Modelling of peak temperature during friction stir processing of magnesium alloy AZ91

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Abstract. Friction stir processing (FSP) is a solid state processing technique with potential to modify the properties of the material through microstructural modification. The study of heat transfer in FSP aids in the identification of defects like flash, inadequate heat input, poor material flow and mixing etc. In this paper, transient temperature distribution during FSP of magnesium alloy AZ91 was simulated using finite element modelling. The numerical model results were validated using the experimental results from the published literature. The model was used to predict the peak temperature obtained during FSP for various process parameter combinations. The simulated peak temperature results were used to develop a statistical model. The effect of process parameters namely tool rotation speed, tool traverse speed and shoulder diameter of the tool on the peak temperature was investigated using the developed statistical model. It was found that peak temperature was directly proportional to tool rotation speed and shoulder diameter and inversely proportional to tool traverse speed.

1. Introduction
The environmental conservation policies drive industrial focus on the need for weight reduction of automobiles, thereby increasing the fuel efficiency and reducing the impact of greenhouse gases. Magnesium alloy usage in automobiles make them lighter and environment friendly [1]. Magnesium alloy AZ91D possesses good castability and is used for manufacturing valve covers, clutch housing, steering column, cam covers, brackets, computer parts etc. [2, 3]. However the applications of magnesium alloys are limited by their poor formability and corrosion resistance. The hexagonal close packed structure of the alloys demands high temperature for forming process and hence requires high energy to activate more slip systems. Magnesium alloys are highly susceptible to intergranular corrosion, galvanic corrosion and stress corrosion cracking in corrosive environments [4].

Friction stir processing (FSP) is one of the solid state techniques to concoct the properties of the material through microstructural modifications. In FSP, a rotating tool is traversed along the length of the workpiece under an axial load. During FSP of materials, generation of heat and evolution of microstructure are similar to that of friction stir welding process [5]. FSP is one of the efficient methods for grain refinement, dispersion and partial dissolution of the secondary phases in the matrix, which results in enhanced mechanical and corrosion properties. During FSP, the material is plasticized by the
frictional heat generated at the interface of FSP tool and the material [6, 7]. As reported in literature, the material properties are influenced by the microstructural evolution (phase transformation) in the course of FSP. The nucleation for phase transformation are initiated by the effective strain rate, which is dependent on the activation energy and the temperature [8]. Hence it is authenticated that the FSPed material properties are greatly influenced by the thermal cycles and the material flow in the course of FSP.

The FSP process parameters that influence the rise of material’s temperature are tool rotation speed, tool traverse speed, tool geometry, axial load and backing plate temperature [9]. Chen et al., [10] developed a finite element model to analyse the thermal history of FSW process. Schmidt et al., [11] developed an analytical model for heat generation phenomenon based on the contact condition of FSW tool with the workpiece. They suggested the sticking condition between the FSW tool and the workpiece, which was evident from lack of proportionality between the axial load and the amount of heat generated. Darras et al., [12] proposed model to predict the grain size of FSPed magnesium alloy AZ31. The developed model included the effects of dynamic recrystallization and grain growth, in line with that of Schmidt’s analytical model [11]. Lipscomb et al., [13] developed a FEM model to predict the extent of plastic zone formation in FSPed magnesium alloy.

Aljoaeba et al., [14] developed a computational fluid dynamics model to analyze the material flow during FSP of magnesium alloy. Aljoaeba et al., [15] modelled the effect of coolant on the grain refinement of magnesium alloy during FSP. Yu et al., [16] combined the Lagrangian and Eulerian formulation to develop a numerical model and analyzed the transient heat and material flow characteristics during friction stir processing of magnesium alloy AZ31B with threaded FSP tool. Albakri et al., [17] found that the tool traverse speed had dominant effect on the temperature and strain field using the numerical model developed to predict the thermo-mechanical aspect during FSP of magnesium alloy AZ31B. Asadi et al., [18] developed a thermo–mechanical model using Lagrangian implicit technique to predict the effective strain rate and temperature profile during FSP of magnesium alloy AZ91.

A number of works attempted to generate numerical models for predicting the temperature profile, effective strain rate, material flow and grain refinement during FSP of magnesium alloy AZ91. The peak temperature obtained by the material during FSP greatly influences the dynamic recovery and dynamic recrystallization of the FSPed magnesium alloy AZ91. Hence a study on obtaining the peak temperature becomes mandatory. In this study, a numerical model was developed to predict the peak temperature (\(T_p\)) obtained during FSP of magnesium alloy AZ91. The validated numerical model was used to predict the \(T_p\) by varying the TRS, TTS and SD at five levels as per central composite design. The influence of FSP process parameters TRS, TTS and SD on \(T_p\) was analysed using the developed statistical model.

2. Methodology

2.1. Numerical model

In the present work, Comsol Multiphysics software was selected to simulate the FSP of magnesium alloy AZ91. In the developed model, it was assumed that tool pin is rigid and cylindrical, with no heat flow into the workpiece other than the frictional heat. During FSP, the FSP tool moves at a constant velocity along the processing length of the workpiece. The developed model had a moving co-ordinate system fixed at the tool axis, which did not necessitate to model the complex friction stir process near the pin.

The co-ordinate transformation of the model assumes that the workpiece is infinitely long. Therefore the effects near the edges of the workpiece were neglected. The model geometry had two infinite domains along the x axis. As the temperature of the upper side of the workpiece (which undergoes FSP) changes with time and FSP process parameter, non-uniform boundary conditions were defined for the upper side of the workpiece.
2.1.1. Heat generation

In the present model, heat generation at the interface of tool shoulder – workpiece and tool pin – workpiece were considered. The heat generated at the interface of tool shoulder and the workpiece was assumed as frictional work and is given by the equation (1).

\[
q_{\text{shoulder}}(r, T) = \begin{cases} 
\mu \left( \frac{F_n}{A_s} \right) \omega r, & \text{if } T < T_{melt} \\
0, & \text{if } T > T_{melt}
\end{cases}
\]  

(1)

The coefficient of friction between the tool and the workpiece is supposed to vary during FSP. But an effective constant coefficient of friction was used in the model. The shear stress of the material is bound to vary with variation in temperature \[19\]. An interpolation function \(Y(T)\) depicting the variation of shear stress with temperature was developed from the data available in literature. The heat generated by the tool pin consists of the heat generated by the shearing of the material and the heat generated by friction on the surface of the pin. The tool pin was assumed to be cylindrical and non-threaded profile. The expression for heat generation by the tool pin is given by the equation (2).

\[
q_{\text{pin}}(T) = \begin{cases} 
\mu \sqrt{3(1 + \mu)}^2 \frac{r_p}{r} \omega Y(T), & \text{if } T < T_{melt} \\
0, & \text{if } T > T_{melt}
\end{cases}
\]  

(2)

Beyond the melting point of magnesium alloy AZ91, the friction becomes very low between the tool and the workpiece \[20\]. When the temperature of the workpiece exceeds the melting point of the magnesium alloy, the heat generation at the interface between the tool and the workpiece was set as zero in the model.

2.1.2. Heat transmission

The free surfaces of the work piece were surrounded by the atmosphere at ambient temperature, which results in convective heat transfer occurring between the surface of the workpiece and the ambient. The heat transfer in the workpiece is governed by the equation (3) \[9\]. The fixing of the co-ordinate system in the FSP tool drives a need to add a convection term in addition to the conduction term in the heat transfer equation.

\[
\rho C_p \nu \cdot \nabla T + \nu \cdot (-k \nabla T) = Q
\]  

(3)

The backing plate was not included in the model. However the effect of backing plate was realised with an enhanced heat transfer coefficient in the bottom of the workpiece (which is in contact with the backing plate). Convective heat transfer coefficients \(h_u\) and \(h_d\) were considered for upper side and down side of the workpiece. The corresponding heat fluxes at the upper side and down side of the workpiece is given by the following equation (4) and equation (5).

\[
q_u = h_u(T_0 - T) + \epsilon \sigma (T_{\text{amb}}^4 - T^4)
\]  

(4)

\[
q_d = h_d(T_0 - T) + \epsilon \sigma (T_{\text{amb}}^4 - T^4)
\]  

(5)

2.1.3. Meshing scheme

Free quadrilateral fine mesh was generated for the infinite domains and the upper side of the workpiece. The tool shoulder and the tool pin was meshed with extremely fine triangular mesh. The meshing scheme of the FSP tool and the workpiece is shown in the figure 1. Direct stationary solver was used for solving the model.
2.2. Statistical model
The numerical model was used to predict the $T_p$ by varying the FSP process parameters TRS, TTS and SD at five levels as per central composite design. The design matrix is shown in the table 1. Using the FSP process parameters (TRS, TTS, SD) and response variable ($T_p$), a statistical model was developed by relating the process parameters with the response variable. The statistical model was developed by integrating polynomial function and radial basis function. The information regarding the development of polynomial – radial basis function could be found elsewhere [21]. A polynomial function of degree one is known as linear function and a typical linear – radial basis function is given by the equation (6).

$$y = \sum_{i=1}^{n} a_i \times x_i + \text{RBF}$$

Where $a_i$ is the coefficient of the process parameter $x_i$, $y$ is the response variable and RBF is radial basis function.

3. Results and Discussion

3.1. Numerical model
During FSP, the plasticizing, stirring and forging action of the rotating tool modifies the microstructure of the material. The amount of heat generation majorly influences the evolution of microstructure through the above actions. Thus the fundamental requirement of FSP is to generate frictional heat to plasticize the material with a suitable temperature. The developed numerical model was used to predict $T_p$ of the specimen processed at TRS of 900 rpm, TTS of 40 mm/min and SD of 15 mm [18].

Figure 1. Meshing scheme of the workpiece and the FSP tool
Figure 2. Surface temperature of the workpiece being friction stir processed at TRS of 900 rpm, TTS of 40 mm/min and SD of 15 mm

Table 1. Peak Temperature during FSP of AZ91 predicted using numerical model

| Sl. | FSP Process Parameters | Peak Temperature (K) |  
|-----|------------------------|----------------------|  
|     | Real value             | Coded value          | Numerical model | Statistical model |
|     | TRS (rpm) | TTS (ms⁻¹) | SD (mm) | TRS (rpm) | TTS (ms⁻¹) | SD (mm) |                     |                     |
| 1   | 700       | 0.50       | 15     | -1       | -1       | -1       | 574.65 | 575.39 |
| 2   | 1300      | 0.50       | 15     | 1        | -1       | -1       | 795.85 | 795.83 |
| 3   | 700       | 1.00       | 15     | -1       | 1        | -1       | 569.06 | 568.61 |
| 4   | 1300      | 1.00       | 15     | 1        | 1        | -1       | 789.58 | 789.84 |
| 5   | 700       | 0.50       | 21     | -1       | -1       | 1        | 667.80 | 667.42 |
| 6   | 1300      | 0.50       | 21     | 1        | -1       | 1        | 916.84 | 917.03 |
| 7   | 700       | 1.00       | 21     | -1       | 1        | 1        | 660.42 | 661.43 |
| 8   | 1300      | 1.00       | 21     | 1        | 1        | 1        | 913.31 | 913.04 |
| 9   | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 10  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 11  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 12  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 13  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 14  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 15  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 16  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 17  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 18  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 19  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
| 20  | 1000      | 0.75       | 18     | 0        | 0        | 0        | 779.37 | 779.70 |
The surface temperature of the workpiece during FSP at the specified FSP process parameters is shown in the figure 2. The peak temperature was obtained using a probe in the numerical model and was found to be 651.19 K. The predicted \( T_p \) value was comparable to the experimentally determined \( T_p \) value, which was found in the literature. Hence the developed numerical model was validated positively. The validated numerical model was used to predict the \( T_p \) during FSP of AZ91 at various levels of process parameter combination as given in the table 1.

### 3.2. Statistical model

![](image.png)

**Figure 3.** Peak temperature – Numerical model vs. Statistical model

The generated statistical model which was a hybrid of linear function and radial basis function (RBF) is given by the equation (6). The RBF was formed with a multiquadratic kernel with seven centres, global width of 1.3119 and regularization parameter of 0.00022575.

\[
T = 996.9889 - 23.1688 \times SD + 52.5972 \times TRS + 2.321522 \times TTS + RBF
\]  

A linear trend was observed between the \( T_p \) value predictions of numerical model and statistical model as shown in the figure 3. The statistical parameters that determine the efficiency of the model are coefficient of determination and root mean squared error value. The equality of \( R^2 \) to one indicated that \( T_p \) predictions of the developed statistical model were exactly similar to that of the numerical model. The RMSE value of the statistical model was found to be 0.757, which also indicates that the statistical model is high efficient in predicting the \( T_p \) value similar to that of the numerical model.

### 3.3. Effect of process parameters

The effect of TRS and TTS on \( T_p \) is shown in the figure 4 (a). It is observed that the specimens processed with low TRS and high TTS resulted in ineffective heat generation. \( T_p \) increased with increase in TRS up to 1200 rpm and remained fairly constant at all levels of TTS. A crest parabolic trend is observed in \( T_p \) for the specimens processed at high TRS and TTS ranging between 30 mm.min\(^{-1}\) to 60 mm.min\(^{-1}\). At high TRS, \( T_p \) increased up to TTS of 45 mm.min\(^{-1}\) and reduced thereof. Specimens processed at high TRS and TTS between 40 mm.min\(^{-1}\) to 45 mm.min\(^{-1}\) produced high \( T_p \).
Figure 4. Effect of (a) TRS and TTS; (b) TRS and SD; (c) TTS and SD on the peak temperature obtained during FSP of AZ91

The effect of TRS and SD on $T_p$ is shown in the figure 4 (b). It is observed that the specimens processed with low TRS and low SD resulted in poor heat generation. $T_p$ increased with simultaneous increase in TRS and SD. High $T_p$ is produced in the specimens processed at high TRS of 1300 rpm and high SD of 21 mm. This demonstrates that TRS and SD majorly contributes to the heat generation.
The effect of TTS and SD on T_p is shown in the figure 4 (c). It is observed that the specimens processed with SD less than 18 mm resulted in meagre heat generation. Specimens processed with SD of 20 mm to 21 mm and TTS between 35 mm.min^{-1} to 45 mm.min^{-1} resulted in high T_p. However the T_p produced at this parameter combination was lesser than the TRS – SD parameter combination.

4. Conclusion

A numerical model was developed to predict the peak temperature obtained during FSP of magnesium alloy AZ91. The model was validated from the experimental results obtained from literature. The FSP process parameters namely TRS, TTS and SD were varied at five levels as per central composite design. The validated numerical model was used to predict the T_p with the process parameters as per the design matrix. The variation of the T_p with the process parameters was modelled using a linear – radial basis function. The model efficiency was determined by the statistical parameters R^2 and RMSE and the model was used to study the effect of FSP process parameter on T_p. The results indicates that TRS, TTS and SD majorly contribute to the heat generation. The most influential process parameter affecting the heat generation during FSP of magnesium alloy AZ91 is TRS, while the TTS had comparatively lesser influence.

5. References

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