

A Comprehensive Review on Friction Welding

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Abstract—This review paper presents a comprehensive overview of recent research on friction welding (FW) of similar and dissimilar alloys, focusing on the influence of process parameters and surface modifications on joint quality and mechanical properties. Friction welding, increasingly favored over traditional fusion welding, enables the joining of metals that are otherwise difficult to weld. It has gained significant traction in industries such as aerospace, automotive, submarine engineering, and heavy-duty vehicle manufacturing, which demand innovative material combinations and advanced joining techniques. The review highlights how welding parameters—such as friction pressure (FP), axial shortening, and the geometry of faying surfaces—affect weld efficiency, joint strength, and microstructural characteristics. For instance, hemispherical bowl-type faying surfaces under 18 bar FP exhibit less than 25 mm axial shortening, while bevel-type surfaces increase shortening. Narrow weld interfaces (5–10 μm) and up to 92% joint efficiency are achievable with optimized low FP and modified faying surfaces, especially in small-diameter soft metals. Surface geometries like U- and V-shapes not only enhance bonding but also expand the contact area, further improving joint strength. This paper consolidates advancements in FW techniques, providing valuable insights for future research and industrial applications.

Keywords—Friction Welding (FW), Weld Joint Efficiency, Friction Pressure (FP), Microstructure Modification, Fusion Welding Alternative.

I. INTRODUCTION

Friction welding (FW) is a solid-state joining process used to produce high-quality weld joints between components of similar or dissimilar chemical compositions. According to the American Welding Society (AWS C6.1-89), it involves the application of compressive force and relative motion—typically by rotating one component while keeping the other stationary—generating heat at the interface to achieve coalescence without melting. This process eliminates the need for filler metals, flux, or shielding

gases. FW is widely favored for its advantages, including precise control of parameters, minimal material waste, reduced fabrication time, high production rates, and excellent weld quality, particularly in dissimilar metal joining. However, challenges such as the formation of brittle intermetallic compounds, control of the heat-affected zone (HAZ), and achieving optimal interface temperature remain critical.



Fig.1 Friction welding process

Rotary friction welding (RFW) specifically combines rotational motion and pressure to produce strong, defect-free joints with narrow HAZ and minimal intermetallic formation. Traditional fusion welding struggles to join dissimilar metals like austenitic stainless steels (SS304/SS316) with aluminum alloys (e.g., AA6063) due to their differing thermal and mechanical properties. Research on advanced surface modifications—such as tapering, buttering, interlayers (e.g., Cr), deep recesses, and threaded or hemispherical interfaces—has been limited, but this study addresses these gaps to improve joint efficiency and performance.

II. TYPES OF FRICTION WELDING

Friction welding is a solid-state joining process that uses mechanical friction between workpieces in relative motion to produce heat, followed by the application of axial pressure to forge the materials together. This method is known for producing high-

strength joints without melting the base materials. Several variations of friction welding exist, each tailored to specific materials, geometries, and application requirements. Below are the major types

A. Linear Friction Welding (LFW):

Linear friction welding involves a reciprocating linear motion across the interface of two components under constant axial pressure. Unlike rotational methods, one part is oscillated back and forth in a straight line, while the other remains stationary.

Applications: Commonly used in aerospace and automotive industries for joining non-axisymmetric parts such as blades to disks in jet engines.

Advantages:

- Capable of joining complex geometries.
- Produces high-quality, full-strength joints.
- Minimal material loss.

Challenges: Requires precise control of oscillation and pressure, and typically uses specialized machinery.

B. Rotary Friction Welding (RFW):

Also known as spin welding, rotary friction welding is the most widely adopted form. In this process, one component is rotated at high speed while the other remains stationary. The two parts are then brought into contact under pressure, and frictional heat is generated at the interface.

Applications: Ideal for round or symmetrical parts such as shafts, rods, and tubes.

Advantages:

- Short welding cycles and high production rates.
- Repeatable and clean welds without the need for filler materials or shielding gases.

Limitations: Only suitable for axisymmetric parts.

C. Direct Drive Friction Welding (Continuous Drive):

In direct drive friction welding, a motor continuously drives one of the workpieces during the frictional heating phase. Once sufficient heat is generated, rotation is stopped abruptly, and axial forging pressure is applied to complete the weld.

Applications: Suitable for a wide range of metals including dissimilar metal combinations.

Advantages:

- Excellent control over welding parameters like rotational speed, friction time, and forging force.
- Produces high-integrity joints with minimal defects.

D. Inertia Friction Welding:

This process is similar to direct drive welding but incorporates a flywheel to store rotational energy. The flywheel is brought up to a specific speed and then disconnected from the drive motor. The stored kinetic energy is transferred to the rotating component, generating heat through friction.

Applications: Common in aerospace, automotive, and heavy machinery manufacturing.

Unique Feature: No power input during the actual welding phase, enhancing energy efficiency and process stability.

E. Friction Stir Welding (FSW):

Unlike other forms of friction welding, friction stir welding uses a non-consumable rotating tool with a specially designed probe (or pin) that is plunged into the joint line between two fixed workpieces. The tool generates heat through friction, softening the material without melting it. The tool then traverses along the seam, mixing the plasticized material and forging a solid-state weld.

Applications: Widely used in aluminum welding (e.g., aerospace, marine, automotive industries), and increasingly for steel and titanium.

Advantages:

- Produces welds with superior mechanical properties.

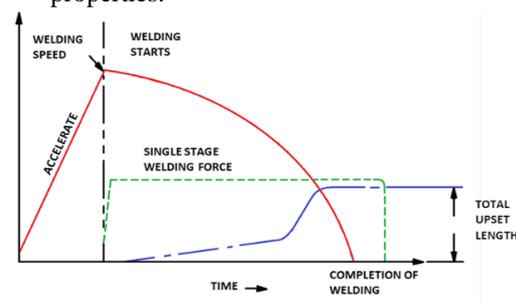


Fig.2 Friction welding parameters with respect to time so there is no melting of the base material takes place during this process.

- Low distortion and minimal post-weld cleanup.
- Environmentally friendly—no emissions or filler materials.

F. Friction Surfacing:

Friction surfacing is a surface modification technique derived from friction welding. A rotating consumable rod (typically made of a wear-resistant or corrosion-resistant alloy) is pressed against the surface of the workpiece. The frictional heat generated plasticizes the rod material, which then deposits as a coating layer on the substrate.

Applications: Used to enhance surface properties such as wear resistance, corrosion protection, or thermal conductivity in components like tools, dies, and machine parts.

III. WORKING PRINCIPLE

The fundamental concept behind friction welding involves the transformation of mechanical motion into thermal energy at the contact surface between the components. Typically, one of the parts is rotated, while the other remains stationary but is free to move along the axial direction. Once the desired rotational speed (RPM) is achieved, axial force is exerted along the X-axis. The relative motion and surface contact between the components generate heat due to friction at the interface. When the appropriate temperature is reached, the rotation is halted, and a forging pressure is applied axially to complete the joint. During this stage, flash (excess material) is expelled, and the grain structure in the welded region undergoes refinement due to the effects of hot working. Since thermal energy is concentrated solely at the contact zone, the surrounding material remains unaffected, preserving its original properties.

In addition to the fundamental principles, several critical process parameters influence the quality and integrity of the friction welding process (as illustrated in Figure 1). These include rotational speed, axial force, friction time, forge time, and material properties. The procedure is generally executed in a three-step sequence, each phase playing a vital role in achieving a successful weld joint.

Step 1: Friction Phase (Initial Rotation and Contact): In the first stage, one of the workpieces is secured in a rotating spindle, while the other component is held stationary but mounted such that it can move axially. The rotating part is accelerated to a predetermined angular velocity (rotational speed). Once this desired speed is attained, a calculated axial load or friction force is applied, pressing the stationary component against the rotating one. The mechanical interaction at the interface produces frictional heating, which gradually raises the temperature of the material at the joint line. This phase is essential for initiating the thermal softening required for plastic deformation.

Step 2: Friction Heating and Plastic Deformation: During this phase, the rotational motion and axial pressure are maintained for a specific duration,

referred to as the friction time. The continuous rubbing action under pressure elevates the temperature at the interface to the point where the materials reach a plastic state, yet remain solid (i.e., below their melting points). At this point, the material at the joint interface begins to deform plastically, allowing for the removal of surface oxides and contaminants, and promoting intimate contact between the two surfaces. The quality of the final weld is significantly influenced by the duration and consistency of this heating phase.

Step 3: Forging Phase (Upset and Bond Formation): Once sufficient thermal energy has been generated and the material at the interface has become plastic, the rotational motion is rapidly stopped. Immediately following this, a higher axial force, known as forge pressure or upset pressure, is applied for another specified period (forge time). This increased pressure causes the softened material to extrude laterally, forming flash around the joint and consolidating the two materials into a solid-state bond. The intense pressure, combined with the elevated temperature, results in dynamic recrystallization, leading to grain refinement at the weld interface. This phase is crucial for ensuring high joint strength and structural integrity.

Together, these three sequential steps—friction, plastic deformation, and forging—enable the formation of a robust and defect-free weld, without the need for external heat sources, filler materials, or shielding gases. The process is highly repeatable and energy-efficient, making it suitable for both similar and dissimilar material combinations in various industrial applications.

IV. LITERATURE REVIEW

Gaurav Verma et al. [1] conducted an experimental investigation focusing on the performance of similar and dissimilar metal joints produced using rotary friction welding. The study aimed to analyze the mechanical characteristics of various welded combinations and assess how different process parameters influence joint strength. For the experiments, a conventional horizontal lathe machine was utilized, modified appropriately to simulate friction welding conditions.

The research encompassed the welding of three specific material pairings:

- Mild Steel – Mild Steel (similar)

- Stainless Steel – Stainless Steel (similar)
- Mild Steel – Stainless Steel (dissimilar)

Each of the cylindrical specimens used in the study had a diameter of 10 mm and a length of 100 mm (10 cm). A total of six experiments were conducted, with two trials for each material combination. To examine the influence of rotational speed on joint performance, the researchers varied the rotational speed (RPM) between the two trials for each combination—one at a lower RPM and the other at a higher RPM.

The study underscores the importance of optimizing rotational speed in friction welding to achieve high-performance joints, especially when working with dissimilar materials, which are often more challenging to weld due to differences in thermal and mechanical properties.

P. Venkat Koushik et al. [2] conducted a detailed study on the rotary friction welding of dissimilar metals, specifically focusing on the joining of H30 aluminum alloy and BS970 mild steel. The primary objective of the research was to investigate how variations in upset pressure and upset (forging) time affect the quality and mechanical performance of the welded joints, while all other process parameters—such as rotational speed and friction time—were held constant to isolate the influence of these two variables.

The specimens used in the experiments were cylindrical rods with a diameter of 8 mm and a length of 200 mm, chosen to reflect typical dimensions used in industrial applications. A total of four welded joints were fabricated, each with different combinations of upset pressure and forging time. These variations allowed for a systematic exploration of the relationship between forging parameters and weld integrity.

The results of the experiments demonstrated a clear correlation between upset pressure, upset time, and joint strength. It was observed that as the upset pressure and forging time were increased up to certain optimal values, the strength of the joint also increased. However, when these parameters were pushed beyond their optimum levels, the mechanical strength of the welds began to deteriorate significantly, eventually leading to complete joint failure.

The optimum conditions identified through the study were:

- Upset pressure: 200 MPa

- Upset time (forging time): 6 seconds

The findings emphasize the critical importance of optimizing forging parameters in dissimilar friction welding. The study confirmed that both upset pressure and upset time are directly related to the strength and structural integrity of the welded joints, and that surpassing the optimal threshold can negatively affect joint formation, especially in combinations involving materials with different thermal conductivities and mechanical properties, such as aluminum and steel.

C. Shanjeevi et al. [3] carried out a comprehensive experimental investigation on the friction welding of dissimilar metals, specifically targeting the joining of austenitic stainless steel (AISI 304) and pure copper—a combination known to be particularly challenging due to significant differences in their thermal and mechanical properties. The aim of the study was to analyze the influence of key process parameters on the quality and strength of the welded joints.

The specimens used in the trials were cylindrical, with each measuring 24 mm in diameter and 75 mm in length, dimensions chosen to represent components typically used in engineering applications. To design the experiments systematically and efficiently, the researchers employed a Taguchi orthogonal array methodology consisting of 27 experimental runs, based on four process variables, each evaluated at three distinct levels. This robust statistical approach allowed for a detailed analysis of parameter interactions and their impact on joint characteristics.

- The four process parameters selected for optimization were upset pressure, friction pressure, forging (upset) pressure, and rotational speed.

Burn-off length (the material displaced during the friction phase before forging)

Through this structured experimental design, the research revealed several key findings. It was observed that a higher friction pressure combined with a lower forging pressure generally led to the formation of more sound and defect-free weld joints. This combination facilitated sufficient heating and plasticization at the joint interface without excessively disturbing the material alignment or causing premature consolidation.

The optimal process parameters identified through the Taguchi analysis for achieving the best

combination of joint strength and microstructural integrity were:

Friction pressure: 33 MPa

Upset (forging) pressure: 108 MPa

Rotational speed: 1500 RPM

Burn-off length: 1 mm

These conditions were found to minimize intermetallic formation while ensuring sufficient heat generation and plastic flow at the interface, thereby promoting a strong metallurgical bond.

Overall, the study underscores the critical role of parameter optimization in dissimilar metal friction welding and highlights the delicate balance required to prevent the formation of detrimental intermetallic layers while achieving adequate joint strength. This research provides valuable insights for industries such as electrical, automotive, and heat exchanger manufacturing, where joining copper and stainless steel is a common but technically complex requirement

R. N. Shubhavardhan et al. [4] conducted an insightful study on the rotary friction welding of dissimilar metals, specifically examining the joint characteristics between AISI 304 austenitic stainless steel and AA6082 aluminum alloy. These two materials are often used in structural and automotive applications due to their respective corrosion resistance and lightweight properties, but they pose significant challenges during welding due to inherent differences in their thermal conductivity, melting temperatures, and mechanical behaviors.

The experimental setup employed step-cut bar specimens, designed to facilitate precise alignment and controlled material interaction during the welding process. The AISI 304 stainless steel specimens featured an outer diameter of 18 mm and a reduced (extruded) section of 14 mm, while the AA6082 aluminum alloy specimens had a step profile with an outer diameter of 17 mm and an inner diameter of 15 mm. This step-cut design ensured concentric contact and effective engagement during the welding operation.

To counteract this issue, the researchers increased the friction time and friction pressure, which improved heat generation and temperature uniformity across the joint interface. As these parameters were elevated, the mechanical strength of the friction-welded joints increased, reflecting improved bonding conditions throughout the cross-section of the weld. However, beyond a certain threshold, further increases in friction pressure and friction time

resulted in a decline in joint strength. This deterioration was likely due to excessive flash formation, thermal degradation, or the onset of intermetallic compound formation at the weld interface, which negatively affected the structural integrity of the joint.

The optimum process conditions for achieving maximum joint strength were identified as follows:

- Friction pressure: 104 MPa
- Friction time: 5 seconds
- Forging (upset) pressure: 210 MPa
- Forging time: 6 seconds
- Rotational speed: 1400 RPM

These parameters provided a balanced combination of heat input, pressure, and deformation, enabling effective bonding without introducing defects.

This study highlights the critical influence of thermal distribution and parameter optimization in the friction welding of dissimilar materials, especially when significant differences in thermal conductivity exist. It also underscores the importance of step geometry design, as well as the need for fine-tuned control of process variables, to ensure uniform bonding across the weld interface.

Jeswin Alphy James et al. [5] conducted an in-depth study on the rotary friction welding of dissimilar steels, specifically focusing on the joining of AISI 304 austenitic stainless steel and AISI 1040 medium carbon steel. The research aimed not only to evaluate the feasibility of welding these two distinct materials but also to assess the impact of a Nickel (Ni) interlayer on the microstructural and mechanical properties of the resulting joints.

The experimental work involved two distinct setups: one in which the nickel interlayer was incorporated at the interface, and one without it. The purpose of including the interlayer was to investigate whether it could enhance the bond quality by acting as a diffusion buffer, thereby minimizing the formation of undesirable intermetallic compounds (IMCs) that often compromise joint strength in dissimilar metal welding.

The specimens used in the experiments were:

- AISI 1040 cylindrical rods with a diameter of 10 mm and a length of 75 mm
- AISI 304 stainless steel specimens with a length of 55 mm, diameter of 10 mm, and a holding side machined to 20 mm in diameter to facilitate proper gripping during the welding operation.
- A Nickel interlayer with a thickness of $50 \pm 3 \mu\text{m}$ was precisely inserted at the joint interface in

selected samples. This interlayer was chosen for its excellent compatibility with both base materials, high melting point, and ability to promote diffusion bonding without encouraging brittle phase formation.

The key process parameters that were varied in this study included:

- Rotational speed
- Upset (forge) pressure
- Burn-off length (the axial shortening during the friction phase)

Through a series of carefully controlled trials, it was found that the inclusion of the nickel interlayer significantly improved the joint strength, compared to samples welded without the interlayer. This improvement was attributed to the reduction in intermetallic compound formation at the weld interface, which typically occurs due to direct bonding between dissimilar materials like stainless steel and carbon steel. The nickel interlayer acted as a diffusional transition zone, which helped in accommodating the mismatch in physical and metallurgical properties, thereby enhancing the overall joint integrity.

The optimal welding parameters that resulted in the highest mechanical performance of the joint were determined to be:

Rotational speed: 2200 RPM

Upset (forge) pressure: 1.570 tons

Burn-off length: 8 mm

The findings from this research offer valuable insights for applications in aerospace, automotive, and energy industries, where strong, reliable joints between dissimilar steels are often required, and where the use of interlayers can significantly enhance weld quality.

Mariane Chludzinski et al. [6] successfully fabricated large-diameter girth welds on API 5L X46 grade steel pipes using the friction welding (FW) process, achieving efficient joint formation in a significantly shorter processing time. The welds were found to be free from visible defects or discontinuities, indicating a high-quality joining process.

However, a noticeable reduction in mechanical strength was observed at the central region of the weld interface. Detailed analysis suggested a potential risk of hydrogen-induced cracking and brittle fracture, which appeared to be associated with the presence of manganese sulfide (MnS) inclusions. These microstructural features can act as initiation

sites for cracks, especially under stress or in hydrogen-rich environments.

The study highlights both the efficiency and limitations of using friction welding for pipeline applications, particularly emphasizing the need for careful microstructural evaluation to mitigate the risks of brittle failure mechanisms.

Deep Barua et al. [7] introduced a novel approach for joining a circular rod or tube to a flat metal plate or sheet using the friction welding (FW) technique. This work is particularly noteworthy from a practical and industrial application perspective, as it expands the versatility of the FW process to accommodate dissimilar geometries. The study focused on evaluating the influence of key process parameters—including feed rate, spindle rotational speed, frictional torque, and penetration depth—on the overall quality and performance of the welded joint. Among these parameters, frictional torque was identified as the dominant factor contributing to the generation of sufficient thermal energy at the interface, which is critical for achieving a strong and consistent bond.

The findings revealed that an increase in spindle speed led to a decrease in both frictional torque and axial thrust force, suggesting a reduction in heat generation and material displacement under high-speed conditions. Conversely, an increase in feed rate resulted in a higher torque requirement, indicating a greater resistance to deformation and enhanced energy input for bonding.

This study provides valuable insights into the process-structure-property relationship in friction welding of non-traditional configurations and underscores the critical role of torque control in ensuring effective heat generation and joint integrity.

Wei Liu et al. [8] conducted a study on predicting the upset displacement in friction-welded joints using an artificial neural network (ANN) model. This approach is noteworthy for its innovative and adaptable nature, offering applicability to both rotary and linear friction welding (FW) processes.

In this research, the predicted outputs from the neural network were systematically compared with results obtained through finite element method (FEM) simulations. The comparison demonstrated that the primary heat generation during the welding process is strongly influenced by rotational speed, while axial frictional pressure significantly contributes to the

accumulation and distribution of heat at the weld interface.

The accuracy of the neural network model was validated by a prediction error of less than 8%, highlighting its reliability. Furthermore, the correlation coefficients for the ANN model were found to be 0.998 for rotary friction welding and 0.963 for linear friction welding, indicating excellent agreement with the simulated results.

This study showcases the potential of machine learning techniques in process modeling and optimization for advanced welding technologies, providing a powerful tool for enhancing predictive accuracy and process control.

Guilong Wang et al. [9] investigated the influence of energy input on the mechanical performance of rotary friction-welded joints made from AISI 304 stainless steel. The study involved varying the welding duration between 4 and 20 seconds, while applying a friction pressure ranging from 25 to 200 MPa. Throughout the process, the forging pressure was consistently maintained at a level higher than the applied friction pressure, ensuring adequate material consolidation during welding.

The experimental findings revealed that an increase in total energy input—primarily through extended welding time and elevated pressure—resulted in a notable improvement in the tensile strength of the welded joints, particularly when the forging pressure was held constant at 170 MPa. This suggests that energy input plays a crucial role in enhancing joint integrity and bonding effectiveness.

To further analyze the process behavior, the researchers developed an empirical predictive model to optimize key process parameters. The model's outputs were compared with actual experimental results, and the comparison demonstrated a high degree of accuracy. The tensile strength prediction coefficient, which quantifies the model's reliability, was found to be in the range of 90% to 96%, validating the model's effectiveness for parameter optimization and process prediction.

This research highlights the importance of controlling energy input and pressure conditions in rotary friction welding to achieve superior mechanical properties in stainless steel joints, and demonstrates the potential of empirical modeling for predictive process control in advanced welding applications.

Palanivel R. et al. [10] investigated the mechanical and microstructural characteristics of friction-welded

titanium tubes, highlighting the critical role of friction welding in effectively joining thin-walled tubular components. The study emphasized the influence of the rotational speed of the specimen held in the chuck on both the weld quality and the resulting microstructure of the joint. It was observed that as the chuck's rotational speed increased, the generated frictional torque decreased, which in turn led to an extension of the welding duration. This inverse relationship between rotational speed and frictional torque was found to significantly impact the heat generation and material flow during the welding process.

The results demonstrated that higher rotational speeds promoted superior grain refinement, particularly at the center of the weld joint, whereas the outer region near the flash exhibited relatively coarser grains. Specifically, average grain sizes of 2.5 μm and 1.2 μm were recorded at rotational speeds of 1600 RPM and 2800 RPM, respectively, confirming that an increase in rotational speed effectively reduced the grain size.

Correspondingly, the maximum microhardness was attained at the highest speed of 2800 RPM, indicating enhanced mechanical properties due to finer microstructural features. Additionally, the study found no significant microstructural variation between the heat-affected zone (HAZ) and the base metal, suggesting a stable weld region without adverse thermal effects. The welding process achieved a peak weld efficiency of 98% at the maximum rotational speed, reinforcing the critical influence of rotational speed as a key parameter governing the weld performance. Overall, this research clearly establishes rotational speed as a dominant factor affecting the microstructural evolution and mechanical integrity of friction-welded titanium tubes.

V. CONCLUSION

Friction welding (FW) is a versatile solid-state joining process widely studied for its ability to produce high-quality welds in both similar and dissimilar materials. Through extensive literature review, several critical process parameters have been identified that significantly influence weld quality, including:

- Friction pressure
- Friction time
- Rotational speed
- Forging pressure

- Forging time
- Burn-off length

Optimization of these parameters is crucial to achieving optimal weld properties. For example, if the rotational speed is too low while the applied force is excessively high, the fusion zone at the joint interface tends to be narrow, resulting in weaker bonding. Conversely, an excessively high rotational speed combined with low applied force produces a thick fusion zone, which can adversely affect the joint integrity. Therefore, carefully balancing these parameters enhances the microstructural refinement and mechanical strength of the weld.

Moreover, optimization is highly material-specific, and other factors such as the use of interlayers, interlayer thickness, geometric modifications (e.g., tapered or pin-shaped specimen ends), diameter ratios of the components, cooling methods, and pre/post-weld heat treatments also play a vital role in improving weld quality. For instance, the addition of interlayers like Nickel for similar steel joints, Aluminum for steel-ceramic welds, or Silver for stainless steel-aluminum joints has been shown to significantly reduce the formation of detrimental intermetallic compounds at the weld interface.

From the observations made, it is evident that rotational speed is the dominant parameter influencing tensile strength in stainless steel welds, with higher speeds correlating to increased strength. For aluminum variants, burn-off length emerges as the primary factor affecting weld strength. Additionally, maintaining optimal friction and forging pressures is essential to avoid weld defects, minimize interface inconsistencies, and control welding time. These parameters are especially critical in dissimilar welds such as aluminum to stainless steel combinations.

Geometrical considerations such as changing specimen shapes—round headed tips, tapered pins—and variations in diameter ratios also affect the weld quality. Notably, process parameters optimized for specimens of equal diameters may not be applicable for welding components with differing diameters, underscoring the need for tailored approaches.

This review highlights FW's remarkable effectiveness, especially in joining aluminum alloys with ferrous, non-ferrous, and ceramic materials. With increasing industrial demand for joining low-carbon ferrous alloys to heat-treatable non-ferrous alloys in small-diameter rods, there remains a noticeable gap in research, particularly concerning direct-drive friction welding of small-diameter rods

under low forging pressure conditions. Such studies are essential for advancing the practical application of FW in precision industries. Encouragingly, some research has demonstrated that friction welding can be performed with minimal axial shortening, low energy consumption, and enhanced operator safety by employing lower welding pressures without compromising weld integrity. However, to date, continuous drive friction welding of small-diameter rods like AISI 304L stainless steel and AA6063-T6 aluminum at low forging and upset pressures, especially with varying faying surfaces, remains scarcely explored.

Further studies suggest that increasing the axial penetration rate and upset time positively correlates with improved weld strength. Additionally, modifications to the faying surface geometry—such as hemispherical bowl-shaped interfaces—have been shown to reduce friction time and increase tensile strength, achieving over 100% joint efficiency under optimized conditions. While these surface modifications enhance tensile properties, their effects on other mechanical characteristics still require comprehensive investigation.

Despite these advancements, there is a notable lack of modeling, numerical simulations, and computational analyses, including structural and thermal distribution studies at the weld interface during friction welding. Integrating these tools could substantially improve understanding and optimization of the welding process, enabling better prediction of weld quality and mechanical performance.

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