The effect of friction stir welding parameters on the microstructure, defects, and mechanical properties of AA7075-T651 aluminium alloy joints

Jafar Langari¹, Farhad Kolahan² *

¹,² Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

ABSTRACT

This study aims to examine how friction stir welding parameters, such as welding speed and rotational rate, affect the microstructure, defects, and mechanical properties of AA7075-T651 aluminium alloy joints. It also assesses the relation of the defects and microstructures with the mechanical properties. Microstructural investigations using optical microscopy (OM) and scanning electron microscopy (SEM) indicated remarkable grain structure variations among different welding zones especially, it was found out that the interface between welding nugget zone (WNZ) and thermo-mechanically affected zone (TMAZ) is a dominant determinant of the mechanical properties of joints. The importance of the interface comes from the fact that it is the most prone region to cracks, micro-cavities and tunneling defects. The WNZ and TMAZ interfaces as well as their grain structures can be influenced by the heat generated from the friction between the rotating tool and workpiece material. Therefore, coarser grain structures observed at the WNZ-TMAZ interfaces of the samples welded at higher rotational rates or lower welding speeds is due to the greater heat generated in such cases. Besides, microstructural variations in the weld zone affect the hardness and mechanical properties of weld joints. Thus, samples with coarse-grained structures display lower values of yield stress and microhardness.

Keywords: Friction stir welding; Microstructure; Mechanical properties; Welding defects; AA7075–T651 aluminium alloy.

1. Introduction

Friction stir welding (FSW) was invented in 1991 at The Welding Institute (TWI) of UK [1]. It is a solid-state process for joining low-melting-temperature metals (such as alloys of aluminium, copper, and magnesium), which occurs at temperatures below the melting point of the materials to be joined. Unlike some joints made by fusion

* Corresponding Author. Phone: +98 9153114112, fax: +98 51 38806055, Email: kolahan@um.ac.ir
welding methods, the joints obtained by FSW process feature lower residual stresses, insignificant distortion, etc [2-3]. In the recent years, the unique advantages of FSW process have given it widespread industrial applications [4]. In the case of 2xxx and 7xxx series aluminum alloys, in particular, fusion welding causes a drop in the strength and ductility in the heat affected zone. This, in turn, leads to brittle fracture, thermal cracks, porosity and fusion defects [5]. The welding behavior of 7xxx series aluminum alloys deserves examination since, according to ASTM B209M-14, they are utilized in the manufacture of plates and sheets used in aerospace, military vehicles, road construction machinery, bridges, marine and rail applications [4,6].

In general, FSW process as used for joining aluminium alloys has motivated relatively widespread studies. The studies deal with the effect of welding parameters on the mechanical and metallurgical properties of joints [7-8]. Mahmoud et al. [9] studied a number of parameters affecting the heat input and material flow behavior in an FSW process. The parameters include rotational rate and welding speed, vertical pressure on the tool, tool tilt angle and tool geometry. Xue et al. [10] concluded that the tool rotational rate and welding speed are important parameters which affect the mechanical properties and microstructure of the joints resulting from FSW. Ghorbanzade et al. [11] reported that when the rate of rotation increases, AA2024-T3 alloy joints show a brittle behavior, increased strength and decreased ductility.

Vatankhah Barenji [12] reported that greater welding speed enhances the hardness and strength, and decreases the elongation of defect-free joints in AA7020-T6 alloy. Rajakumar et al. [8] made use of the AA7075-T6 aluminum alloy plates with a thickness of 5 mm and strength of 485 MPa for FSW procedure. They showed that the main requirement for achieving desirable mechanical properties is a defect-free stir zone with a regular grain pattern and homogeneous distribution of MgZn2 precipitates. Ren et al. [13] achieved a maximum efficiency of 75% in the FSW of AA7075-T651 aluminum alloy plates with a thickness of 8 mm and a strength of 574 MPa. Their results showed that the fracture of the joint occurred in the HAZ region in shear mode with an angle of 45° relative to the tensile axis.

Palanivel et al. [14] used a neural network method and predicted the tensile strength of dissimilar plates joined by FSW with an error less than 5%. They investigated the effect of welding parameters, such as rotational rate and tool pin profile, on the microstructure and defects of the joints. The influence of FSW parameters on welding defects has been the subject of a number of research studies [15-17]. In order to achieve a strong welding joint with very few defects, the parameters of an FSW process should be set at optimum values [8,18-20].
In this paper, 6.3 mm thick joints of AA7075-T651 aluminum alloy were exposed to FSW under different parameters. The objectives of this study were: (1) to estimate the joinability of AA7075-T651 aluminum alloy under different welding parameters, (2) to find out the effect of FSW parameters (welding speed \( \nu \) & rotational rate \( \omega \)) on the mechanical properties and the microstructure of the joints and (3) besides, to examine how the failure of the tensile specimens occurs due to defects in the FSW joints. For a detailed investigation of weld defects, SEM & OM images of the fractured surface and joints cross-sections were produced.

2. Experimental procedure

Rolled plates of AA7075-T651 aluminum alloy (Kamensk-Uralsky Co., Russia) were used as the joint specimens in this study. The chemical composition and mechanical properties of AA7075-T651 aluminum alloy have been shown in Table 1 and Table 2.

The welding parameters were selected through consulting numerous publications, e.g. [21-24], and conducting pilot tests. As seen in Table 3, the welding process was performed at different tool rotational rates (\( \omega \)) and welding speeds (\( \nu \)). Also, 1.2344 hot work tool steel (Bohler W302 premium H13, Germany) with the geometry shown in Figure 1b was selected as the welding tool. The tool tilt angle was set at 2.5° relative to the vertical axis. To obtain integrated welding, a 0.3 mm distance between the tool tip and the lower surface of the plates was kept during welding. The concavity of the tool shoulder caused a more effective contact with the workpiece surface.

Microstructure of the base metal and as-welded samples were determined by means of Optical Microscopy (OM, Olympus GX-51) and Scanning Electron Microscopy (SEM, LEO 1450VP). The samples for microstructural analyses were produced using a wire cut machine, polished by SiC abrasive papers and etched by chlorine (150 ml H2O, 3 ml HNO3 and 6 ml HF). According to ASTM E-112 standard [25], one of the most common techniques to estimate an average grain size is the intercept technique. A random straight line is drawn through the micrograph. The number of grain boundaries intersecting the line is counted. The average grain size (dm) in each microstructure was calculated by Clemex image analysis software using Eq. 1:
\[ d_m = \frac{1}{z} \sum_{i=1}^{n} \frac{L_i}{m_i} \quad \text{Eq. (1)} \]

where \( z \) is the number of lines, \( L_i \) is the length of the \( i \)th line and \( m_i \) is the number of grains located on it.

Samples for the uniaxial tensile tests were prepared in their transverse cross-sections according to ASTM E8M-97a standard (Figure 1c). The tensile tests were carried out by a Zwick/Roell servo-hydraulic machine (model Amsler AB100) at the strain rate of \( 0.0053 \, \text{mm}^{-1} \), and each test was repeated three times at room temperature. In addition, Vickers microhardness tests were performed in different weld zones according to ASTM: E384-11e1 standard. The microhardness of the samples was measured in the middle of their transverse cross-sections at intervals of 1 mm while they were under 200-gr loading for 10- seconds dwell time.

3. Results and discussion

3.1. Microstructural analysis

A typical SEM micrograph of 7075-T651 aluminum alloy and a cross-sectional image of one of the FSW joints are shown in Figure 2a and 2b, respectively. Four distinct zones are recognized in the cross-sectional microstructure of an FSW joint. According to the granular microstructure of the FSW joint in Figure 2b, we distinguished the zones of base metal (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and weld nugget zone (WNZ). OM images obtained in different zones (Figure 2c-e) suggest significant microstructural variations across the range spanning from WNZ to BM sections. While BM microstructure consisted of large elongated grains with homogenous distribution of Al (Zn, Mg, Cu) precipitates, the microstructures of the three other weld zones were affected by the weld heat, which proportionally brought about dissolution of precipitates and created porosities and variations in the grain structures. More importantly, we distinguished the interfaces between WNZ and TMAZ as a notable region in the weld section. Aggregation of porosities in the interfaces and the great variations in the grain structures in the weld section makes the interfaces the dominant failure sections. The choice of suitable parameters can decrease the defects leading to a modification in the microstructures of the WNZ and TMAZ zones. This technique may be effective in improving the mechanical properties of the joint samples [12, 26].

Placement of Figure 2.

Since FSW is a solid-state joining process, WNZ and TMAZ interfaces as well as their grain structures can be influenced by the heat generated by the friction between the rotating tool and the workpiece material. Cross-
sectional micrographs of S1 to S5 joints (Figure 3) confirmed that the FSW parameters of rotational rate and welding speed lead to changes in the weld zones microstructures. These results indicated that heat input is influenced by the FSW parameters of rotational rate and welding speed. Further, if there is insufficient or excessive heat input in FSW process, prepared joints are prone to show welding defects such as pinhole, tunneling, cavity, kissing bonds and cracks [12, 26]. Thus, we recognized welding defects such as a cavity in S3 and S4 samples (Figs. 3c and 3d, respectively) and tunneling defect in S5 joint (Figure 3e). These results suggested that welding defects are more likely to appear when rotational rate and welding speed are higher.

Placement of Figure 3

High magnification OM and SEM micrographs of WNZ-TMAZ interfaces are clearly seen in Figure 4. It indicates that, in addition to tunneling and cavity defects, small cracks are also present in the WNZ-TMAZ interfaces of the samples welded at higher rotational rates. More detailed SEM investigations reveal that the above-mentioned cracks were actually originated by the integration of numerous microcavities aggregated in this area. Generation of tunneling, cavity and crack defects in the WNZ-TMAZ interfaces of the samples which were welded at higher rotational rates (Figure 4c, 4d and 4e) can be attributed to the inadequate material flow. Besides, SEM investigations indicated that lower rotational rates were not suitable for FSW process since inadequate heat input can lead to generation of microcavities in the WNZ-TMAZ interfaces (Figure 4a). These results suggested that the tool rotational speed must be low enough to facilitate flow of material, and high enough to increase the frictional heat in the weld zone. Therefore, defect-free WNZ-TMAZ interfaces can be obtained by FSW process at a rotational speed of 1000 rpm and a welding speed of 20 mm/min. Considering the five fabricated joints and using various welding parameters, the fabricated joint mentioned before exhibited superior mechanical and metallurgical properties in comparison to other fabricated joints (Figure 4b).

Differing grain structures were also observed at the WNZ and TMAZ sides of the welded samples as shown in Figure 4. While the existence of fine-equiaxed grains implies dynamic recrystallization phenomenon in WNZ area [27], the TMAZ microstructure is in agreement with the elongated grain pattern along a flow perpendicular to the WNZ–TMAZ interface [26, 28].
The Shape and size of grains in the weld zones can be extremely affected by the heat input and cooling rate of FSW processes. In this study, the effects of different heat inputs on the microstructure of the weld samples, at a constant cooling rate, were investigated.

Frigaard et al. [29] introduced the following equation for the effect of rotational rate ($\omega$) on the heat input ($q$) generated by a FSW process:

$$ q = \frac{4}{3} \pi^2 \mu P_z \omega r^3 $$ \hspace{1cm} Eq. (2)

where $\mu$, $P_z$, and $r$ denote the friction coefficient, tool pressure, and radius of shoulder, respectively. Further, the relation expressing the effect of welding speed ($v$) on heat input per unit length ($Q$) was suggested by Kim et al. [30] as below:

$$ Q = \frac{\eta q}{v} = \frac{4}{3} \pi^2 \frac{\eta \mu P_z \omega r^3}{v} $$ \hspace{1cm} Eq. (3)

where $\eta$ is the heat input efficiency.

Considering constant values for $\eta$, $\mu$, $P_z$, and $r$, heat input per unit length ($Q$) versus rotational rate ($\omega$) and welding speed ($v$) can be written as:

$$ Q = \beta \frac{\omega}{v} $$ \hspace{1cm} Eq. (4)

where $\beta = \frac{4}{3} \pi^2 \eta \mu P_z r^3$.

According to Eq. 4, heat input increases with rotational speed ($Q_{S1} < Q_{S2} < Q_{S3}$) and reduces with welding speed ($Q_{S3} > Q_{S4} > Q_{S5}$). Since greater heat inputs lead to the growth of recrystallized grains, higher rotational rates or lower welding speeds are expected to increase the average size of grains in the WNZ, TMAZ and even HAZ areas.

The weld nugget zones of the samples welded with various heat inputs are shown in Figure 5 through SEM micrographs of two different magnifications. Based on the results of image analysis, the average grain size increased from 4.4 to 5.8 $\mu$m in the samples welded at a constant welding speed of 20 mm/min while the rotational rate increased from 630 to 1250 rpm (Figure 5a, 5b and 5c, respectively). Also, at the constant rotational rate of 1250 rpm, the average grain sizes were 5.8, 4 and 3.7 $\mu$m for the samples welded at the welding speeds of 20, 40 and 60 mm/min, respectively.
3.2. Microhardness

Microstructural variations in the weld zone are expected to affect the hardness and mechanical properties of the weld joints. The microhardness of the weld zone gradually decreased from 170 HV in BM to about 100 HV in WNZ. The reduction of microhardness can be attributed to grain growth and precipitates dissolution in the heat affected weld zones [12,27, 31-33]. A drop in microhardness was observed in the WNZ-TMAZ interfaces of some samples. The unexpected drops are due to some defects in the WNZ-TMAZ interfaces as well as coarser grain structures in TMAZ (Figure 4).

The variations in the microhardness of a typical sample involving a variety of grain structures can be explained by Hall–Petch strengthening mechanism [34]. According to the mechanism, grain boundaries impede dislocation motions. Therefore, any decrease in the number of grain boundaries (resulting from grain growth) can lead to microhardness reduction. Based on Hall–Petch strengthening mechanism, higher microhardness values are expected for the samples with smaller grain sizes, which are those welded at lower rotational rates or higher welding speeds. A comparison of the values of microhardness confirms that, at the constant rotational rate of 1250 rpm, higher welding speeds led to increased microhardness of weld zones (Figure 6a). Besides, lower rotational rates, which result in smaller grain sizes, led to higher microhardness values (Figure 6b). The hardness indicates the asymmetrical distribution in the weld centerline and the maximum hardness is observed on the advancing side, not the weld center. The reason is referred to the plastic flow field of the two sides of weld center which is not uniform [35-37]. The piling of materials on the advancing side is more noticeable than that of the retreating side. The larger distorted grains and distortion energy is related to strain-hardening increasing considerably, leading to the asymmetrical microhardness distribution.

3.3. Tensile properties

Figure 7 illustrates the tensile test stress - strain curves of the as-welded samples and 7075 aluminum alloy at room temperature and at the strain rate of 0.0053 1/min. Using the stress – strain curve, the values of yield stress, tensile strength and elongation of the samples were obtained and the results are reported in Table 3. According to our
expectations, yield stress variations are in agreement with the observed grain growth trend. The relation between yield stress and grain size is mathematically described by the Hall–Petch equation [34]:

\[
\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}} \quad \text{Eq. (5)}
\]

where \(\sigma_y\) is the yield stress, \(\sigma_0\) is a material constant denoting the stress which triggers dislocation movement, \(k_y\) is the strengthening coefficient, and \(d\) is the average grain diameter. The relationship of yield stress to WNZ mean grain size agreed well with the predictions of Hall–Petch mechanism and indicated that the yield stress of the welds decreased at higher rotational rates or lower welding speeds, i.e. the process conditions which caused greater grain growth.

The results in Table 4 also suggest that the ultimate tensile strength decreased for the samples welded at higher rotational rates and welding speeds. Lower ultimate tensile strength of the S4 and S5 samples can be explained by the crack and tunneling defects in the WNZ-TMAZ interfaces. Joint efficiency, defined as the ratio of the ultimate tensile strength of the joint to that of base metal [38], ranged from 58% to 71% in this study. In addition, the elongation values of the joints were in the range 1.15-5.27%, which are much lower than that of the base metal. In accordance to the other reports in the literature, smaller elongation of joints can be related to the presence of tunneling, cracks and microcavity defects in the WNZ-TMAZ interfaces and subsequent stress localization in those regions [39].

Placement of Figure 7.

Placement of Table 4.

The fracture surfaces of the base metal and FSW joints, at different magnifications, are shown in Figure 8. According to the cross-sectional images of the tensile tests failures, fracture occurs in the middle region of all the samples where stress is localized at the defects in the WNZ-TMAZ interfaces. The failure angle of 45° relative to the direction of the tensile axis suggested that the fracture, in both the base metal and FSW joints, happened in shear mode. The existence of deep, shallow and sheared dimples as well as cleavage planes observed in the SEM fractographs are in agreement with ductile fracture mechanism. Decrease in the rotational rate led to drop in the number of the dimples. Besides, the samples welded at the rotational rate of 630 rpm displayed a behavior suggestive of combined ductile-brittle fracture mechanisms (Figure 8).
4. Conclusion

The microstructure, defects and mechanical properties of FSW joints made of AA7075-T651 aluminum alloy plates were studied. The main conclusions are listed below:

1. During the FSW process, weld heat affects the microstructure of the weld zones through dissolution of precipitates, porosity creation, grain growth and also changing the grain structures.

2. Due to the effects of heat input, higher rotational rates or lower welding speeds increase the average grains size of the WNZ and TMAZ areas.

3. FSW at higher rotational rates and higher welding speeds leads to the generation of tunneling, cavity and crack defects in the WNZ-TMAZ interface, which makes the interface prone to failure.

4. Tool rotational speed must be low enough to facilitate material flow, and high enough to increase the frictional heat in the weld zone. Therefore, defect-free WNZ-TMAZ interfaces can be obtained by FSW process at a rotational speed of 1000 rpm and a welding speed of 20 mm/min.

5. Grain growth and precipitates dissolution in the heat affected weld zones lead to decreased microhardness from BM to WNZ areas.

6. In agreement with Hall–Petch strengthening mechanism, higher rotational rates and lower welding speeds lead to grain growth in the WNZ area and to decreased yield stress and microhardness values.

7. Ultimate tensile strength increases in the case of the sample welded at lower rotational rates, but decreases for those welded at higher welding speeds due to the creation of crack and tunneling defects in WNZ-TMAZ interfaces.

8. Lower elongation of joint (1.15-5.27 %) compared to base metal can be related to the presence of cracks, tunneling and microcavity defects in the WNZ-TMAZ interfaces and subsequent stress localization in those regions.

9. Decreasing the rotational rate leads to decrease in the number of deep, shallow and shared dimples in the SEM fractographs of joint and transfers ductile fracture mechanism to combined ductile-brittle mechanism.

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REFERENCES
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Table 1. Chemical composition of AA7075-T651 aluminum alloy (wt. %)

Table 2. Mechanical Properties of AA7075-T651 aluminum alloy

Table 3. The FSW parameters of the experiments with AA7075-T651 aluminum alloy plates.

Table 4. Mean grain size, hardness, yield stress, tensile strength and elongation of the different samples investigated in this study
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Figure 2. a) An SEM micrograph of 7075-T651 aluminum alloy, b) cross-sectional image of weld zones in S1 sample, c-e) OM micrograph of S1 weld sample in different weld zones.

Figure 3. Cross-sectional micrographs of different weld zones in S1 to S5 joints.

Figure 4. OM and SEM micrographs of WNZ-TMAZ interfaces in S1-S5 samples (a to e, respectively).

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Figure 6. Microhardness variations in the zones of samples welded at; a) the constant rotational rate of 1250 rpm and different welding speeds b) the constant welding speed of 20 mm/min and different rotational rates, (RS: retreating side, AS: advancing side).

Figure 7. The Engineering strain-stress diagrams of 7075 aluminum alloy and the as-welded samples.

Figure 8. SEM fractographs of 7075 aluminum alloy and the as-welded samples.
Table 1.

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Table 2.

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<th>Elongation (%)</th>
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<th>Poisson ratio</th>
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Table 3.

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<th>Welding speed (mm/min)</th>
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</tr>
<tr>
<td>S5</td>
<td>1250</td>
<td>60</td>
</tr>
<tr>
<td>Sample no.</td>
<td>Mean grain size in WNZ (μm)</td>
<td>Mean hardness of WNZ (HV)</td>
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<tr>
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<td>S5</td>
<td>3.7</td>
<td>113</td>
</tr>
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Figure 1.
Figure 3.
Figure 4.
Figure 6.
Figure 7.
Biographies

**Jafar langari** is currently a Ph.D. student of Mechanical Engineering in the Department of Mechanical Engineering at Ferdowsi University of Mashhad, Iran. He was born in September 20, 1977 in Bojnurd, North Khorasan, Iran. He received his B.Sc. degree in Mechanical Engineering from Ferdowsi University of Mashhad, Iran (2001) and his M.Sc.degree in Automotive Engineering from Iran University of Science and Technology (2004). His main research interests are welding, artificial neural networks, optimization.

**Farhad Kolahan** is an Associate Professor in the Department of Mechanical Engineering at Ferdowsi University of Mashhad, Iran. He was born in September 1965 in Mashhad, Iran. He received his B.Sc. degree in Production and Manufacturing Engineering from Tabriz University, Iran. He then continued his postgraduate studies abroad and graduated with a PhD degree in Industrial and Manufacturing Engineering from Ottawa University, Canada, in 1999. Dr. Kolahan's research interests include welding, production planning and scheduling, manufacturing processes optimization, and applications of heuristic algorithms in industrial optimization.