Achieving High-Quality Aluminium Alloy Welded Joint with Fine Grains Using Submerged Friction Stir Welding

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Abstract: The purpose of this study is to reveal the microstructure and mechanical properties of friction stir welding (FSW) joints prepared in water/air. For comparable analysis, the submerged FSW (SFSW) and conventional FSW are both conducted on 6061-T6 aluminum alloy plates at the combination rotation speed of 800 r/min and the traverse rate of 50 mm/min. The results show that a greatest grain refinement is achieved by SFSW, which is remarkably smaller than that of the base material (BM) and air FSW (AFSW) samples, leading to a significant improvement of tensile strength from 202.5 MPa in the AFSW sample to 232 MPa in the SFSW sample.

Key words: submerged friction stir welding (SFSW); air friction stir welding (AFSW); mechanical properties; micro-structure

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0 Introduction

Friction stir welding (FSW) is a solid joining process created by the Welding Institute (TWI) in the U.K.[1], which aim to join two similar or different alloy types. During the analysis of the FSW sample, the sample can be devised into three categories containing base material (BM) zone, stir zone (SZ) and thermal mechanical heat affected zone (TMAZ)[2]. BM, HAZ (Heat affected zone) & TMAZ are the main microstructural zones presented in almost all welding processes.

FSW is the first discovery before giving to many other solid-joining process place to innovate the solid joining processes. During FSW, the material is plasticized and flow around the friction stirring tool under the frictional heat and deformation heat. It is obvious that the heat input is comprehensively determined by the welding parameters, such as rotational rate and welding speed.

WP standing for weld pitch is a welding parameter being a ratio of the rotation speed of the shoulder over the traverse velocity of the process, which is directly related to the heat input during the welding. In other words, a low rotational speed with a high welding speed confirmed a relatively low heat input. It is found that WP defined as the ratio of rotational rate and welding speed, can effectively reflect the heat input during FSW process. The corresponding relationship between the aforementioned parameters can be expressed as follows

$$\mathrm{WP} = \omega / v$$

where ω stands for rotation speed and v the translational speed of the weld. Many studies have been conducted on the FSW process to optimize the resultant joint properties. Park et al.[3] studied the effect of the shoulder diameter and WP on the lap weld of aluminium alloys AA6111 and AA5023, where they found that the hardness of TMAZ and HAZ improved after a relative decrease of the WP. Never-

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theless, there are still several problems in FSW of aluminum alloys. The surface of the weld often exhibits overheating due to the seriously friction between the shoulder and the workpiece surface. In addition, for precipitates strengthening materials, owing to the dissolution of strengthening phases in weld nugget zone (WNZ), TMAZ and HAZ caused by the excessive heat input, the regions in FSW precipitated joints generally presents softening with degraded mechanical properties[4-5]. Based on the previous researches, it is demonstrated that too much heat input during FSW can not only impair the weld surface performance, but also easily lead to the unfavorable phase transformation, resulting in the reduction of joint performance. Previous studies have proved that submerged FSW (SFSW) is a highly effective method of reducing the peak temperature and the holding time at high temperature due to strong heat absorbing ability of water, leading to the achievement of high-quality joints in different materials[6].

For example, Zhao et al.[7] conducted SFSW to control the heat input during welding, and found the effectiveness of water cooling in the process of FSW of spray formed 7075 aluminum alloy. Also, Sabari et al.[8] performed SFSW on the AA2519-T87 aluminium alloy. They manifested that the coarsening and dissolution of the strengthening precipitates caused by the welding thermal cycles during conventional air FSW (AFSW) process can be effectively constrained, leading to a superior tensile performance at relatively higher welding speed.

So far, scanty literature has been focused on aluminum using SFSW with flowing water. Specially, the relationship between the microstructure and their mechanical properties is still lacking. The aim of this research is to determine the effectiveness of an in-cooling process by conducting the weld underwater, and comparing the result with non-cooled weld process. In addition, the resultant microstructure and mechanical properties are also investigated.

1 Experiment

The research uses a 5 mm thickness aluminium alloy of type AA6061 having the nominal composition of Al-1.0Mg-0.6Si-0.2Cu-0.25Zn-0.15Mn-0.1Cr-0.7Fe (weight percent), with a 200 mm lengthwise and 155 mm width, the choice of the alloy has been made for it is numerous characteristics such as lightweight, strong electrical conductivity, strong corrosion resistance. Adding to that aluminium is widely used in all domains for the previously mentioned characteristics. As shown in Figs. 1 and 2, two types of FSW joints under water and air cooling conditions are obtained, respectively.

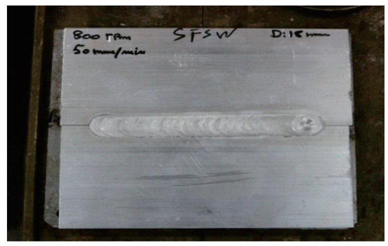

Fig.1 Result of SFSW

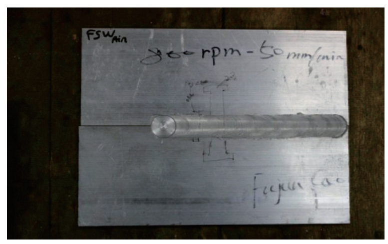

Fig.2 Result of AFSW

In order to obtain a clear contrast, the same parameters with rotation speed of 800 r/min and welding speed of 50 mm/min are used for SFSW and AFSW.

When the SFSW welds a container, the base of this container is formed by the Al alloy plane to be welded, and the two alloy planes are connected using PVC in order to maintain the water inside preventing from leaking. As shown in Fig.3, to prevent from the water being heated, a pump is used to pump the water inside the container to the submerged plane and then flow out of the container, thus passing the water through the container.

Fig. 4 shows the diagram of FSW processes, revealing the difference between the SFSW and AFSW joints. The measurements of various FSW samples are also presented.

Fig.3 Process of SFSW

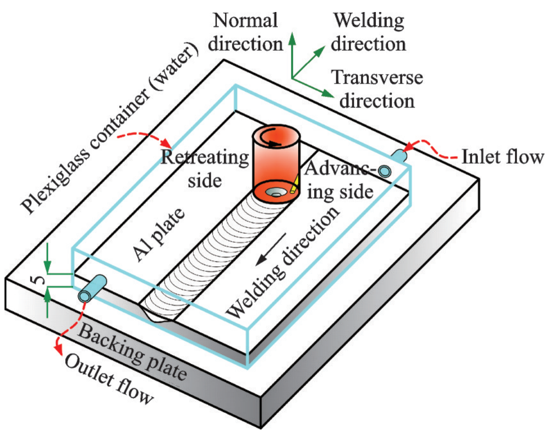

Fig.4 Diagram of FSW process (unit: mm)

Fig.5 shows the sample preparation methods for microstructural characterization and properties testing, where T1—T5 are the dog-bone shaped tensile samples obtained from horizontal and vertical welds; XRD and OM samples are abstracted from the center of the weld. While the measurement of the sample are represented in Figs.6 and 7. Dog-bone shaped samples of T1 and T2 with thickness of 4 mm are abstracted from the center of the weld along the welding direction. Meanwhile, the sample T3 has been cut in the same way on the BM area composed of aluminium only. The sample T4 is representing a dog-bone shaped sample with a thickness of 5 mm that has been cut vertically in the center of weld, thus the sample T4 is formed only by the stir zone of weld. The sample T5 has been cut following the same size of the sample T4 on the BM area. On the welded area a sample has been pre-cut befitting an XRD test. This sample has been polished using sand papers (No:6,5,3,2) until resulting a perfect smooth area, then we use a Al_2O_3 solution to smooth the topography of our sample. The same steps has been conducted for the preparation of OM samples.

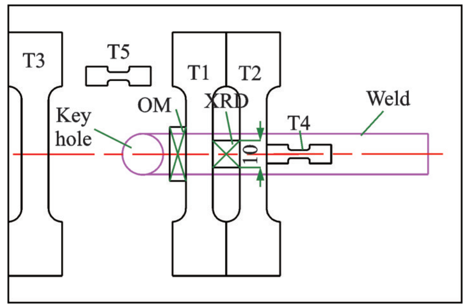

Fig.5 Diagram for sample preparation

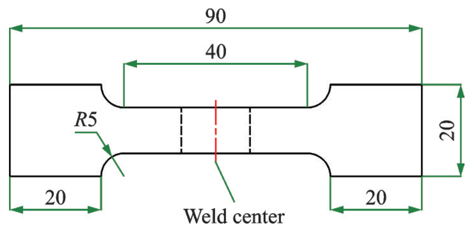

Fig.6 Dog-shaped tensile sample (Horizontal)

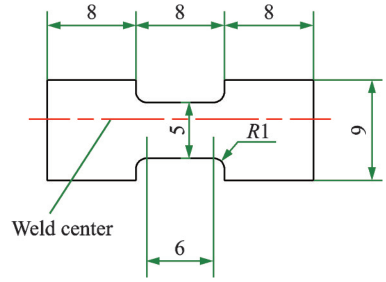

Fig.7 Dog-shaped tensile sample (Vertical)

2 Results

The mechanical properties of the resulting dissimilar FSW joints can be evaluated by the uniaxial tensile tests. For each joint, the tensile test is performed at least three times to confirm the repeatability of the results. Identifying the phase and the texture through Cu-Kα, the XRD standing for X-ray diffraction is employed. EBSD testing is employed to determine a map of the structure of the results after welding.

2.1 Tensile test

The peak stress on the samples is obtained by using a Instru-Met Instron tensile test. The samples have been milled on sand papers (No:6,3) to fit the jaws of the tensile tester. A velocity of displacement of 2 mm/min has been fixed while the experiment.

Figs.8 and 9 display the horizontal and longitudinal tensile curves from BM, AFSW and SFSW samples, respectively. As compared with AFSW samples, SFSW samples show an increased ultimate tensile strength (UTS) from 202.5 MPa to 232 MPa, which reveals that SFSW is beneficial to the enhancement of joint strength. While the strength of both FSW joints are reduced in comparison to the BM. Additionally, the ductility of the SFSW sample is slightly lower than that of the AFSW sample. This phenomenon is in agreement with the reverse relationship between the strength and ductility.

We can summarize from these results that SFSW can withstand high stress and offer relative higher elasticity, while AFSW offer more strain without breaking.

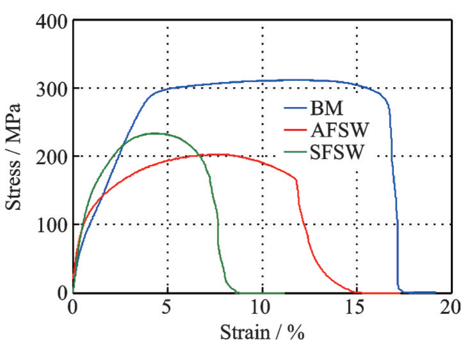

Fig.8 Horizontal tensile results of BM, AFSW and SFSW samples

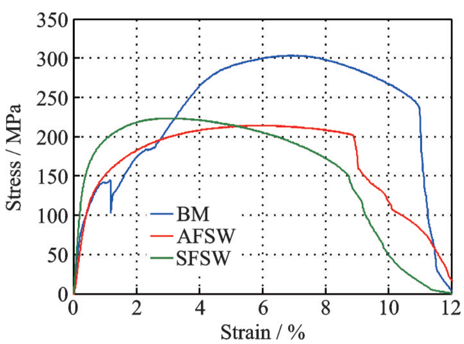

Fig.9 Longitudinal tensile results of BM, AFSW and SFSW samples

2.2 X-Ray diffraction

The results of the XRD represented in Fig. 10 shows that the crystal structure of the alloy changes on the SFSW where the intensity on the plane (111) becomes relatively high on the AFSW, and even more in SFSW, while it is relatively low on the BM. It is also shown that on the SFSW a plane (311) appears on the curve.

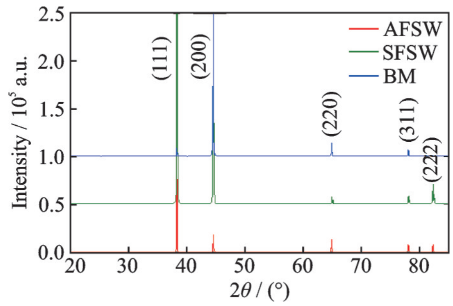

Fig.10 X-Ray diffraction

2.3 EBSD

EBSD analysis provides additional information about the joint region. The corresponding observation direction and color legend are shown in Fig.11. In the cross section of the resulting samples, the SZ regions are examined. Figs.12—14 show that there is a significant difference in grain sizes, comparing these samples. The mean grain area in the AFSW is 8.36 μm^2 while a shrinkage of the area can be noticed in the SFSW of a value 3.70 μm^2, which is significant smaller than that of BM shown in Fig.12. It is revealed that the smallest grains are obtained in SFSW sample, which are higher than that of BM and AFSW samples, indicating that SFSW greatly refines the grains.

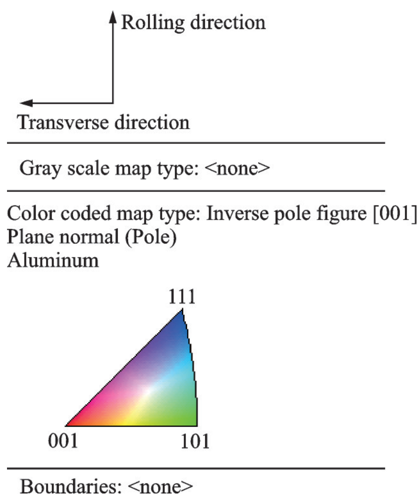

Fig.11 Scale for EBSD map reading

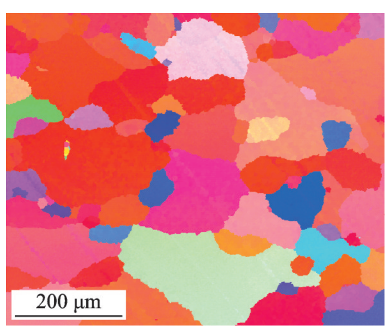

Fig.12 Grain structure of BM

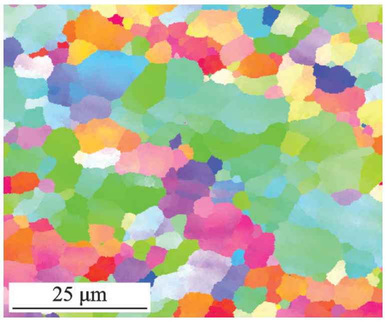

Fig.13 Grain structure of AFSW

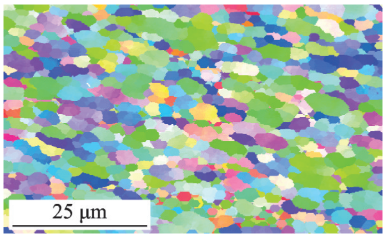

Fig.14 Grain structure of SFSW

3 Discussion

The target of this study is to reveal the variation of microstructure and mechanical properties between SFSW and AFSW samples. The result from the tensile test (Fig.8) shows that the performance of the sample from SFSW is increased by 14.6%. We can relate the improved mechanical properties in SFSW to the microstructure of the grain structure with varying diameter. In other words, the extreme refinement of SFSW samples significantly promote the enhancement of the mechanical properties.

Su et al.[9] used an indirect method to measure the tool torque, traverse force, and axial force during friction stir welding of aluminium alloys AA2024-T4. The measured value is consistent with the data captured by rotation component dynamometers and load cells. Tool torque is indirectly proportional to the tool rotational speed and directly proportional to the welding speed. The tool rotation speed and the longitudinal force are related. The axial force is much greater than the traverse force.

Based on the macrostructural analysis, Lakshminarayanan et al.[10] developed a friction stir welding window for joining 2219 aluminum alloy efficiently. A lack of solidification results in a number of defects in aluminum alloy fusion welding, including cracks, porosity, slag inclusion, etc. Weld quality and joint properties are affected by these defects. As friction stir welding is a solid-state welding process, no melting occurs during the welding process, so there are no defects. FSW process with different cooling conditions has been performed on the dissimilar joint of AA6061 and steel mild, using various welding parameters[11]. It proves that both great increment of hardness and average tensile shear strength occur for FSW joints under water and dry ice cooling conditions.

It has been demonstrated that grain refinement plays an important role in strengthening of polycrystalline materials since the grain boundary can greatly inhibit the dislocation motions, resulting in the improvement of strength.

In this study, the significant grain refinement is produced in SFSW sample, improving the resultant tensile strength, which is in accordance with the Hall-Petch relationship between the strength σ and the average grain diameter d of the material. It is indicated that the decrease of grain size will increase the tensile strength. The Hall-Petch equation is shown as follows[12]

$$\sigma = \sigma_0 + kd^{-1/2}$$

where σ_0 is the dislocation stress, k and d denote the Hall-Petch constant and average grain diameter, respectively.

4 Conclusions

The weld ability of SFSW of 6061Al has been demonstrated by the significant enhancement of tensile strength of 14.28% in comparison to the AFSW joint (Figs.8 and 9). SFSW not only affects the mechanical properties but also modifies the grain structure where the diameter of the grain in SFSW decreases relatively to AFSW, owing to the rapid cooling rate and lower thermal welding cycle.

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Author contributions Mr. **YOUSSEF Elmeknasssi** contributed to the investigation, methodology, data curation, soft ware and original draft. Dr. **CAO Fujun** contributed to experiments, writing-reviewing and editing. Prof. **FENG Xiaomei** contributed to conceptualization, methodology, original draft, review & editing. Prof. **SHEN Yifu** contributed to conceptualization, methodology and and project administration. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

基于水下搅拌摩擦焊工艺制备高质量的铝合金焊接接头

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摘要：本研究的目的是揭示水下/空气中制备的搅拌摩擦焊(Friction stir welding, FSW)接头的组织和力学性能。采用相同工艺参数(800 r/min, 50 mm/min)对6061-T6铝合金板分别进行了水下和空气搅拌摩擦焊接，结果表明，相比传统的空气搅拌摩擦焊接工艺，水下搅拌摩擦焊工艺体现出强烈的细晶强化作用，大幅细化了焊后组织，且明显提高了焊后接头的抗拉强度。焊后接头的抗拉强度由空气搅拌摩擦焊接头的202.5 MPa提高到水下搅拌摩擦焊接头的232 MPa。

关键词：水下搅拌摩擦焊；空气搅拌摩擦焊；力学性能；微观组织