Microstructure and mechanical properties of 6061-T6 aluminum alloy and Q235 steel via probeless friction stir extrusion joining

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Abstract

Aluminum alloy and steel composite structures are increasingly and widely used in the automotive industry and other fields owing to their advantages of light weight and high comprehensive performance. The high-quality joining of aluminum alloy and steel has become the research focus in China and overseas. The current study proposes a probeless friction stir extrusion joining (P-FSEJ) process to avoid intermetallic compounds, reduce wear of tools, and obtain a spot joint without keyhole defects. Strong mechanical interlock is formed after that the plasticized aluminum alloy (AA) 6061-T6 is extruded into the prefabricated threaded hole of a Q235 steel plate in the P-FSEJ process. Three distinct zones in the typical symmetrical "basin-shaped" P-FSEJed joint are observed. In addition to the rotation speed, the diameter of the threaded hole is also specifically used to study the influence on the mechanical properties of the joint. When the rotation speed is 1200 rpm, the maximum tensile-shear loads of the M6 and M7 threaded hole joints are 2882.93 N and 3344.74 N, respectively, while the M8 threaded hole joint is 4139.58 N at rotation speed of 1000 rpm. Two typical fracture failure modes of the P-FSEJed joints, namely, rivet shear and rivet pullout-shear fractures, are obtained under tensile-shear loading. Lastly, the P-FSEJed joints with mode "P" fracture failure generally have high strength and energy absorption capability.

1 Introduction

With the worsening global climate change, environmental pollution, and energy crisis, lightweight automobiles have become essential for the automotive industry to save energy and reduce emissions [1–3]. Aluminum alloys have numerous advantages, such as low density, high specific strength, corrosion resistance, and good thermal conductivity [4–6]. Moreover, aluminum alloy and steel composite structures are increasingly used in the body [7, 8]. However, these composite structures present a huge challenge to the existing body welding process while achieving a lightweight body [9, 10].

Owing to the large physical and chemical property differences between aluminum alloy and steel [11, 12], such as thermal expansion coefficient, thermal conductivity, and specific heat capacity, the joining of aluminum and steel has consistently become a research focus in dissimilar joining techniques [13]. Although such methods as fusion welding and brazing can realize the joining of aluminum and steel [14], internal stress, cracks, and pores in joints often lead to poor joint quality and mechanical properties [15, 16].

Friction stir welding (FSW) is a promising technique for joint dissimilar materials, such as aluminum and steel, which effectively eliminate existing problems in fusion welding and brazing techniques [17]. In 1993, Mazda Corporation of Japan developed a friction stir spot welding (FSSW) technology [18], and the first dissimilar material FSSWed joint of aluminum alloy and steel was obtained successfully in 2005 [19]. To date, FSW and FSSW have gradually developed into one of the most advanced joint technologies in aerospace, shipbuilding, automobile, and other industrial fields, which will replace traditional joint technologies, such as resistance spot welding and riveting [20–22]. Given that the traditional FSSW joint

has keyhole and hook defects [23–25], the GKSS Research Center of Germany developed the refill friction stir spot welding process. Although keyhole defects can be eliminated, this process is complicated and requires high equipment rigidity and control accuracy [26–28].

Bakavos et al. achieved a high lap shear strength joint without keyhole defect of a thin AA6111-T4 sheet using the pinless friction stir spot welding (P-FSSW) process. P-FSSW mainly depends on the sufficient plastic flow of the material at the welding point under the friction and extrusion action of the pinless tool shoulder [29]. Similarly, the solid-state joining of a 38.1-mm thick AA6061 to 12.7-mm thick steel plate has been achieved using a new process called friction stir dovetailing (FSD) by Md. Reza-E-Rabby et al. [30], who studied the effects of welding parameters on joint strength and microstructure.

Plasticized aluminum alloy material was extruded to the groove pre-processed on the titanium sheet by FSW. Evans et al. obtained a metallurgical bonding joint with mechanical lock of aluminum alloy and titanium sheet [31]. Jarrell et al. also obtained T-joints of low carbon steel and AA6061 sheet by extruded aluminum into a concave groove cut into the top edge of a steel sheet using friction stir extrusion (FSE) [32]. To avoid hard and brittle intermetallic compounds during FSW of aluminum alloy and steel, Wang et al. proposed a novel friction stir rivet welding (FSRW) process for spot joining AA6061 and DP600 galvanized steel [33]. This process is attributed to the fact that plasticized aluminum alloy is extruded into the pre-fabricated hole on a steel sheet, thereby forming an "aluminum rivet." However, this process uses a low die with cavity, and the exterior protrusion on the bottom surface of the FSRWed joint has greatly limited its applications in the visible areas and functional surfaces.

The preceding studies have mainly focused on the principle of friction stir welding process and the influence of process parameters on the mechanical properties of joints. Whether the dovetail groove or hole is pre-fabricated on the steel sheet, the influence of its geometric size on the joint mechanical properties has been rarely discussed. Moreover, the FSRWed joint obtained by Wang et al. has a exterior protrusion at the bottom, thereby affecting its practicability. Therefore, the current study proposes a probeless friction stir extrusion joining process for aluminum and steel dissimilar metals, in which the bottom of the joint is flat. The microstructure distribution of the joint is analyzed using electron back scattered diffraction (EBSD). The influence of rotational speed and diameter of the pre-fabricated threaded hole on the joint mechanical properties are substantially discussed. Lastly, different joint failure modes are examined using scanning electron microscope (SEM).

2 Mechanism Of Probeless-friction Stir Extrusion Joining

Figure 1 illustrates the P-FSEJ process of aluminum and steel sheets and mainly includes four stages: positioning, plunge and friction, dwell, and retract. First, the oxide layer and burrs on the surface of the aluminum and steel sheets with pre-fabricated threaded hole are polished before they are clamped in the form of a lap joint. Thereafter, an aluminum sheet is placed above the steel sheet. Second, the aluminum sheet is heated using high-speed rotating P-FSEJ tool via friction, and the plasticized aluminum material is gradually extruded into the thread hole by imposing the upsetting force in the vertical direction until the

P-FSEJ tool shoulder reaches the setting plunge depth. To ensure that the threaded hole is fully filled with plasticized aluminum material, the rotating P-FSEJ tool continues input frictional heat for a certain time, which is called "dwell time." Lastly, the plasticized aluminum material is cooled in the threaded hole, and a "threaded-aluminum rivet" is formed after the P-FSEJ tool retracts to the coordinate origin and stops rotating.

3 Experimental Details

3.1 Materials and experimental setup

This study used a 3-mm thick AA6061-T6 sheet and 1.8-mm thick Q235 sheet with dimensions of 25 mm × 100 mm as base materials. The microstructure cross-section of the AA6061-T6 base metal (BM) perpendicular to the rolling direction is shown in Fig. 2 (a). Threaded hole with the same pitch (1 mm) but different thread diameters (6, 7, 8 mm) were pre-fabricated on Q235 sheets. Figure 2 (b) shows the P-FSEJ tool, the shoulder diameter of which is 15 mm and used in the P-FSEJ process, was made of GH4169 steel treated at 50 HRC and with six grooves machined on the shoulder surface as windmill type. The P-FSEJ tests were conducted on a modified CNC machine with the same plunge depth, dwell time, and feeding speed (i.e., 0.2 mm, 10 s, and 10 mm/min, respectively) of the FSRW tool during the test but with varying rotation speeds of 600, 800, 1000, 1200, and 1500 rpm. Thereafter, a set of the P-FSEJed joints was obtained for each threaded hole at different rotation speeds.

3.2 Mechanical property testing and microstructural characterization

After welding, the static tensile-shear strength of the P-FSEJed joints were tested on the INSTRON 5982 universal testing instrument. The test method for the tensile-shear of the P-FSEJed joints refers to international standard (i.e., ISO 14323 – 2006) and China's national standard (i.e., GB/T 15111-94). Figure 3 illustrates the geometric characteristics of the tensile-shear strength test specimen. Room temperature tensile-shear tests were performed at a loading speed of 1 mm/min (the red arrows in Fig. 3 show the loading directions). To maintain the joint's interfaces being parallel to the loading direction, supporting plates were added to the ends of the tensile-shear test specimen, as shown in Fig. 3. In the current research, the tensile-shear failure load corresponding to each set of the P-FSEJ parameters represents an average of at least three joints. The metallographic specimens were prepared after the samples were taken along the rolling direction of BM, which should through the diameter of the threaded-aluminum rivet. After mechanical grinding and polishing, AA6061-T6 on the specimens were etched using Keller reagents, and the joint macro and microstructures were studied thereafter using optical microscope and EBSD. SEM was utilized to observe the fracture surface appearances of the joint.

4 Results And Discussion

4.1 Macrograph and microstructure of the joints

The top and bottom surfaces of the P-FSEJed joint are considerably smooth, as shown in Fig. 4. Although a minimal flash formed around the edge of the stir zone, no keyhole defect was observed on the top side of the P-FSEJed joint. The threaded hole of the Q235 sheet is fully embedded with plastic rheological AA6061-T6 material in the form of "threaded-aluminum rivet" under the friction and extrusion of the P-FSEJ tool. Meanwhile, the Q235 material around the P-FSEJed joint appears tawny tempering shade with the influence of welding heat.

Figure 5 (a) shows the transverse section macrostructure of a typical P-FSEJed joint obtained at a rotational speed of 1000 rpm and appears a typical symmetrical "basin" shape. Three distinct zones have been identified on the bases of plastic deformation diversity and grain characteristic distribution. (1) The stir zone (SZ) has uniform and dense appearance, which experiences the greatest plastic deformation and welding heat input. (2) The thermo-mechanically affected zone (TMAZ) is affected by extrusion deformation and welding thermal cycle. (3) Lastly the heat-affected zone (HAZ) is only affected by a small amount of welding thermal cycle. Note that a clear boundary exists between SZ and TMAZ, whereas the boundary between TMAZ and HAZ is relatively fuzzy.

Figure 5 (b) illustrates the AA6061-T6 material flow behavior in the P-FSEJ process. The material in zone A initially starts to soften and flows thereafter along the direction of arrow 1, driven by the rotation of the P-FSEJ tool. With feeding of the P-FSEJ tool, the majority of the materials expand to zone B along the direction of arrow 2, and gradually fill in the threaded hole of the Q235 plate. However, a small amount of material is extruded out of zone A along the direction of arrow 3, thereby forming a flash. The streamline distribution shown in Fig. 5 (a) also strongly agrees with this explanation.

4.2 Mechanical property

4.2.1 Static tensile-shear strength

For M7, changes in the tensile-shear load and breaking elongation of the obtained joint at different rotating speeds are shown in Fig. 7. In particular, Fig. 7 (a) shows that the change law of the joint displacements and tensile-shear load curves is similar under different rotating speeds. With an increase in rotational speed, the welding heat input increases gradually, the mixing head on the material deformation effect of grain refinement and mechanical properties increases, but the amount of heat input may cause serious joint metal over-aging phenomenon, thereby affecting the joint connection strength. (AA6061-T6 belongs to solid solution treatment + artificial aging aluminum alloy, its strengthening mainly alloy precipitation phase, and precipitated phase at high temperature alloy over-aging grew up tended to increase, and over-aging make material softening, micro-hardness is reduced, so the welds of shear load capacity and reduce.) Therefore, the peak shear load of the joint initially increases and decreases thereafter. When the rotation speed is 1200 rpm, the maximum shear load of the M7 threaded hole joint is 3344.74 N.

When the diameter of the threaded hole is the same, the joint strength obtained at high rotating speed is relatively low, which is mainly caused by the softening of the aluminum alloy. AA6061-T6 belongs to heat-treatable and reinforced aluminum alloy, and its main strengthening phase is Mg_2Si. This alloy is

affected by heat cycling during the welding process, resulting in severe softening of the "aluminum rivet" and deterioration of the mechanical properties of the joints.

Energy absorption, E, is another important structural analysis index of spot joint [34]. That is, the energy required for the joint to reach the maximum tensile shear load Fmax, which can be characterized by integral calculation of the area from the tensile-shear load-displacement curve to the maximum tensile displacement Xmax, as shown in Fig. 7 (a). Generally, the joint appears better mechanical properties which have a better energy absorption capacity to absorb more energy before failure [35]. The calculation Eq. (1) as follows.

$$E = \int_0^{X_{max}} Fdx \qquad (1)$$

For different diameters of the threaded hole, if the welding heat input is similar, then the heat treatment strengthening effect on AA6061-T6 is relatively the same, and the shear strength of the material is similar. Therefore, the larger the diameter of the threaded hole, the larger the shear area, the larger the shear load and the higher energy absorption of the joint. Fig.8 shows the effects of rotating speed on the shear load of joints with different thread diameters and energy absorption of the P-FSEJed joints. For M6 and M8, the variation pattern of the peak shear load obtained at different rotating speeds is approximately the same as for M7. The maximum shear load of M6 threaded hole joint is 2882.93 N at rotation speed of 1200 rpm, and the M8 threaded hole joint is 4139.58 N at rotation speed of 1000 rpm. The highest energy absorption of M8 threaded hole joint is 4.52 J at rotation speed of 1600 rpm.

4.2.2 Fracture morphology under tensile-shear loading

This study determined two typical fracture failure modes of the P-FSEJed joints, namely, rivet shear fracture (mode "S") and rivet pullout-shear fracture (mode "P"), under tensile-shear loading. Given that the stiffness and hardness of Q235 are significantly higher than those of AA6061, all fracture failures occur on the side of AA6061. The diameter of the threaded-aluminum rivet determines the stress distribution during the tensile-shearing process. For joints with small threaded-aluminum rivet diameter, the shear stress on the lap interface reaches the critical value initially, and the joints tend to mode "S" failure thereafter. By contrast, tensile stress reaches the critical value considerably early, and the joints tend to mode "P" failure. As shown in Fig. 9 (a), the shear stress on the lap interface is the dominant driving force for mode "S" failure under tensile-shear loading, thereby causing the fracture failure along the lap interface between TMAZ and SZ. To ensure that the tensile-shear force F acting on the two plates is collinear, the threaded-aluminum rivet is twisted at torsion angle θ during mode "P" failure, as shown in Fig. 9 (b). In this case, the tensile-shear force F can be decomposed into tangential component force F_T and normal component force F_N. In particular, F_N is considered the dominant driving force of the mode "P" failure, which pulls out the threaded-aluminum rivet, and F_T fractures the threaded-aluminum rivet along the deformation streamline in TMAZ. The experimental results confirm the preceding viewpoint. Moreover, the M6 threaded hole joints obtained at different rotation speeds tend to mode "S" failure, and

the threaded-aluminum rivet of which is relatively not twisted. Evidently, mode "P" failures were observed in the M7 and M8 threaded hole joints, which had large diameter threaded-aluminum rivet. However, the torsion angle θ increases from 0.5° to 4.2° when rotation speed is changed from 600 rpm to 1500 rpm, as shown in Fig. 9 (c). This result is mainly caused by the different softening degrees of the material around the threaded-aluminum rivet caused by thermal cycling at different rotation speeds and the competition between shear stress and tensile stress.

The fracture failure of the P-FSEJed joints experienced three stages: crack initiation, crack propagation, and instantaneous fracture. In addition, shear lip zone (SLZ), crack propagation zone (CPZ), and final fracture zone (FFZ) can be observed in the macro fracture morphologies of mode "S" and mode "P" failures, as shown in Figs. 10 (a) and 11 (a). However, no evident differences exist in the macro and micro fracture morphologies of SLZ and CPZ for the two fracture failure modes. Owing to the different stress distributions, FFZ of the mode "S" failure appears darker than that of CPZ, and shows a clear boundary between them. In another fracture failure mode, the two regions have similar characteristics, and their boundary is difficult to distinguish. The SEM analysis of the fracture surface morphologies showed that shallow shear sliding bands and cracks with small and shallow shear dimples can be observed in smooth SLZ, as shown in Figs. 10 (b) and 11 (b). CPZ surfaces have numerous elongated and shallow parabolic shear dimples, the parabolic opening direction of which is consistent with the shear stress direction. Moreover, the fracture characteristics are determined to be consistent with type II fracture, as shown in Figs. 10 (c) and 11 (c). In the instantaneous fracture stage, the threaded-aluminum rivet deforms to resist the large tensile-shear force and eventually fractures under tensile force. As shown in Fig. 10 (d), mode "S" failure is considered a type I fracture at this stage in view of the quasi equiaxed dimples present in FFZ, even though equiaxed dimples exhibit slight deformation under small shear stress. For mode "P" failure, the threaded-aluminum rivet twisted under the action of F_N, and F_S drive the shear crack propagation thereafter along the deformation streamline in TMAZ. Therefore, this fracture failure mode is considered type II fracture because numerous parabolic shear dimples are observed and the parabolic opening direction consistent with the shear stress direction in FFZ, as shown in Fig. 11 (d). Consequently, mode "S" failure is mixed of types I and II fracture, and mode "P" failure is type II fracture.

5 Conclusions

This study proposes P-FSEJ of aluminum alloy and steel to avoid the intermetallic compounds that affect joint mechanical properties. Moreover, this research investigates the macrograph, microstructure, and mechanical properties of 3-mm thick AA6061-T6 to 1.8-mm thick Q235 steel P-FSEJed joints obtained without keyhole defects. The conclusions are drawn as follows.

(1) Strong mechanical interlock is formed after that the plasticized aluminum alloy is extruded into the prefabricated threaded hole of the steel plate in the P-FSEJ process. Three distinct zones in the typical symmetrical "basin-shaped" P-FSEJed joint (i.e., stir, thermo-mechanically affected, and heat-affected zones) are observed, which contain equiaxed recrystallized grains with an average diameter of 6.39 μm,

recrystallized grains in two different regions with an average diameter of 25.34 μm and 29.86 μm respectively, and highly deformed grains with an average diameter of 37.18 μm.

(2) With the increase in rotational speed, the maximum tensile-shear load of the joint initially increases and decreases thereafter. Therefore, the larger the diameter of the threaded hole, the larger the shear area, the larger the shear load of the joint. When the rotation speed is 1200 rpm, the maximum tensile-shear loads of the M6 and M7 threaded hole joints are 2882.93 N and 3344.74 N, respectively, while the M8 threaded hole joint is 4139.58 N at rotation speed of 1000 rpm.

(3) Two typical fracture failure modes of the P-FSEJed joints (i.e., rivet shear and rivet pullout-shear fracture) are obtained under tensile-shear loading. Under the condition of the higher the rotational speed and the larger the threaded hole diameter, the fracture failure of the joint appears as mode "P" fracture failure, and the greater the bending angle of the joint, which generally has a considerably high strength and energy absorption capability.

(4) Fracture failure of the P-FSEJed joints experienced three stages, namely, crack initiation, crack propagation, and instantaneous fracture. Moreover, shear lip, crack propagation, and final fracture zones are observed in the macro fracture morphologies of the mode "S" and mode "P" failures. Mode "S" failure is mixed of types I and II fracture, the final fracture zone of which presents quasi-equiaxial dimples, while mode "P" failure is type II fracture and parabolic shear dimples.

Declarations

Conflicts of interest: The authors declare that they have no conflicts of interest.

Availability of data and material: The authors confirm that the supporting data in this journal is presented within the manuscripts itself and will make raw data presented in this study available upon request to the corresponding author (Peng Zhang).

Authors' contributions: All authors were involved in the detailed analysis and discussions presented in this paper. Shengdun Zhao and Chuanwei Zhang contributed to the research concept. Peng Zhang and Zheng Chen made important contributions to the analysis and preparation of the manuscript, conducted data analysis, and wrote the manuscript. Jiaying Zhang, Liangyu Fei, and Peng Dong had a constructive discussion and helped with the analysis.

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