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# Enhancing Friction Stir Welding Quality of Inconel 718: An Approach of Numerical Modeling and Fuzzy Logic-Based Temperature Control

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## Abstract

Friction stir welding (FSW) is a revolutionary technique for joining high-strength materials, offering superior mechanical properties compared to traditional fusion welding methods. However, achieving optimal surface quality in FSW of Inconel 718 is challenging due to the material's sensitivity to temperature variations. This study leverages the advanced capabilities of COMSOL for numerical modeling and analysis to refine the FSW process for Inconel 718. Comprehensive numerical simulations in COMSOL generate a robust dataset, identifying critical process parameters such as rotational speed, transverse speed, and axial force. This dataset is then employed in MATLAB for system identification, resulting in a precise and reliable model of the FSW process dynamics. Building on this model, a fuzzy logic controller (FLC) is designed to dynamically adjust welding parameters in real-time, ensuring consistent temperature control. This innovative approach mitigates temperature fluctuations, reducing surface defects like roughness and voids. Validation through rigorous simulations underscores the FLC's efficacy in maintaining optimal temperature conditions, significantly enhancing weld integrity and surface quality. The seamless integration of numerical modeling, system identification, and fuzzy logic control exemplifies a sophisticated approach to advancing FSW technology for Inconel 718.

**Keywords:** *Friction stir welding, Inconel 718, COMSOL Numerical modeling, Fuzzy logic control, Temperature control.*

## 1. Introduction

Friction stir welding (FSW) is a solid-state welding process that uses a non-consumable tool to join metal or thermoplastic pieces. The tool rotates at high speeds, generating frictional heat that softens the metal without melting it. As the tool traverses the joint, it mixes the softened metal, resulting in a solid-state weld. FSW provides advantages over traditional welding techniques like gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW), including reduced distortion and enhanced mechanical properties. Its ability to weld dissimilar materials and thin sections makes it highly versatile. The process involves three stages: penetration, probing, and withdrawal. Various tools, such as shouldered, pin, or flat tools, are selected based on the material and application requirements[1, 2].

Inconel 718 is a nickel-based superalloy known for its high strength, ductility, and corrosion resistance at both ambient and elevated temperatures. The feasibility of components made from such alloys hinges on their ability to be joined with similar and dissimilar materials. Traditional methods like arc welding, electron beam welding, and laser welding have been utilized for manufacturing, refurbishing, and repairing Inconel 718 and other nickel superalloys. Recently, research has focused on developing precise models to predict the microstructure and mechanical properties of friction stir welded Inconel 718. These models aim to optimize the welding process and ensure joint quality by targeting areas such as the heat-affected zone (HAZ) and thermo-mechanically affected zone (TMAZ). Researchers also examine the effects of welding parameters like speed and force on the weld's microstructure and mechanical properties. Additionally, efforts are being made to create models that predict residual stress and distortion, which are critical for structural stability [3-5].

There is limited research on the friction stir welding and processing of Inconel 718 alloy. Successful outcomes have been reported under specific conditions, including low tool rotations (100-500 rpm), slow welding speeds (30-150 mm/min), and high axial loads (approximately 35kN) [6-11]. While these parameters have yielded promising results, such as refined grain structures and increased microhardness, they also limit the industrial application of FSW for Inconel 718 due to economic feasibility concerns [10, 11]. Despite these challenges, studies have demonstrated improved mechanical properties in welds, including microhardness and tensile strength, attributed to grain refinement. However, achieving successful FSW welds across a broader range of process parameters remains a significant technical challenge. While some research[10, 12] has explored FSW applications for other nickel-based alloys like Inconel 625 and 718, most studies have focused on Inconel 600 due to its lower yield strength, making it more weldable. Research on high-yield-strength alloys like Inconel 718 in the context of FSW is still limited[13].

Temperature control is crucial in FSW to ensure optimal weld properties within a specific thermal process range. Initially, FSW was performed on adapted milling machines with sporadic temperature monitoring, leading to temperature fluctuations during welding[14]. Early temperature regulation attempts often involved adjusting spindle speed[15]. Various techniques have been used to measure stir zone temperature, including placing a thermocouple closer to the tool-plate interface to significantly reduce system response time, enhancing control effectiveness. By regulating temperature and other welding parameters, weld quality can be maintained even in the face of external disruptions to the system[16, 17].

Initially, FSW was conducted by setting specific parameters for depth, travel speed, and spindle rotation speed, techniques that have proven effective over time[18, 19]. However, maintaining constant input parameters during welding can lead to temperature fluctuations within the weld due to transients and external disturbances. Given that FSW heavily relies on temperature control, deviations in weld temperature can adversely affect the strength and integrity of the weld. Poor temperature regulation can even render the welded piece unusable in certain instances[20].

Fuzzy logic control has been widely studied and applied in the field of FSW. Williams et al.[21] reviewed resistance spot welding of steel sheets and highlighted the importance of modeling and control of weld nugget formation. Niekerk et al.[22] proposed a neuro-fuzzy control scheme for complex curvature FSW to maintain tool/workpiece contact. Mantegh[23] presented a thermal feedback control method for FSW process control using a neural network-based modeling technique. Das et al.[24] focused on the application of a fuzzy logic control strategy for temperature control in FSW, suggesting a fuzzy logic controller with a triangular membership function. Senthilkumar et al.[25] reported the development of a fuzzy logic model for monitoring weld tensile strength and nugget hardness in FSW. Additionally, a study by Maha et al.[26] optimized the natural frequency of AA6061 aluminum alloy plate welded by FSW using a fuzzy logic control system. Lashin et al.[27] investigated the control of static and dynamic parameters using a fuzzy controller to optimize friction stir spot welding strength, particularly focusing on solid-state welding as a derivative of FSSW.

## 2. Background/Theoretical Framework

## 3. Methodology and modeling approach

### 3.1 Experimental setup

Finite element simulations using COMSOL Multiphysics v5.3 are conducted to analyze the interaction between process parameters and workpiece temperature in FSW of Inconel 718. These simulations are validated against experimental data to generate a dataset detailing relationships among rotational speed, welding speed, shoulder diameter, pin diameter, and axial force.

### 3.2 Model description and assumptions

### 3.3 System domain

The simulation domain consists of two Inconel 718 plates (250 by 75 by 3 mm), flanked by infinite domains as shown in Fig.x. The tool, made of tungsten carbide with 10% cobalt, features a flat circular shoulder (25 mm diameter) and a cylindrical pin (5 mm diameter, 2.7 mm depth). Adaptive meshing using the ALE technique maintains mesh quality, utilizing 108,000 elements with an average quality of 0.81. Simulations run on a 16 GB Intel i7 system, taking approximately 6 hours.

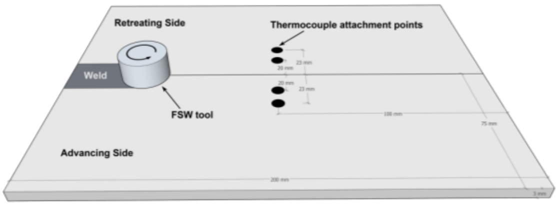


*Figure 1. FSW system geometry*

### 3.4 Governing equations

Key governing equations for finite element model construction are described as follows:

a)The coduction and convection heat transfer effect on plates

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q \tag{1}$$

*where ρ is the material density, Cp is the specific heat capacity,* ***u*** *is the velocity vector, ∇T is the temperature gradient, k is the thermal conductivity, and Q is the internal heat generation per unit volume.*

b) The surface heat source represents the heat generated between the workpieces and the tool’s pin

$$q_{\mathrm{pin}}(T) = \frac{\mu}{\sqrt{3(1+\mu^2)}} r_{\mathrm{p}} \omega \bar{Y}(T) \tag{2}$$

*where μ is the coefficient of friction,* $r_p$ *is the pin radius, ω is the rotational speed, and* $\bar{Y}(T)$ *is the flow stress as a function of temperature T.*

c) the heat generated from the friction of the workpieces and the tool’s shoulder is represented in Equation.3, where it is counted as heat flux (W/m$^2$) at r distance from the center axis

$$q_{\mathrm{shoulder}}(r,T) = \begin{cases} \frac{\mu F_n}{A_s} \omega r & \text{if } T < T_{\mathrm{melt}} \\ 0 & \text{if } T \geq T_{\mathrm{melt}} \end{cases} \tag{3}$$

*where $\mu$ is the coefficient of friction, $F_n$ is the normal force, $A_s$ is the shoulder area, $\omega$ is the rotational speed, r is the radius, and $T_{melt}$ is the melting temperature.*

d) The heat loss due to the natural convection and surface-ambient radiation to and from the surroundings are considered in Equation 4

$$\begin{aligned} q_\mathrm{u} &= h_\mathrm{u}(T_0 - T) + \varepsilon\sigma(T_\mathrm{amb}^4 - T^4) \\ q_\mathrm{d} &= h_\mathrm{d}(T_0 - T) + \varepsilon\sigma(T_\mathrm{amb}^4 - T^4) \end{aligned} \tag{4}$$

*Where $q_u$ and $q_d$ are the heat fluxes, $h_u$ and $h_d$ are the heat transfer coefficients, $T_0$ is the reference temperature, T is the current temperature, $\epsilon$ is the emissivity, $\sigma$ is the Stefan-Boltzmann constant, and $T_{amb}$ is the ambient temperature.*

The developed model integrate heat fluxes from friction between the rotating tool and contact surfaces, considering normal force and rotational speed, and excluding them if temperatures exceed the melting point. Heat transfer is modeled through surface-to-ambient radiation and convection. Temperature-dependent workpiece properties, derived from literature, and the below Johnson-Cook model for strain and strain rate effects ensure accurate simulations.

d) Johnson-Cook model for flow stress behavior

$$\sigma_{JC} = [A + B\epsilon^n]\left[1 + C\ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \tag{5}$$

$\sigma_{JC}$ is the flow stress, $A$, $B$, $C$, $n$ and m are material constants, $\epsilon$ is the equivalent plastic strain, $\dot{\epsilon}$ is the equivalent plastic strain rate, $\dot{\epsilon}_0$ is the reference strain rate, $T$ is the current temperature, $T_0$ is the reference temperature, and $T_m$ is the melting temperature.

Material properties, including sensible heat, density, thermal conductivity, expansion coefficient, Young's modulus, and Poisson's ratio, are temperature dependent. The Johnson-Cook plasticity model simulates material behavior during FSW, accounting for strain hardening, strain rate, and thermal softening.

Dataset produced from the model was analyzed and validated. Verification shows a 4% discrepancy with experimental results, indicating close alignment with published data. The finite element model explores the effects of varying axial force, rotational speed, welding speed, shoulder diameter, and pin diameter on the thermal profile. A non-linear regression analysis of this dataset guided the development of a non-linear state-space system model, which was also rigorously tested and validated. Below is the developed state-space system model:

$$\mathbf{A} = \begin{bmatrix} -10.43 & -12.86 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.056 & 0 & 0 \\ 0 & 0 & -0.0555 & -11.25 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -8.75 & -8.25 \end{bmatrix}$$

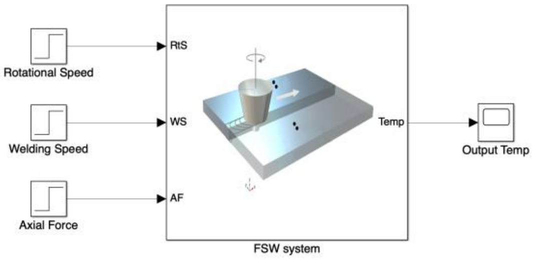
$$\mathbf{B} = \begin{bmatrix} 12.86 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.0011 & 0 \\ 0 & 12.5 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 8.75 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 0 & 1.21 & -1 & 0 & 21.3 & 0 \end{bmatrix}$$

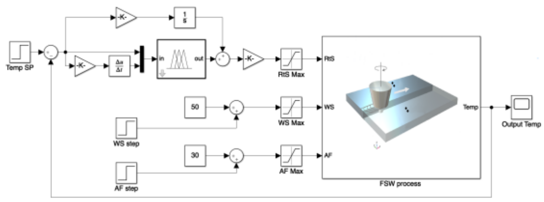
$$\mathbf{D} = \begin{bmatrix} -0.00075 & 0 & -0.2396 \end{bmatrix}$$

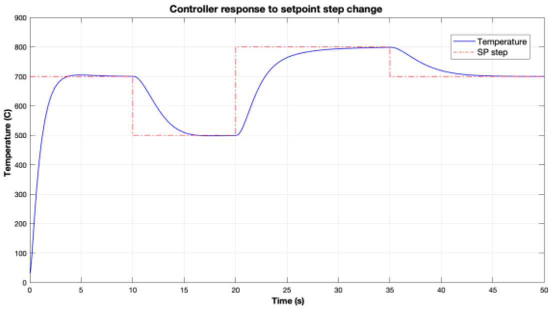
*Where A, is the system matrix, B, is the input matrix, C, is the output matrix and D is the feedthrough matrix.*

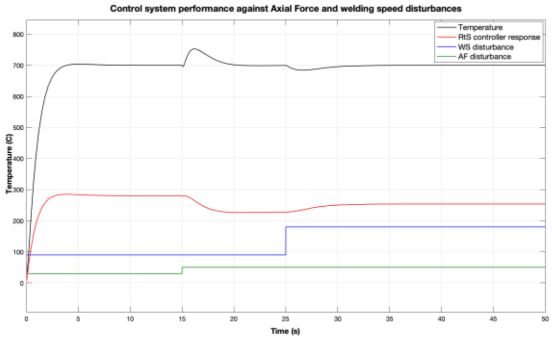
For process control, preprocessed input-output data from experiments or simulations are used to design the state-space model in MATLAB. An advanced fuzzy logic control (FLC) system was then designed and implemented using Simulink to manage the welding process. This FLC ensures optimal thermal management, reducing temperature fluctuations and enhancing surface quality and microstructural uniformity. This approach, focusing on rotational speed as the main control parameter with axial force and welding speed as disturbances, ensures optimal welding temperature and process stability.



## 4. Results and Discussion







## 5. Conclusions

This paper investigates the enhancement and control of weld quality for Inconel 718, a material highly sensitive to temperature fluctuations. Through finite element numerical modeling and simulations in COMSOL, a comprehensive dataset was generated to understand the system dynamics. This dataset was subsequently analyzed and used for system identification and process control in MATLAB, leading to the development of a state-space model that accurately mimics the FSW process. A fuzzy logic-based control system was designed to regulate the weld temperature. The proposed control system design proved to be successful in stabilizing weld temperature within optimal limits even under disturbance conditions. This work distinguishes itself from other research by addressing the challenges specific to Inconel 718, a material not extensively explored in similar studies, thereby contributing valuable insights to the field of advanced welding technologies.

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