



MODELING THERMAL–MECHANICAL INTERACTIONS IN FRICTION STIR WELDING FOR IMPROVED JOINT INTEGRITY

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Abstract

The solid-state welding procedure known as Friction Stir Welding (FSW) relies heavily on the interaction between plastic deformation and heat generation along the revolving tool to produce joints of high quality. The temperature distribution, material flow rates, strain rate, and residual stress during the welding of AA6061 aluminum alloy plates were investigated using a three-dimensional coupled thermo-mechanical finite element model. Incorporating frictional heating, plastic deformation-induced heat, and temperature-sensitive material properties into the model, the tool-workpiece contact was considered. To determine how different rotational and traverse rates affected weld production and structural integrity, computer simulations were conducted. Results showed that tunnel flaws and inadequate plasticization occurred when the heat source was insufficient, but grain coarsening and significant residual stresses occurred when the heat source was too high. A constant nugget zone, material homogenization, and little residual stress were the outcomes of the optimal parameter combination, which included a rotational speed of around 900 rpm and a material traverse rate of 80 mm/min. With its accurate weld behavior prediction capabilities, the developed model has the potential to be a reliable tool for optimizing process parameters, which in turn reduces the number of experimental trials and improves the performance of joints at the industrial level.

Keywords: *Friction Stir Welding, Thermo-Mechanical Modeling, Residual Stress, Finite Element Analysis, Joint Integrity.*



1. INTRODUCTION

One of the best solid-state welding techniques is FSW, which involves inserting a non-consumable rotating tool into adjacent workpieces and guiding it along the joint line to produce coalescence through frictional heating and severe plastic deformation. The material is not heated to its melting point, but it is highly plasticized and flows around the tool, unlike typical fusion welding. The most typical fusion-welding flaws, including as porosity, hot cracking, segregation, and solidification shrinkage, will be eradicated because the process will be carried out below melting point.

Factoring in the importance of structural reliability and a high strength-to-weight ratio, FSW has become a preferred joining technique for precipitation-hardened aluminum alloys in many industries such as aerospace, marine, rail, and automotive.

Friction stir weld quality is controlled by complex mechanical and thermal interactions. Welding generates heat primarily through the contact area between the tool shoulder and the workpiece surface, and it also causes plastic deformation of the material around the revolving pin. The reduced flow stress allows the material to plastically flow from the moving to the moving side, forming a solidified nugget zone, as a result of the heat created. Void, tunnel, and bonding faults occur when the material fails to plasticize adequately due to insufficient heat generation. Joint strength and fatigue life are both diminished as a result of grain coarsening, soluble strengthening precipitates, and significant residual stresses caused by overheating. By maintaining an optimal ratio of thermal expansion to mechanical deformation, the strength of the welded junction may be assured.

Due to the extreme circumstances in plastic flow and tool workpiece contact, it is difficult to directly quantify the internal temperature field, strain rate distribution, and residual stress during FSW. Thermocouples and infrared imaging can report surface temperatures, but they can't tell you anything about the tool pin's internal thermo-mechanical behavior. Consequently, numerical modeling has established itself as a trustworthy method for analyzing the process and forecasting the weld quality. To optimize welding parameters without a lot of trial and error, a linked thermo-

mechanical finite element model can be used to evaluate heat generation, material flow, strain rate, and residual stress all at once.

In order to understand how FSW of aluminum alloy plates causes plastic deformation and heat production, the present study employs a three-dimensional coupled thermal-mechanical finite element model. The model considers the tool-workpiece interactions, material properties at different temperatures, frictional and deformational heat, and thermal expansion. Finding the right process parameters to improve joint integrity and decrease weld faults requires investigating temperature distribution, plastic flow behavior, and the formation of residual stress.

1.1.Objectives of the Study

The study's goals are as follows:

- To forecast temperature, material flow, and residual stress during friction stir welding, a thermo-mechanical model must be developed.
- To investigate how welding parameters affect the quality of the weld and the development of defects.
- To identify the best circumstances for enhancing joint integrity.

2. LITERATURE REVIEW

Zhang et al. (2019) designed a thermo-mechanical simulation model, which is based on a friction stir spot welding model which depends on microstructure of AA6061-T6 aluminum alloy. Their experiment proved that temperature history plays an important role in determining refinement of grains and distribution of hardness in the stir zone. It was demonstrated that dynamic recrystallization takes place when there is adequate plastic strain and a high temperature, taken together. They also noted that poor heat input will result in insufficient mixing of the material and poor bond strength and the need to couple mechanical deformation and thermal softening. This study established that the predictability of microstructural changes can be done only when strain rate, temperature, and material flow are analyzed together, and not as a single factor, which is temperature.

Dialami et al. (2017) talked about the significant computational problems that were encountered when using thermo-mechanical modeling of FSW. They underscored that this is a process that deals with all nonlinear material behavior, large plastic deformation, complicated contact conditions and material properties that are temperature-dependent. They found that an accurate prediction of the quality of the weld requires the modeling of frictional heat generation at the tool shoulder, and plastic dissipation close to the pin. The authors also observed that the residual stresses and distortion are caused by dissimilar heating/cooling processes between the weld area. Their work provided the rationale behind fully coupled temperature displacement finite element analysis as opposed to simplified thermal models.

Chen et al. (2023) suggested an algorithm to foresee bonding defects in the course of FSW through in-process thermal-mechanical analysis. The experiment showed that bonding defect is experienced when the stress on the material flow is high because there is a lack of temperature rise. According to them, the rate of strain and temperature should be within a critical range in order to facilitate metallurgical bonding. They were able to make successful predictions of the incidence of tunnel defects and lack-of-penetration defects through the correlation of plastic strain and temperature fields. The study identified weld integrity as a factor that is regulated by the concurrent action of strain rate and temperature but not heat input.

Yang et al. (2025) studied the formation of residual stress with a thermo-mechanical coupled simulation. Their results indicated that steep thermal gradients and inhibited plastic deformation that occurs during cooling are the main sources of residual stresses. The tensile forces were concentrated in the center of the weld and compressive forces were observed at the sides of the weld. They reached the conclusion that a high rotational speed causes more heat input and enhance thermal gradient, which results in more residual stress and worse fatigue performance. The experiment validated that the selection of the parameters required is to achieve balance between the heat generation and deformation.

3. MATHEMATICAL MODELING

Due to the simultaneous generation of heat and plastic deformation, the FSW process was described as a coupled thermo-mechanical issue that is dependent on the weld quality. Mechanical stirring causes severe plastic flow in the weld area, and the rotating tool softens the material by creating heat at the tool-work piece contact.

3.1. Heat Generation

Total heat input = frictional heat plus deformation heat:

$$Q = Q_f + Q_p$$

The frictional heat that is produced at the tool shoulder

$$Q_f = \mu P \omega R^3$$

The axial force is denoted by P, the angular velocity is denoted by ω , and the shoulder radius is represented by R. The coefficient of friction is μ . The plastic deformation in the stir zone causes heat to be released as

$$Q_p = \beta \sigma \dot{\epsilon} V$$

The variables mentioned are the deforming material volume V , the strain rate $\dot{\epsilon}$, the flow stress σ , and the heat conversion factor β , which is 0.9.

3.2. Heat Transfer

The transient heat conduction controls temperature distribution in the plate:

$$\rho C_p \frac{\partial T}{\partial t} = k \nabla^2 T + Q$$

where ρ stands for density, C_p for specific heat, k for thermal conductivity, T for temperature, and Q for internal heat generation.

3.3. Mechanical Behavior

At elevated temperatures, the substance solidifies into a viscoelastic state. A function of both strain rate and temperature, the stress of flow is expressed as:

$$\sigma = K(\dot{\varepsilon})^n \exp\left(\frac{-Q_a}{RT}\right)$$

The variables K, n, R, Q_a, and T stand for the strength coefficient, strain hardening exponent, activation energy, gas constant, and absolute temperature, respectively.

3.4. Residual Stress

The temperature-elastic-plastic relation is used to measure the residual stresses following the cooling process:

$$\sigma = E(\varepsilon - \varepsilon_{th} - \varepsilon_p)$$

In which E is the modulus of Young, ε is the total strain, ε_{th} is the thermal strain and ε_p is the plastic strain. With the help of this model, temperature field, material flow, and stress distribution that influence joint integrity can be predicted.

4. NUMERICAL SIMULATION

A finite element simulation that is connected in three dimensions with temperature and displacement was used to study friction stir welding. The analysis was conducted using commercial finite element software (ANSYS / ABAQUS). The tool in motion was modeled as a rigid body, while the workpiece was modeled as a viscoelastic material that changes with temperature. The addition of plastic deformation in the stir zone and friction between the tool and workpiece increased the heat generation. Convection and heat loss to the supporting plate, which are correct thermal boundary conditions, were even considered.

The alloy material in the simulation was aluminum alloy AA6061 mainly used in structural and transportation applications because it is good in strength and easily fuses. The plates were expected to be firmly clamped to limit too much distortion during the welding process.

The instrument was made up of a shoulder and cylindrical pin. Table 1 is a table giving the geometric dimensions of the tool.

Table 1: Tool geometry parameters

Parameter	Value
Shoulder diameter	18 mm
Pin diameter	6 mm
Pin length	5.7 mm

In the investigation of the impact of welding condition various combinations of process parameter were used. Table 2 shows the chosen ranges.

Table 2: Process parameters used in simulation

Parameter	Range
Rotational speed	600 – 1200 rpm
Traverse speed	40 – 120 mm/min
Axial force	6 – 10 kN

The rotating tool was given a constant angular velocity when it was traversing the joint line at a given traverse velocity. Contact between the tool and workpiece allowed for frictional heat generation, and material qualities that depended on temperature were also accounted for. The results of the simulation showed the evolution of residual stress during welding as well as the temperature field, distribution of strain rates, plastic flow behavior, and more.

5. RESULTS AND DISCUSSION

Friction stirs welding's effect on the temperature field, plastic deformation, strain rate, and residual stress was predicted using a thermo-mechanical simulation. Results reveal that the ratio of heat output to mechanical churning controls the weld integrity. Excessive or insufficient heat causes flaws and degradation of mechanical qualities, whereas adequate heat helps the material flow around the tool.

5.1. Temperature Distribution

The hottest place was directly under the tool shoulder as the area of contact and frictional heating was greatest. Gradually the temperature fell off towards the center of the weld by heat conduction to the base material and backing plate. When the rotating tool is rotated, as shown in Fig. 1, an obvious temperature gradient is established around the rotating tool, which is the hottest around the area of the shoulder and less so in the outer areas of the workpiece. It appears that the primary cause of heat during FSW is the contact between the tool shoulder and the surface of the plate, which occurs due to friction.

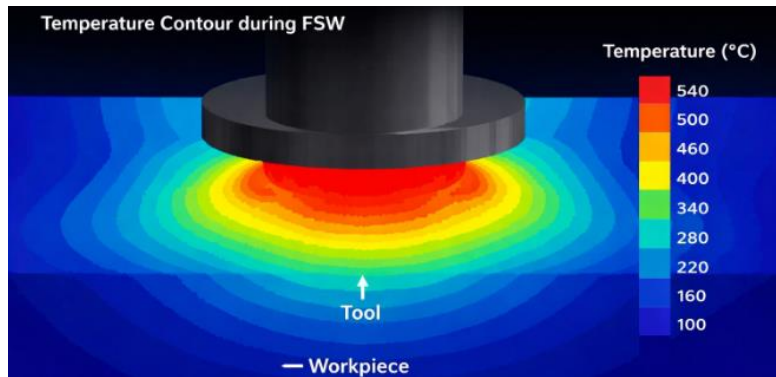


Figure 1: Temperature contour around the rotating tool

The impact of tool rotating speed on peak temperature is illustrated in Table 3.

Table 3: Impact of angular velocity on maximum temperature

Rotational Speed (rpm)	Peak Temperature (°C)
600	420
800	460
900	495
1000	515
1200	545

The amount of heat produced by friction at the point where the tool and workpiece come into

contact increases as the rotating speed increases. The highest temperature at 600 rpm was relatively lower (420°C) and this was not enough to completely plasticize the aluminum alloy. This led to ineffective flow of materials and internal holes. When the speed was approximately 900 rpm, the temperature became adequate (~495°C) to provide a similar softening and solidification. Nevertheless, at 1200 rpm, the rate of heat input was too large and it led to overheating that can result into coarsening of the grains and loss of hardness.

5.2. Material Flow and Plastic Zone

The melted material around the rotating pin created a plasticized zone referred to as nugget or stir zone. The heat input and the rate of the traverse of the tool were very powerful factors that determined the size and steadiness of this zone. It is observed that the equivalent plastic strain region is concentrated in a high amount around the tool pin which means that the contemporary material is strained heavily and mixed in the stir region as shown in Fig. 2. The strain spreads from the pin to the TMAZ and the base material, indicating that the most significant deformation is occurring in the tool's rotational local area.

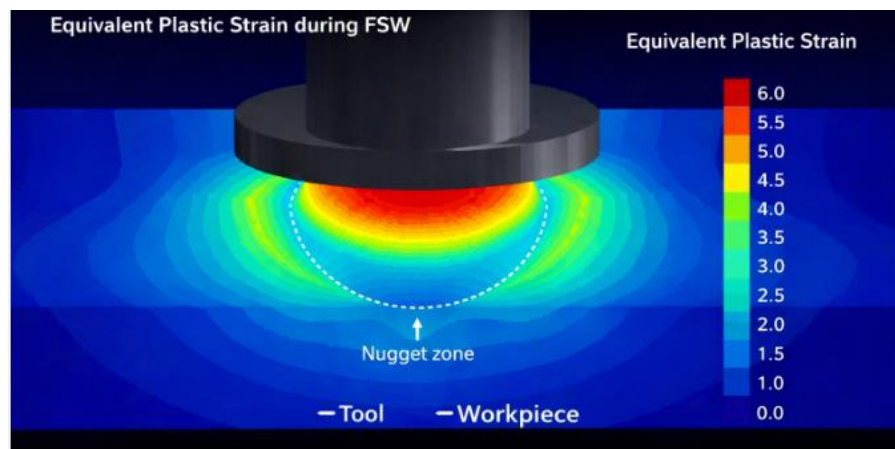


Figure 2: Equivalent plastic strain distribution showing nugget zone

The impact of traverse speed on weld formation is summarized in Table 4.

Table 4: The impact of traverse speed on the quality of the weld

Traverse Speed (mm/min)	Observed Weld Condition
40	Excessive flash formation
60	Sound weld
80	Optimal weld
100	Minor voids
120	Tunnel defect

The tool was longer at a given point at the low traverse speed (40 mm/min) resulting in too much heat generation and expulsion of the material (flash). When the traverse speed was adjusted to 80 mm/min, the balance of heat input and material flow were appropriate and this led to a stable plasticized zone and flawless weld. Traverse speed was found to be more than 100 mm/min and in this case, the tool was too fast and it did not create enough heat and failed to mix properly resulting in internal voids and tunnel defects.

5.3. Strain Rate and Residual Stress

Due to the significant plastic deformation that occurred in the stir zone, the tool pin and its immediate surroundings saw the highest strain rate. Non-uniform thermal contraction allowed residual stress in the welded joint to occur after cooling. Some tensile residual stress as shown in Fig. 3 is concentrated at the weld centerline and compressive stresses are generated at the locations other than the weld. Such distribution of stress is attained by heating and consequent cooling of the material around the rotating tool rapidly.

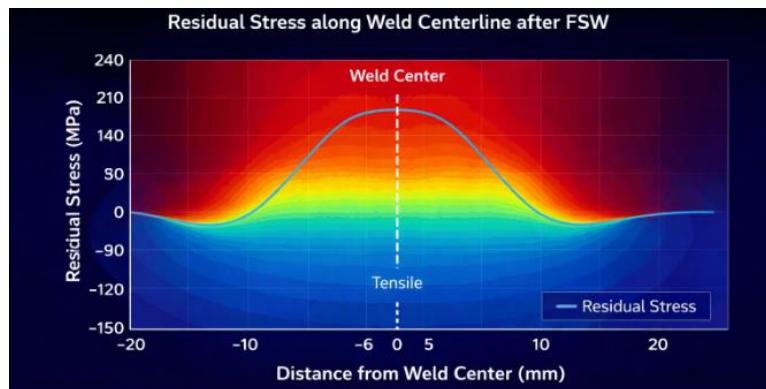


Figure 3: Residual stress distribution across weld centerline

Table 5 shows the residual stress variation with the rotational speed.

Table 5: Residual stress versus rotational speed

Rotational Speed (rpm)	Residual Stress (MPa)
600	185
800	162
900	145
1000	168
1200	210

Initial effects of rotational speed were residual stress decreasing with increasing rotational speed due to better plasticization which minimized thermal gradients. The minimum residual stress was found to be at about 900 rpm. In addition to this value, high levels of heat input generated high cooling gradients that enhanced tensile residual stresses. Service also can be subjected to distortion and fatigue cracking because of the high levels of residual stress.

6. CONCLUSION

In order to investigate friction, stir welding of AA6061 aluminum alloy, the present study developed a three-dimensional coupled thermo-mechanical finite element model. Temperature distribution, plastic flow around the tool, strain rate change, and residual stress creation during

welding were all predicted by the simulation. The results showed that the mechanical stirring to heat generation ratio significantly affected the weld quality. Poor plasticization and internal defects such tunnel gaps resulted from insufficient heat generation, while grain coarsening and residual strains were produced by an overabundance of heat. The optimal processing window was identified by the highest residual stress and the lowest variance in nugget formation at a rotational speed of around 900 rpm and a traverse speed of 80 mm/min. Generally speaking, the model that was created provides a reliable method for understanding the thermo-mechanical interactions that occur during friction stir welding. It could be used to optimize process parameters, improve joint integrity, and reduce experimental cost in industrial manufacturing.

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