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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR LAP WELDED DISSIMILAR Al/Ti ALLOYS BY ULTRASONIC ASSISTANCE

Dissimilar Al/Ti alloy sheets were lap welded with ultrasonic assistance in this work. The influence of ultrasonic vibration on formation, intermetallic compounds (IMCs) and tensile failure load of the obtained joints was discussed. The results showed that voids formed at the lap interface without ultrasonic assistance. No voids can be observed on the joint welded with ultrasonic because the vibration during welding improved the material flow. No obvious IMC formed at the Al/Ti bonding interface of the joint welded without ultrasonic assistance. An IMC layer formed at the bonding interface of Al/Ti with ultrasonic assistance and its thickness increased with decreasing the welding speed. The failure load of the joint welded with ultrasonic assistance was higher than the joint without ultrasonic because the void was eliminated and the thin IMC layer formed at the bonding interface was beneficial to joint strength. All joints presented shear failure mode during the tensile shear tests.

Keywords: Friction stir lap welding; ultrasonic; intermetallic compounds; failure load; fracture

1. Introduction

To date, the extensive usage of Al alloy and Ti alloy inevitably involves different kinds of welding technologies [1-3]. Friction stir welding (FSW), a novel solid-state joining method [4-7], serves as a promising welding technology in joining dissimilar Al/Ti. Much attention has been given to study the applicability of FSW on joining Al/Ti [8-12]. Kar et al. [8] butt welded Al/Ti with a Nb interlayer to depress the intermetallic compounds (IMCs). They reported that the Nb interlayer restricted Al/Ti reaction, thereby decreasing Al_3Ti phase. Chen et al. [11] lap welded Al/Ti and found that 0 penetration depth resulted into thin interlayer and high joint strength. Wei et al. [12] reported that the surface layer of titanium sheet was cut off by a cutting pin in lap joint. Ultrasonic-assisted FSW (UAFSW) is a novel method invented recently and has attracted wide attentions [13-18]. Liu et al. [13] reported that ultrasonic vibration was helpful to eliminate defect and they also reported that ultrasonic enlarged joint effective joining area. Lv et al. [17] reported that ultrasonic could break Al/Mg IMCs. Ji et al. [16] found that ultrasonic improved the tensile strength of Al/Mg butt joint.

To the best of our knowledge, no papers have focused on the microstructure and mechanical properties of Al/Ti lap joints with ultrasonic. Therefore, in this work, we applied ultrasonic when joining dissimilar Al/Ti alloys. The effect of ultrasonic vibration and welding parameters on IMC thickness was studied. Joints were also fabricated without ultrasonic to give a good knowledge of the ultrasonic effect.

2. Experimental

The base metals were 6061-T6 Al and Ti-6Al-4V alloys. The base metals were lap welded using a width of 50 mm. The tool was made of W-25%Re alloy and had a 15 mm shoulder and a 2.73 mm pin. The bottom and tip diameters of the pin were 7 mm and 4 mm. The schematic of welding and experimental setup are shown in Fig. 1. The tool was rotated at 300 rpm and moved forward at various speeds of 20, 30, and 40 mm/min. The 40 mm ultrasonic sonotrode had a power of 1000 W and a frequency of 20 kHz. Ultrasonic was applied on the lower surface of TC4 sheet.

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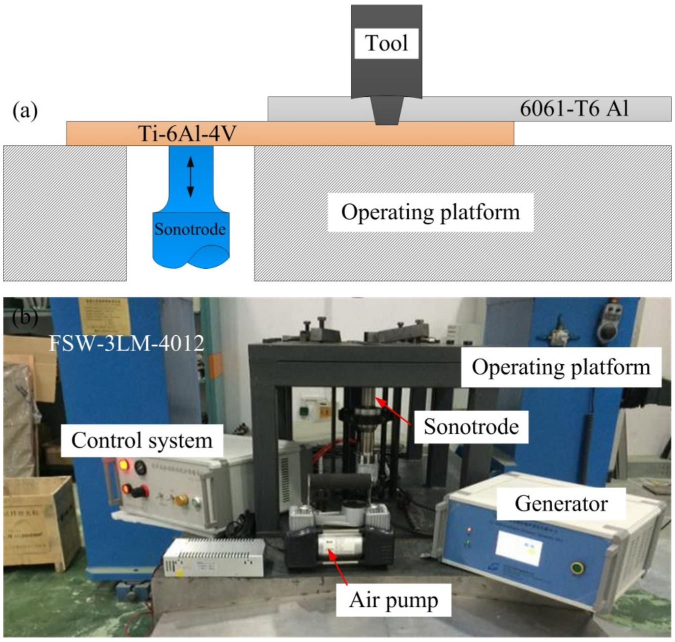

Fig. 1. Schematic of ultrasonic assisted FSLW process (a) and experiment setup (b)

Welded samples were cut to fabricate metallographic and tensile shear specimens. The width of the tensile specimen was 20 mm according to (JIS) Z 3136-1999. Metallographic analysis was performed on an optical microscopy (OM, Olympus-GX71) and a scanning electron microscopy (SEM-SU3500). Room temperature tensile tests were performed using a constant speed of 3 mm/min. Fracture surfaces were analyzed by SEM.

3. Result and discussion

3.1. Joint formation and microstructure

Fig. 2 displays the joint cross sections without (Fig. 2a) and with ultrasonic (Fig. 2b). Ti alloy sheet bended upwards near the stir zone (SZ) at both the advancing side (AS) and the retreating side (RS) of two joints, which was called hook. Yue et al. [19] claimed that such hook played a positive role on joint strength because the up-bending characteristic prevented relative movement of the Al/Ti alloys. However, a hook having an extra height could reduce the effective sheet thickness of a joint [20]. Fig. 2c shows the joint interface microstructure without ultrasonic. Small voids, indicating weak bonding, appeared at the Al/Ti interface. With the assistance of ultrasonic, compact bonding without voids was observed in Fig. 2d, showing that Al/Ti alloys were well bonded. No macroscopic IMC layer formed on any joint because the entire welding process was performed at a solid state. Only a small amount Ti and Al atoms diffused into each other under this condition. Ti fragment, formed by the intense stirring, was observed at Al side (Fig. 2e), which can act as a strengthening phase [20].

The element distributions of Al and Ti are shown in Fig. 3. In Fig. 3a, a diffusion layer with a thickness of approximately 1.5 μm formed at the lap interface at 40 mm/min without ultrasonic. This layer was formed because of element diffusions of Ti and Al by the tool stirring action and the welding heat input. The thickness of the diffusion layer increased at 20 mm/min and such value increased to approximately 2 μm at this moment (Fig. 3b).

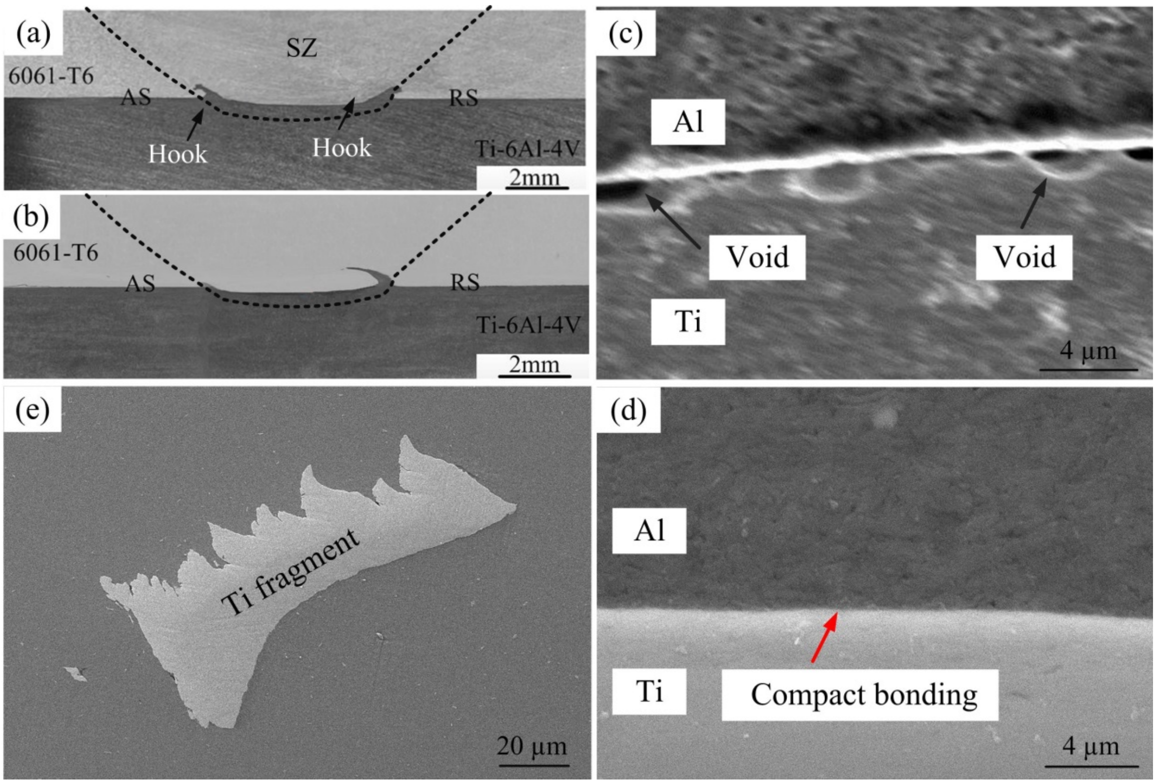

Fig. 2. Joint cross sections welded (a) without ultrasonic, (b) with ultrasonic, joint interface characteristic (c) without ultrasonic, (d) with ultrasonic, and (e) Ti fragment

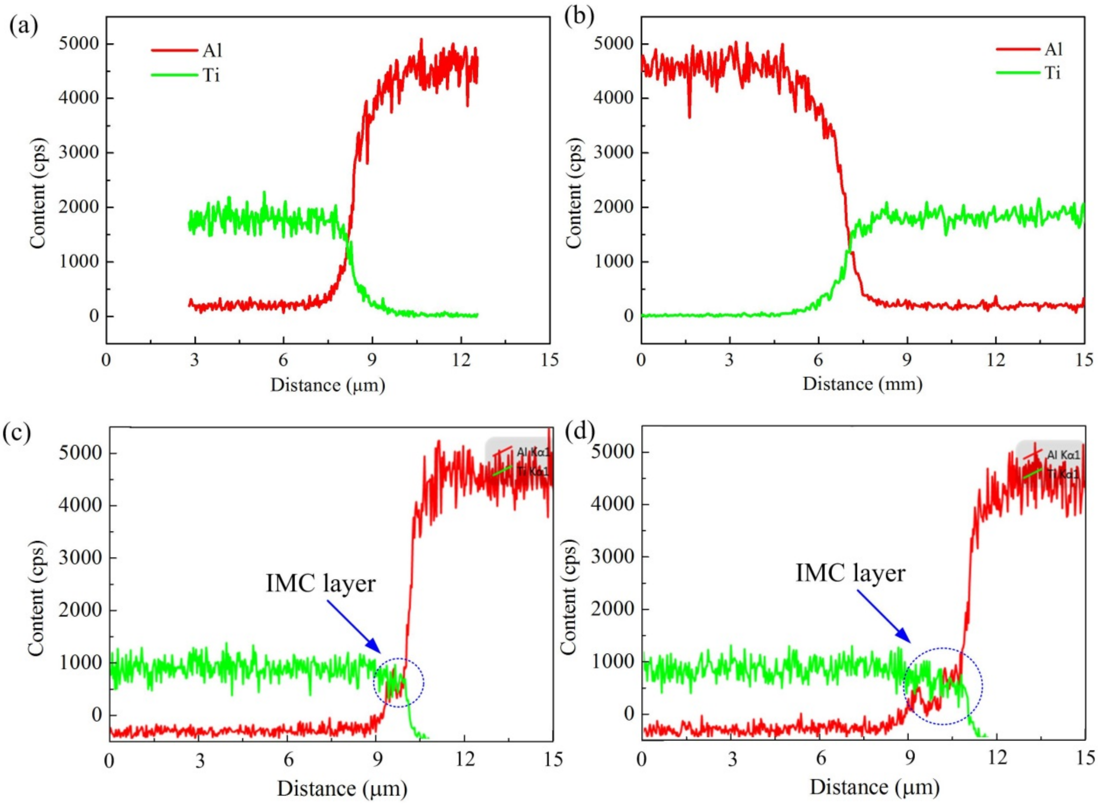

Fig. 3. Element at interface characteristic of joints welded at (a) 40 mm/min and (b) 20 mm/min without ultrasonic, (c) 40 mm/min and (d) 20 mm/min with ultrasonic

We can see from in Figs. 3a and 3b that no obvious IMC layer formed without ultrasonic since the IMC always has stable element content in EDS results. Fig. 3c shows the element distributions of the joint at 40 mm/min with ultrasonic. An obvious IMC layer having a thickness of approximately 1 μm was observed. This was attributed to rather sufficient element diffusion caused by ultrasonic during the welding process. The thickness of the IMC layer increased to approximately 3 μm at 20 mm/min.

Fig. 4 shows the element distributions of Al and Ti at joint center with and without ultrasonic. Element diffusion was recog-

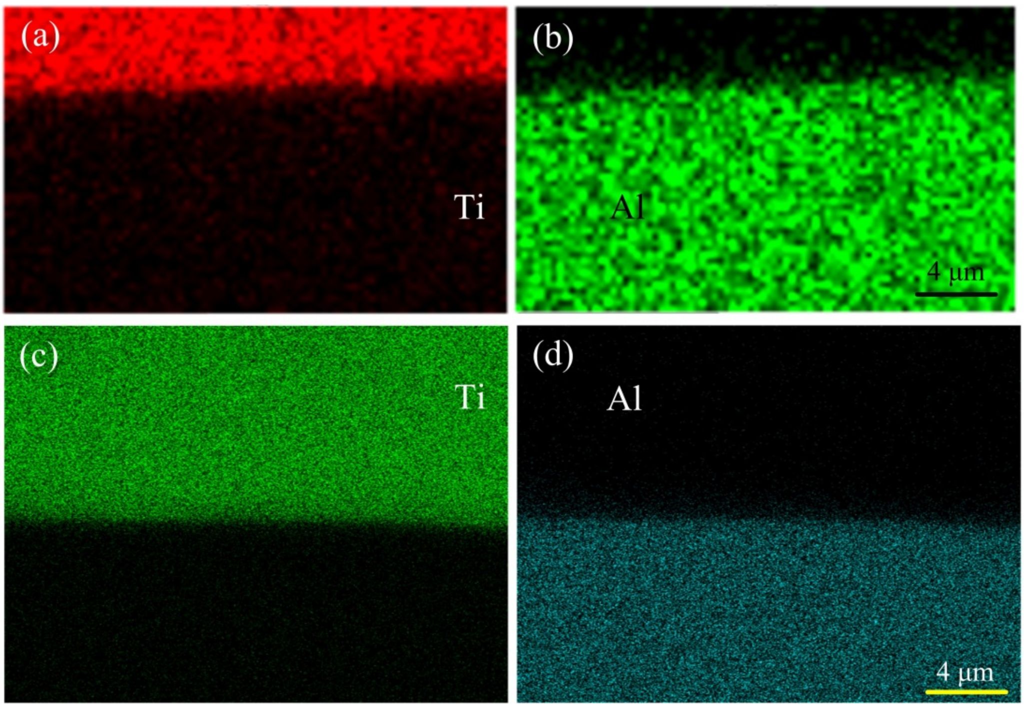

Fig. 4. Element distribution at interfaces welded at 20 mm/min with (a) and without (b) ultrasonic

nized but no obvious IMC layer formed at 20 mm/min without ultrasonic (Figs. 4a and 4b). Al element was recognized at Ti side because TC4 had a 6 % quality ratio of Al. An obvious diffusion layer was recognized under the action of ultrasonic (Figs. 4c and 4d), indicating that an IMC layer formed. This can be attributed to increased element diffusion with ultrasonic assistance. The IMC layer could form at a solid state under this condition.

3.2. Joint mechanical properties

Fig. 5 shows the fracture loads of the joints. The joints welded without ultrasonic had increased failure load when increasing welding speed. The minimum and maximum failure loads of 7201 N (corresponding shear strength of 75.5 MPa) and 7767 N (corresponding shear strength of 87.5 MPa) were respectively obtained at 20 and 40 mm/min, showing that lower heat input was beneficial to joint strength. This result corresponded well with the work of Yue et al. [19], in which they reported that low rotating speed resulted into higher strength of lap welded Al/Ti joints. Ultrasonic was beneficial to joint strength. For the joints welded at 20 and 30 mm/min, the failure load increased approximately 700 N compared to joints fabricated without ultrasonic, which can be attributed to increased material mixing and diffusion caused by ultrasonic. As shown in Fig. 3, IMC layers with small thickness formed at the bonding interface with ultrasonic assistance. As reported by Fereiduni et al. [22], such a thin IMC layer was beneficial to enhancing the bonding at the lap interface and can increasing the load-bearing properties [23]. Furthermore, the void at the bonding interface can be eliminated because ultrasonic can improve the material flow behavior. The elimination of void can effectively avoid stress concentration when the joint bears external forces. These two reasons help to explain the improvement of increase of joint strength. However, the failure load of the joint welded at 40 mm/min assisted by ultrasonic presented a slight decrease. Fig. 6 shows joint fracture positions of the joints welded under different conditions. Joint welded at 20 mm/min without ultrasonic fractured through the upper sheet (Fig. 6a). The RS of the lower sheet was pulled off from the joint after fracture. Similar fracture mode was observed for the joint welded with ultrasonic (Fig. 6b). These results showed that bonding at lap interface was strong. The joint strength decrease at 40 mm/min may be because the relative high hook formed with ultrasonic.

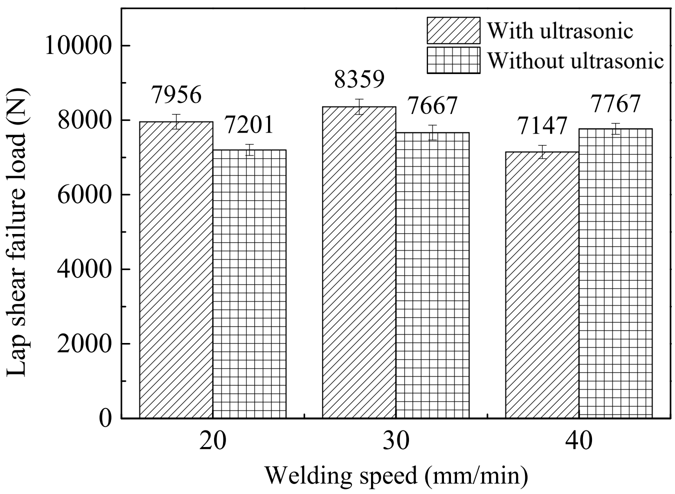

Fig. 5. Lap shear failure loads of joints

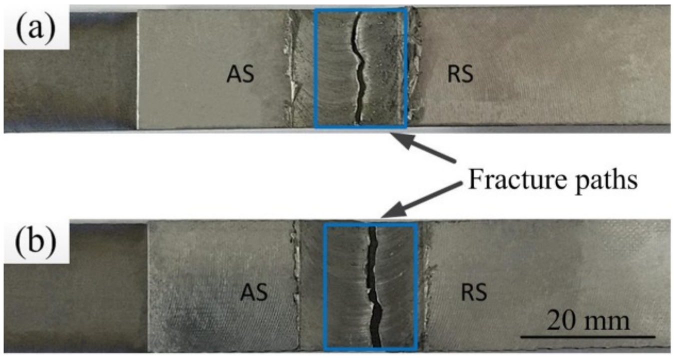

Fig. 6. Fracture positions of the joint without ultrasonic (a), and with ultrasonic (b)

Fig. 7a shows the general fracture morphology at a welding speed of 20 mm/min without ultrasonic. Therein, two distinct regions marked in Fig. 7a were recognized. Fig. 7b shows the magnified image of region b. Lots of dimples, indicating typical ductile fracture mode, were observed. In fact, such region was the typical fracture morphology of 6061 Al alloy. Fig. 7c shows the magnified image of region c, and no dimples were observed inside this region. Such morphology indicated that region c was hook, where no effective bonding was formed (Fig. 8a). This was attributed to short time for diffusion between Al and Ti atoms. The fracture morphology in Fig. 7c showed that hook reduced the effective bonding area of the upper sheet. Such result corresponded well with the result that the joint welded without ultrasonic had low strength. Fig. 7d shows the general fracture morphology at 20 mm/min with ultrasonic. Much different morphology compared to that shown in Fig. 7a was observed. Fig. 7e shows the magnified image of region e. Such morphology is very much like that shown in Fig. 7b and was 6061 Al. The morphology of the unbonded hook was shown in Fig. 7f, where no dimple was observed, either. The bonding condition at the hook with the assistance of ultrasonic is shown in Fig. 8b. Smaller crack compared with Fig. 8a was observed, which can be attributed to ultrasonic assistance.

3.3. Applicability of ultrasonic on joining dissimilar Al/Ti alloys

Ultrasonic vibration enhances the material flow of plastic materials during FSW [23], which can lead to wider joint and can eliminate defects such as void or tunnel [24]. Lots of works have been done to study the effect of ultrasonic vibration on the joint formation and mechanical properties of FSW joints. Liu et al. [13] found that the application of ultrasonic vibration

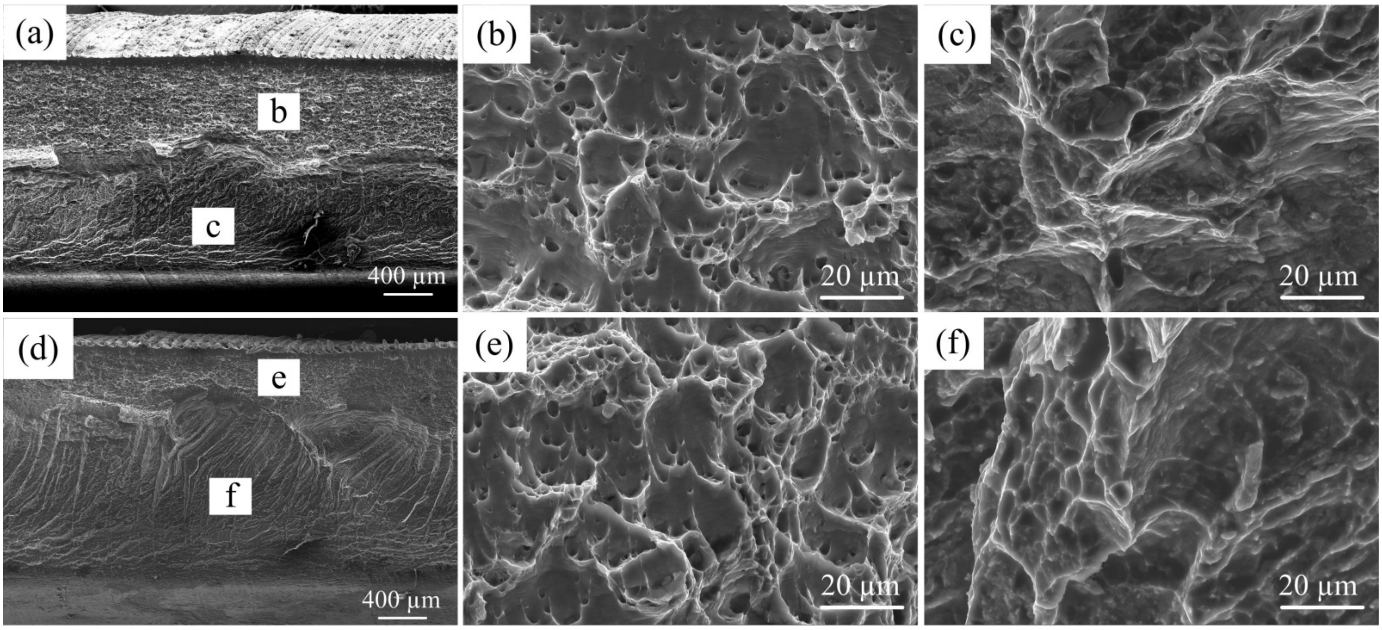

Fig. 7. Fracture morphology of the welded joints: (a) general morphology without ultrasonic, (b) region b, (c) region c, (d) general morphology with ultrasonic, (e) region e, and (f) region f

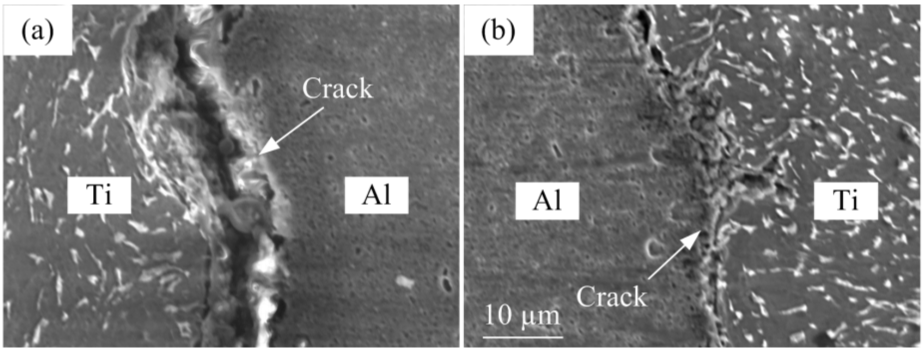

Fig. 8. Interface characteristic outside the hooks (a) without and with (b) ultrasonic

can eliminate the tunnel in 2024-T3 Al alloy FSW joint. Shi et al. [15] simulated the material flow behavior of FSW with and without ultrasonic and found that ultrasonic increased the material flow velocity, enlarged the flow region and reduced the material viscosity. For lap joint, ultrasonic could enhance the material mixing and diffusion between the upper and lower sheets. Rostamiyan et al. [25] joined AA6061 Al with ultrasonic assistance and found that ultrasonic increased the lap shear force and hardness of the welded joint. Ultrasonic could also increase the material mixing and diffusion if it is used to join dissimilar materials [26]. IMCs easily form when joining dissimilar materials [27,28]. Thick IMC layers, which are prone to crack and detrimental to joint strength could form if ultrasonic vibration time is too strong [29,30].

Both the Al and Ti alloys are extensively used transportation industries as structural materials for weight reduction [27], causing the increasing demand for the Al/Ti joining to utilize the excellent properties of both materials with reasonable costs. However, the joining technologies of dissimilar Al/Ti alloys remain a large challenging task because thick IMCs formed during the conventional welding processes [31,32], which significantly decrease the mechanical properties of joints. Hence, it is imperative to explore a reliable welding process for Al/Ti dissimilar joining. The results in this work showed that ultrasonic assisted FSLW was suitable to joining dissimilar Al/Ti alloys and higher joint strength can be obtained. The further work was to study suitable ultrasonic intensity, welding parameters to avoid large amount of IMC formation.

4. Conclusions

1. Dissimilar Ti/Al alloy sheets were successfully welded by FSLW assisted by ultrasonic vibration. Small voids formed at the lap interface were eliminated with ultrasonic because ultrasonic increased the material flow.
2. No obvious IMC layer formed at the bonding interface without ultrasonic assistance. An IMC layer with a thickness of 3 µm formed at 20 mm/min with ultrasonic because ultrasonic can accelerate the atom diffusion during welding.

3. Joint failure load with ultrasonic was higher than joint without ultrasonic because the thin IMC layer formed at the bonding interface was helpful to joint strength improvement.

Disclosure statement

No potential conflict of interest was reported by the authors.

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REFERENCE

[1] S.D. Ji, Q. Wen, Z W. Li, J. Mater. Sci. Technol. **48** (1), 23-30 (2020).
[2] S.D. Ji, Z.W. Li, L.G. Zhang, Y. Wang, Mater. Lett. **188**, 21-24 (2017).
[3] S.J. Doshi, A.V. Gohil, N.D. Mehta, S. R. Vaghasiya, Materials Today: Proceedings **5** (2), 6370-6375 (2018).
[4] Y.C. Chen, H.J. Liu, J C. Feng, Mater. Sci. Eng. A **420**, 21-25 (2006).
[5] H.J. Liu, H. Fujii, M. Maeda, K. Nogi, J. Mater. Process. Technol. **142**, 692-696 (2003).
[6] U. Suhuddin, V. Fischer, F. Kroeff, J.F. dos Santos, Mater. Sci. Eng. A **590**, 384-389 (2014).
[7] G. Casalino. Metals **10** (1), 80 (2020).
[8] A. Kar, S.K. Choudhury, S. Suwas, S.V. Kailas, Mater. Charact. 1**45**, 402-412 (2018).
[9] A. Kar, S. Suwas, S.V. Kailas, Mater. Sci. Eng. A **733**, 199-210 (2018).
[10] K. Gangwar, M. Ramulu, Mater. Des. **141** (5), 230-255 (2018).
[11] Z.W. Chen, S. Yazdanian, Mater. Sci. Eng. A **634**, 37-45 (2015).
[12] Y. Wei, J. Li, J. Xiong, F. Huang, F. Zhang, S.H. Raza, Mater. Charact. **71**, 1-5 (2012).
[13] X.C. Liu, C.S. Wu, G.K. Padhy, Sci. Technol. Weld. Join. **20** (4), 345-352 (2015).
[14] Z.L. Liu, S.D. Ji, X.C. Meng, Z.W. Li, Can. Metall. Quart. **57** (2), 181-185 (2018).
[15] L. Shi, C.S. Wu, X.C. Liu, J. Mater. Process. Technol. **22**2, 91-102 (2015).
[16] S.D. Ji, X.C. Meng, Z.L. Liu, R.F. Huang, Z.W. Li, Mater. Lett. **201**, 173-176 (2017).
[17] X. Lv, C. Wu, C. Yang, G.K. Padhy, J. Mater. Process. Technol. **254**, 145-157 (2018).
[18] N.A. Muhammad, C.S. Wu, W. Tian, J. Alloy. Compd. **785**, 512-522 (2019).
[19] Y. Yue, Z. Zhang, S. Ji, Z. Li, D. Yan, Int. J. Adv. Manufact. Technol. **96** (5-8), 2285-2291 (2018).
[20] Y. Yue, Z. Li, S. Ji, Y. Huang, Z. Zhou, J. Mater. Sci. Technol. **32** (7), 671-675 (2016).
[21] Z.W. Ma, Y.Y. Jin, S.D. Ji, X.C. Meng, L. Ma, Q.H. Li, J. Mater. Sci. Technol. **35** (1), 94-99 (2019)
[22] E. Fereiduni, M. Movahedi, A.H. Kokabi, Sci. Technol. Weld. Join. **21** (6), 466-472 (2016).
[23] L. Shi, C.S. Wu, G.K. Padhy, S. Gao, Mater. Des. **104**, 102-115 (2016).
[24] X.C. Liu, C.S. Wu, J. Mater. Process. Technol. **225**, 32-44 (2015).
[25] Y. Rostamiyan, A. Seidanloo, H. Sohrabpoor, R. Teimouri, Arch. Civ. Mech. Eng. **15** (2), 335-346 (2015).
[26] Y. Liu, W. Yu, Y. Liu, Ultrason. Sonochem. **50**, 67-73 (2019).
[27] M. Yu, H. Zhao, F. Xu, T. Chen, L. Zhou, X. Song, N. Ma, J. Mater. Process. Technol. **282**, 116676 (2020).
[28] G. Casalino, S. D'Ostuni, P. Guglielmi, P. Leo, M. Mortello, G. Palumbo, A. Piccininni, Optik. **148**, 151-156 (2017).
[29] Z. Li, Z. Xu, D. Zhu, Z. Ma, J. Yan, J. Mater. Process. Technol. **255**, 524-529 (2018).
[30] Z. Xu, Z. Li, J. Li, Z. Ma, J. Yan, Ultrason. Sonochem. **46**, 79-88 (2018).
[31] G. Casalinoa, M. Mortello, P. Peyre, J. Mater. Process. Technol. **223**, 139-149 (2015).
[32] P. Li, Z. Lei, X. Zhang, J. Liu, Y. Chen, Opt. Laser. Technol. **124**, 105987 (2020).