

Article

Microstructure and Mechanical Properties of Shoulder-Assisted Heating Friction Plug Welding 6082-T6 Aluminum Alloy Using a Concave Backing Hole

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Abstract

Shoulder-assisted heating friction plug welding (SAH-FPW) experiments were conducted to repair keyhole-like volumetric defects in 6082-T6 aluminum alloy, employing a novel concave backing hole technique on a flat backing plate. This approach yielded well-formed plug welded joints without significant macroscopic defects. Notably, the joints exhibited no thinning on the top surface while forming a reinforcing boss structure within the concave backing hole on the backside, resulting in a slight increase in the overall load-bearing thickness. The introduction of the concave backing hole led to distinct microstructural zones compared to joints welded without it. The resulting joint microstructure comprised five regions: the nugget zone, a recrystallized zone, a shoulder-affected zone, the thermo-mechanically affected zone, and the heat-affected zone. Significantly, this process eliminated the poorly consolidated ‘filling zone’ often associated with conventional plug repairs. The microhardness across the joints was generally slightly higher than that of the base metal (BM), with the concave backing hole technique having minimal influence on overall hardness values or their distribution. However, under identical welding parameters, joints produced using the concave backing hole consistently demonstrated higher tensile strength than those without. The joints displayed pronounced ductile fracture characteristics. A maximum ultimate tensile strength of 278.10 MPa, equivalent to 89.71% of the BM strength, was achieved with an elongation at fracture of 9.02%. Analysis of the grain structure revealed that adjacent grain misorientation angle distributions deviated from a random distribution, indicating dynamic recrystallization. The nugget zone (NZ) possessed a higher fraction of high-angle grain boundaries (HAGBs) compared to the RZ and TMAZ. These findings indicate that during the SAH-FPW process, the use of a concave backing hole ultimately enhances structural integrity and mechanical performance.

Keywords: shoulder-assisted heating friction plug welding; concave backing hole; microstructure; mechanical properties



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1. Introduction

Friction stir welding (FSW) is recognized as an environmentally friendly welding method [1] and is widely adopted for aluminum alloys [2]. It demonstrates significant advantages in joining both similar and dissimilar lightweight or novel alloys. However, excessive heat input or excessive tool plunge depth during FSW can cause flash formation, resulting in weld thinning and stress concentration. Conversely, insufficient heat input may

lead to inadequate material flow, generating defects such as cavities [3], tunnel defects [4], groove defects [5], and kissing bonds [6]. These defects, arising from suboptimal process parameters, impair the joints' mechanical properties and are typically mitigated through parameter optimization [7]. Furthermore, the keyhole formed at the weld termination point upon tool retraction represents an inherent feature of conventional FSW and remains a region of reduced strength. Since the keyhole is intrinsically linked to the FSW process, it is unavoidable in conventional procedures. With increasing industrial applications of FSW, inherent limitations such as the keyhole defect have garnered significant attention.

To repair or mitigate keyholes and other volumetric defects in friction stir welded joints, techniques such as friction plug welding (FPW) [8], friction taper plug welding [9], filling friction stir welding [10], active-passive filling friction stir welding [11], and refill friction stir spot welding [12] have been employed, all demonstrating effective repair outcomes. While these methods address keyhole defects, each has distinct limitations. For instance, many require high spindle speeds, imposing demanding equipment requirements. Additionally, Wang G.Q. [13] used a solid-phase filling technique combined with subsequent FSW to repair large volumetric defects in 2219 aluminum alloy, achieving joint strengths exceeding 335 MPa. However, this process and the aforementioned composite repair method are relatively complex. Hao Y.F. [14] applied a sequential approach using Tungsten Inert Gas (TIG) welding to fill the keyhole, followed by FSW repair for 2219 aluminum alloy. This hybrid method refined the repaired zone's microstructure, transforming dendritic as-cast structures into fine equiaxed grains characteristic of wrought material, thereby enhancing the repaired region's integrity and performance. Nevertheless, the TIG welding component results in suboptimal joint performance. Recently, Friction Stir Additive Deposition (FSAD) [15]—a technology garnering significant academic interest—has demonstrated potential for repairing keyhole-like defects [16]. However, research remains in the early development stages [17], with active investigations into process optimization [18] and performance enhancement [19]. Thus, further refinement of keyhole repair techniques is essential to improve effectiveness and promote wider industrial adoption of FSW.

To mitigate the demanding equipment requirements of friction plug welding (FPW), our prior work [20] proposed a modified FPW method incorporating auxiliary frictional heating between the tool shoulder and the base material surface. Experimental studies on 6082-T6 aluminum alloy (widely used in high-speed train bodies) using this Shoulder-Assisted Heating FPW (SAH-FPW) technique showed promising results. Joint microstructures remained consistent across tested plug rotational speeds. Based on distinct microstructural features, SAH-FPW joints in 6082-T6 aluminum alloy exhibited six characteristic zones: nugget zone (NZ), filling zone (FZ), recrystallization zone (RZ), shoulder-affected zone (SAZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) [21]. Optimal joint properties were achieved at 2000 rpm plug rotation, yielding 260.08 MPa tensile strength (83.9% of base metal) and 6.5% elongation at fracture (65% of base metal). Tensile specimens consistently failed through the following: (1) crack initiation at the joint root, (2) propagation along the TMAZ, and (3) final fracture on the top surface between the plug and shoulder-affected region. This failure mode indicates stress concentration and potential inadequate bonding at the joint root, limiting joint efficiency. Subsequent investigations therefore focused on enhancing root integrity. Using a concave-backing-hole backing plate to improve root material flow significantly enhanced joint performance.

2. Materials and Methods

2.1. Materials

To promote the application of friction-based welding technologies, particularly friction plug welding (FPW), in the rail transportation sector, experiments were conducted using

6082-T6 aluminum alloy. This material was commonly employed for high-speed train car bodies and was used for both the base metal and the plug. The chemical composition and mechanical properties of this alloy are detailed in Tables 1 and 2, respectively. The base metal thickness was 5 mm. Both the plug and the plug hole had a diameter of 10 mm and featured a matching 90°/90° taper angle configuration (indicating the included angles for the plug tip and hole preparation). Shoulder-assisted heating FPW tests were performed using identical base metal and plug materials, employing the technique with a concave backing hole machined into the backing plate.

Table 1. Chemical composition of 6082-T6 aluminum alloy (wt.%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.89	0.3	0.04	0.58	0.93	0.06	0.04	0.01	BAL

Table 2. Physical and mechanical properties of 6082-T6 aluminum alloy.

Material	Sampling Method	Tensile Strength/MPa	Elongation/%	Microhardness/HV	Melting Point/°C
6082-T6	Transverse Direction	310	10	98	555

2.2. Methods

The principle of shoulder-assisted heating friction plug welding (FPW) utilizing a concave backing hole is schematically illustrated in Figure 1. A flat backing plate, featuring a machined concave backing hole, is positioned beneath the base metal. The plug diameter is 10 mm, with cone angles of 80° for both the plug and the keyhole. The plug feed rate is 1.5 mm/s, with a plunge depth of 8 mm. The upsetting force is 5 kN. The base metal thickness is 5 mm. The concave backing hole has a diameter of 3 mm and a depth of 1.5 mm. Experiments were performed on a device developed by our research group. Based on prior experiments and within the optimal parameter ranges, three tests were conducted for each parameter set. Prior to welding, the concave backing hole, plug, and plug hole are coaxially aligned.

The sequence of the shoulder-assisted heating friction plug welding (FPW) process employing the concave backing hole technique is depicted in Figure 2.

- Initially, friction between the rotating shoulder and the base metal generates heat at the faying surfaces. This heat conducts into the workpiece, preheating the plug hole surface. The plug rotational speed matches that of the FPW process, with an auxiliary heating time of 65 s.
- Upon completing preheating, the rotating plug advances axially into the plug hole. Contact under feed force initiates friction at the plug–plug hole interface. Continued axial feeding generates viscoplastic material that flows to fill the plug hole, constrained by the tool shoulder, the concave backing hole, and surrounding base metal.
- When flash extrudes from the shoulder periphery, axial feeding terminates. Simultaneously, the shoulder retracts axially until its lower face aligns coplanar with the base metal upper surface, while sustained rotational contact maintains friction for continued heating. A rapid plug plunge then applies upsetting force (5 kN) to consolidate the nascent weld.
- Post-upsetting, the rotating shoulder traverses horizontally across the base metal at 3 mm/s. The distance at which the remaining plug is sheared off during lateral movement is 5 mm. Shear forces at the shoulder–base metal interface sever the excess plug, forming a flush joint surface.

- (e) Finally, the shoulder fully retracts from the workpiece, and the severed plug remnant retained in the tool holder is ejected.

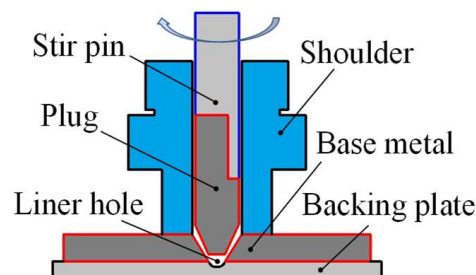


Figure 1. Schematic diagram of the concave backing hole technique.

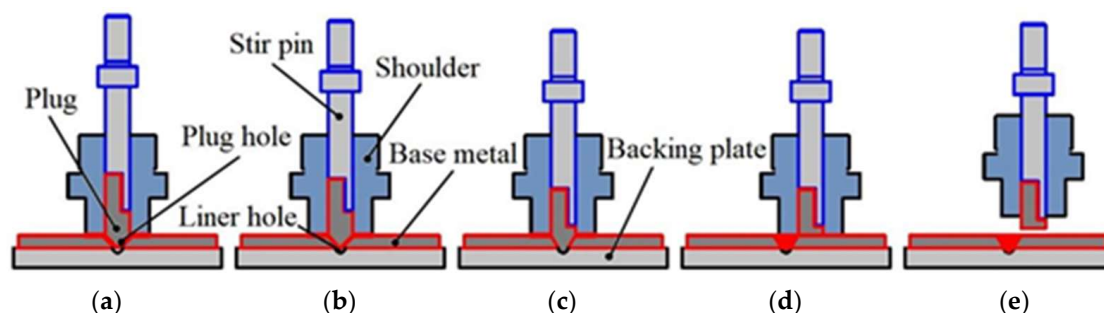


Figure 2. Schematic diagram of the shoulder-assisted heating FPW process with the concave backing hole technique: (a) preheating; (b) plug feeding; (c) upsetting loading; (d) tool traverse and fracture; (e) lifting and ejection.

3. Experimental Results and Analysis

3.1. Macroscopic Morphology of Joints

With a plug diameter of 10 mm and fixed values for other welding parameters (plug-plug hole taper angle match, auxiliary heating time, upsetting time, upsetting force, and feed rate), Figure 3 presents the macroscopic morphologies of joints produced using the concave backing hole technique at plug rotational speeds of 1600 rpm, 1800 rpm, and 2000 rpm. Under optimized parameters, shoulder-assisted heating FPW joints in 6082-T6 aluminum alloy exhibit no significant macroscopic defects. The crown surface remains smooth, while a distinct heat-affected zone (HAZ) is clearly visible on the root side. Notably, a pronounced boss structure forms within the concave backing hole region at the joint root. No thinning occurs on the crown. This joint configuration increases the effective load-bearing thickness.

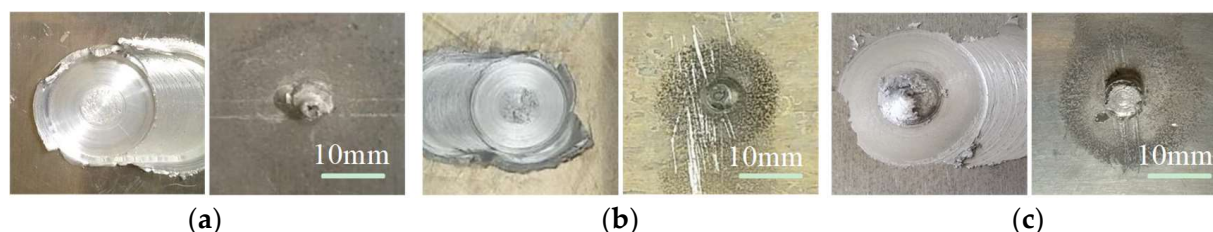


Figure 3. Macroscopic morphology of joints fabricated with the concave backing hole process at different plug rotational speeds: (a) 1600 rpm; (b) 1800 rpm; (c) 2000 rpm.

The concave backing hole promotes the flow of viscoplastic material into its cavity under pressure applied by the advancing plug. This geometric feature expands the constraint

region bounded by the tool shoulder, surrounding base metal, and backing plate, promoting viscoplastic material flow within the enlarged volume to form joints with enhanced root integrity and interfacial bonding. Furthermore, experiments show that this technique broadens the operable processing window for achieving defect-free 6082-T6 aluminum alloy shoulder-assisted heating FPW joints.

3.2. Cross-Sectional Morphology of Joints

After the welding experiments, metallographic specimens were sectioned along the joint centerline using wire electrical discharge machining (WEDM). The specimens underwent sequential grinding and mechanical polishing, followed by etching with Keller's reagent (composition by volume: 1 mL HF, 1.5 mL HCl, 2.5 mL HNO₃, 95 mL H₂O) for 15 s. The macroscopic and microstructural characteristics of the plug welded joints were then observed and photographed using an Axio Scope A1 optical microscope (Lanzhou, China).

Three samples were prepared for each set of parameters. According to the test results, the cross-section morphology of the joint is similar under different plug speeds. The corresponding cross-sectional morphologies of these joints are illustrated in Figure 4, where the white line demarcates the original location of the plug hole boundary. A distinct SAZ with measurable thickness is observed at the interface between the base metal upper surface and the tool shoulder. Compared to the original plug hole dimensions, the final filled weld region (weld nugget) is significantly expanded, indicating displacement inwards into the base metal. Specifically, near the upper surface adjacent to the shoulder, the width of the filled material exceeds the original plug hole diameter, and the opening at the lower part of the plug hole also expands significantly.

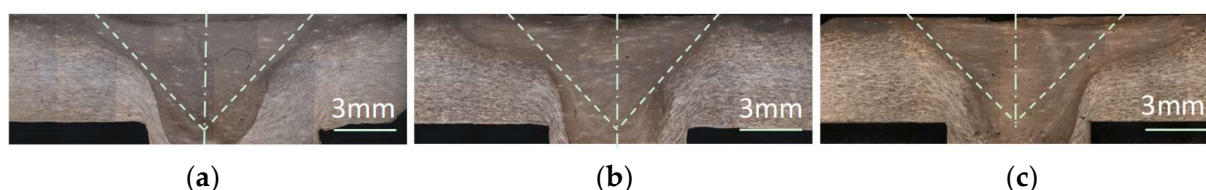


Figure 4. Cross-sectional morphology of joints fabricated with the concave backing hole process at different plug rotational speeds: (a) 1600 rpm; (b) 1800 rpm; (c) 2000 rpm.

Frictional contact between the plug and the plug hole, combined with the effects of frictional heat and upsetting force, induces softening of the material at the contact interface, causing it to reach a plastic state. This plasticized material then flows along the interface under the influence of the plug's upsetting force and stirring action. Influenced by the geometric fit between the plug and bore, as well as the temperature field distribution, the dominant flow direction of the plasticized material shifts at a demarcation point (flow divide) along the joint's thickness direction. Under the constraints imposed by the shoulder and the surrounding cold base metal, material located above this critical demarcation point flows upward, while material below it flows downward, filling the concave backing hole cavity. This ultimately results in the formation of an expanded weld region, with both the upper and lower sections exceeding the dimensions of the original plug hole location.

Therefore, under identical welding parameter combinations, the implementation of a process utilizing a concave backing hole in the backing plate facilitates the elimination of weak bonding at the joint root and enhances the overall quality of joint formation. Such a process design not only mitigates weak bonding defects at the joint root but also increases the effective load-bearing thickness, thereby contributing to improved overall mechanical performance of the joint. Furthermore, the incorporation of the concave backing hole promotes the flow of plasticized material, particularly within the joint root region. This

configuration aids in optimizing the joint's microstructure while potentially enabling better control over the mechanical properties within specific micro-zones of the weld.

3.3. Microstructure of Joints

Fracture surface morphologies of the tensile-tested specimens were examined and imaged using a Quanta450 field-emission scanning electron microscope (FESEM) (Lanzhou, China). The tensile properties of the joints were tested according to GB/T2652-2022 [22].

The cross-sectional morphology of the joint is similar at different plug rotational speeds, including 1600 rpm, 1800 rpm and 2000 rpm. At a plug rotational speed of 1800 rpm, the cross-sectional morphology and distinct microstructural zones of the joint fabricated using the concave backing hole technique are illustrated in Figure 5. The joint is categorized into five distinct regions: the nugget zone (NZ), the recrystallization zone (RZ), the shoulder-affected zone (SAZ), the thermo-mechanically affected zone (TMAZ), and the heat-affected zone (HAZ) [21].

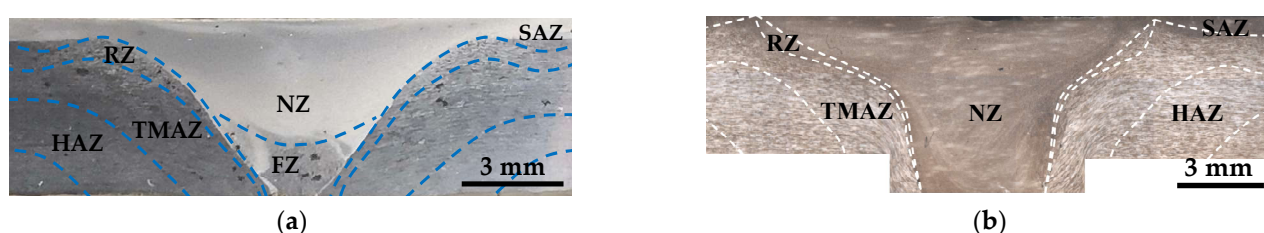


Figure 5. Cross-sectional morphology and schematic of zonal partitioning in joints fabricated with/without the concave backing hole process at the plug rotational speed of 1800 rpm: (a) without the concave backing hole process; (b) with the concave backing hole process.

The microstructure and distribution characteristics of different zones in the joint exhibit significant differences, as shown in Figure 6.

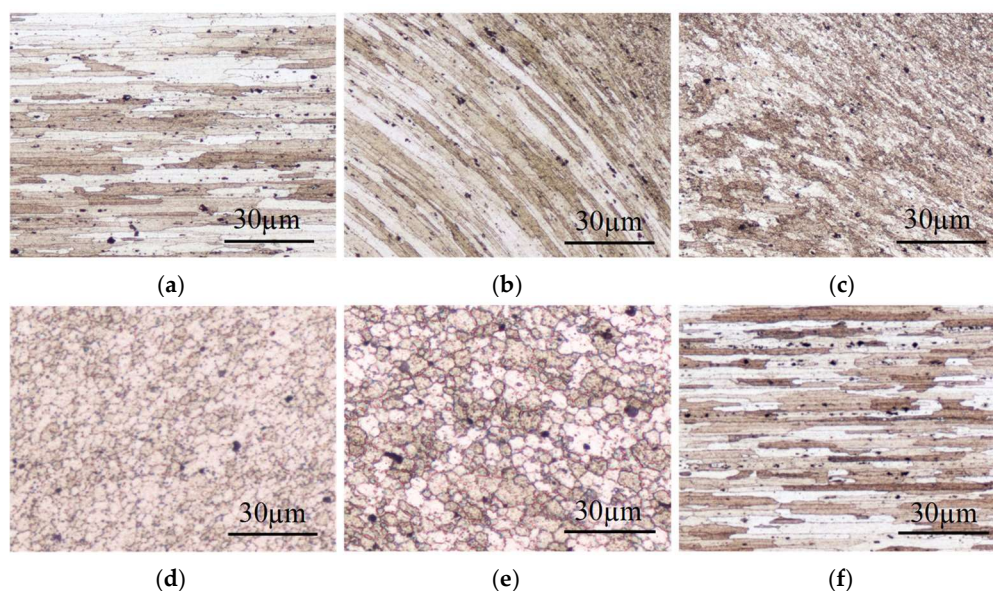


Figure 6. Microstructure and distribution in different zones of the joint: (a) HAZ; (b) TMAZ; (c) RZ; (d) NZ; (e) SAZ; (f) BM.

The RZ is characterized by uniformly fine, equiaxed grains. Its orientation deviates from the original conical surface of the plug hole. Closer to the shoulder, the RZ tends to widen, and its boundary becomes less distinct. The SAZ is a fine-grained region of measurable thickness formed by the combined effects of shoulder friction, adhesion, and

shear. As the distance from the shoulder's lower surface increases, the grain size within this zone generally decreases. Although also composed of equiaxed grains, the SAZ typically exhibits slightly larger grain sizes compared to the NZ. A notable shift in the microstructural flow direction is observed at the interface between the SAZ and the NZ (as potentially shown in Figure 6c).

The TMAZ corresponds to regions of the base metal near the original plug hole and under the shoulder's influence where the material undergoes bending deformation due to the combined effects of the upsetting force and frictional shear from the shoulder. The extent of this zone generally aligns with the heat-affected range on the joint's backside, maintaining a relatively consistent width. In addition to pronounced grain reorientation (deformation), the TMAZ exhibits minor grain growth. In contrast, the HAZ is the region influenced solely by the welding thermal cycle, without significant plastic deformation. Unlike the TMAZ, where grains experience significant bending deformation, the HAZ largely retains the original lath-like structure of the base metal, although slight grain growth may be observed due to the thermal exposure [23]. When the rotational speed of plug is 1600 rpm and 2000 rpm, the joint partition and grain distribution characteristics of each zone are similar to those of 1800 rpm.

3.4. Mechanical Properties of Joints

Microhardness testing was performed on metallographic specimens using a Wilson VH1102 microhardness tester (Lanzhou, China), in accordance with the GB/T 2654-1989 [24]. A load of 10 N was applied for a dwell time of 10 s. To characterize the heterogeneity through the thickness, three hardness profiles were measured at distances of 1 mm, 2.5 mm, and 4 mm from the upper surface of the joint. The interval between adjacent indentations along each profile was 0.5 mm. At a plug rotational speed of 1800 rpm, the resulting microhardness values and their distribution across the joint are illustrated in Figure 7.

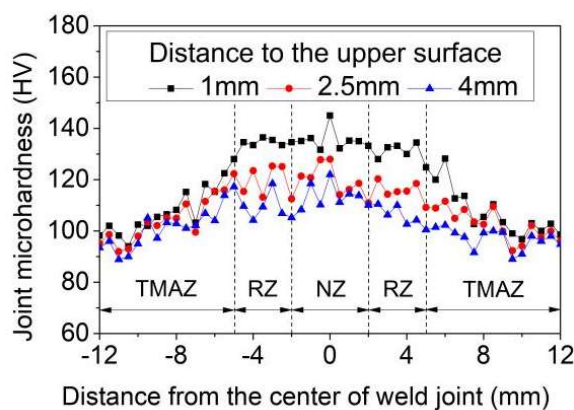


Figure 7. Microhardness and its distribution in joints fabricated with concave backing hole process at the plug rotational speed of 1800 rpm.

Proximity to the tool shoulder intensifies the stirring effect on the viscoplastic material and promotes grain fragmentation during thermomechanical deformation. The consequent grain refinement strengthening results in microhardness values within the joint that exceed those of the base metal [25]. The microhardness of the NZ is the highest, and the HAZ is the lowest due to the influence of the temperature field distribution and is slightly lower than that of the base metal. With the increase in the distance from the lower end face of the shoulder, the stirring effect of the plug and the shoulder on the material is gradually weakened. And the assisted heating effect of the friction between the shoulder and the base

metal is correspondingly reduced. Therefore, as the distance from the upper surface of the joint increases, the microhardness of the joint at the same vertical position decreases slightly. When the rotational speed of the plug is 1600 rpm and 2000 rpm, the microhardness and the distribution characteristics of the joint are similar to the situation at 1800 rpm.

Process parameter optimization and experimental welding trials revealed that for the shoulder-assisted heating friction plug welding (FPW) of the aluminum alloy, plug rotational speeds below 1400 rpm led to an increased defect rate and, consequently, inferior joint mechanical properties. Conversely, plug rotational speeds exceeding 2200 rpm resulted in unsatisfactory joint formation, such as excessive flash or surface irregularities. Therefore, holding other process parameters constant, the influence of plug rotational speed on the mechanical performance of the joints was investigated using speeds of 1600 rpm, 1800 rpm, and 2000 rpm as representative cases.

For joints fabricated using the concave backing hole technique, any protruding boss at the joint root was removed by machining. This ensured that the tensile specimens possessed a thickness identical to that of specimens prepared from joints welded without a concave backing bore. The tensile strengths of the joints obtained under various process parameter combinations are presented in Figure 8.

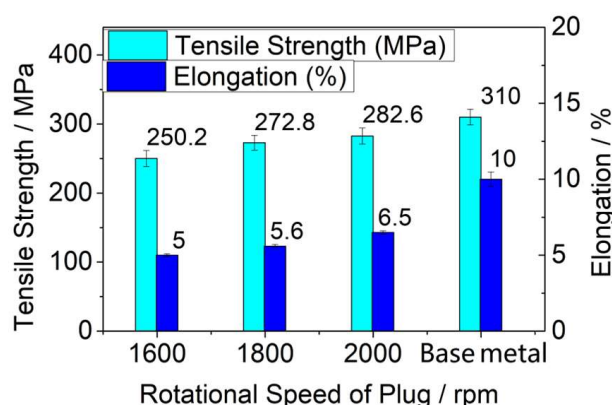


Figure 8. Tensile strength and post-fracture elongation of joints fabricated with concave backing hole process at different plug rotational speeds.

With other process parameters held constant, both the ultimate tensile strength and the elongation at fracture of the joints increased with increasing plug rotational speed. A maximum joint strength of 278.10 MPa was achieved, equivalent to 89.71% of the base metal's strength, accompanied by an elongation at fracture of 9.02%.

These tensile strength results indicate that higher plug rotational speeds increase the power input (energy input per unit time), which considerably enhances the mechanical performance of shoulder-assisted heating FPW joints. Moreover, elevated plug rotational speeds augment the heat generation efficiency from the two principal frictional heat sources: the shoulder/base metal interface and the plug/bore interface. This, combined with the more vigorous mechanical stirring at higher rotational speeds, synergistically promotes the formation of sound shoulder-assisted heating FPW joints exhibiting superior mechanical properties.

3.5. Fracture Characteristics of Joints

Tensile testing of the 6082-T6 aluminum alloy shoulder-assisted heating FPW joints was conducted on an AGS-X 300 kN universal testing machine (Lanzhou, China), adhering to the GB/T 2651-2023 [26], with a constant crosshead displacement rate of 0.2 mm/min.

Fracture surface morphologies of joints fabricated using the concave backing hole technique, under identical welding parameters, are depicted in Figure 9. The fracture morphology shown in the figure is near the joint rather than the base material part. Although this technique enhanced material flow at the joint root and eliminated issues of weak bonding in this region, the root nevertheless remained a zone of stress concentration. Consequently, even after machining to remove any backside boss, the tensile specimens consistently initiated cracks at the joint root during testing, with ultimate fracture occurring within the TMAZ. This indicates that while the concave backing bore technique improves the soundness of the joint root formation, the TMAZ persists as the microstructurally weakest region governing the tensile failure of the joint. Under identical welding parameter combinations, the fracture surface morphologies of the 6082-T6 aluminum alloy shoulder-assisted heating FPW joints produced with and without the concave backing bore technique exhibited similar overall features. For joints made with the concave backing bore, Region A typically comprised dimples and tear ridges; Region B displayed large and deep dimples; and Region C showed predominantly equiaxed dimples of significant size and depth. All fracture surfaces clearly exhibited the characteristics of ductile fracture. Furthermore, despite the fracture location (TMAZ) being consistent for both techniques, the concave backing bore technique—by enhancing the effective load-bearing thickness and promoting superior material flow and consolidation at the joint root—positively contributes to improving root formation quality and thereby enhancing the overall mechanical performance of these aluminum alloy FPW joints.

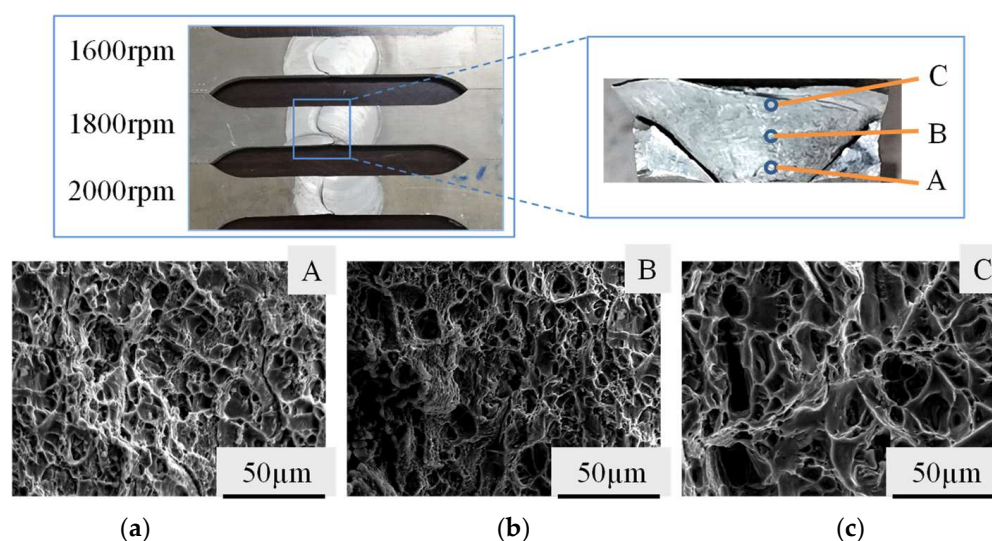


Figure 9. Tensile-fractured specimens and fracture morphology of joints fabricated with concave backing hole process: (a) Region A; (b) Region B; (c) Region C.

4. Discussion

4.1. Effect of Concave Backing Hole Process on Microstructure of Joints

Figure 10 illustrates a comparison of the microstructural zones in shoulder-assisted heating friction plug welded (FPW) 6082-T6 aluminum alloy joints, fabricated with and without a concave backing hole. When a concave backing hole is employed in the backing plate, the pressure generated by the plug feed during welding enhances the flow of plasticized material at the base of the plug hole and expands the affected area. This facilitates effective filling of the concave backing hole and simultaneously eliminates the accumulation of original plug material at the joint root. By increasing the effective load-bearing thickness of the joint, this approach also prevents the formation of a FZ, which would

otherwise consist of original plug material remnants, thereby enabling the development of a complete NZ at the joint center.

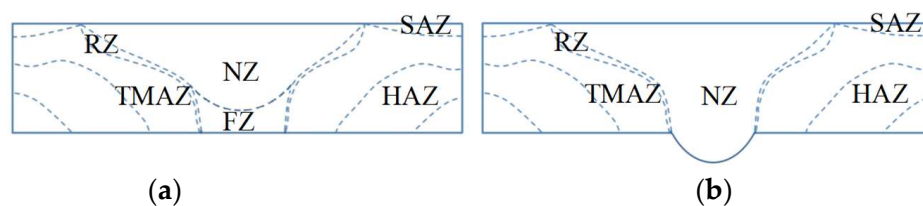


Figure 10. Schematic comparison of microstructural zoning in joints with and without a concave backing hole: (a) without a concave backing hole; (b) with a concave backing hole.

The introduction of a concave backing hole substantially expands the flow range of plasticized material at the base of the plug hole, leading to a significant increase in the NZ thickness in the lower joint region compared to joints produced without this feature. Furthermore, owing to the temperature gradient through the joint thickness, the grain morphology within the NZ also displays a gradient when the concave backing hole is utilized. Prior analyses have established that the NZ comprises fine, equiaxed grains. In contrast to the FZ, which might retain the elongated grain structure of the original plug material, the NZ grains are further refined, yielding a more consolidated microstructure and superior macroscopic mechanical properties. Consequently, the concave backing hole technique effectively mitigates weak bonding at the joint root, eliminates root defects, and improves the overall quality of joint formation in friction plug welding.

4.2. Effect of Concave Backing Hole Process on Mechanical Properties of Joints

With the exception of a slightly lower hardness in the FZ of joints fabricated without a concave backing hole, the use of this technique has minimal impact on the overall microhardness profile and its distribution across the joint. The presence of an FZ (when a flat backing plate is used) results in a reduced thickness of the RZ, which adversely affects the overall joint strength. Conversely, the concave backing hole technique promotes the extrusion of plasticized material from the region beneath the joint center out through the lower part of the plug hole. This facilitates an expanded flow range for the viscoplastic metal at the joint root, thereby eliminating weak bonding in FPW joints. Moreover, the plasticized material extruded by the plug feed fills the concave backing hole, increasing the effective load-bearing thickness of the joint. This enhances the overall mechanical performance of the FPW joint. Figure 11 presents a comparison of the tensile strength of joints fabricated with and without the concave backing hole under identical process conditions.

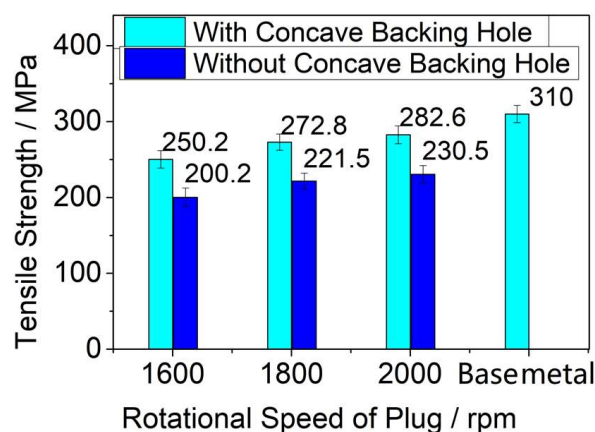


Figure 11. Tensile strength comparison of joints fabricated with and without a concave backing hole.

Under identical process conditions and for tensile specimens of consistent thickness, joints fabricated using the concave backing hole technique exhibited superior mechanical performance compared to those produced without this feature. Consequently, within an appropriate range of process parameters, the concave backing hole technique not only facilitates the effective repair of volumetric defects, such as keyholes, via plug welding but also increases the joint's effective load-bearing thickness, leading to enhanced mechanical properties. This approach may therefore offer a novel solution to concurrently address two inherent challenges in friction stir welding (FSW): keyhole defects and weld thinning. Such an advancement holds considerable potential for expanding the engineering applications of FSW technology.

4.3. Mechanism of Concave Backing Hole Process Influencing Joint Formation

Electron Backscatter Diffraction (EBSD) specimens, with dimensions of $5\text{ mm} \times 5\text{ mm} \times 2\text{ mm}$, were sectioned from the base metal. These specimens were prepared by coarse grinding with SiC paper, followed by mechanical polishing. Final surface preparation involved ion milling using a Leica EM TIC 3X system (Lanzhou, China). EBSD analysis was performed using a Quanta 450 FEG field-emission (Lanzhou, China) scanning electron microscope (FE-SEM) equipped with an Aztec X-Max80 EBSD detector (Lanzhou, China). The analysis was conducted at an accelerating voltage of 20 kV, a sample tilt of 70.0° , and a step size of $3\text{ }\mu\text{m}$.

To preserve the transient microstructural state of the joint developed during welding, dry ice quenching was employed immediately upon completion of the shoulder-assisted heating FPW of the 6082-T6 aluminum alloy. EBSD specimens were subsequently rapidly sectioned from the NZ, RZ and TMAZ, specifically from locations 1 mm below the upper surface of the joint. Following sequential grinding (coarse and fine) and polishing, EBSD analysis was performed independently on specimens from these distinct regions. The analysis parameters included a sample tilt of 70° , an accelerating voltage of 20 kV, and a step size of $1\text{ }\mu\text{m}$. After EBSD data acquisition and indexing, data processing was conducted using HKL Channel5 2019 software v5.12. Grain boundaries with misorientation angles in the range of 2° to 15° were defined as low-angle grain boundaries (LAGBs), depicted as white lines, while those with misorientation angles exceeding 15° were classified as high-angle grain boundaries (HAGBs), represented by black lines.

As depicted in Figure 12, the base metal, in its initial T6 condition, exhibited a microstructure resulting from prior rolling and subsequent solution treatment, which led to full recrystallization. Significant grain growth was apparent, with an average grain size measured as $31.1\text{ }\mu\text{m}$.

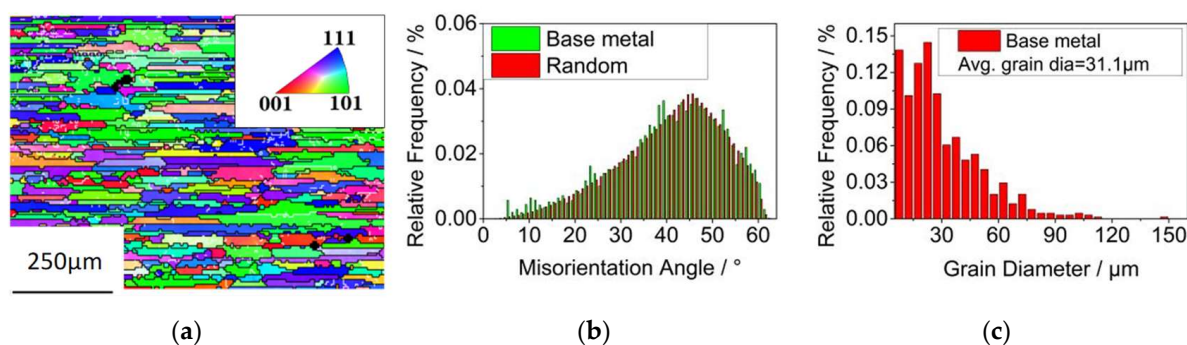


Figure 12. Grain morphology, neighboring misorientation angles, and grain size of base metal: (a) grain morphology; (b) neighboring misorientation angles; (c) grain size.

As illustrated in Figure 13, at a plug rotational speed of 1800 rpm, the misorientation angle distributions between adjacent grains in the NZ, RZ, and TMAZ of the joint all deviated from a random distribution. This deviation indicates the occurrence of dynamic recrystallization (DRX) in these three regions. The average grain sizes were determined to be 2.1 μm in the NZ, 4.7 μm in the RZ, and 8.7 μm in the TMAZ. The NZ was characterized by equiaxed grains and possessed the smallest average grain size. The grain size in the RZ was larger than that in the NZ, while the TMAZ exhibited the largest grain size among these three weld zones, though still finer than the base metal.

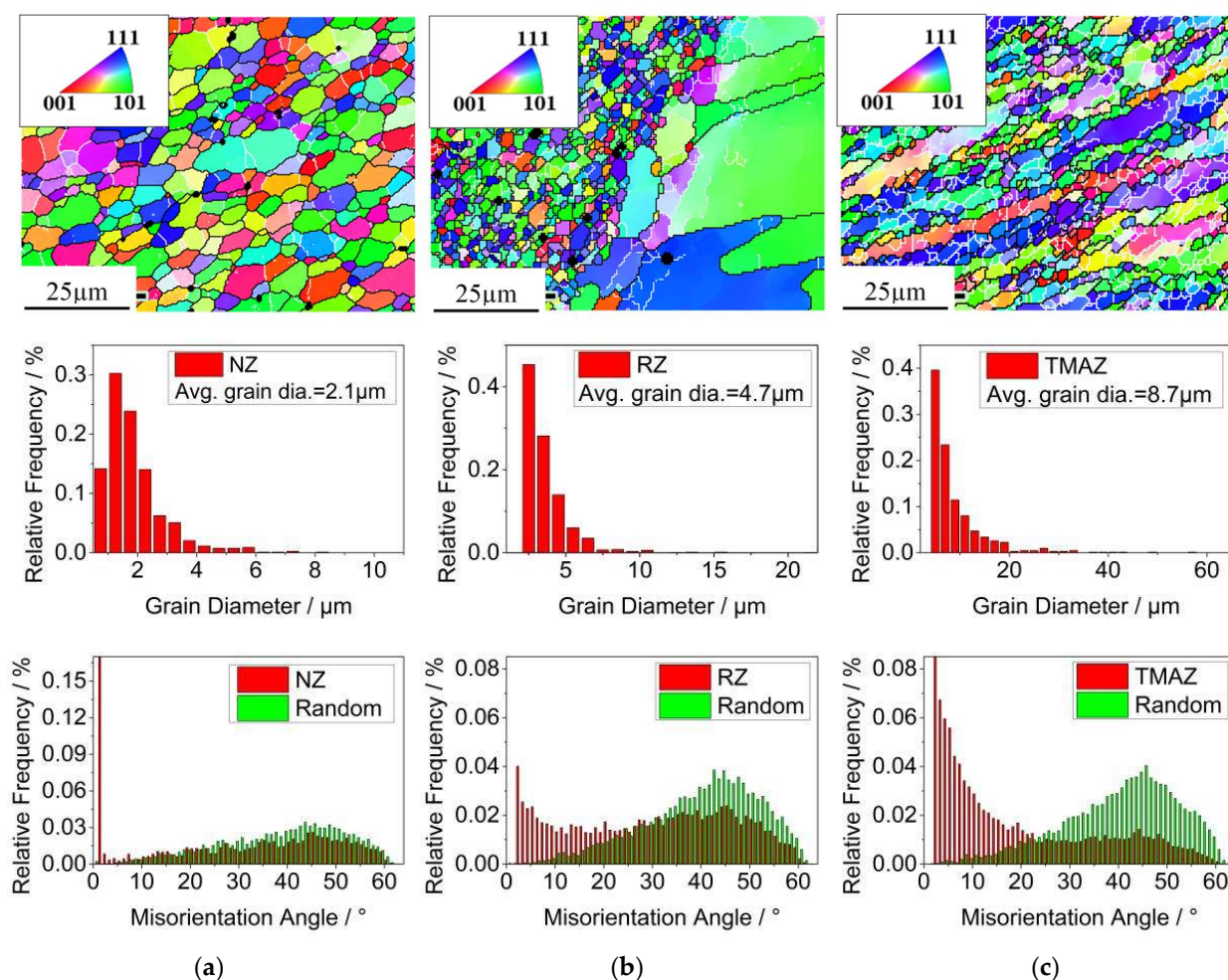


Figure 13. Grain morphology, average grain size, and neighboring misorientation angle distribution in different joint regions: (a) NZ; (b) RZ; (c) TMAZ.

Figure 14 reveals that the NZ possessed a higher fraction of high-angle grain boundaries (HAGBs) than the RZ and the TMAZ, signifying a more extensive degree of dynamic recrystallization (DRX) in the NZ. The RZ and TMAZ, being situated farther from the joint centerline, experienced severe plastic deformation induced by the rotating plug during the shoulder-assisted heating FPW process. In comparison to the NZ and RZ, the TMAZ displayed a lower extent of recrystallization, suggesting that this region predominantly underwent thermomechanical-induced plastic deformation with incomplete recrystallization. The TMAZ also exhibited a lower proportion of recrystallization texture components but contained the highest dislocation density and stress concentration, rendering it the structurally weakest region of the joint. Consequently, tensile test fractures consistently initiated and propagated within the TMAZ. The significantly lower HAGB fraction in the TMAZ compared to the NZ and RZ implies that the TMAZ was less responsive to varia-

tions in strain rate and deformation temperature resulting from changes in plug rotational speed; the DRX kinetics in the TMAZ were considerably slower than in the NZ and RZ under equivalent nominal speeds. Furthermore, these observations underscore that during shoulder-assisted heating FPW of 6082-T6 aluminum alloy, the auxiliary heat generated by friction between the tool shoulder and the base metal, in conjunction with the frictional heat from the plug-bore interaction, effectively promoted DRX in the NZ and RZ. This synergistic heating is crucial for refining and optimizing the joint microstructure, thereby enhancing its mechanical properties.

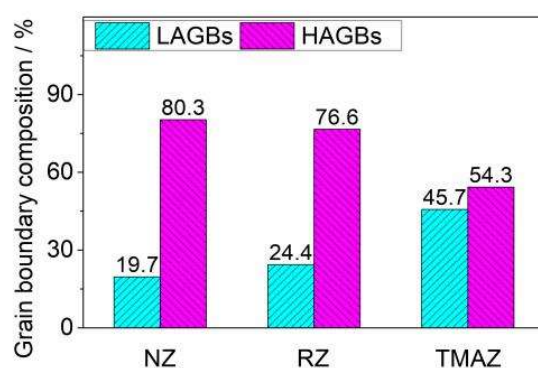


Figure 14. Fractions of high-angle and low-angle grain boundaries in different joint zones.

Therefore, the grain morphology and its distribution within the RZ and TMAZ result from the combined effects of temperature and deformation experienced during the plug welding process. This underscores the critical role of thermomechanical coupling in the microstructural evolution across different regions of the joint. Within these regions, localized heat input and mechanical stirring collectively govern the recrystallization kinetics and the resultant grain boundary characteristics.

5. Conclusions

- (1) The concave backing hole technique influenced the flow of plasticized material during shoulder-assisted heating FPW, thereby affecting the formation and characteristics of the joint's microstructural zones. The resulting microstructure and its distribution across the joint were heterogeneous. Specifically, the NZ and SAZ consisted of fine, equiaxed grains, while the RZ served as a transition region. The TMAZ exhibited significant grain deformation (bending), and the HAZ retained the lath-like microstructure characteristic of the base metal.
- (2) The concave backing hole technique accelerated the flow of plasticized material during welding, promoting the formation of a more consolidated and refined microstructure and enhancing the overall mechanical performance of the joint. With the exception of a slight reduction in microhardness within the HAZ, hardness values in other regions of the joint exceeded that of the base metal. Hardness exhibited heterogeneity through the thickness, generally decreasing with increasing distance from the upper surface at a given vertical position.
- (3) Employing the concave backing hole technique eliminated the FZ, expanded the extent of the NZ, and improved the microstructural homogeneity within the weld. By eradicating weak bonding defects at the joint root, this approach increased the ultimate tensile strength to 278.10 MPa (equivalent to 89.71% of the base metal strength) and the elongation at fracture to 9.02%.
- (4) The misorientation angle distributions between adjacent grains in the NZ, RZ, and TMAZ all deviated from a random distribution, indicating the occurrence of dynamic

recrystallization (DRX). The NZ possessed the highest fraction of high-angle grain boundaries (HAGBs) compared to the RZ and TMAZ. The NZ consisted of fine, equiaxed grains with the smallest average grain size (2.1 μm), whereas the TMAZ exhibited the largest grain size (8.7 μm) among these zones. The interplay between temperature and deformation during the plug welding process governed the resulting grain morphology and its distribution across the different joint regions.

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