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A Relation between Grain Size and Process Parameters in Friction Stir Processing of AZ31B

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Abstract

Introduced in this work is a relation that captures the behavior of grain size with the varying process parameters in friction stir processing of AZ31B. The relation was based on the results of a 3D FE model that was used to run simulations of the process at different tool rotational and traverse speeds. The model was validated by comparing its state variable outputs to experimental results found in the literature. The coefficients of the proposed relation were determined for magnesium alloy AZ31B. This proposed relation will aid in controlling the output grain size in computerized friction stir processes.

Keywords: Friction stir processing, grain size refinement, AZ31B

Introduction

Friction stir processing (FSP) is a microstructure reforming processes that was developed by [1] and is based on the same principles of friction stir welding (FSW). FSP is used to adjust the microstructure of a single plate as opposed to FSW where two plates are welded together. Both processes utilize a rotating tool that comprises a shoulder and a pin. The tool is plunged into the material to be processed and is traversed across areas of interest to be modified. Severe mechanical deformation and frictional heating associated with FSP initiates dynamic recrystallization (DRX) that is the main mechanism behind grain refinement. Magnesium alloy AZ31B is one of the light weight alloys that have potential future in being adopted by the automotive industry. FSP of magnesium AZ31B is desirable due to the improvements it grant to the material’s mechanical properties. These improvements are mainly achieved by grain refinement and homogeneity that results in superplastic behavior of alloys. Fine and more homogenized grain structure of AZ31 was attained by friction stir processing [2]. Ultrafine-grained microstructures with an average grain size of 100-300 nm were achieved in solution-hardened AZ31 alloy prepared by friction stir
processing equipped with a rapid heat sink [3]. The same approach was followed by another author who used two-pass FSP to achieve an average grain size of 85 nm [4]. A recent publication by [5] presented AZ31 magnesium alloy prepared by friction stir processing which exhibited 268% elongation at 723K and $10^{-2}$ s$^{-1}$ indicating that high strain rate superplasticity could be achieved.

None of the presented FSP applications had control on the resulting material microstructure. Changing the process parameters in a controlled manner would affect the state variables (such as temperature and strain rates) thus changing the conditions at which DRX is occurring resulting in a controlled grain size. Successful control of the friction stir process requires establishing a reliable relation between the process parameters and the resulting average grain size. This can be arrived at by either conducting thorough experiments or by utilizing virtual reliable simulations. The latter option was adopted by the authors since simulations are more sustainable and less time consuming than experiments. An experimentally validated 3D FE model was used to construct the proposed mathematical relation that relates the tool rotational and traverse speeds to the resulting grain size in friction stir processing of AZ31B.

**The Zener-Hollomon parameter**

The Zener-Hollomon parameter ($Z$) that is best described as a temperature compensated strain rate has been related to the average grain size ($d$) of DRX of magnesium alloys [6] according to:

$$\ln d = 9 - 0.27\ln Z$$  \hspace{1cm} (1)

where $Z$ is defined by:

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right)$$  \hspace{1cm} (2)

with $Q$ being the activation energy, $R$ the universal gas constant and $T$ the absolute temperature.

Combining Equations 1 and 2 would provide a direct relation between the average grain size and the state variables $T$ and $\dot{\varepsilon}$. These equations will be used to calculate the average grain size of FSP from the state variables predicted by the FE model to establish the relation between $d$ and the process parameters.

**FE model**

A 3D thermo-mechanically coupled FE model was developed using the FEA software DEFORM-3D™. The meshed model shown in Figure 1 consists of a tool, a workpiece, and backing plate. Both the tool and the backing plate were modeled as rigid un-deformable bodies where only heat transfer was accounted for while the workpiece was modeled as a plastic body subject to both deformation and heat transfer.
The considered tool had an 18 mm cylindrical shoulder with a 6 mm diameter smooth unthreaded pin that extrudes 6 mm from the bottom of the shoulder. The tool was tilted 3° about the vertical axis to further improve material flow. Both the workpiece and the backing plate had an area of 80x54 mm² and a height of 10 mm. Materials used in the FE model were H13 steel for the tool, AISI-1025 steel for the backing plate and AZ31B for the workpiece. The Sellars and Tegart law, which considers the material to be rigid visco-plastic, was used for the workpiece where the flow stress ($\sigma$) is related to temperature ($T$) and strain rate ($\dot{\varepsilon}$) according to

$$
\sigma = A \alpha^{-1} \text{sinh}^{-1} \left( A^{-1} \dot{\varepsilon} \exp \left( Q R^{-3} T^{-1} \right) \right)^{3n}
$$

where $A$, $\alpha$, and $n$ are material constants, $Q$ being the activation energy, and $R$ the universal gas constant. Table 1 lists the values of the constants used by Equation 1.

<table>
<thead>
<tr>
<th>Constant</th>
<th>$A$</th>
<th>$\alpha$</th>
<th>$Q$</th>
<th>$n$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>27.5e6 s⁻¹</td>
<td>0.052 MPa⁻¹</td>
<td>130 kJ/mol</td>
<td>1.8</td>
<td>8.314 J/(kg K)</td>
</tr>
</tbody>
</table>

Tetrahedral elements were used in the FE model with active local re-meshing triggered by a relative interference ratio of 70% between contacting edges. The tool and the backing plate were meshed for thermal analysis purposes with each containing around 6000 and 5000 elements respectively while the workpiece had around 16000 elements. To further capture the state variables at the tool-workpiece interface, a rectangular mesh control window was applied around the processing area of interest where finer mesh elements were created. Heat transfer with the environment was accounted for all the three meshed objects with a convective heat coefficient of 20 W/(m² °C) [7] at a constant temperature of 293K. The heat transfer coefficient between the tool-workpiece and backing plate-workpiece interfaces was set to 11 kW/(m² °C) [7]. The friction coefficient used at the tool-workpiece interface was set
as function of temperature with an initial value of 0.28 at room temperature that increases to 0.32 at 908K and drops to 0.02 as temperature exceeds 910K[8].

The model was validated with experimental data available in the literature by tracking the temperature history of an observation point on the traverse line at a distance of 8.5 mm below the surface for two different test cases. The tool traverse speed was fixed at 90 mm/min whereas the tool rotational speed was 800 RPM for test cases 1 and 1400 RPM for test case 2. Figures 2a and 2b shows a comparison between the simulated temperature histories and the experimental results obtained from the literature [6]. The two figures reflect the good accuracy of the presented FE model with the simulated data almost matching the experimental one.

![Figure 2: Experimental VS simulated temperature profiles for (a) test case 1;90 mm/min - 800 RPM and (b) test case 2; 90 mm/min - 1400 RPM](image)

### Results

The validated FE model was used to run FSP simulations for the 16 possible combinations of the tool rotational speed and feed shown in Table 2. The predicted state variables (namely $T$ and $\dot{\varepsilon}$) for each of the 16 simulations were used to calculate the resulting average grain size according to Equations 1 and 2. The calculations were made for points located along the processing line underneath the surface of the workpiece and the results are shown in Figure 3.

<table>
<thead>
<tr>
<th>Table 2: Process parameters used in the FSP simulations</th>
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<tbody>
<tr>
<td>Rotational speed (RPM)</td>
</tr>
<tr>
<td>Feed (mm/min)</td>
</tr>
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</table>

Increasing the feed from 60 to 150 mm/min at constant rotational speed had no clear effect on the resulting grain size. The average grain size seemed to fluctuate by around ± 5% when the feed was changed with a tendency to increase with increasing feed. The effect of changing the tool rotational speed was more noticeable where the grain size increased by an average of 16% as the rotational speed was incremented according to the values of Table 2.
A power relation was proposed to capture the behavior of the average grain size with the varying process parameters according to
\[ d = d_0 N^\alpha f^\beta \] (4)

where \( d_0, \alpha, \) and \( \beta \) are the coefficients determined by fitting the predicted grain size \( (d) \) to the tool rotational speed \( (N) \) and feed \( (f) \).

Using nonlinear regression the values of \( d_0, \alpha, \) and \( \beta \) were found to be 0.115, 0.044, and 0.649 respectively. For the calculated coefficients, an R-squared value of 0.921 was obtained which indicates good fit as shown in Figure 3.

**Figure 3:** FEM grain size predictions and Fit values obtained from Equation 4 for the 16 test cases of Table 2

**Summary**

In this work friction stir processing of AZ31B, presented is a mathematical relation between input process parameters (namely tool rotational and traverse speeds) and output grain size. The relation was constructed from the results of an experimentally validated 3D FE model. The obtained relation had an R-squared value of 0.921 which is a testament to the good statistical agreement between the results of the FE model and the predictions of the proposed equation (valid for rotational speed of 600-1200 RPM and traverse speeds of 60-150 mm/min).

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