Effect of Tool Rotational Speed on Temperature Distribution of Friction Stir Welded AA5083-H112/AA6061-T6 Joints: A Numerical Study

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Abstract

Friction stir welding (FSW) is a solid-state welding technology that has been increasingly adopted in transportation industries, including automotive, railway, and aircraft manufacturing, due to its ability to produce high-quality joints without melting the base materials. However, obtaining the temperature distribution around the weld zone experimentally remains challenging because of rapid thermal transients and limitations in sensor placement, even though temperature strongly governs the formation of the weld zones (HAZ/TMAZ), microstructural evolution, and joint quality. Previous studies have reported the influence of process parameters on heat generation and the temperature asymmetry between the advancing and retreating sides, yet the available evidence is often limited to discrete measurement points, indicating a need for more systematic full-field thermal prediction. This study aims to predict the temperature distribution and evaluate the effect of tool rotational speed in dissimilar FSW of aluminum alloys AA5083-H112/AA6061-T6. A finite element method (FEM) based numerical simulation was developed using ABAQUS Student Version 2021 with a simplified geometric model and appropriate thermo-mechanical contact conditions to represent heat generation in FSW. The results show that the peak welding temperature increases with tool rotational speed; the maximum temperature reaches 479°C at 2280 rpm. Validation against experimental data confirms the same trend, with differences ranging from approximately 1% to 6%. These findings indicate that the proposed numerical model can reliably capture the thermal response of FSW and can support parameter selection for improved joint quality.

Keywords: FSW, numerical simulation, aluminum alloy, temperature distribution

Abstrak

Friction stir welding (FSW) merupakan teknologi pengelasan keadaan padat yang semakin luas diterapkan pada industri transportasi (otomotif, perkeretaapian, dan pesawat) karena mampu menghasilkan sambungan berkualitas tanpa mencairkan material. Namun, distribusi temperatur di sekitar daerah las sulit diperoleh secara eksperimen akibat perubahan temperatur yang sangat cepat dan keterbatasan penempatan sensor, padahal temperatur berperan penting dalam pembentukan zona las (HAZ/TMAZ), mikrostruktur, dan kualitas sambungan. Studi terdahulu melaporkan pengaruh parameter proses terhadap panas dan perbedaan temperatur *advancing–retreating side*, tetapi masih terbatas pada titik pengukuran tertentu sehingga pemetaan temperatur secara menyeluruh dan studi parameter yang sistematis masih diperlukan. Penelitian ini bertujuan memprediksi dan menganalisis distribusi temperatur serta pengaruh kecepatan putaran *tool* pada FSW paduan aluminium tak sejenis AA5083-H112/AA6061-T6. Metode yang digunakan adalah simulasi numerik berbasis *finite element method* menggunakan ABAQUS Student Version 2021 dengan pemodelan geometri sederhana dan penentuan kondisi kontak termal-mekanik untuk merepresentasikan sumber panas proses FSW. Hasil simulasi menunjukkan bahwa temperatur maksimum meningkat seiring kenaikan kecepatan putaran *tool*; temperatur maksimum tertinggi mencapai 479°C pada 2280 rpm. Validasi terhadap data eksperimen menunjukkan tren yang konsisten dengan selisih hasil sekitar 1%–6%. Dengan demikian, model numerik yang dikembangkan mampu merepresentasikan respons termal FSW dan dapat digunakan sebagai dasar evaluasi parameter proses untuk pengendalian kualitas sambungan.

Kata kunci: FSW, simulasi numerik, paduan aluminium, distribusi temperatur

1. Introduction

Joining processes are widely used in manufacturing to permanently combine materials, and welding remains one of the most important joining routes for structural applications. Among welding technologies, friction stir welding (FSW) is a solid-state process that joins materials using a rotating non-consumable tool consisting of a shoulder and a pin, producing bonding without melting the parent materials and typically without filler metal [1]. These characteristics make FSW attractive for aluminum alloys where conventional fusion welding may induce defects and degrade properties, and consequently FSW has been extensively adopted in aerospace, automotive, shipbuilding, and related industries [2]. In practice, the weld quality and joint performance in FSW are strongly governed by a limited set of process parameters—most notably tool rotational speed and welding/traverse speed—which control heat generation, plastic flow, and the resulting microstructure [3].

Thermal conditions during FSW are critical because the temperature distribution directly affects the extent of the thermomechanically affected zone (TMAZ) and heat-affected zone (HAZ), grain evolution, and ultimately mechanical performance. Prior studies have demonstrated that process variables significantly alter the thermal field and weld response. For example, variations in tool design—such as pin geometry—have been reported to influence weld quality and joint strength [4-5], and commonly used pin profiles include square, cylindrical, and threaded/tapered configurations [6-7]. Experimental observations also indicate that the advancing side often experiences higher temperatures than the retreating side, reflecting asymmetric heat generation and material flow around the tool [8]. In dissimilar welding of aluminum alloys (e.g., AA6061–AA5052), heat input has been linked to microstructural differences between the weldment and the base materials; increased tool speed can raise heat generation, affecting grain size and thermal conditions across the weld zone [9].

Despite these contributions, a persistent limitation in experimental FSW research is that capturing full-field temperature distribution near the weld line is challenging due to rapid thermal transients, restricted sensor placement, and severe local deformation. As a result, many studies report limited temperature points rather than a spatially resolved thermal map, which complicates systematic evaluation of how individual parameters (e.g., rotational speed) alter the temperature field. This motivates the use of numerical simulation, particularly finite element modeling, to provide spatially and temporally resolved temperature predictions under controlled parameter variations.

Full-field temperature distribution in the vicinity of the FSW tool is difficult to obtain experimentally, yet it is essential for understanding and controlling weld quality; therefore, a validated numerical framework is required to quantify how key process parameters influence the thermal field. Existing literature confirms that process parameters and tool design affect heat generation and that the advancing/retreating sides exhibit different thermal behavior [10-13]. However, the available findings are often reported as isolated observations or limited measurement points, and there remains a need for a systematic, parameter-focused thermal study that generates spatial temperature distributions and evaluates the influence of tool rotational speed within a consistent modeling framework. This study develops an FEM-based numerical model in ABAQUS to simulate the FSW process and to predict the temperature distribution in the weld region. The primary objective is to quantify the effect of tool rotational speed on the thermal field, including the predicted peak temperature and the temperature distribution characteristics across the weld zone, thereby providing thermal insight relevant to weld quality control.

2. Material and Methods

2.1 Materials

This study investigates the temperature distribution in friction stir welding (FSW) of an aluminum-alloy plate using finite element analysis. The workpiece material is an aluminum alloy, while the welding tool is modeled as steel. The plate and tool geometries were created in a simplified form using CAD and kept constant for all simulation cases to isolate the influence of the selected process parameter. The welding path length was set to 300 mm. Tool–workpiece interaction was represented by a frictional contact model with a constant coefficient of friction of 0.25. Relevant thermophysical properties required for the thermal analysis (e.g., density, specific heat, and thermal conductivity, including temperature dependence when available) were adopted from established references and implemented in the model.

2.2 Methods

2.2.1 Numerical Modeling in ABAQUS

A finite element model was developed in ABAQUS to predict the transient temperature field generated during FSW. The CAD-based geometry of the plate and tool was imported into ABAQUS, material properties were assigned, and a contact interaction was defined at the tool–workpiece interface. Heat input was modeled to represent thermal energy generation associated with the FSW process, primarily driven by frictional interaction and (where applicable) deformation-related heating within the weld zone. Thermal boundary conditions were specified to represent initial temperature and heat losses to the surroundings. A locally refined mesh was applied in the welding region to capture steep temperature gradients, while a coarser mesh was used away from the weld zone to reduce computational cost. Post-processing focused on spatial temperature contours, peak temperature (T_max), and comparative trends across process conditions.

2.2.2 Experimental Perspective and Validation Criterion

Although the study is primarily numerical, an experimental perspective is incorporated through literature-based expectations of peak temperature behavior in FSW of aluminum alloys. The predicted maximum temperature was evaluated using a commonly applied validity criterion for solid-state welding: the simulation was considered acceptable when T_max fell within approximately 70–90% of the melting temperature of the aluminum alloy [14]. If the predicted peak temperature did not satisfy this range, model inputs were adjusted until the criterion was met.

2.2.3 Process Variables

To examine the influence of process conditions on the thermal response, tool rotational speed was selected as the independent variable and varied across simulation cases. Constant parameters included plate and tool dimensions, welding path length (300 mm), plate material (aluminum alloy), tool material (steel), and the coefficient of friction (0.25). The primary response variable was the temperature distribution in the workpiece during welding, including the peak temperature and its spatial evolution.

3. Results and Discussion

1.1 Modeling

The geometry of the workpiece and FSW tool is created in a simplified model using CAD software. Figure 1 shows the tool geometry used in the simulation.

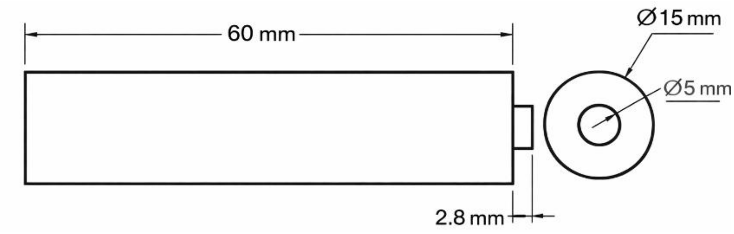

Figure 1. FSW tool

1.2 Determining Variable Values

Determining the value of process variables, which are independent variables such as tool rotation speed. These independent variable values are then used as input in the simulation process, which then produces output in the form of temperature distribution during the welding process.

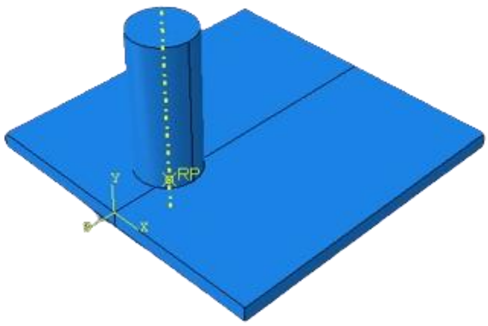

Figure 2. Modeling

Figure 2 shows the model that has been created. The simulation uses the Coupled Eulerian-Lagrangian method and Figure 3 shows the meshing tool and the Eulerian model.

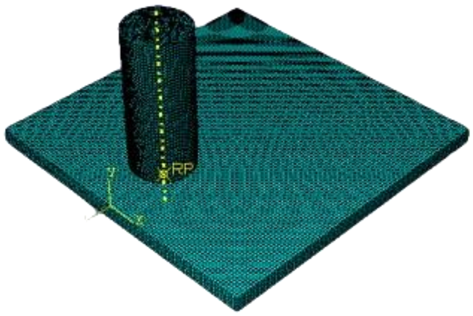

Figure 3. Meshing of the FSW model

1.3 Simulation

In this study, a simulation was conducted using finite element modeling using ABAQUS Student Version 2021 to determine the magnitude of the temperature distribution in the friction stir welding process. In addition, modeling the heat generated and the phenomena that occur in the welding area, as well as the effects accompanying the welding process, are other topics that can be covered by the FSW simulation. The simulation process was successful. Figure 4 is one of the results of the temperature distribution visualization from the simulation process that has been created.

1. Temperature Distribution

The maximum temperature that occurs is also influenced by the tool rotation speed. The higher the tool rotation speed, the higher the maximum temperature produced because the heat generated during the welding process is directly proportional to the tool rotation speed. This occurs because the maximum temperature in the FSW process is a function of the tool rotation speed [15].

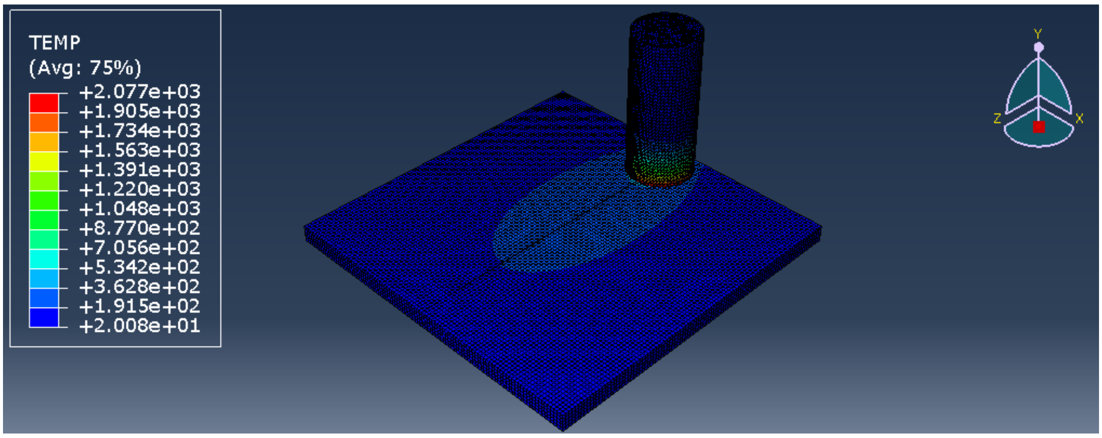

Figure 4. Temperature distribution

As seen in Figure 4, the maximum temperature occurred at a tool rotation speed of 2280 rpm with a value of 479°C. This value is still below the melting point of aluminum (~660°C), so the welding process does not melt the materials being joined.

2. Stress Distribution

From the simulation results in Figure 5 and Figure 6, the area shown has maximum stress (red area) and minimum stress based on color degradation.

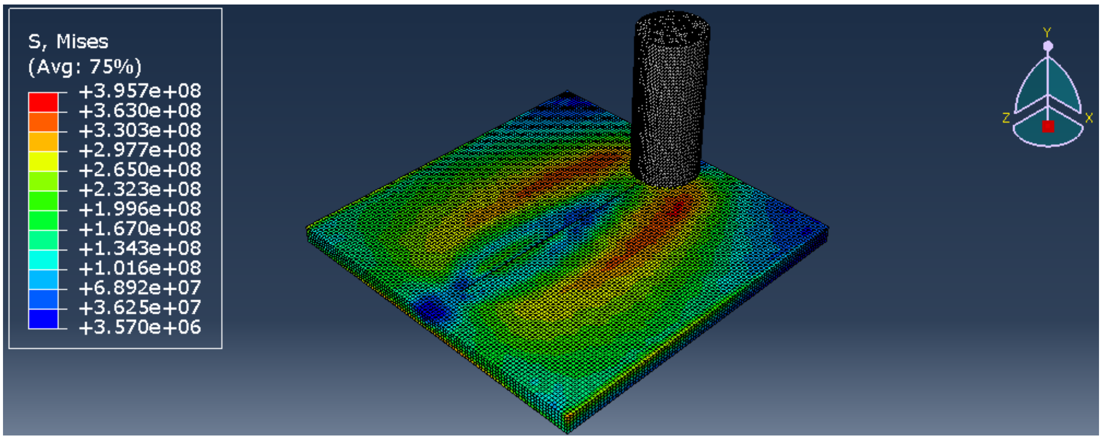

Figure 5. Stress distribution von Mises

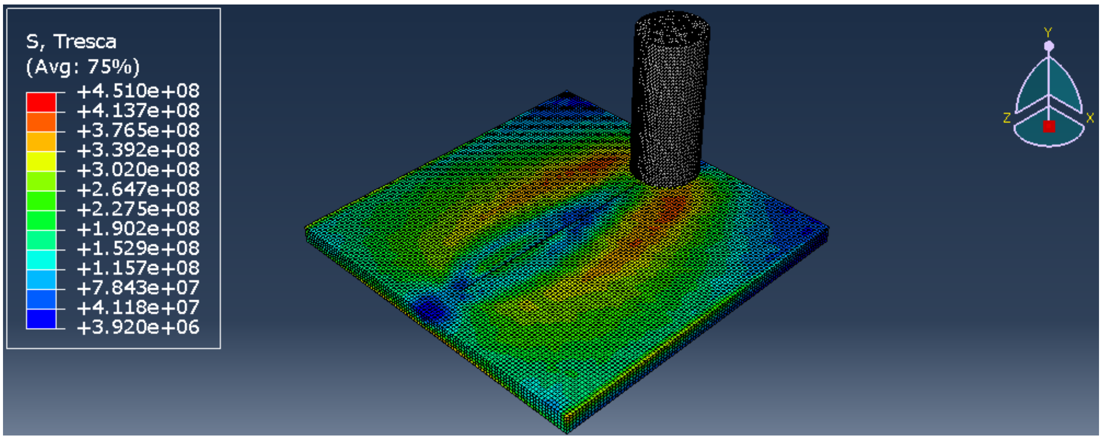

Figure 6. Stress distribution Tresca

The maximum stress that occurs is approximately 400 MPa for both the von Mises and Tresca approaches. This indicates that the FSW process occurs in the plastic region.

1.4 Simulation

Validation is the process of checking the suitability of the simulation process by checking the simulation. Validation is used to prove that the simulation conducted in this study is correct. The temperature distribution value obtained from the simulation can be said to be valid if the percentage of the maximum temperature produced is in the range of 70–90% of the melting point of the aluminum alloy. Figure 6 shows the thermal cycle of the FSW process observed experimentally. This data shows a maximum temperature value of 452°C which occurs at a tool rotation speed variation of 2280 rpm. [16].

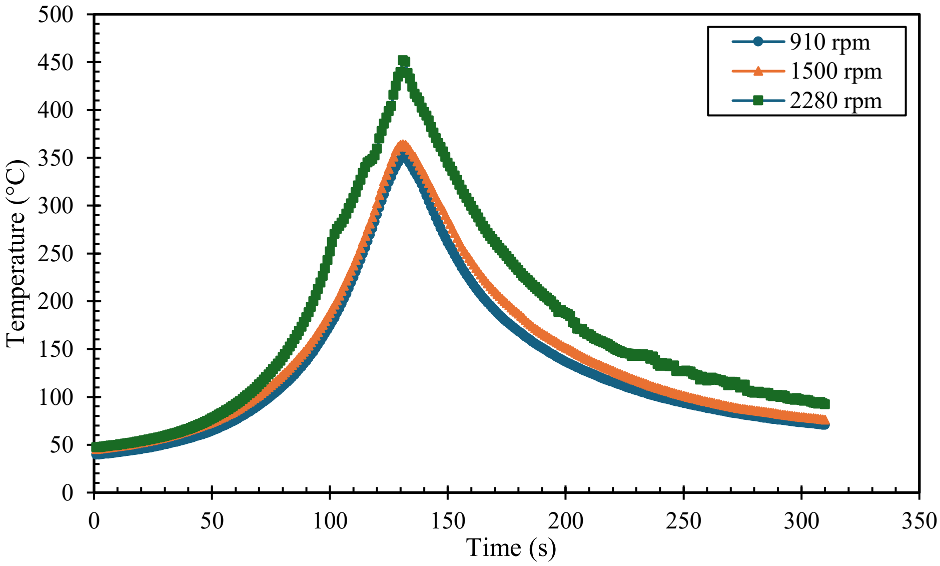

Figure 6. FSW thermal cycle using experimental data [16]

Figure 7 shows the maximum temperature curves from the experimental and simulation results. Both show the same trend: the faster the tool rotation speed, the higher the maximum temperature.

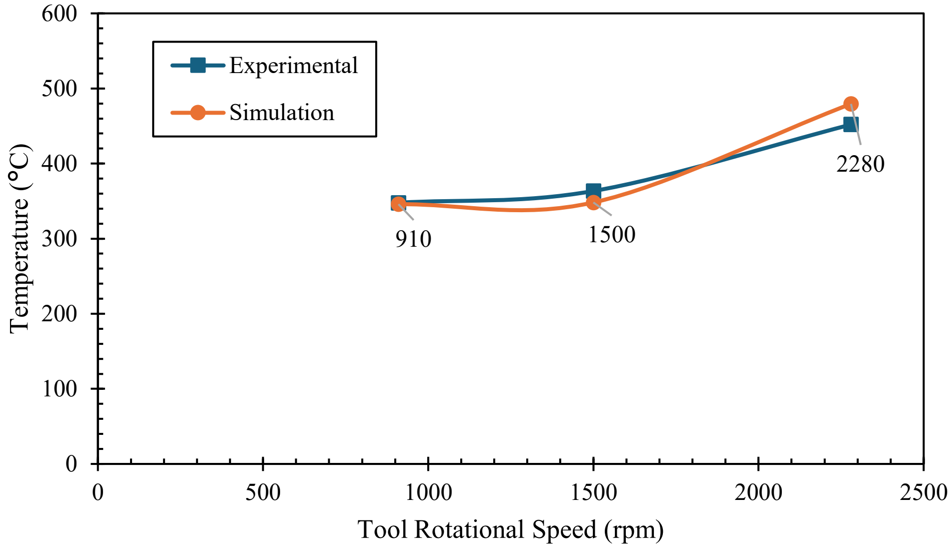

Figure 7. Comparison of maximum temperatures

The difference in maximum temperature values between the experimental and simulation results ranged from 1% to 6%. This difference is still acceptable. With validity values close to the experimental results, the model can also be used for simulations, for example, of the FSW process with different process parameters.

4. Conclusions

The maximum temperature of FSW welding is influenced by the tool rotation speed. The higher the tool rotation speed, the higher the maximum temperature produced. The maximum temperature occurs at a tool rotation speed of 2280 rpm with a value of 479°C. The maximum temperature of FSW welding from experimental data and simulation results shows the same trend. The difference in maximum temperature values between experimental data and simulation results ranges from 1% to 6%. Further studies can use additional process parameters as independent variables such as geometry or pin shape and welding speed and combine process parameters to obtain optimal results (optimization).

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