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A Numerical Model for Predicting the Zener-Hollomon Parameter in the Friction Stir Processing of AZ31B

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Abstract

Grain size determines to a large degree the mechanical properties of the friction stir processed (FSP) material. Developed in this work is a numerical (FEM) based-model for predicting values of the Zener-Hollomon parameter (*Z-parameter*) as function of input process parameters during friction stir processing of AZ31B. Prediction of *Z* values is desirable given that direct relations exist between the *Z-parameter* and the average grain size in the dynamically recrystallized zone (DRX). For this purpose, utilized in this work is a robust finite element model with a suitable constitutive equation and boundary conditions the results of which have been previously validated against published experimental data. A virtual test matrix constituting of 16 cases (4 spindle speed, N , x 4 feed, f) was run. Based on resulting state variables of strain rates and temperatures at a representative point within the stir zone, a statistically-validated power equation model was developed that relates *Z-parameter* values to input parameters of speed and feed. The results of the numerically developed power equation were validated against experimental results. This model can be readily used in future control frameworks to FSP produce AZ31B sheets of a predefined target grain size.

Introduction

Friction stir processing (FSP) [1] is a processing technique used primarily for microstructure refinement and it uses the same principle as friction stir welding. Both processes involve a rotating tool comprising a shoulder and a pin which is plunged into the material to be welded or processed. The tool then advances through the material as illustrated in Fig. 1. The material exhibits extensive plastic deformation and heat is generated mainly due to the shear friction between the tool and workpiece. The action results in material softening and in material flow along the tool rotation direction. Fig. 1 illustrates the three different zones of the processed area. The stir zone (SZ) is the area with the most severe mechanical deformation and frictional heating which induces dynamic recrystallization (DRX). Surrounding this zone is the thermo-mechanically affected zone (TMAZ) which is subject to both mechanical deformation and thermal effects that deform the original microstructure. The heat affected zone (HAZ) is subject to thermal effects from the nearby zones.

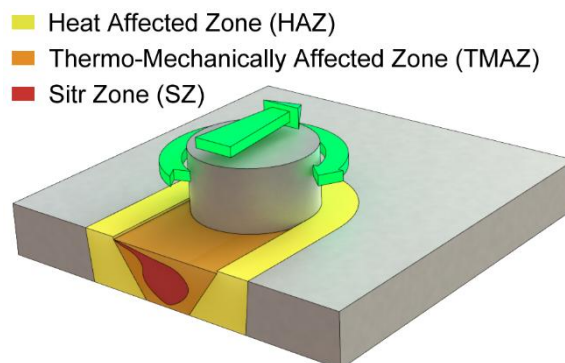


Figure 1: FSP Illustration showing affected zones

Friction stir processing has been widely applied to lightweight alloys such as magnesium. Mg is being increasingly used in many industries including aerospace and automotive with processing applications including surface composite fabrication [2], grain size refinement and homogeneity [3], and superplasticity enhancement [4].

Many processing challenges of magnesium alloys originate from their low melting point and of the susceptibility of the metal's microstructure to high temperature. In order to control such output parameters as temperature, process input parameters such as tool feed, rotational speed, geometry, and tilt angle should be carefully defined. In combination with temperature, strain rates directly affect the material microstructure and, hence, the mechanical properties of processed material [5].

Therefore, controlling the FSP process parameters is essential for achieving a predefined homogenous material microstructure. Finding a relation between the input process parameters, such as tool speed and feed, and the output state variables, such as material microstructure (i.e. grain size) is a challenging task that can be approached either experimentally or through numerical simulations. The traditional experimental approaches being time and money consuming, urged the need for numerically simulating the friction processing techniques. Early modeling of the process utilized thermal models which were later upgraded to coupled thermo-mechanical models using several commercial finite element (FE) software such as DEFORM [6, 7] and ABAQUS [8]. These models are used to predict the state variables of the friction stir processes and when coupled with artificial intelligent techniques, such as artificial neural networks (ANN), can be powerful tools to predict the output material microstructure similar to what has been done by [9].

One important state variable is the Zener-Hollomon parameter (Z), a temperature-compensated strain rate relation. This parameter is directly related to the grain size during dynamic recrystallization [10] and can be readily extracted from FE simulations. In this paper a numerical relation between the input process parameters (tool rotational speed and feed) and the Zener-Hollomon parameter is established using a 3D thermo-mechanical FE model. The utilized model was previously validated among experimental data [11]. One important aspect of such a numerical model is that it is based on the Z -parameter that couples the process temperature and strain rate and, as such, it is controllable.

Running the FE model for fully populated 4x4 test matrix (of tool speed and feed), the temperature and strain rates were determined at representative points along the tool path. These values were fit to a simple power law equation relating the Z -parameter values to these input parameters. Such condensed finding model can be readily used in control frameworks architectures to fabricate AZ31B sheets with predefined mechanical properties.

Methodology

The FE model was developed using the FE software DEFORM 3D (from SFTC [12]). The model geometry (shown in Fig. 2) consists of tool, workpiece, and backing plate.

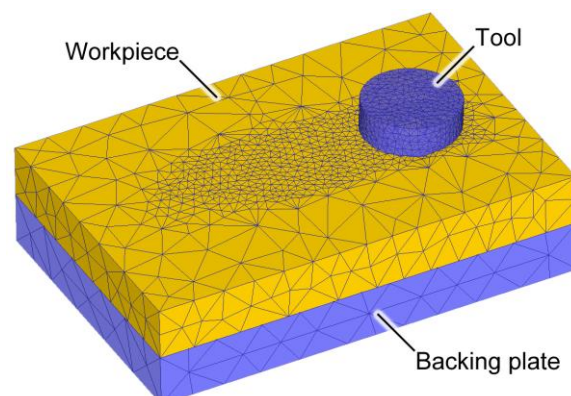


Figure 2: The meshed FEM model showing tool, workpiece, and backing plate.

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 in the processing direction 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 FEM model were H13 steel for the tool, AISI-1025 steel for the backing plate and AZ31B for the workpiece. A rigid visco-plastic material model was used for the workpiece where flow stress (σ), temperature (T), and strain rate ($\dot{\epsilon}$) are related by

$$\sigma = \alpha^{-1} \sinh^{-1} \left(A^{-1} \dot{\epsilon} \exp(QR^{-1}T^{-1}) \right)^{1/n} \quad (1)$$

where A , α , and n are material constants, Q the activation energy, and R the universal gas constant. Table 1 lists the values for the constants of Eq. 1 that are used in the FE model.

The two main factors that directly affect the simulation time and the result's conversion for any FEM simulation are the mesh size and time step. Tetrahedral elements were used in the FEM model with active local re-meshing triggered by a relative interference ratio of 70% between contacting edges. This would ensure the integrity of the workpiece geometry during deformation.

Table 1: AZ31B Material model constants [13].

Property	Value
Material constant A	27.5 [s ⁻¹]
Material constant α	0.052 [MPa ⁻¹]
Activation energy Q	130 [kJ mol ⁻¹]
Material constant n	1.8
Universal gas constant R	8.314 [J kg ⁻¹ K ⁻¹]

Friction at the tool-workpiece interface is a significant factor in any FSP/FSW simulation. It is determined that 86% of the heat generated is due to frictional forces [14]. Determination of the friction factor is a daunting challenge due to the variation of temperature, strain rate, and stress. Different publications found in literature investigated the value of friction coefficient in magnesium alloys [15-17]. Most authors use the ring upsetting and compressions tests for determining the coefficient of friction. It is agreed that the friction factor increases with temperature [18]. However, this increase of friction factor with temperature is valid until the liquidus temperature of AZ31B (630°C) is reached where the friction drops drastically. The values of experimental data [15] were entered to the model and then extrapolated by tuning different runs and analyzing state variables. The friction coefficient vs. temperature used in the FE model is shown in Fig. 3. This is based on experimental data [15] as well as on sensitivity analysis for model calibration as previously published by the authors [19].

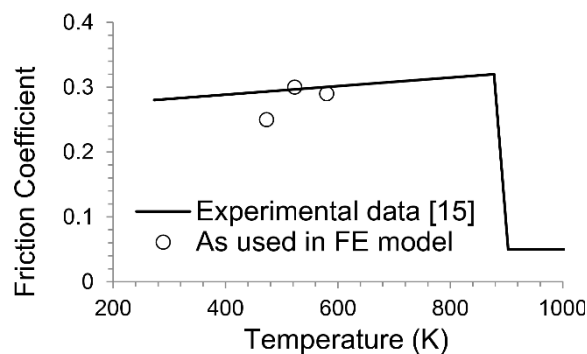


Figure 3: Friction coefficient VS temp. as used in FE model; shown compared with experimental data [15].

The Zener-Hollomon parameter is related to temperature and strain rate by Eq. 2 with Q being the activation energy and R the universal gas constant (values as in Table 1)

$$Z = \dot{\epsilon} \exp(QR^{-1}T^{-1}). \quad (2)$$

Z is related to the average grain size d using Eq. 3 where Z is the Zener-Hollomon parameter and the constant values in the equation for AZ31 were obtained from the literature [10]. The material was assumed to have an initial average grain size of 8 μm which was then updated as per Eq. 3 during the simulation.

$$\ln d = 9 - 0.27 \ln(Z). \quad (3)$$

The fully populated test matrix for the tool rotational speed and feed shown in Table 2 was used in the FE simulations. The ranges of the tool RPM and feed were selected based on optimized processing ranges for AZ31B as previously determined by the authors [19].

Table 2: Process parameters test matrix.

Process parameters		Tool feed [mm/min]			
		60	90	120	150
Speed [RPM]	600	A1	A2	A3	A4
	900	A5	A6	A7	A8
	1000	A9	A10	A11	A12
	1200	A13	A14	A15	A16

The 16 simulations of the test matrix shown in Table 2 were run and the state variables of each run were further processed to calculate the Zener-Hollomon parameter as described by Eq. 2.

The state variable history of a 4 mm line lying just beneath the surface of the workpiece was recorded as the tool traversed it. The average Z -values of this line were determined and reported across the process parameters of the run being considered. Since the values of Z are in the 10^{10} ranges, the log of Z was considered. This is corroborated by Eq. 3 where $\ln(Z)$ is used in calculating the grain size.

Results

The reported Z -values showed an increasing trend with increasing feeds and decreased with increasing tool rotational speeds. This was expected since increasing the tool RPM would produce higher strain rates and temperatures that would, consequently, result in lower Z values according to Eq. 2.

Developed below is a mathematical expression that relates the simulation predictions of the Z -parameter values of the FE model to input process variables: spindle speed, N , and feed, f . The developed expression comprises a power equation with the base f raised to an exponent that is function of N . This will give an increasing trend of $\ln(Z)$ with increasing feed. The exponent itself is another power relation with a negative exponent, n , that will decrease the parent exponent of f with increasing N thus decreasing $\ln(Z)$ with increasing speed. The resulting expression is

$$\ln(Z) = A_0 + A_1 f^{(\alpha_0 + \alpha_1 N^n)}. \quad (4)$$

where A_0 , A_1 , α_0 , α_1 , and n are constants determined by fitting the calculated Z -parameter with feed and speed; values of these constants were 22.32, 1.02, -1.25, 5.25, and -0.19 respectively. The R^2 value of the fitted data was 0.918 that indicates a good statistical fit and results in the model

$$\ln(Z) = 22.32 + 1.02f^{(-1.25 + 5.25N^{-0.19})} \quad (5)$$

Eq. 5 constitutes the proposed model used in predicting the Zener-Hollomon parameter within the ranges of process parameters described in Table 2.

Fig. 4 shows the calculated $\ln(Z)$ values using Eq. 5 superimposed over those of the FE simulations. It can be clearly seen that the model performs well in fitting the FE-predicted Z -parameter values and, consequently, may predict grain size as function of the input process parameters speed and feed.

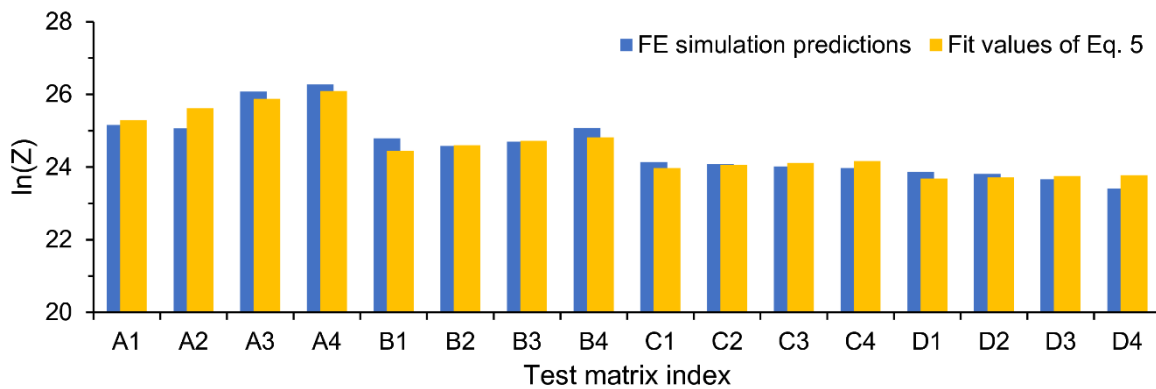


Figure 4: FE model simulation predictions of $\ln(Z)$ superimposed over fit values from Eq. 4.

Summary

Presented in this work is a numerical model for predicting the Zener-Hollomon parameter in the friction stir processing of AZ31B. The proposed numerical model showed good agreement with the simulated values reported from the experimentally validated FE model. This numerical model can be readily used in future control frameworks architectures to fabricate AZ31B sheets with predefined mechanical properties.

Acknowledgements

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