Study of grain distribution during friction stir welding of Al-Zn-Mg alloys using numerical simulation

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Abstract. During friction stir welding (FSW) of Al-Zn-Mg alloys, the grain size of the welded material significantly affects its mechanical properties. In this study, the FSW process was simulated using the finite element method (FEM). Subsequently, the Zener-Hollomon parameters and grain size were calculated using the results of the stimulation of the temperature and strain rate fields. Also, the accuracy of numerical simulation was proved by experiments. It was found that the Zener-Hollomon relationship correctly predicted the grain size for the weld stirring zone (SZ) and thermal-mechanical affected zone (TMAZ), and we concluded that low rotating and high welding speeds resulted in smaller grain sizes for the SZ. Moreover, the high welding speed could effectively improve the grain condition at the edge of the TMAZ and the specific relationship between Zener-Hollomon parameters and the average grain diameter of SZ can be expressed as: \( Z = 9.09 \times 10^{13} d^{-4.74} \).

1. Introduction

Recently, the worldwide demands for high-speed railways and subways have increased rapidly. There are currently thousands of high-speed trains traveling on railways in Europe, Japan, China, and other countries, at speeds that can rival propeller-driven airplanes. Aluminum alloys are increasingly used for building high-speed trains and subways to meet the lightweight, environmental safety, and other requirements for these vehicles, as indicated by Yang and Lin[1]. Currently, aluminum alloy railway car bodies are manufactured combining aluminum alloy-extruded profiles using metal inert gas (MIG) welding to achieve structural integration and body weight reduction. Generally, 6 and 7 series aluminum-extruded profiles are MIG-welded using ER5356 aluminum soldering wires to achieve good mechanical properties. However, previous reports [2-5] indicated that the aluminum alloys welded by traditional MIG fusion welding is prone to defects, such as blow holes, cracks, coarse grains, and insufficient welding joints during the welding process, which could become limiting factors in the development of aluminum alloy car bodies.

Friction stir welding (FSW) was developed by The Welding Institute in 1991[6]. As a solid phase connection process, in addition to being a non-polluting process, FSW presents advantages that cannot be achieved through conventional fusion welding of aluminum alloys, like high joint mechanical properties, cracks-free joint, low distortion, as well as low energy consumption, as indicated by many researchers[7-9]. However, the FSW process is quite complicated; therefore, it is difficult to formulate suitable process parameters for various FSW procedures. Poor process parameters increase production costs and the risk of defects, especially when manufacturing high-speed trains. Generally, the welding quality depends on parameters including the traverse speed and the rotating speed of the tool, tools
shapes, and slope. However, primary studies should be carried out, and many expensive extrusion profiles would be wasted. Therefore, the numerical simulation of the FSW process has been widely studied. Recently, lots of efforts have been spent on studying the influences of the welding speed, tool shape, and slope.

Chen et al.[10] used computational fluid dynamics (CFD) to analyse the effect of the pin thread on the flow and temperature of materials and concluded that pin thread play an important role on the temperature distribution. Zhu et al.[11] predicted and analysed the effects of welding parameters and tool pin profile using the Abaqus software based on the Coupled Eulerian–Lagrangian (CEL) method and concluded that welding and rotating speeds affected hole defects. Moreover, their study indicated that the properties of the joint can be benefit from a low welding speed and high rotating speed.

A tool pin with a special feature may enhance the materials flow during welding and achieve defect-free welds, compared with smooth tool pins. Long et al.[12] focused on tool tilt angle during FSW. They employed the DEFORM-3D software which has the Computational Solid Mechanics (CSM) method to simulate the effort of tool tilt angle, and determined that using non-tilt FSW would cause worm hole defects in the advancing side of the weld line, but using 2° inclination FSW would not. Moreover, compared to FSW featuring no tool tilt angle, FSW using a tool tilt angle exhibited higher peak temperature and better material flow. Carlone et al.[13] researched the influence of the welding parameters of FSW on fatigue cracks using numerical simulation methods. Ajri and Shin[14] researched the effects of welding and rotating speeds on welding quality using experiments and numerical simulation methods.

To date, most research has focused on temperature field distribution and material flow during FSW using experiments as well as finite element simulations. For example, Tutunchilar et al.[15] predicted the shape and defects of the weld stirring zone (SZ) by simulating the flow of material during FSW. Asadi et al.[16] predicted the width of the SZ and temperature and deformation required for recrystallization at the bottom of the SZ using material flow simulations and experimental techniques. Shi et al.[17] simulated the material flow and temperature distribution. Their research indicated that the shape and size of the thermal-mechanical-affected zone (TMAZ) was greatly affected by rotating speeds of the shoulder and pin. Hasan et al.[18] studied the effects of using unworn vs. worn tools on material flow using the FLUENT CFD software, and determined that the worn tool causes a different flow behaviour around and under the pin comparing to the unworn one. However, the microstructure of the material significantly influences its mechanical properties and is one of the key FSW research tasks. Buffa et al.[19] predicted grain size by establishing two different models for continuous dynamic recrystallization. Arora et al.[20] researched the temperature histories at different locations of FSW samples to further estimate the growth rate and size of grains.

To investigate the grain size distribution of welding Al-Zn-Mg alloy under different process conditions, we investigated the temperature field and strain rate in different regions and at different times during FSW using the DEFORM-3D commercial finite element software. Then, the grain sizes of different areas were calculated using the Zener-Hollomon parameter. We analysed the microstructure of materials subjected to welding and used numerical simulations to analyse the distribution of grain size during the FSW process.

2. Simulation details

2.1. Geometric model
In this study, we used a 120 × 100 × 12.3 mm Al-Zn-Mg alloy sample. The stirring pin was conical, featuring a conical angle of 20° and a shoulder exhibiting a concave shape with a concave angle of 8°. The diameter of the shoulder, diameter of the bottom pin, and height of the pin were 26, 7.5, and 11 mm, respectively. The length, width, and height of the back plate were 160, 160, and 3 mm, respectively. The FEM model is illustrated in figure 1.
In this simulation, the DEFORM-3D finite element software was employed, and the simulation used the implicit Lagrangian code proposed by Buff et al. [21]. All models adopted tetrahedral mesh cells, to improve computational efficiency and calculation accuracy. In addition, the meshes of the workpiece and tool were locally refined using a mesh window, and the mesh window followed the movements of the tool. The workpiece presented a total of 19,451 mesh elements and the mesh size transitioned from 0.7 to 6, while the tool featured 17,812 mesh elements and the mesh size transitioned from 0.33 to 4. Since the back plate only experienced heat transfer, the mesh was not locally refined and it exhibited 11,677 mesh elements while the mesh size transitioned from 1.1 to 4.

To simplify the simulation, many assumptions were made as followed: (1) the workpiece was continuous and the material model was rigid-visco-plastic; (2) the stir pin and back plate were rigid; (3) the environmental temperature was 20 °C; (4) the speeds of the workpiece along the X, Y, and Z directions were set to zero; (5) heat was exchanged between the free surfaces of the workpiece, tool, back plate, and environment, and the heat transfer coefficient was set as constant; furthermore, the contact surface between the stirring pin and workpiece, and that between the workpiece and back plate also experienced heat exchange, and the heat exchange coefficient was also set as constant; and (6) the friction coefficient between the workpiece and stirring needle was constant. The welding simulation parameters are listed in Table 1.

| Pin rotating speed (rpm) | 300 | 450 | 600 |
|-------------------------|-----|-----|-----|
| Welding speed (mm/min)  | 150 | 50  | 150 |

2.2. Material model
The workpiece was considered to be rigid-visco-plastic, and the elastic deformation of the material was neglected. The flow stress of the material followed the Arrhenius equation (equation (1)), which describes the relationship between the temperature, stress, and strain of the material at high temperature.

$$\dot{\varepsilon} = A[\sinh(a\dot{\sigma})]^n \exp \left(\frac{-\Delta H}{RT}\right)$$

(1)

Where $\dot{\varepsilon}$ is the strain rate, $\dot{\sigma}$ is the flow stress, $R$ is the gas constant, $T$ is the temperature of the material, and $A$, $a$, and $n$ are material constants. Liu et al. [22] determined the specific parameters in equation (1) using a hot compression test. Table 2 lists the values of the material parameters.
Table 2. Parameters and constant of the Arrhenius equation.

| Material         | A (1/s)   | n       | Q (kJ/mol) | α       | R (J/(mol·K)) |
|------------------|-----------|---------|------------|---------|---------------|
| Al-Zn-Mg alloy   | $2.41 \times 10^{8}$ | 3.55    | 145        | 0.04504 | 8.314         |

2.3. Friction model

The friction conditions during the FSW process are quite complex, and the shear and Coulomb friction models have been commonly used to describe them. Tutunchilar et al.[15] used a shear friction model to simulate the friction stir process using DEFORM-3D software. Therefore, in this work, we also employ the shear friction model. The shear model defines the frictional force as:

$$f = mk$$

where $f$ is the frictional stress, $k$ is the shear yield stress, and $m$ is the friction factor. In this study, $m$ was considered to be a constant. Frigaard et al.[23] indicated that the friction factor of the shear friction model during FSW ranged between 0.2 and 0.6, and $m$ was finally determined to be 0.35.

During FSW, heat generation is mainly derived from two processes: the friction between the stirring tool and workpiece, which was the main source of heat, and the plastic deformation of the workpiece (90% of the energy caused by deformation is transformed into heat during the welding process). The detailed formulae of the governing equations for the thermal model and finite element simulation have been described in detail by Jain et al.[24].

3. Experimental

According to the process parameters given in Table 1, the welding process is carried out. The chemistry of the AL-Zn-Mg alloy was determined by ICP component analysis, and its result shows in Table 3. The welding samples were sectioned vertical to the welding line. Optical microscopy (OM) and electron backscatter diffraction (EBSD) were employed to analyse the microstructure. The preparation of OM specimens was treated by Graff Sargent Corrosion Reagent (1ml HF+16ml HNO₃+3g CrO₃+83ml H₂O). Meanwhile the EBSD specimens was prepared by electro-polishing in a solution (10% HClO₄+90% C₂H₅OH) with voltage of 20V for 10s at 25 Celsius. The metallographic observation was conducting using OLYMPOUS-PMG3 metallographic microscope and the EBSD test was carried out with a field emission gun-environmental scanning electron microscopy device Zeiss EVO MA10 with NordlysMax2 Detector.

Table 3. Chemical composition of Al-Zn-Mg alloy (wt%).

| composition | Fe  | Si  | Cu  | Mn  | Mg  | Zn  | Cr  | Zr  | Ti  | Al   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| content     | 0.089 | 0.057 | 0.19 | 0.36 | 1.45 | 4.29 | 0.26 | 0.1 | 0.013 | Bal  |

4. Results and discussion

The classic FSW model indicated that the welded material could be divided into four areas, as follows: from the centre toward the sides of the weld we identified the SZ, TMAZ, heat-affected zone (HAZ) and base material (BM). To illustrate these four areas more clearly, the point tracking method of DEFOEM-3D software was used to describe the material flow and deformation during the whole process. As shown in figure 2, the areas where the tool caused the point positions to change are the SZ and TMAZ, and the other areas are the HAZ and BM (AS: Advancing side, RS: Retreating side). Figure 3 depicts a typical temperature field and the corresponding strain rate field during FSW when the rotating speed and welding speed were 300 rpm and 150 mm/min, respectively. The HAZ and BM
areas could be distinguished using their temperatures, and the temperature of the BM area was almost the same as the ambient temperature.

During FSW, the SZ and TMAZ were subjected to heat and deformation; as a result, the strain rate and deformation temperature severely affect the grain sizes of these two zones. According to the high-temperature plastic deformation theory, the relationship between the Zener-Hollomon parameters, temperature, and strain rate can be expressed as follows:

$$Z = \dot{\varepsilon}exp\left(\frac{Q}{RT}\right)$$

(3)

where $\dot{\varepsilon}$ is the strain rate, $Q$ is the activation energy, $R$ is the gas constant, and $T$ is the temperature. In addition, Heidarzadeh and Saeid[25] have indicated that the value of the Z parameter is negatively correlated with the grain size, which is shown in equation (4).

$$d = A \times Z^b$$

(4)

where $d$ is the diameter of the grain, and $A$ and $b$ are material constants. Usually $b$ is a negative number; therefore, smaller Z values lead to coarser grains.

![Figure 2. Four areas of material after FSW.](image)

![Figure 3. Typical (a) temperature field and (b) strain rate field of FSW for a pin rotating speed of 300 rpm and welding speed of 150 mm/min.](image)

Figure 4(a) illustrates a typical metallurgical image of the Al-Zn-Mg alloy after FSW. From figures 3 and 4, we concluded that the SZ presented the highest temperature and strain rate of the four above-
mentioned areas. Simultaneously, the grain size of the SZ was the finest of all areas. The TMAZ exhibited a lower strain rate than the SZ and much coarser grains. Ji et al.[26] reached similar conclusions through grain size analysis.

Figure 4(b)~(e) show the metallographic microstructure of the typical four areas from the welded specimen. Figure 4(b) and (c) show that the BM and HAZ has obvious processing microstructure characteristics, and the crystal grains are elongated. Additionally, affected by temperature, the grains of HAZ slightly grow. Meanwhile the TMAZ and SZ have totally different microstructure, showed in figure4(d) and (e). In these two areas, the grains undergo dynamic recrystallization under the influence of deformation and temperature, and the grain morphology changes from elongated to equiaxed. The SZ is directly affected by the stirring needle and experiences the most severe deformation. The new grains formed by recrystallization are broken by the stirring of the pin, so that the region forms a equiaxed grain which is finer than TAMZ.

4.1. Effect of different welding speeds on SZ grain size

Both the temperature and strain rate fields at different welding speeds (50 and 150 mm/min) and the same rotating speed (450 rpm) were predicted using numerical simulations. Uyyuru and Kailas[27] indicated that when the tool advanced a minimum distance equal to its diameter, the process was considered to have reached a steady state. The temperature and strain rate of the YZ plane near the stirring pin in the steady state were analysed. It should be noted that the centre of the bottom surface of the plate was the origin of the coordinate axes.
Figure 4. Typical metallurgical structure of Al-Zn-Mg alloy after FSW for a pin rotating speed of 300 rpm and welding speed of 150 mm/min. (a) weld joint, 50x, (b) BM, 400x, (c) HAZ, 400x, (d) TMAZ, 400x, (e) SZ, 400x

The temperature and strain rate plots of the YZ plane are showed in figure 5. As shown in figure 5(a), the welding speeds of 50 mm/min corresponded to peak temperatures of 526°C while the 150mm/min one is 513 °C. Meanwhile figure 5(b) reveals that the strain rates are almost the same at both welding speeds, thus the traverse speed of the stirring pin has a neglected influence on the strain rate of the FSW. Pashazadeh et al.[28] also reached similar conclusions through finite element simulation. That is, the strain rate was almost constant while the peak temperature during the process decreased as the welding speed increased. The Zener-Hollomon parameter was calculated according to the obtained curves of temperature and strain rate, as shown in figure 6.

Figure 5. (a) Temperature and (b) strain rate plots of SZ of FSW for a rotating speed of 450 rpm and welding speeds of 50 and 150 mm/min.

Figure 6. Zener-Hollomon parameter of SZ of FSW for a rotating speed of 450 rpm and welding speeds of 50 and 150 mm/min.

The Zener-Hollomon parameter increased as the welding speed increased, indicating that as the welding speed increased, the grain size of the material in the SZ became smaller. This phenomenon has been experimentally demonstrated. The EBSD technique was used to observe the grain distribution in joints after welding. The images in figure 7 represent the positions indicated by the white arrow in figure 4. Figure 7 indicated that a higher welding speed result in a smaller grain size distribution of the joint. The average grain diameters were approximately 6.49 and 5.80 µm when the
welding speeds were 50 and 150 mm/min, respectively. Obviously the grain size was much smaller at the welding speed of 150 mm/min.

![Image](image_url)

**Figure 7.** EBSD analysis of SZ of FSW for a rotating speed of 450 rpm and welding speeds of (a) 50 and (b) 150 mm/min.

4.2. Effect of different rotating speeds on SZ grain size

During FSW, the grain size distribution after welding is not only related to the welding speed but also to the tool rotating speed. Keeping the same welding speed (150 mm/min), different rotating speeds (300, 450, and 600 rpm) produce different temperature and strain rate fields. Due to the presence of a pinhole at the location of the stirring pin, the points near the YZ plane of the trailing edge of the stirring pin were taken. These points were located 2 mm from the upper surface of the workpiece and equidistantly distributed on both sides along the centre of the weld. The graphs of the temperature and strain rates are illustrated in figure 8.

It can be seen in figure 8(a), the corresponding peak temperatures at 300, 450, and 600 rpm were 436, 512, and 540 °C, respectively, indicating that the temperature increased as the rotating speed increased. Meanwhile the figure 8(b) reveals that the peak strain rate increases as the rotating speed increases. That is, for same welding speed, increasing the rotating speed of the tool, the temperature and strain rate increased.

It can be seen that when the rotating speed was 300 rpm the average diameter of the grain was 3.88 μm, and the average grain size decreased as the rotating speed increased. When the rotating speed reached 600 rpm, the grain diameter reached 9.24 μm, which was much larger than that obtained at a rotating speed of 300 rpm. Wan et al.[21] used the point tracking simulation method and Heidarzadeh and Saeid[25] used experimental data to demonstrate that the increasing the tool rotating speed, the the grain grow larger.
In summary, the slow welding and high rotating speeds during FSW caused the grains of the SZ to become coarse. From figures 6, 7, 9, and 10, we concluded that the grain size of the SZ was mostly distributed within a 5 μm range when lnZ reached 24, and a relatively uniform fine grain structure was obtained. When lnZ was smaller than 24, the crystal grains tended to be coarse, and the fraction of large-sized crystal grains increased.

![Figure 8](image1.png)

**Figure 8.** (a) Temperature and (b) strain rate plots of SZ of FSW for a welding speed of 150 mm/min and rotating speeds of 300, 450, and 600 rpm.

![Figure 9](image2.png)

**Figure 9.** Zener-Hollomon parameter of SZ of FSW for a welding speed of 150 mm/min and rotating speeds of 300, 450, and 600 rpm.
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Figure 10. EBSD analysis of SZ of FSW for a welding speed of 150 mm/min and rotating speeds of (a) 300, (b) 450, and (c) 600 rpm.

The relationship between Z and grain size in SZ is plotted in figure 11. It indicate that the grain sizes of SZ and Z are inversely proportional. When fitting these data using a power function (equation (4)), the specific relationship between Z and the average grain diameter can be expressed as:

\[ Z = 9.09 \times 10^{13} d^{-4.74} \]  

Figure 11. Relationship between Z and grain size of SZ.

5. Summary
In this study, the temperature and strain rate distributions during FSW were studied by the finite element method. The Zener-Hollomon parameter was calculated using the temperature and strain rate obtained employing numerical simulations to predict the influence of different welding parameters on
the grain size. After welding experiments, the microstructure of the material was studied by OM and EBSD. The experimental data were combined with the simulation results, which further demonstrated the accuracy of the prediction. Considering the discussed results, the following conclusions were drawn:

(1) For a constant rotating speed, the strain rate during FSW was almost constant. The deformation temperature and average grain diameter of the weld nugget zone decreased as the welding speed of the tool increased.

(2) Different rotating speeds presented different effects on grain size during the FSW. The strain rate and temperature increased as the rotating speed increased. Since temperature contributed more than strain rate to grain growth, the grain size increased as the rotating speed increased.

(3) Under the designed processing parameters, the relationship between Zener-Hollomon parameter and SZ grain size can be expressed as $Z = 9.09 \times 10^3 d^{-4.74}$ through simulation calculation and experimental analysis. As can be seen from this equation, the grain size decreases as the Zener-Hollomon parameter increases.

Acknowledgements
This work was supported by the National Key Research and Development Program of China (Project No. 2016YFB0300900). The authors appreciate the kind support offered by Professor Yunlai Deng, the Project leader.

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