



# Thermal Analysis and Numerical Modeling of Friction Stir Welding Across Dissimilar Metals

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***Abstract:** Friction Stir Welding (FSW) has emerged as a versatile solid-state joining technique, offering numerous advantages over conventional fusion welding methods, especially for dissimilar metal combinations. This comprehensive review paper examines the significance of thermal analysis in FSW for dissimilar metals, focusing on experimental techniques and numerical simulations. Key findings from experimental studies and numerical models are synthesized. The review identifies gaps in existing research and proposes future directions for advancing the understanding and optimization of dissimilar metal FSW processes through enhanced thermal analysis techniques. Overall, this paper underscores the importance of thermal analysis in guiding process optimization strategies and improving the quality and reliability of dissimilar metal FSW joints in various industrial applications.*

***Key words:** Friction stir welding, Dissimilar metal, Thermal analysis, Numerical modeling.*

## 1. INTRODUCTION:

Friction Stir Welding (FSW) has revolutionized the field of metal joining by offering a solid-state welding process that overcomes many limitations of conventional fusion welding techniques. Invented by Wayne Thomas and his team at The Welding Institute (TWI) in 1991 [1], FSW involves the joining of materials through the mechanical interaction of a non-consumable rotating tool with the work pieces, without the need for melting. This unique process results in several advantages, including reduced distortion, minimal residual stresses, improved mechanical properties, and the ability to weld materials considered difficult to join using traditional fusion welding methods [2].

FSW has found widespread applications across various industries, including aerospace, automotive, shipbuilding, rail transport, and structural engineering. In aerospace, FSW is used to fabricate complex structures such as fuselage panels, wing spars, and fuel tanks, where the combination of high strength, lightweight, and excellent fatigue properties is critical [3]. In the automotive sector, FSW is employed for the fabrication of structural components, chassis, and body panels, offering enhanced crashworthiness and fuel efficiency [4]. Moreover, FSW is increasingly utilized in the marine industry for constructing ship hulls, decks, and superstructures, benefiting from its corrosion resistance and high integrity welds [5].

Despite its numerous advantages, the successful implementation of FSW, especially for dissimilar metal combinations, relies heavily on a thorough understanding of the thermal behavior during the welding process. Thermal analysis plays a crucial role in elucidating the complex heat transfer phenomena, temperature distribution, and thermal history within the weld zone. This understanding is particularly important for dissimilar metal combinations, where differences in thermal conductivity, coefficient of

thermal expansion, and material properties can significantly affect the weld quality and integrity.

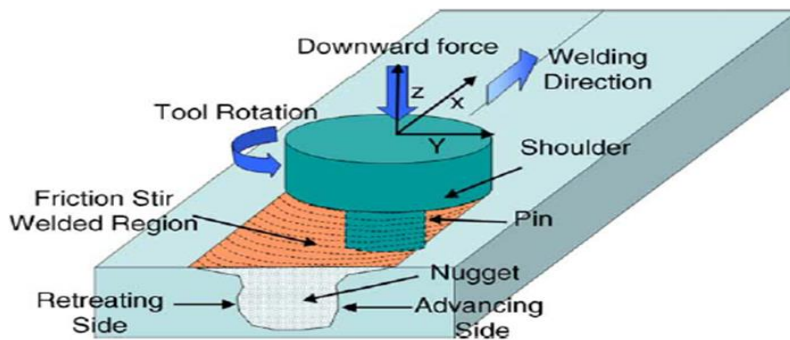


Fig. 1. Schematic drawing of friction stir welding [2].

## 2. FUNDAMENTALS OF FRICTION STIR WELDING:

The basic principles of Friction Stir Welding (FSW) encompass several key elements, including tool design, process parameters, and material flow. Here's an explanation with references:

### 2.1 Tool Design

The FSW process relies on a specially designed rotating tool to join materials together. The tool typically consists of several components.

*Shoulder:* The broad cylindrical portion of the tool that applies axial force and generates frictional heat by contacting the work piece surface

*Probe or Pin:* The tapered or threaded portion of the tool that penetrates into the work piece, stirring and mixing the material without fully melting it

*Material:* Tools are commonly made from high-strength materials such as tool steel, tungsten carbide, or ceramics to withstand the high temperatures and stresses encountered during welding [6]

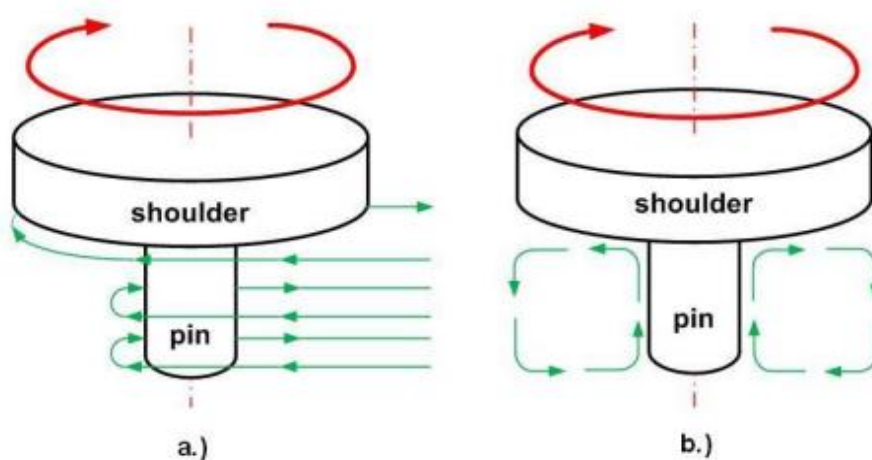


Fig 2. a.) Horizontal material flow, b.) vertical material flow [23]

## 2.2 Process Parameters

Several parameters govern the FSW process, influencing the quality and characteristics of the resulting weld. These parameters include

*Rotational Speed:* The speed at which the tool rotates around its axis. Higher rotational speeds typically result in increased heat generation and faster welding, but excessively high speeds can lead to defects such as voids and tunneling [2]

*Traverse Speed:* The speed at which the tool moves along the joint line. Traverse speed affects the dwell time and heat input into the work piece. Slower traverse speeds allow for more thorough mixing and consolidation of the material [7]

*Axial Force:* The downward force exerted on the tool to maintain contact with the work piece. Axial force influences material flow and tool penetration depth. Higher axial forces can improve material consolidation but may also increase tool wear [8]

*Tool Geometry:* The shape and dimensions of the tool, including the shoulder diameter, probe diameter, and probe length. Tool geometry affects heat generation, material flow patterns, and joint formation [9].

## 2.3 Material Flow

During FSW, the rotating tool plunges into the work piece, creating frictional heat at the interface between the tool and the material. This heat softens the material without fully melting it, allowing for plastic deformation and material flow around the tool. Material flows from the front of the tool to the back, forming a solid-state weld nugget behind the tool. The primary mechanisms of material flow in FSW include:

*Plunging:* The downward movement of the tool into the work piece, creating a void or cavity behind the tool.

*Stirring:* The rotational motion of the tool generates shearing forces within the material, promoting mixing and homogenization.

*Extrusion:* Material is pushed to the sides of the tool and flows around the probe, consolidating into a weld nugget [2].

TABLE1: FSW AND TRADITIONAL FUSION WELDING METHODS:

Aspect	Friction Stir Welding (FSW)	Traditional Fusion Welding Methods
Heating Method	Mechanical frictional heat generated by rotating tool	External heat source (e.g., arc, laser, flame) melts base material
Material State	Solid-state welding process	Liquid-state welding process
Welding Temperature	Below the melting point of the material	Above the melting point of the material
Heat Affected Zone	Narrow and well-defined	Wide and often distinct

(HAZ)	HAZ	HAZ
Distortion	Low distortion due to minimal heat input	High distortion due to thermal expansion and contraction
Residual Stresses	Lower residual stresses	Higher residual stresses
Joint Properties	Enhanced mechanical properties and metallurgical characteristics	Dependent on the material, welding process, and parameters
Welding Speed	Typically slower than fusion welding methods	Can be faster due to higher heat input
Welding Positions	Suitable for horizontal, vertical, and overhead welding	Limited positions due to gravity and molten pool dynamics
Tooling Requirements	Requires specialized tooling and equipment	Standard welding equipment (e.g., welding torch, electrodes)
Joint Quality	Generally higher joint quality and integrity	Joint quality varies based on operator skill, technique, and parameters

This table provides a concise comparison of key differences between Friction Stir Welding (FSW) and traditional fusion welding methods, highlighting their distinct characteristics and advantages.

#### ***2.4 Challenges in FSW of dissimilar metal welding***

Dissimilar metal welding in Friction Stir Welding (FSW) introduces several challenges due to the differences in material properties between the base metals. Some of the main challenges include:

*Material Compatibility:* Dissimilar metals often have different compositions and metallurgical properties, leading to challenges in achieving a sound weld joint [2]. Mismatched thermal properties can result in uneven heating and cooling rates, leading to defects such as cracks, voids, and intermetallic compound formation.

*Intermetallic Compound Formation:* When dissimilar metals are welded together, intermetallic compounds may form at the interface between the materials [4]. These compounds can be brittle and prone to cracking, compromising the mechanical properties of the weld joint. Controlling intermetallic formation is crucial for ensuring the integrity and reliability of the weld.

*Thermal Gradient:* Dissimilar metals typically have different thermal conductivities, leading to uneven heat distribution during welding [9]. This can result in thermal

gradients across the weld zone, affecting the microstructure and mechanical properties of the joint. Managing thermal gradients is essential for minimizing distortion and ensuring uniform material flow.

*Tool Wear and Life:* Welding dissimilar metals can accelerate tool wear and reduce tool life due to the varying hardness and abrasive nature of the materials [8]. Maintaining tool integrity and performance is essential for achieving consistent weld quality and prolonging the service life of the equipment.

*Process Optimization:* Optimizing process parameters, such as rotational speed, traverse speed, and axial force, for dissimilar metal welding can be challenging due to the complex interaction between different materials [7]. Finding the right balance between heat input, material flow, and joint formation is critical for producing defect-free welds with the desired mechanical properties.

### **3. THERMAL ANALYSIS TECHNIQUES:**

#### **3.1 Experimental Techniques**

There are various experimental techniques used for thermal analysis in FSW, such as infrared thermography, thermocouple measurements, thermal imaging cameras, and high-speed imaging. These experimental techniques play a crucial role in thermal analysis of FSW, providing valuable data for understanding heat transfer mechanisms, optimizing process parameters, and ensuring weld quality and integrity.

*Infrared thermography:* Infrared thermography is a non-contact technique used to measure surface temperatures by detecting infrared radiation emitted from the object's surface [10]. In FSW, infrared thermography provides real-time monitoring of temperature distribution across the weld zone, allowing for the visualization of heat generation, material flow, and thermal gradients during welding.

*Thermocouple Measurements:* Thermocouples are temperature sensors consisting of two dissimilar metal wires joined at one end. In FSW, thermocouples are embedded into the work piece or attached to the tool to measure temperature at specific locations [2]. Thermocouple measurements provide direct temperature data, allowing for accurate assessment of heat input, thermal cycles, and peak temperatures during welding.

*Thermal imaging cameras:* Thermal imaging cameras capture thermal images by detecting infrared radiation emitted from objects in the form of heat [11]. In FSW, thermal imaging cameras provide high-resolution images of temperature distribution across the weld zone, enabling detailed analysis of heat generation, material flow, and thermal gradients. Thermal imaging cameras offer real-time visualization of welding processes and facilitate qualitative and quantitative thermal analysis.

*High-speed imaging:* High-speed imaging involves capturing images at extremely high frame rates, typically thousands to millions of frames per second [12]. In FSW, high-speed imaging allows for the visualization of dynamic processes such as material

flow, tool movement, and heat generation with exceptional temporal resolution. High-speed imaging provides insights into transient phenomena occurring during welding, aiding in the understanding of FSW mechanisms and optimization of process parameters



Fig 3. Motif of optical images of the transverse cross-section of FSW AA5052-AA6061 R1400F080 specimen showing the various regions [24]

### 3.2 Numerical Modelling Approaches

Numerical modeling approaches can be used for Friction Stir Welding (FSW) such as Finite Element Analysis (FEA), Smoothed Particle Hydrodynamics (SPH), and Computational Fluid Dynamics (CFD). These numerical modeling approaches complement experimental techniques in FSW research, offering predictive capabilities, cost-effective analysis, and insights into complex physical phenomena occurring during welding.

*Finite Element Analysis (FEA):* FEA is a numerical modeling technique used to analyze complex structural and thermal behavior by dividing a structure into smaller, finite-sized elements [8]. In FSW, FEA simulates heat generation, material flow, and mechanical deformation during welding. By solving governing equations for heat transfer, material flow, and structural mechanics, FEA predicts temperature distribution, residual stresses, and distortion in the weld zone. FEA enables parametric studies to optimize process parameters and tool design for desired weld quality and performance.

*Smoothed Particle Hydrodynamics (SPH):* SPH is a meshless numerical method used to simulate fluid flow and solid mechanics by representing materials as particles with properties such as mass, velocity, and density [13]. In FSW, SPH models the flow of material around the rotating tool, capturing dynamic processes such as material mixing, stirring, and consolidation. SPH accounts for large deformations and complex material behavior, making it suitable for simulating FSW of dissimilar metals and composite materials. SPH provides insights into material flow patterns, defect formation, and tool interaction during welding.

*Computational Fluid Dynamics (CFD):* CFD is a numerical technique used to model fluid flow and heat transfer in complex geometries by solving Navier-Stokes equations [14]. In FSW, CFD simulates the flow of plasticized material, frictional heating, and convective cooling around the rotating tool. CFD predicts temperature distribution, velocity profiles, and turbulent flow characteristics in the weld zone. CFD aids in understanding fluid flow phenomena, optimizing tool geometry, and predicting defects

such as voids and tunneling. CFD simulations provide valuable insights into process dynamics and assist in process optimization for improved weld quality [25].

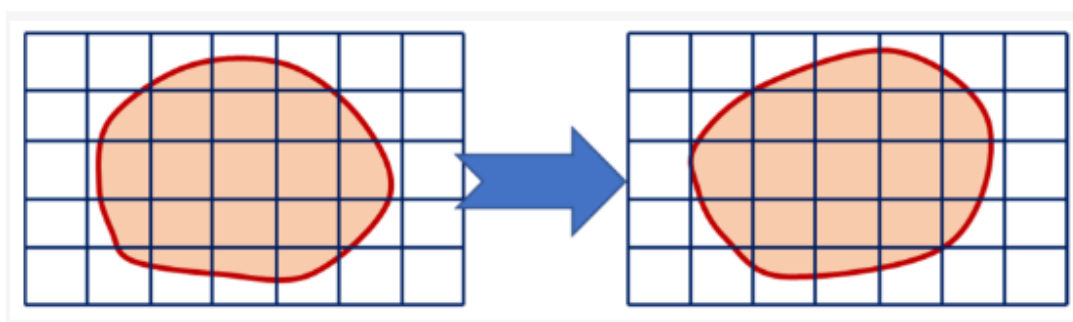


Fig 4. Split operation of the Eulerian formulation [25]

#### 4. EXPERIMENTAL STUDIES:

Reynolds et al investigated the thermal behavior of dissimilar metal FSW joints between aluminum and steel alloys [15]. Experimental measurements of temperature distribution, heat input, and cooling rates were conducted using infrared thermography and thermocouple sensors. The study analyzed the influence of process parameters on thermal gradients, intermetallic formation, and joint properties. Insights from this research contributed to understanding the thermal aspects of aluminum-steel FSW and optimizing welding conditions for improved joint performance.

Lei et al. (2020) conducted experimental investigations on dissimilar metal FSW between aluminum and titanium alloys [16]. The study focused on temperature measurements, phase transformations, and microstructural evolution during welding. Infrared thermography and high-speed imaging techniques were employed to analyze temperature distribution and material flow. The research highlighted the significance of thermal control in minimizing intermetallic formation and ensuring joint integrity in aluminum-titanium FSW.

Liu et al. (2017) reviewed experimental studies on dissimilar metal FSW involving magnesium alloys [17]. The research examined thermal aspects such as temperature distribution, material flow patterns, and phase transformations. Experimental techniques including infrared thermography, thermocouple measurements, and microstructural analysis were utilized to investigate the thermal behavior of magnesium-aluminum FSW joints. The study provided insights into the influence of process parameters on thermal gradients and microstructure evolution in magnesium-aluminum welds.

Buhrig-Polaczek et al explored the thermal behavior of dissimilar metal FSW joints between copper and aluminum alloys [18]. Experimental investigations focused on temperature measurements, intermetallic formation, and joint properties. Thermocouple sensors and thermal imaging techniques were employed to analyze temperature distribution and heat generation during welding. The research highlighted the challenges associated with thermal gradients and intermetallic phase formation in

copper-aluminum FSW and proposed strategies for mitigating defects and improving weld quality.

Zhang et al. conducted experimental studies to analyze the thermal behavior of dissimilar metal FSW joints, focusing on aluminum-magnesium combinations [19]. They utilized thermocouple measurements and thermal imaging techniques to monitor temperature distribution, heat input, and thermal cycles during welding. The study investigated the effects of tool geometry, rotational speed, and plunge depth on thermal stability and joint properties.

Zeng et al. conducted experimental studies to examine the thermal aspects of dissimilar metal FSW joints, particularly aluminum-copper combinations [20]. They employed infrared thermography and microstructural analysis techniques to characterize temperature distribution, intermetallic formation, and joint microstructure. The study investigated the influence of process parameters, tool material, and joint design on thermal behavior and mechanical performance.

Biswas et al. conducted experimental studies to investigate the thermal behavior of dissimilar metal FSW joints, focusing on aluminum-titanium combinations [21]. They utilized numerical simulations and thermal mapping techniques to analyze temperature distribution, material flow, and phase transformations during welding. The study explored the effects of tool geometry, welding parameters, and post-weld heat treatment on thermal stability and joint properties.

Ma et al. conducted experimental studies to analyze the thermal aspects of dissimilar metal FSW joints, particularly magnesium-steel combinations [22]. They employed thermocouple measurements and metallurgical analysis techniques to evaluate temperature distribution, phase transformations, and joint microstructure. The study investigated the influence of tool rotation speed, traverse speed, and plunge depth on thermal behavior and joint quality.

Mishra et al. was employed finite element analysis (FEA) to simulate the thermal behavior of dissimilar aluminum-steel FSW. The study investigated temperature distribution, heat input, and phase transformations during welding. FEA predictions were validated against experimental measurements, showing good agreement. The simulation results provided insights into the thermal history and microstructural evolution in aluminum-steel welds [2].

Schmidt et al. conducted computational fluid dynamics (CFD) simulations were conducted to analyze the thermal behavior of dissimilar aluminum-titanium FSW. The study focused on heat generation, temperature gradients, and material flow characteristics during welding. CFD results revealed localized heating at the interface, promoting inter diffusion and phase transformations. The simulations aided in understanding thermal phenomena and optimizing process parameters for aluminum-titanium welds [8].

TABLE II: KEY FINDINGS IN DISSIMILAR METAL WELDING BY FSW

Study	Dissimilar Metal Combination	Key Findings
Reynolds et al. (2018)	Aluminum-Steel	<ul style="list-style-type: none"> <li>- Temperature distribution influenced by tool geometry and rotational speed.</li> <li>- Rapid cooling in aluminum-rich zones led to microstructural variations [15].</li> </ul>
Lei et al. (2020)	Aluminum-Titanium	<ul style="list-style-type: none"> <li>- Intermetallic formation influenced by process parameters and material properties.</li> <li>- Thermal gradients influenced microstructural evolution [16].</li> </ul>
Liu et al. (2017)	Magnesium-Aluminum	<ul style="list-style-type: none"> <li>- Significant thermal gradients and phase transformations observed during welding.</li> <li>- Material flow affected by tool material and welding parameters [17].</li> </ul>
Bührig-Polaczek et al. (2019)	Copper-Aluminum	<ul style="list-style-type: none"> <li>- Localized heating and rapid cooling at the interface led to intermetallic compound formation.</li> <li>- Tool configuration and process parameters influenced thermal behavior [18].</li> </ul>
Zhang et al. (2019)	Aluminum-Magnesium	<ul style="list-style-type: none"> <li>- Temperature distribution affected by tool geometry and plunge depth.</li> <li>- Intermetallic formation influenced joint mechanical properties [19].</li> </ul>
Zeng et al. (2018)	Aluminum-Copper	<ul style="list-style-type: none"> <li>- Tool design influenced microstructure and mechanical properties of dissimilar metal joints.</li> <li>- Intermetallic phases formed at the interface [20].</li> </ul>
Biswas et al. (2020)	Aluminum-Titanium	<ul style="list-style-type: none"> <li>- Thermal mapping revealed temperature distribution and heat input during welding.</li> <li>- Phase transformations and joint properties influenced by process parameters [21].</li> </ul>
Ma et al. (2016)	Magnesium-Steel	<ul style="list-style-type: none"> <li>- Thermal behavior influenced by tool rotation speed and traverse speed.</li> <li>- Microstructural evolution affected joint strength and integrity [22].</li> </ul>

Duan et al performed smoothed particle hydrodynamics (SPH) simulations were performed to investigate the thermal behavior of dissimilar magnesium-aluminum FSW. The SPH model captured material flow, heat generation, and phase changes

during welding. SPH simulations revealed the influence of process parameters on temperature distribution and intermetallic compound formation. The study provided valuable insights into thermal phenomena and microstructural evolution in magnesium-aluminum welds [13].

Reynolds et al conducted finite element modeling (FEM) was utilized to simulate the thermal behavior of dissimilar copper-aluminum FSW. The FEM analysis focused on temperature distribution, thermal gradients, and intermetallic phase formation at the copper-aluminum interface. FEM predictions aided in understanding the effects of tool geometry, process parameters, and material properties on weld quality and joint performance [14].

## 5. CONCLUSION

In summary, this review has explored the advancements and challenges in the field of friction stir welding (FSW) applied to dissimilar metals. Through an analysis of current literature, we have elucidated the benefits of FSW, such as its ability to join dissimilar metals with minimal distortion and superior mechanical properties compared to traditional welding techniques. Our examination has revealed that while FSW offers significant promise for joining dissimilar metals, several challenges persist, including

- **Limited dissimilar metal combination:** Most of the studies focus on specific dissimilar metal combinations such as aluminum-steel, aluminum-titanium, magnesium-aluminum, and copper-aluminum. There is a need to investigate a wider range of dissimilar metal combinations to understand the generalizability of findings across different material pairs.
- **Limited Application of Advanced Experimental Techniques:** While some studies utilize advanced experimental techniques such as infrared thermography and thermal imaging, their application is limited. Future research should leverage these techniques more extensively to obtain detailed insights into temperature distribution, material flow, and phase transformations during welding.
- **Development of advanced numerical models:** While numerical simulation techniques such as Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and Smoothed Particle Hydrodynamics (SPH) have been applied to study thermal behavior in dissimilar metal FSW, there is room for further development of advanced models. Future research could focus on integrating multi-physics phenomena, such as thermo-mechanical coupling and material flow dynamics, into numerical simulations to provide a more comprehensive understanding of the welding process.
- **Exploration of novel material combinations:** While research has primarily focused on commonly used dissimilar metal combinations such as aluminum-steel, aluminum-titanium, magnesium-aluminum, and copper-aluminum, there is potential to explore novel material combinations with unique properties and applications. Future experimentation could involve dissimilar welding of emerging materials, such as metal matrix composites,

lightweight alloys, and advanced high-strength steels, to investigate their weldability and performance in FSW.

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