

Optimization of Dissimilar Steel Solid Rods in Friction Welding Using the Taguchi Method

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Abstract: Welding has long been an essential process in manufacturing and fabrication industries, enabling the joining of materials to create components that are structurally sound and durable. However, as engineering applications become more complex, the demand for joining dissimilar materials—such as steel and aluminium, or copper and stainless steel—has grown. This present work investigates the rotary friction welding of dissimilar ferrous materials—stainless steel and mild steel—with the aim of exploring the mechanical integrity, visual characteristics, and weld behaviour under varying process conditions. The original intent was to develop a hybrid friction welding setup incorporating external induction heating to enhance temperature control and reduce thermal imbalance. However, due to equipment limitations, the welding trials were conducted using conventional rotary friction welding only. A total of twelve cylindrical specimens were welded under four rotational speeds—2000, 3000 and 4000 RPM—combined with three different cooling environments: air, water, and oil. Results showed that weld quality improved with higher speeds, and oil-cooled samples at 3000 RPM exhibited the highest tensile strength of 396 MPa, with failure occurring outside the weld zone. All samples passed surface-level inspection without visible cracks or defects.

1. Introduction

Traditional fusion welding methods struggle in these scenarios due to varying melting points, thermal expansion rates, and metallurgical incompatibilities between the materials. These differences can lead to weak joints, cracks, and undesirable intermetallic formations. To overcome these limitations, researchers have introduced hybrid friction welding techniques that combine frictional heat with an external heat source—such as induction heating. The aim of this approach is to preheat the harder or less thermally responsive material (usually stainless steel), improving its deformability and enhancing heat balance at the interface. This hybridization reduces mechanical load on the tool, minimizes flash asymmetry, and enhances the overall quality of the weld. Such process modifications open new possibilities for dissimilar material joining in critical applications where mechanical strength and long-term reliability are essential [1]. A structured review of the existing literature on friction welding and hybrid methods, with particular attention to the challenges and solutions related to dissimilar metal joining. It begins with a summary of key friction welding processes—including rotary, inertia, and friction stir variants—followed by an examination of research studies addressing dissimilar combinations, especially involving ferrous alloys. Finally, it explores published work on hybrid

techniques, identifying gaps in the existing research and highlighting the relevance of this project's focus [2].

Inertia friction welding of dissimilar ferrous alloys. Their findings confirmed that optimizing burn-off length and forge pressure can significantly influence weld quality. Nonetheless, even under ideal conditions, the stainless steel consistently resisted deformation longer than its counterpart, leading to uneven material flow. Microstructural examination revealed partial mixing zones and increased hardness at the interface, particularly on the stainless side—suggesting that temperature control is critical to prevent embrittlement or localized strain [3]. Friction stir welding, although primarily used for aluminium alloys, has also been tested for steel combinations. stainless-mild steel plates were welded using a specially designed tool with controlled heat input. The researchers concluded that tool geometry, rotational speed, and plunge depth needed to be precisely managed to avoid defects like voids, tunnelling, or micro cracks. Still, a major takeaway was that even in friction-based techniques, thermal mismatch remains the core limitation in achieving uniformly bonded, defect-free dissimilar joints [4]. Experimented with induction-assisted rotary friction welding to join titanium to stainless steel. Their work demonstrated that preheating the titanium side using a coil allowed for better plastic flow and reduced tool loading during the friction phase. The joint quality improved significantly in terms of strength and structural uniformity, indicating that external heating could help neutralize the mismatch in thermal properties [5]. Developed a controlled induction-coil setup integrated with a rotary friction welding system to join aluminum and steel rods. Their study highlighted how variable-frequency induction heating could be tuned dynamically to match the energy demand at the joint interface. They observed that the hybrid approach reduced weld cycle time, produced more uniform flash, and enhanced bond integrity, particularly on the harder steel side. This result reinforces the idea that hybrid welding is not just about increasing heat—but about improving thermal symmetry between dissimilar materials [6].

Although most hybrid studies have focused on aluminium-steel or titanium-alloy pairs, there has been growing interest in ferrous dissimilar systems. Investigated the hybrid friction welding of stainless steel and carbon steel using resistance coil heating. Their work revealed that the additional thermal input helped the stainless steel enter the plastic state more quickly, reducing asymmetry in deformation and improving overall mechanical properties of the weld. However, their setup lacked real-time control and spatial targeting, which led to occasional

overheating and microstructural coarsening [7]. Explored induction heating specifically in the context of stainless steel to mild steel hybrid friction welding, despite the practical relevance of this material pair in structural and industrial applications. The absence of dedicated research in this domain forms a crucial gap in the current literature. Most work remains experimental and isolated, lacking a standardized methodology or validated thermal control strategy. Moreover, studies rarely explore the combined mechanical and microstructural consequences of hybridization across the entire weld zone [8]. To address that gap by developing a coil-assisted hybrid friction welding setup specifically for joining stainless steel to mild steel. By incorporating controlled induction heating into the welding cycle, it seeks to achieve balanced plastic deformation, reduced thermal gradients, and improved joint strength. The results are expected to validate the hybrid method's potential as a robust and scalable solution for industrial dissimilar metal joining applications [9]. Friction welding and its application to dissimilar material joining reveals both the strengths and the limitations of current techniques. Solid-state welding methods such as rotary, inertia, and friction stir welding offer clear advantages over fusion-based approaches by eliminating the need for melting, reducing thermal distortion, and improving joint cleanliness. However, when applied to dissimilar materials like stainless steel and mild steel, these methods still encounter considerable challenges related to thermal mismatch, uneven plastic deformation, and interface defects [10].

Dissimilar ferrous welding consistently highlight how stainless steel, with its lower thermal conductivity and higher hardness, resists softening under friction compared to mild steel. This results in asymmetric flash formation, incomplete bonding, and stress accumulation. Even with optimized process parameters, conventional friction welding cannot fully compensate for the unequal thermal response of the two materials. This shortfall has prompted researchers to explore hybrid approaches, where external heating—especially induction heating—is used to precondition one or both materials before or during the weld cycle [11]. Hybrid friction welding shows significant potential. When induction heating is used in conjunction with mechanical friction, the process achieves improved thermal balance, lower mechanical loading, and more uniform material flow. While early studies focused on aluminium–steel and titanium–steel pairs, limited but relevant research has demonstrated similar advantages in ferrous systems. However, most of this work remains exploratory, with few examples of full-system integration or dedicated focus on stainless steel to mild steel joints—a material pair highly relevant to infrastructure, fabrication, and industrial equipment sectors [12]. The key takeaway from the literature is that while hybrid friction welding is a promising evolution, there remains a clear gap in experimental validation and process optimization for joining stainless and mild steels using controlled induction heating. No widely accepted methodology currently exists for configuring the induction system, synchronizing thermal input with mechanical motion, or evaluating the resulting microstructure and mechanical properties of such hybrid joints [13]. Pointed out that Friction Stir Welding (FSW) has drawn widespread interest because it possesses a large number of benefits, most notably its capacity to weld together materials generally regarded as impossible or troublesome to weld with conventional techniques. Originally designed for aluminum alloys deemed unweldable, FSW is now considered for other materials, even for ferrous materials like stainless steels. The high academic and research demand for FSW in these materials

is because it can make high-quality solid-state welds. As there is no melting, the process is carried out at significantly lower temperatures than the other fusion welding processes [14]. Characterized FSW as an extrusion process, where on each revolution of the tool, a cylindrical volume of material is extruded about the probe and gives rise to a banded structure in the weld. These typical bands, also called "onion rings," are seen as concentric circles or semicircles based on the cross-sectional perspective and are thought to be produced by surface oxidation of the semi-cylindrical layers. For dissimilar welding of 5052 aluminum alloy and AZ31 magnesium alloy with plates of 6 mm thickness, the welds were found to be sound at a rotation rate of 600 rpm and a welding speed of 40 mm/min. The microstructure in the stir zone was immensely finer with a complex flow pattern characterized by interleaving lamellae [15].

2 Materials and Methodology

The experimental procedure followed to study the effectiveness of conventional friction welding for joining dissimilar ferrous materials — AISI 304 stainless steel and MS1018 mild steel. Although the initial intent of the project was to develop and test a hybrid friction welding setup with induction heating, the coil system could not be activated due to technical limitations. Therefore, the welding was conducted using a rotary friction welding machine without external heating. A total of 12 specimens were welded under varying rotational speeds and cooling conditions. The two dissimilar metals selected for the experiment were AISI 304 stainless steel and MS1018 mild steel as shown in table 1. These materials were chosen for their practical relevance and their contrasting physical and thermal properties, which pose a known challenge in welding. The dimensions of the cylindrical rods were 12 mm in diameter and 60 mm in length.

Table - 1: Material Specification

Property	AISI 304 Stainless Steel	MS1018 Mild Steel
Material Type	Austenitic SS	Low Carbon Steel
Diameter	12 mm	12 mm
Length	60 mm	60 mm
Surface Finish Target	Ra 1.2–2.4 μm	Ra 1.2–2.4 μm
Condition	Annealed	Machined



Fig - 1: separate pieces of the dissimilar materials

Both rods were cleaned and prepped for face contact welding. The variation in hardness and thermal conductivity between the two materials made the joining process a critical test for the friction welding method as shown in fig. 1.

2.1 Material Preparation

Raw material was sourced in the form of standard 12 mm diameter steel rods, cut into 60 mm lengths using a power hacksaw. Care was taken to minimize heat generation during cutting, especially for stainless steel, to prevent work hardening or surface oxidation.



Fig - 2: mounting of two dissimilar metal rods

Each cut piece was then classified and stored according to its material type to prevent any mix-up between mild steel and stainless steel during the subsequent machining and welding processes. As a result of the equipment limitations, the induction coil was not used in the final welding process, and all specimens were welded using standard rotary friction welding only. While the hybrid setup was not operational, the system design and attempted integration remain an important part of this project, demonstrating the feasibility planning and groundwork for future upgrades. The fixture was used without coil interference, and specimens were friction welded under varying speeds and cooling conditions using only mechanical friction and axial pressure as shown in fig. 2-3.



Fig - 3: welded joint

3. Process Parameters and Design of Experiment

Friction welding performance is heavily influenced by process variables such as rotational speed, axial pressure, burn-off rate, and cooling method. In this project, the key experimental variables were rotational speed and cooling environment, while other operational factors such as axial load and friction time were applied manually and kept consistent as far as practically possible. During welding, the axial pressure was manually applied using a screw-type loading mechanism as shown in table 2. A gauge connected to the loading system displayed pressures in kg/cm², and during most welds, readings were maintained in the range of 9–10 kg/cm², which corresponds to approximately 18–20 MPa considering the specimen contact area. Although manually controlled, the loading was applied carefully and uniformly for all specimens based on visual flash formation and timed operator coordination. Frictional contact was maintained for approximately 10–12 seconds, which was sufficient for visible flash to form and the material at the interface to plasticize. This was immediately followed by stopping the rotation and applying forge pressure for 2–3 seconds.

Table - 2: Welding Trial Matrix

Trial No.	Rotational Speed (RPM)	Cooling Method
1	2000	Air
2	2000	Water
3	2000	Oil
4	3000	Air
5	3000	Water
6	3000	Oil
7	4000	Air

8	4000	Water
9	4000	Oil

Each welded specimen was marked according to its parameters and stored for post-weld inspection and tensile testing. The structure of this trial matrix allowed for comparative analysis of flash formation, surface appearance, and mechanical performance under different thermal and rotational inputs. Among the DOE methods, Taguchi's robust design approach has been widely applied in manufacturing, material science, and mechanical engineering applications. Taguchi emphasized that the primary goal of experimentation is not only to optimize performance but also to reduce sensitivity to uncontrollable variations, often termed as noise factors. The Taguchi method is adopted to design experiments for evaluating the influence of drilling parameters—namely tool speed (rpm), feed rate (mm/min), and shoulder diameter (mm)—on the performance of natural fiber-reinforced composites. These process parameters directly affect delamination, surface quality, and overall machinability of composite laminates.

3.1 Selection of Orthogonal Array

However, using Taguchi's L9 orthogonal array, the same information can be obtained with only 9 trials. The L9 array provides a balanced representation, where each factor level appears exactly three times, ensuring orthogonality and unbiased estimation of factor effects. This reduces experimental effort while maintaining statistical reliability. The adopted L9 orthogonal array with factor assignments is shown in Table 3.

Table - 3: Design of Experiment (L9 Orthogonal Array)

Sr. No.	Tool Speed (rpm)	Feed Rate (mm/min)	Shoulder Dia. (mm)
1	2000	18	14
2	2000	24	16
3	2000	30	18
4	3000	18	16
5	3000	24	18
6	3000	30	14
7	4000	18	18
8	4000	24	14
9	4000	30	16

This structured plan ensures that the influence of each factor across all levels can be studied effectively as shown in table 4 and their corresponding graphs in fig. 4-5.

Table - 4: Response Table for SN Ratio

Level	SPEED (rpm)	FEED (mm/min)	SHOULDER DIA (mm)
1	33.12	34.97	32.93
2	36.60	32.88	32.85
3	32.47	34.34	36.42
Delta	4.13	2.09	3.56
Rank	1	3	2



Fig - 4: Mean of Means plot

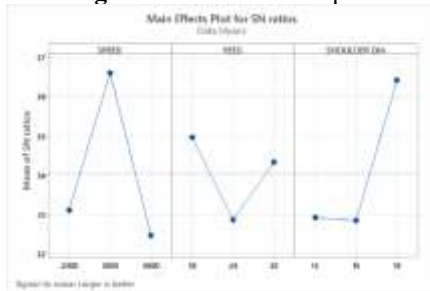


Fig - 5: SN Ratio Plot

4. Results and Discussions

This chapter presents the results and observations obtained from the experimental friction welding of stainless steel and mild steel specimens. The initial objective of the project was to implement a hybrid friction welding setup, combining mechanical friction with external induction heating to improve weld quality in dissimilar metal joints. However, due to limitations in equipment availability and coil system functionality, the induction heating module could not be activated, and the hybrid configuration could not be executed. Therefore, the experimental trials were carried out using conventional rotary friction welding, which formed the foundation of this study. A total of twelve cylindrical specimens were prepared and welded under controlled conditions. The trials were conducted at four different rotational speeds—2000RPM, 3000RPM, and 4000 RPM—and subjected to three different cooling methods: air cooling, water quenching, and oil immersion. These parameters were selected to observe the influence of both speed and cooling environment on the flash formation, visual integrity, and mechanical response of the welded joints.

The welded samples were then evaluated through visual inspection and post-weld mechanical testing. Observations included surface condition, flash symmetry, and material behaviour during and after welding. Mechanical properties such as tensile strength and joint quality were also assessed. The results offer valuable insight into the feasibility and performance of traditional rotary friction welding when applied to dissimilar ferrous materials. After welding, each specimen was subjected to visual inspection to assess flash formation, surface uniformity, and overall weld appearance. A total of twelve specimens were produced using conventional rotary friction welding under four different rotational speeds—2000, 3000, and 4000 RPM—with each speed group followed by one of three cooling methods: air cooling, water quenching, and oil immersion. Visual inspection was conducted immediately after welding and after the cooling stage. Observations focused on flash symmetry, burn-off uniformity, surface discoloration, and potential surface-level defects. The face-contacted ends of the specimens showed full weld contact in all cases, with no visible separation or misalignment between the materials.

At lower speeds (3000rpm), flash was moderate and relatively symmetrical. These samples showed a smoother appearance near the weld interface, with the air-cooled specimens displaying the most uniform finish. Water- and oil-cooled specimens exhibited slight surface discoloration but no defects. At 3000 RPM, flash volume increased slightly. Welds remained visually balanced with no cracking or distortion. In oil-cooled samples, minor darkening was noted around the flash zone but was considered acceptable for process temperatures involved. At 3000 RPM, the highest rotational speed used, flash was more pronounced, particularly on the mild steel side. In water-cooled specimens, rapid cooling led to slight radial deformation around the weld zone, although no surface cracks or separations were visible. Oil-cooled samples at this speed showed the most uniform flash shape despite mild discoloration.

4.1 Tensile Testing Results

To evaluate the mechanical strength of the welded joints, all twelve specimens were subjected to tensile testing using a Universal Testing Machine (UTM). Each specimen was machined to standard sub-size tensile test dimensions after welding and cooling. The test was conducted under a constant crosshead speed, with the load and elongation recorded until fracture.

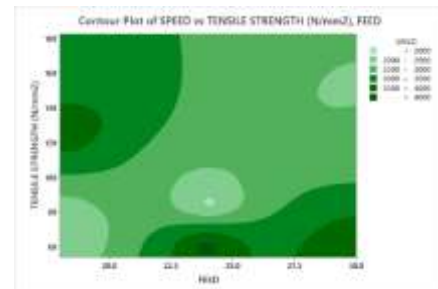


Fig - 6: Tensile strength of specimen based on feed and speed

The primary objectives were to determine the Ultimate Tensile Strength (UTS) and observe the failure mode—whether fracture occurred at the weld zone or in the parent material as shown in fig. 6-7.

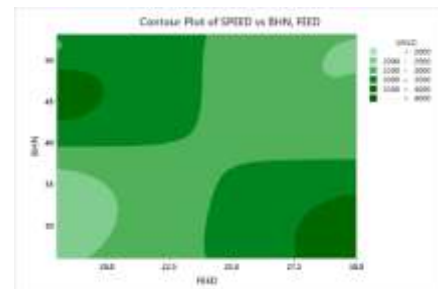


Fig - 7: Hardness base on feed and speed

At 2000 RPM, specimens displayed moderate strength across all cooling conditions. Air-cooled specimens showed slightly higher UTS, with failure typically occurring just outside the weld zone on the mild steel side. Water- and oil-cooled samples recorded slightly lower strength but retained ductile fracture characteristics. At 3000 RPM, the strength improved consistently. Air-cooled specimens again led in performance, with one sample showing fracture away from the interface, indicating a sound weld. Water-cooled specimens had minor strength variation but maintained good bonding. At 2000 RPM, welds performed well across all cooling groups. Oil-cooled specimens recorded the highest strength in this set, while water-cooled specimens showed some strength loss—likely due to internal stress from rapid cooling. At 3000 RPM, flash became

more pronounced, and the weld zone slightly over-softened in some samples. Water-cooled specimens showed reduced tensile values, and some fractured closer to the weld center. Oil-cooled samples at 3000RPM delivered the best UTS of all trials, with stable flash and ductile failure modes.

5. Conclusion

This project aimed to explore the joining of dissimilar ferrous materials—AISI 304 stainless steel and MS1018 mild steel—through the process of friction welding. Although the initial objective was to integrate induction heating to form a hybrid friction welding setup, limitations in equipment and system functionality led to the execution of the project using conventional rotary friction welding only. Despite this, the results obtained from the experimental trials were conclusive, valuable, and demonstrated the practicality and reliability of solid-state welding for such dissimilar material combinations. A total of twelve weld specimens were prepared and tested using four different rotational speeds (2000, 3000, & 4000 RPM), with each speed followed by a different cooling method (air, water, and oil). The welding process produced visually acceptable joints in all cases, with no surface defects, cracks, or porosity detected during non-destructive inspection. Flash formation was consistent and symmetrical in most samples, particularly in air- and oil-cooled conditions. Tensile strength analysis showed that weld quality and performance improved with increasing rotational speed, with the best results observed at 3000 RPM with oil cooling, achieving a peak UTS of 396 MPa. Most specimens fractured in the mild steel base material rather than the weld zone, indicating sound metallurgical bonding and effective joint strength. The process demonstrated repeatability, controllability, and performance levels suitable for structural and fabrication applications. Overall, the project successfully achieved its technical objectives within the limitations of available resources. The findings confirm that rotary friction welding is a viable and efficient method for joining stainless steel and mild steel components and provide a strong performance baseline for future experimentation involving hybrid configurations.

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