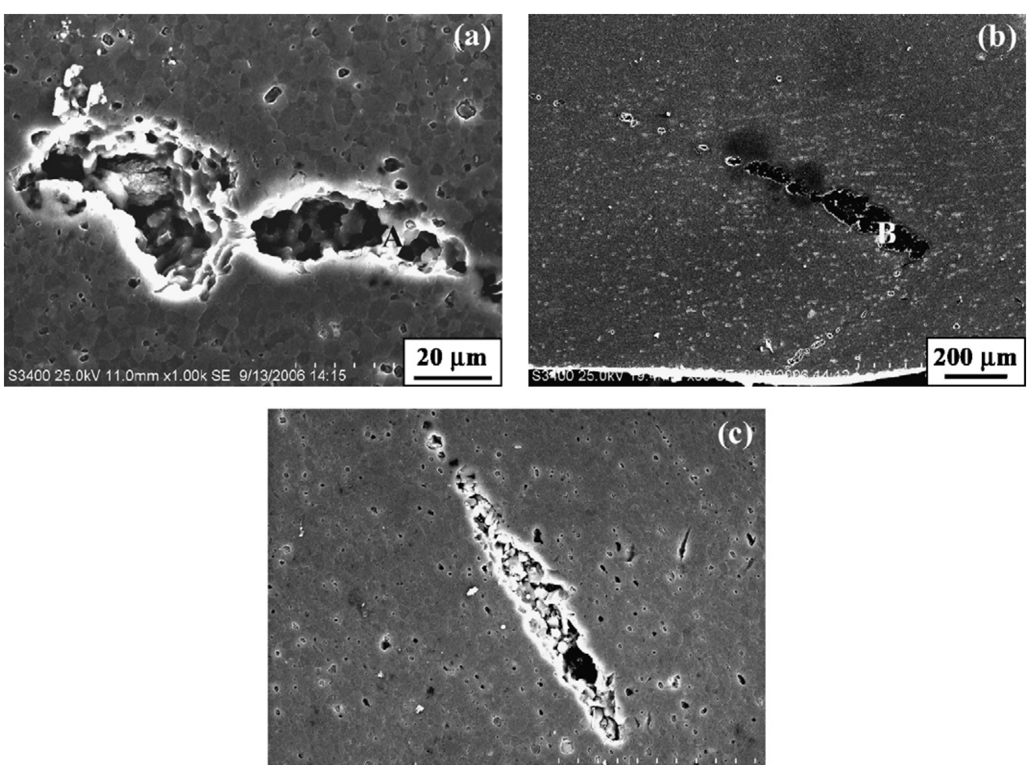

Fig. 4. SEM micrographs showing magnified view of PW-T6 butt weld: (a) cavity (point A in Fig. 3a), (b) zigzag micro-crack (point B in Fig. 3a), and (c) cavity along the onion ring (point C in Fig. 3a).

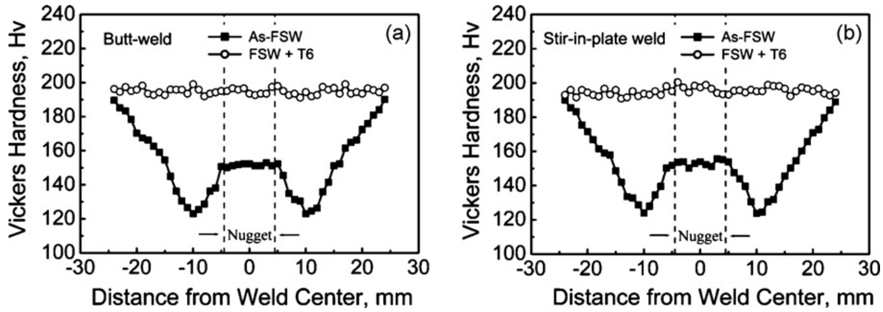

Fig. 5. Vickers hardness distribution of FSW 7075Al-T651 welds: (a) butt weld and (b) stir-in-plate weld (the advancing side is on the right).

Table 2
Transverse tensile properties of FSW 7075Al-T651 joints

Welding procedure	Condition	UTS (MPa)	YS (MPa)	El. (%)	Fracture location
Butt weld	As-weld	430	293	8.0	HAZ
	PW-T6	514	501	1.5	SZ
Stir-in-plate weld	As-weld	425	289	8.1	HAZ
	PW-T6	573	501	11.8	BM

found (Fig. 4b). Again, EDS analyses revealed a higher oxygen content (21 at.%) on the edges of the zigzag micro-crack (point B in Fig. 4b), indicating the intimate relationship between zigzag micro-crack and oxide layer of the initial butt surface.

The hardness profiles of the welds under various conditions were shown in Fig. 5. Under the as-welded condition, the hardness of both butt and stir-in-plate welds were significantly lower than that of the base metal with the lowest hardness being observed in the HAZ due to the coarsening and/or dissolution of the precipitates during the FSW thermal cycle. A similar observation has been made by other investigators [3,17–20]. No difference was observed between the hardness profiles of the butt and stir-in-plate welds because the same FSW conditions were used. After the PW-T6, the hardness of both butt and stir-in-plate welds was completely restored to the level of the base metal. Again, both butt and stir-in-plate welds exhibited quite similar hardness profile under the T6 condition. During the PW-T6, the precipitates in various zones dissolved into the matrix completely and then re-precipitated. In this case, the precipitation-strengthening effect should be quite similar in various zones. Considering the significant grain refinement in the SZ compared to that in the base metal, it appears that the PW-T6 weld might exhibit higher hardness value. However, it was reported that the hardness profile of FSW aluminum alloy joints depended slightly on the grain size, but strongly on the precipitate distribution [18], i.e., the precipitate rather than the grain size is the dominant factor for determining the hardness of the welds. Therefore, the hardness of the SZ was similar to that of other zones for the PW-T6 7075Al-T651 weld.

The tensile properties of the FSW samples are summarized in Table 2. Compared to the base metal (BM), the as-welded 7075Al-T651 butt weld exhibited reduced strength and ductility with the joining efficiency being ∼75%, which is in good agreement with the result obtained by Mahoney et al. [17]. Further, the butt weld exhibited 45° shear fracture in the HAZ on the retreating side (Fig. 6a). This is consistent with the distribution of the lowest hardness in the hardness profile. In this case, the HAZ, rather than the zigzag line (not show up under as-FSW condition) in the SZ, is the weakest zone that dominates the properties of the butt weld. A similar observation has been made in FSW 7075Al-T651 joint by Mahoney et al. [17]. The 45° shear fracture path coincides with the lowest hardness distribution profile of the FSW aluminum alloy joints [20]. It is noted that under as-welded condition, both butt and stir-in-plate welds exhibited similar strength and ductility, as well as fracture characteristics (Table 2 and Fig. 6), which is consistent with the hardness profile (Fig. 5). This indicates that the oxide layer on the initial butt surface exerted no effect on the tensile properties and fracture behavior of the as-welded FSW aluminum joints. This is consistent with the results obtained by Okamura et al. [5] and Sato et al. [6].

After the PW-T6, two kinds of FSW 7075Al-T651 joints exhibited significantly different mechanical properties. The PW-T6 restored the strength and ductility of the stir-in-plate weld

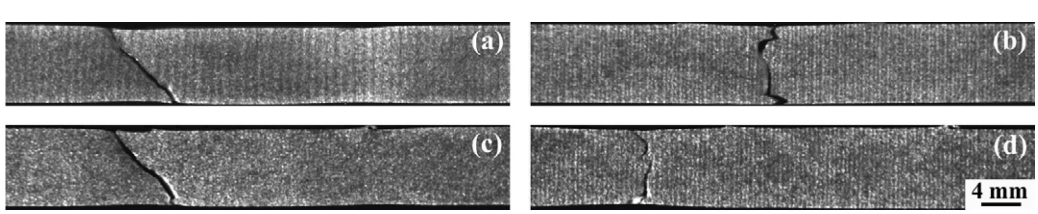

Fig. 6. Appearances of failed FSW joints: (a) as-welded butt weld, (b) PW-T6 butt weld, (c) as-welded stir-in-plate weld, and (d) PW-T6 stir-in-plate weld.

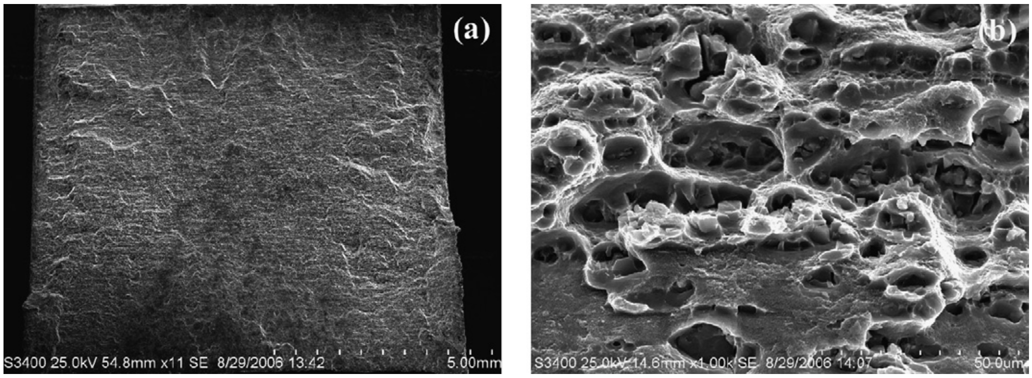

Fig. 7. SEM micrographs showing fracture surfaces of as-FSW butt weld.

completely to the levels of the base metal with the fracture occurring in the base metal zone (Fig. 6d). This indicates that the strength of the stir-in-plate weld is somewhat higher than that of the base metal under the T6 condition. Although the hardness profile of the PW-T6 stir-in-plate weld indicated that the grain refinement did not increase the hardness values of the SZ under T6 condition obviously (Fig. 5b), the tensile results implies that the grain refinement contributed to the increase in the strength

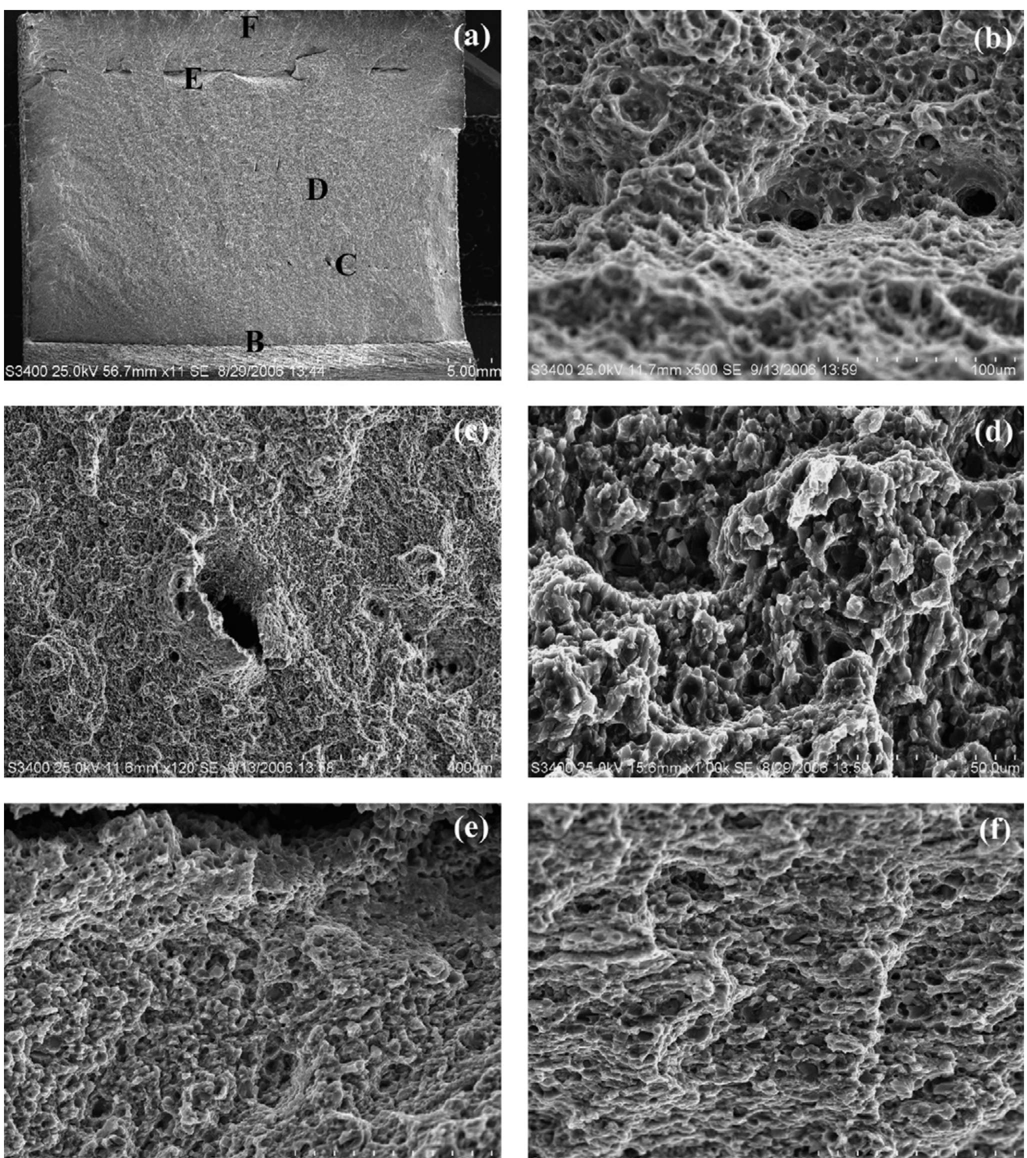

Fig. 8. SEM micrographs showing fracture surfaces of PW-T6 butt weld: (b)–(f) correspond to points B, C, D, E and F in (a), respectively.

of the SZ, resulting in the occurrence of the fracture in the base metal zone. Clearly, the effect of the precipitate distribution and grain refinement on the hardness and strength of the FSW aluminum joints is complicated and needs in-depth investigation. For the butt weld, while 100% of yield strength and 90% of tensile strength were restored by the PW-T6, the ductility of the weld was significantly reduced. The fracture path appeared to be along the distribution of the discontinuous zigzag line (Fig. 6b). By comparing the tensile properties and fracture behavior of the butt and stir-in-plate welds (Table 2 and Fig. 6), it is clear that under the PW-T6 condition, the zigzag line reduced the tensile strength of the weld and deteriorated the ductility significantly.

The as-welded butt weld exhibited a 45° shear fracture without preferential crack initiation source (Fig. 7a). The fracture surfaces were characterized by larger dimples and tearing ridges, indicating extensive plastic deformation (Fig. 7b). Similar fracture surfaces were also observed in the as-welded stir-in-plate weld. For the PW-T6 butt weld, apparently, the fracture initiated at the zigzag micro-crack at the root tip of the weld and propagated towards the top surface along the distribution of discontinuous zigzag line (Fig. 8a–c and e). The fracture surface was characterized by fine and shallow dimples with remarkably reduced tearing ridges (Fig. 7d and f), indicating significantly reduced ductility.

The implication of this study is significant. First, the zigzag line could be weakened, but could not be completely eliminated by clearing the butt surfaces before the FSW. Second, stir-in-plate welding is a very effective approach to verify the effect of the initial butt surface. Third, the zigzag line did not show up under as-welded condition even after etching and exerted no effect on the tensile properties and fracture behavior of the welds. Fourth, after the PW-T6, the zigzag line appeared as a zigzag micro-crack on the root tip and discontinuously distributed cavities of 50–200 μm throughout the weld. In this case, the tensile strength of the welds was reduced and the ductility was significantly deteriorated with the fracture being along the zigzag line. Fifth, although the zigzag line was proposed to be originated from the oxide layer on the initial butt surface, its formation mechanism is still not well understood. This study indicates that the zigzag line showed up only after the PW-T6. The origin of the zigzag micro-crack and discontinuous cavities needs further investigation.

4. Conclusions

1. Stir-in-plate welding is a very effective approach to verify the effect of the initial butt surface and the zigzag line in FSW aluminum alloy butt joint could not be completely eliminated by clearing the surface oxide layer prior to welding.
2. Under as-welded condition, the zigzag line did not show up and exerted no effect on tensile properties and fracture behavior of 7075Al-T651 friction stir welds that exhibited a 45° shear fracture on the HAZ.
3. After post-weld T6-treatment, the zigzag line appeared as a zigzag micro-crack at the root tip of the weld and discontinuously distributed cavities of 50–200 μm throughout the weld and the tensile strength and ductility of the weld were considerably deteriorated with the fracture being along the zigzag line.

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References

[1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Templesmith, C.J. Dawes, GB Patent Application. 9125978.8 (December 1991).
[2] E.D. Nicholas, W.M. Thomas, Int. J. Mater. Prod. Technol. 13 (1998) 45.
[3] R.S. Mishra, Z.Y. Ma, Mater. Sci. Eng. R 50 (2005) 1.
[4] A.P. Reynolds, Sci. Technol. Weld. Joining 5 (2000) 120.
[5] H. Okamura, K. Aota, M. Sakamoto, M. Ezumi, K.Q. Ikeuchi, J. Jpn. Weld. Soc. 19 (2001) 446.
[6] Y.S. Sato, F. Yamashita, Y. Sugiura, Scripta Mater. 50 (2004) 365.
[7] C.Z. Zhou, X.Q. Yang, G.H. Luan, Scripta Mater. 54 (2006) 1515.
[8] M. Cabibbo, E. Meccia, E. Evangelista, Mater. Chem. Phys. 81 (2003) 289.
[9] J.C. Feng, Y.C. Chen, H.J. Liu, Mater. Sci. Technol. 22 (2006) 86.
[10] K.N. Krishnan, J. Mater. Sci. 37 (2002) 473.
[11] Kh.A. Hassan, A. Norman, D. Price, P. Prangnell, Acta Mater. 51 (2003) 1923.
[12] I. Charit, R.S. Mishra, M.W. Mahoney, Scripta Mater. 46 (2000) 631.
[13] H.J. Liu, Y.C. Chen, J.C. Feng, Scripta Mater. 55 (2006) 231.
[14] Z.T. Wang, R.Z. Tian (Eds.), Handbook for Aluminum Alloys and Processing, 3rd ed., Central South University, 2005 (in Chinese).
[15] Y.S. Sato, H. Takauchi, S.H. Park, H. Kokawa, Mater. Sci. Eng. A 405 (2005) 333.
[16] Z.Y. Ma, R.S. Mishra, M.W. Mahoney, Acta Mater. 50 (2002) 4419.
[17] M.W. Mahoney, C.G. Rhodes, J.G. Flintoff, R.A. Spurling, W.H. Bingel, Metall. Mater. Trans. A 29 (1998) 1955.
[18] Y.S. Sato, H. Kokawa, M. Enomoto, S. Jogan, Metall. Mater. Trans. A 30 (1999) 2429.
[19] W.R. Fonda, J.F. Bingert, Metall. Mater. Trans. A 35 (2004) 1487.
[20] S.R. Ren, Z.Y. Ma, L.Q. Chen, Scripta Mater. 56 (2007) 69.