

RESEARCH ARTICLE

Analysis of a sustainable welding process for joining copper alloy C23000 to polyethylene polymer as a hybrid joint

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Abstract - Reliable joining of copper alloys and thermoplastic polymers remains a major challenge because of the substantial differences in their thermal and physical properties, and studies on the direct joining of copper alloy C23000 to polyethylene (PE) using pinless friction spot welding (FSW) remain limited. Using FSW with a pinless cylindrical tool, this study investigated a sustainable approach for producing hybrid metal–polymer joints by joining copper alloy C23000 with PE. Tensile shear testing was used to evaluate joint performance after systematically varying the process parameters, including tool rotational speed (1100, 1400, and 1800 rpm) and welding time (1, 1.5, and 2 min). According to the design of experiments (DOE) analysis, the maximum tensile shear strength of 3256 N was achieved at 1400 rpm and 2 min. Due to thermal degradation of the polymer, an excessive rotational speed (1800 rpm) reduced the joint strength. At the copper–PE interface, scanning electron microscopy (SEM) revealed a well-formed mechanical interlock with an interfacial width of 19–24 µm, indicating good interfacial continuity and a low density of observable defects. The results indicate that pinless friction stir welding is an effective, environmentally friendly solid-state joining technique for producing reliable metal–polymer hybrid joints without additional adhesives or mechanical fasteners. In conclusion, the developed joints demonstrate significant potential for lightweight applications in the automotive, aerospace, and electronics industries, where mechanical reliability, recyclability, and weight reduction are critical requirements.

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1. Introduction

The demand for novel materials and joining technologies that enable weight reduction, cost efficiency, and multifunctionality has increased with the advancement of modern manufacturing, particularly in the transportation, electronics, and energy sectors. One possible approach involves using hybrid joints that combine metals and polymers to take advantage of the unique qualities of both material types. In particular, the combination of thermoplastics and copper alloys is highly desirable because of its complementary mechanical, thermal, and electrical properties [1]–[3]. Friction spot welding (FSW), a solid-state welding method developed primarily for lightweight aluminium alloys, has, due to its ability to generate controlled and localized heat, been gaining increasing popularity as a means of joining dissimilar materials [4]–[6]. FSW applications allow a portion of the polymer material near the metal interface to soften without completely melting the metal component and induce mechanical interlocking between the two materials under appropriate processing conditions [7]–[9]. Compared with typical fusion-based joining methods, this method results in lower defect rates because it reduces the likelihood of the following: porosity, excessive damage to the interface, and associated polymer degradation. However, excessive heat input into the polymer matrix can still degrade the polymer and reduce joint quality [10]–[12]. Red brass, also called copper alloy C23000, is a high-strength, corrosion-resistant material with exceptional thermal and electrical conductivity, making it ideal for automotive and electronic connectors [13]–[15]. In contrast, polyethylene (PE) is an inexpensive, chemically resistant polymer frequently used in insulation, lightweight construction, and pipes [16]–[18]. Hybrid constructions in smart grids, electric vehicles, and lightweight consumer electronics can be enabled by joining C23000 brass to PE [19]–[21]. Because copper alloys and PE differ in thermal conductivity, coefficients of expansion, bonding behaviour, and surface energy, joining them is challenging [22]–[24]. If these differences are not properly addressed, they can lead to interfacial flaws such as voids, delamination, or weak mechanical interlocks. The primary bonding mechanism in metal-to-polymer hybrid joints produced by friction-based joining processes is not metallurgical bonding, but rather mechanical interlocking and polymer flow. As the metal/plastic joint is welded, frictional heat softens the polymer layer, allowing the polymer to flow and fill surface irregularities and imperfections in the metal substrate. When the polymer cools, it resolidifies, forming a mechanical interlock that makes a major contribution to the integrity of the joint. Therefore, the quality of the joint is strongly influenced by the degree of polymer softening, the interfacial morphology, and the effectiveness of the mechanical interlocking developed at the metal–polymer interface [25], [26].

With FSW, a strong and reliable joint between such dissimilar materials can be achieved through a combination of mechanical interlocking, localized heat control, and tool design optimization [27], [28].

R. N. Bulacu et al. investigated a unique method that uses a cylindrical pinless tool to join copper alloy C23000 to PE by combining FSW with mechanical interlocking. Tensile shear testing was used to evaluate the mechanical performance of the joints, while non-contact 3D optical scanning and scanning electron microscopy (SEM) were used to characterize the failure morphology. Furthermore, a temperature-dependent finite element method (FEM) was used to predict the heat

distribution across the joint interface in a comprehensive thermal model. The study investigated key variables and correlated them with joint strength and defect formation, including heat input, tool plunge depth, rotation speed, and holding duration [18].

Furthermore, by promoting hybrid lightweight assemblies that improve material efficiency and recyclability, particularly in the automotive and aerospace industries, Q. Chen et al. contributed to the global sustainability trend. By reducing the use of mechanical fasteners and adhesives, hybrid joints support material recovery during recycling and simplify disassembly [19]. These findings add to the growing body of knowledge on joining metals and polymers and demonstrate the versatility of FSW as a sustainable and commercially viable process for complex, multi-material parts. The findings contribute to the growing body of research on metal–polymer joining and demonstrate the versatility of FSW as a sustainable and commercially viable method for complex, multi-material components.

Most existing research on using friction welding to join metals and polymers focuses primarily on aluminium or steel joined with polymers. In practice, joint formation often depends on the workpieces being heated through the mechanical action of interfacial flow, the softening of polymer materials due to possible shear effects, and the mechanical creation of interlocking features. Sufficient evidence already exists in the literature to show that friction-based joining methods are feasible alternatives to traditional adhesives for joining dissimilar materials into a single joint, but many of these studies and the associated processes are limited by: (1) the use of pin-assisted tooling; (2) the need for surface treatments prior to joining; and (3) the requirement to pre-drill holes in the metallic components before friction welding, thus increasing the complexity of interlocking. Another limiting factor is that most current research studies use aluminium alloys as the metallic component, leaving very few studies that explore the direct joining of high-conductivity copper alloys to thermoplastic polymers. Using copper alloys for joining presents unique challenges because their high thermal conductivity causes the generated friction heat, or friction energy, to dissipate rapidly into the copper alloy workpieces. This directly affects polymer softening at the particulate interface, so further research and analysis are required to investigate the feasibility of producing viable Cu–PE joints using an agglomerate-free and pinless FSW method [29]–[32]. This study aimed to develop and experimentally evaluate a sustainable joining method for the copper alloy C23000 and PE polymer using a pinless cylindrical FSW tool, while assessing the effects of parameters such as rotating speed and welding time on joint strength and interfacial morphology, as supported by tensile shear testing and SEM analysis. This is a new method for joining copper alloy C23000 and PE using a pinless friction spot welder as the welding process, and the effects of the welding parameters and the interfacial microstructure on the mechanical performance will be evaluated without using mechanical or adhesive fasteners. This research uniquely demonstrates the feasibility of directly joining C23000 copper alloy to PE through localized heat control and optimized process parameters, unlike prior studies on metal–polymer joining that mainly focused on aluminium-based alloys or surface treatments, thus enhancing the applicability of FSW to high-conductivity metals in hybrid structures.

Previous research on metal–polymer FSW has mostly been limited to conventional pin-assisted tools and commonly used aluminium/polymer or steel/polymer systems. However, the literature lacks studies on joining copper alloy C23000 with PE using a pinless friction stir-based method. Therefore, this study aims to fill this gap by investigating the feasibility of producing Cu C23000–PE hybrid joints through shoulder frictional heating without pin penetration. The novelty of this work involves the correlation of the process parameters with the welding temperature, interfacial layer thickness, and joint strength, providing a better understanding of the bonding behaviour in copper–PE hybrid joints.

2. Materials and Methods

Copper alloy C23000 and PE polymer were selected as the base materials for this research. Copper alloy C23000 is a brass alloy composed of 70% copper and 30% zinc. This alloy exhibits excellent corrosion resistance in seawater and other environments, along with good mechanical properties. Copper alloy C23000 sheets with a thickness of 0.5 mm were obtained in the as-received condition. At the same time, PE polymer is a thermoplastic polymer with good chemical resistance and weldability. PE plates with a thickness of 2 mm were fabricated using CNC machining (CNC vertical milling machine (3-Axis CNC Mill) (Haas Mini Mill (VF-2))). FSW tools were made from high-speed steel with a hardness of approximately 63 HRC. The tool's geometric configuration included a shoulder diameter of 13 mm. The pinless tool was manufactured using a CNC lathe machine (CNC turning machine, Haas ST-10, USA). The pinless tool reduces penetration into the PE layer, polymer tearing and material expulsion, and keyhole-related defects, while increasing more uniform heat generation through shoulder friction. These features make the pinless configuration more suitable for achieving stable interfacial bonding in Cu–PE hybrid joints than traditional pin-assisted FSW tools.

A vertical milling machine was retrofitted to support FSW processes. The milling machine's vector drive head was modified with an inverter to control the spindle rotation speed. This study used a hybrid joint configuration with a copper alloy on the upper metal side and a polymer on the bottom side. The samples used for joining were fabricated with dimensions of 100 × 25 mm for the copper alloy and plastic polymer. Figure 1(a) illustrates the samples and the joint. Figure 1(b) illustrates the joining tool, while Figure 1(c) shows the FSW process used to join PE to copper metal. The copper alloy and PE specimens were prepared in a lap joint configuration with an overlap area of 25 mm × 25 mm. During the welding process, the copper sheet remained on top, while the PE remained underneath at all times.

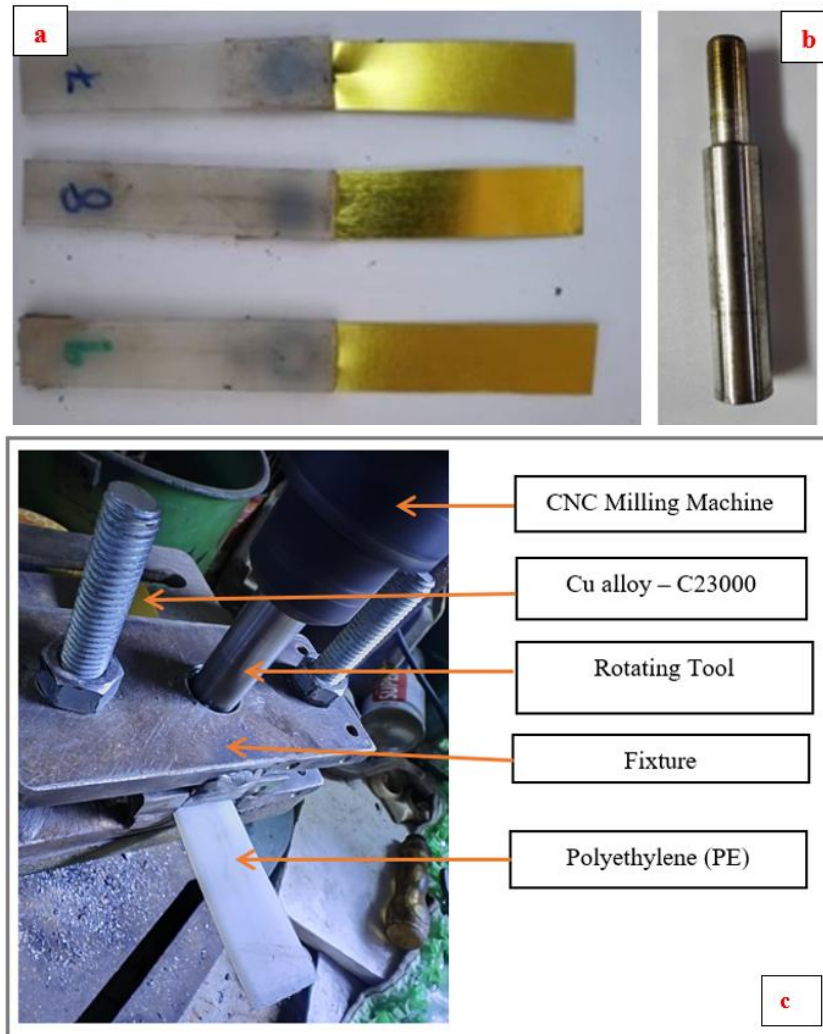


Figure 1. FSW welding process for joining copper to PE: a) samples after joining, b) tool used for joining, and c) welding setup

2.1 Experimental Methods

The FSW process was used to join copper alloy C23000 to PE polymer. The process was carried out on a horizontal milling machine with a simple modification. A rotating percussion tool was used to generate rotary motion and release heat on the surface of the copper specimen, thus creating a hybrid joint configuration between the welded copper and PE. During the FSW process, the temperature at the tool tip could reach 150°C because of heating of the copper material. To monitor the temperature generated by FSW, we attached a K-type thermocouple to the upper surface of the copper alloy workpiece near the tool/parent workpiece contact region. In this experiment, the thermocouple measured temperature continuously throughout the entire welding cycle. The maximum temperature produced during the welding process (under the welding conditions used) was approximately 150°C. Temperature measurements were taken to ensure that sufficient heat had been generated to soften the PE and bond it to the parent material at the interface.

The welding parameters were designed to vary the tool's rotation speed (RS) at 1100, 1400, and 1800 rpm, while the times (Ts) were set to 1, 1.5, and 2 min. The tool was fabricated from high-speed steel (HSS) using a computer numerical control (CNC) milling machine and then hardened at 650°C for 1 h to achieve good wear resistance. The welding tool has a cylindrical shape with a diameter of 13 mm. Table 1 shows the parameters for joining copper C23000 to the polymer (PE).

The experimental matrix was constructed using the Taguchi method with an L9 orthogonal array. The two process parameters employed in this investigation were rotation speed and welding duration, each at three levels. The Taguchi experimental design used a systematic evaluation of the effects of welding parameters on tensile shear performance while minimising the number of experiments. As a result, nine experimental conditions were created and analysed using Design of Experiments (DOE) and ANOVA techniques to determine parameter trends and optimum welding conditions.

Each experimental condition was repeated three times to ensure the reliability and reproducibility of the results obtained. Furthermore, mean values and standard deviations were calculated and included in the analysis to estimate the error and improve the statistical reliability of the experimental findings.

Table 1. Parameters used to join copper C23000 to the polymer (PE)

Sample No.	Rotational Speed (rpm)	Time (min)
1	1100	1
2	1100	1.5
3	1100	2
4	1400	1
5	1400	1.5
6	1400	2
7	1800	1
8	1800	1.5
9	1800	2

2.2 Mechanical Tests

FSW samples were subjected to tensile shear testing using a tensile testing instrument with a maximum capacity of 100 KN. The dimensions of the lap joints of the examined sample were 175 mm in length and 25 mm in width. Two shims were positioned in opposite directions, as shown in Figure 2, to prevent slippage and bending during the tensile shear test, and the cross-head velocity for the tensile shear test was 10 mm/min.

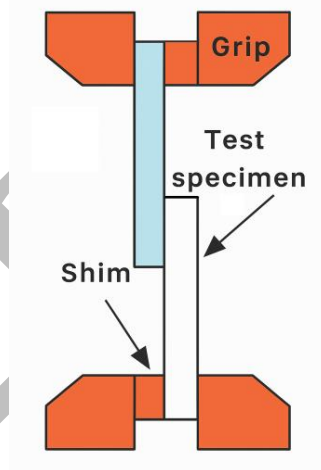


Figure 2. Schematic of the tensile shear test

2.3 Scanning Electron Microscope

In accordance with ASTM E 407-99, the sample microstructure was examined by grinding the surface with SiC emery papers of various grit sizes (P400, P600, P800, P1000, P1200 and P2000) [7]. Alumina particles of different sizes (0.3, 0.05, and alumina 3) were used during the polishing procedure. After cleaning it with water and alcohol, the specimen was left to air dry.

The joint features were examined and analysed using energy-dispersive spectroscopy, which revealed the percentage distribution of the elements. The microstructure of the joint cross-section and the metal–polymer interface was inspected using a scanning electron microscope.

3. Results and Discussion

3.1 Mechanical Testing

The results of the tensile shear strength test for the nine specimens joined using the FSW process are shown in Figure 3. As shown in Figure 1, all samples are fully welded. Specimen number six achieved the highest tensile shear force when welded at a rotation speed of 1400 rpm for 2 min, resulting in a tensile shear force of 3256 N. Specimen number one showed the lowest tensile shear force when welded at a rotation speed of 1100 rpm for 1 min, with a tensile shear force of 1210 N, as illustrated in Figure 3.

The tensile shear strength increased notably under the optimum welding process conditions with appropriate parameters and was reduced to a minimum with other parameters, according to the data shown in Figure 3. The welded hybrid joint of copper C23000 to PE polymer samples was thus affected differently by the FSW joining method.

The highest maximum tensile shear force of 3256 N, measured under the most favourable welding conditions (1400 rpm and 2 min of weld time), demonstrates excellent interfacial bonding between Cu and PE, as supported by previous literature. Specifically, earlier studies have shown that sufficient frictional heating significantly influences the bonding quality and strength of metal–polymer joints produced using rotational friction methods [22], [32]. In contrast, extremely high rotational speeds have generated excessive thermal energy input, causing polymer damage and/or excessive mechanical degradation of the joint [29]. Therefore, our results support the conclusions reported in the literature regarding the effectiveness of pinless friction spot welds for producing Cu–PE hybrid welds.

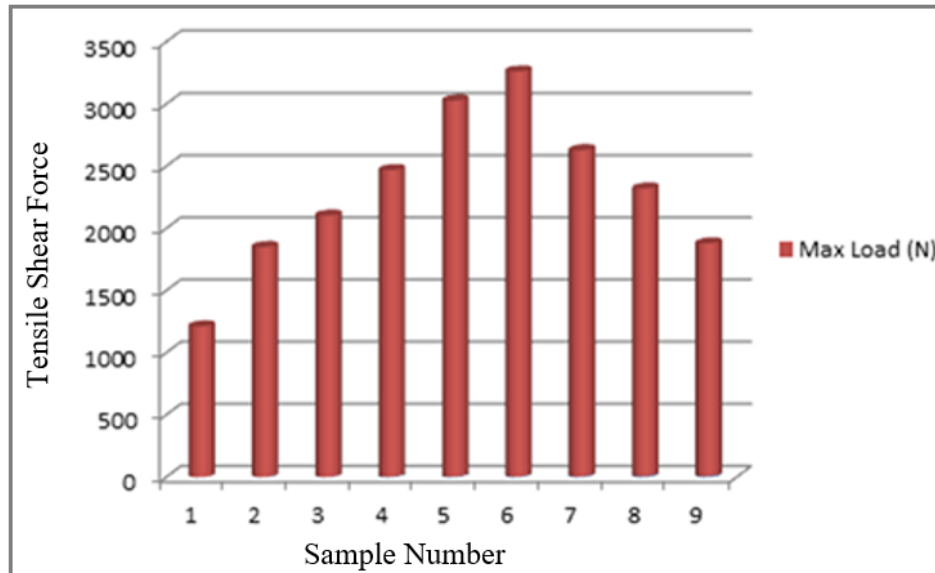


Figure 3. Tensile-shear force results for C23000 copper alloy-to-PE polymer hybrid joints welded at different rotational speeds and welding times

3.2 Design of Experiment (DOE)

The Taguchi analysis method was used to evaluate tensile shear force with the Minitab application to determine the optimal parameter levels. This method enables investigation of the effect of joining parameters on joint strength. It yields an improved tensile shear force. Figure 4 illustrates how rotational speed and time influence joint strength. The tensile shear force increases as the processing time increases from 1 to 1.5 min and continues to increase at 2 min. Additionally, joint strength improved when the tool's rotational speed was increased from 1100 to 1400 rpm. However, the tensile shear force of the strength of the joint decreased when the rotational speed was continuously increased to 1800 rpm, as shown in Figure 4.

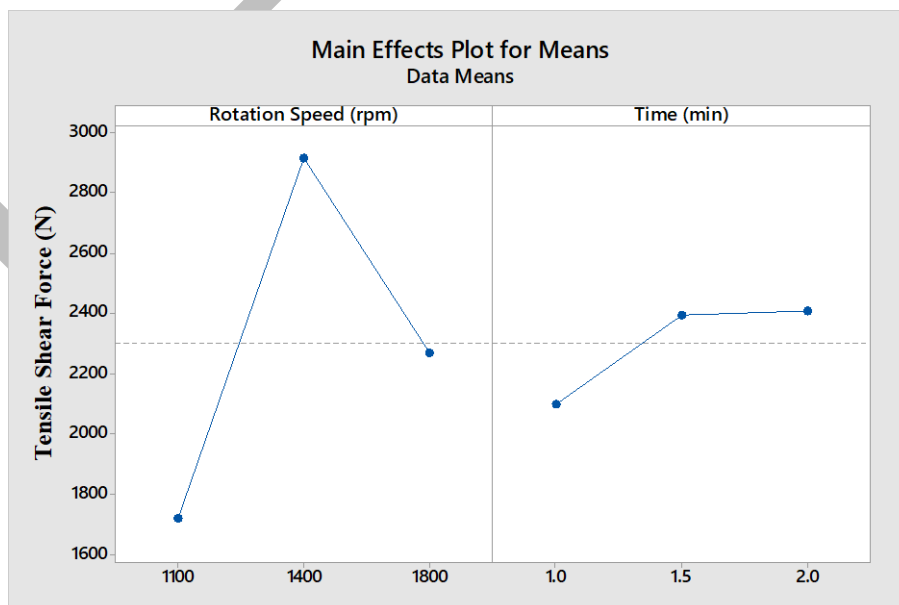


Figure 4. Main effects plot of the process parameters and their effect on tensile shear force

By analysing the main effects plot to determine whether there were any clear patterns of variation in joint performance as the process parameters changed, we could assess how sensitive the hybrid joining process was to various welding

parameters. Based on these findings, the discussion was refined to more effectively distinguish the dominant variables from the other less influential process parameters, improving our understanding of the effects of those parameters on joint performance.

To further examine the effect of welding parameters on armature-specific transactional operations via the mechanical performance levels of hybrid joints, we conducted a statistical evaluation of the experimental data using the Taguchi experimental approach. The analysis showed that both welding speed and duration affected the joint's tensile shear strength, with rotational speed having a greater practical effect than welding time. The best combination of welding speed and duration is 1400 rpm and 2 minutes, respectively, which yields a maximum tensile shear strength due to the satisfactory generation of high frictional heat and bond formation between the copper alloy and polyethylene. On the contrary, increasing the welding speed to 1800 rpm reduces tensile shear strength because excessive heat generated during welding causes local degradation of the polyethylene. The experiment shows that the critical aspect of producing hybrid joints with good mechanical properties is finding a balance in thermal input. Table 2 shows the ANOVA results for the tensile shear strength of the copper C23000\PE polymer joints.

Table 2. ANOVA results for the tensile shear strength of Cu–PE hybrid welded joints

Source	DF	Sum of Squares	F-Value	p-Value
Rotational Speed	2	2,155,950	5.02	0.081
Welding Duration	2	197,617	0.46	0.661
Error	4	859,474	—	—

The analysis of variance showed that the tensile shear test results were more dependent on rotation speed than on welding time. The test confirmed no significant impact at the 95% confidence level, which contradicts the experimental data showing a significant effect of rotation speed on the value of tensile shear strength, which can be assumed to take place at a moderate value of rotation speed (1400 rpm) and welding time (2 min).

The contour plot showing the effect of rotation speed and welding time on tensile shear test results is shown in Figure 5. The colours and shades on the plot, particularly the greenish hues, indicate performance zones: darker hues mark stronger connections, while paler colours indicate weaker performance.

From the data obtained so far, it can be concluded that heat input and processing time influence the joint connection, but only to a certain degree, as these parameters soften the polymer. The response surface shows that combinations of rotation speed and welding time yield relatively high tensile shear strength values. As a result, the ideal conditions derived from the presentation should be treated only as trends. The analysis has revealed the maximum tensile strength at 1400 rpm and 2 minutes, which corresponds to the data obtained from Design of Experiments approaches used during testing. Based on the contour plots, relatively high tensile shear values could be achieved using various combinations of rotational speed and welding time (e.g. high rotational speeds with short welding times or moderate rotational speeds with longer welding times). However, because this contour plot is an interpolated graphical response surface generated from the experimental data, it represents only a trend in the experimental results rather than actual experimental results from the collected data. Based on these two sources of evidence (i.e. experimental data (Figure 3) and interaction analysis data (Figure 8)), the optimal welding conditions were determined based on the experiments that produced the maximum measured value at 1400 rpm for 2 min, which was 3256 N.

These findings are consistent with the DOE results and confirm the critical importance of parameter adjustment in hybrid metal–polymer FSW applications.

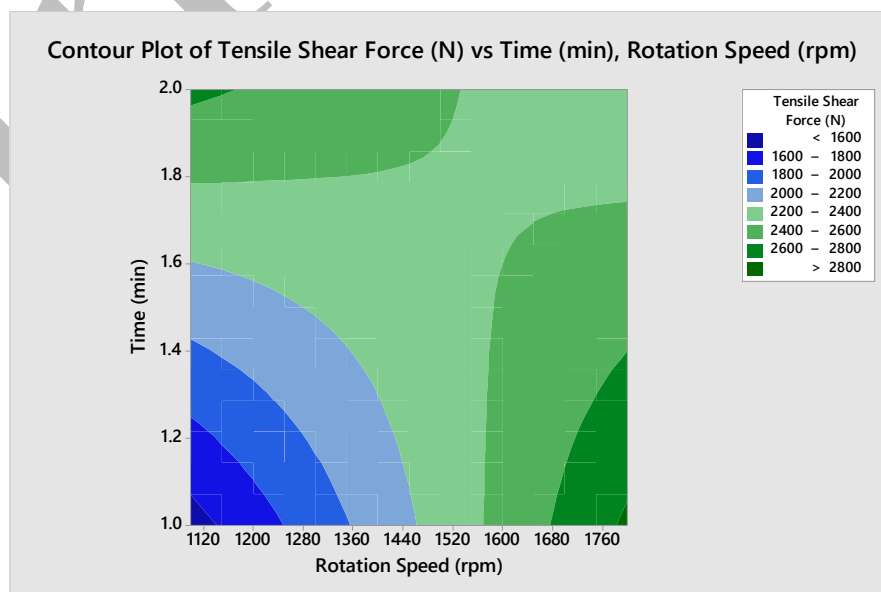


Figure 5. Contour plot of the effect of process parameters on tensile shear force

Figure 6 shows a Pareto chart of the standardized effects of the process parameters: rotation speed (A), welding time (B), and their interaction (AB) on the tensile shear force of the copper–PE hybrid joints. The red vertical reference line indicates the critical t-value (2.571) at a significance level of $\alpha = 0.05$, serving as the threshold for statistical significance. The chart shows that the individual factors and their interaction did not reach the significance threshold indicated by the reference line. Therefore, within the studied parameter range, the effects of rotor speed, welding time, and their interaction on tensile shear force were not statistically significant at the 95% confidence level. However, the relative values of standardised effects provide a good indication of the magnitude of these factors' influence on the joints' properties. The interaction effect (AB) has the highest standardised value, indicating that the combination of rotor speed and welding time affects strength more than either factor alone. The rotor speed (A) has a greater impact than the welding time (B), which has the lowest standardised effect.

In practical terms, even though the statistical assessment indicates no significance at the chosen α value, the larger contribution of the interaction term aligns with the trends depicted in the contour plot (Figure 5), showing that the highest strength is observed for specific combinations of moderate-to-high rotor speed and long welding time. This means that it is more important to improve both factors simultaneously than to improve either one separately.

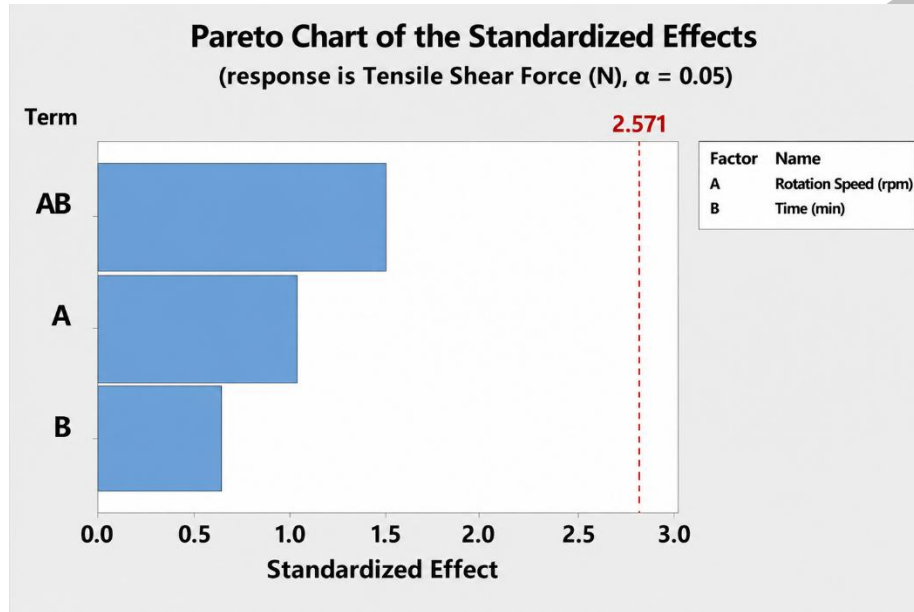


Figure 6. Pareto chart of the effect of process parameters on tensile shear force

Figure 7 shows the residual plots for the tensile shear force model, including the normal probability plot, residuals versus fits, histogram, and residuals versus order. These plots are used to evaluate the validity of the statistical model assumptions and the adequacy of the fit.

Figure 7 shows the results of the residual analysis, indicating that the statistical model adequately describes the relationship among rotational speed, weld time, and shear force. The clustering of residual points around the reference line in the normal probability plot suggests that the normality assumption is reasonable. However, residuals deviating from the normal distribution at both ends are attributable to variations in experimental execution and the limited sample size (observations). The residuals are randomly distributed near zero, indicating no significant nonlinearity or heteroscedasticity with respect to the predicted values. In addition, the histogram of residuals shows an approximately symmetric distribution centred near zero, further supporting the assumption of normality. No systematic trend in the residuals with respect to the sequence of experiments has been observed, indicating stable testing conditions and no run-order effect. Hence, the residual analysis supports the validity and appropriateness of the statistical model developed to assess the tensile shear characteristics of Cu–PE hybrid joints.

The residual analysis confirms that the regression model used to represent the relationship between rotation speed, welding time, and tensile shear force is statistically adequate and does not violate the model assumptions.

Figure 8 shows the interaction plot between rotation speed and welding time for the tensile shear strength of the copper–PE joints. The three curves represent rotational speeds (1100 rpm, 1400 rpm, and 1800 rpm), while the welding durations of interest (1 min, 1.5 min, and 2 min) are shown on the x-axis.

At 1100 rpm, the increase in tensile shear force goes hand in hand with the welding time, climbing from about 1200 N at 1 min to more than 2000 N at 2 min. Thus, longer processing times at relatively low speeds can generate more heat, thereby enhancing polymer softening and mechanical interlocking.

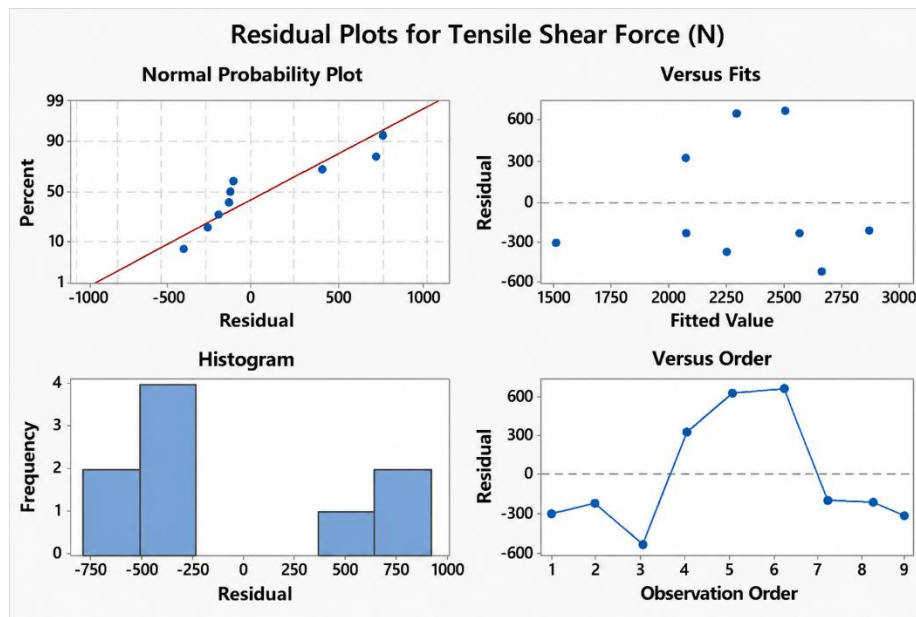


Figure 7. Residual plots showing the effects of process parameters on tensile shear force

At 1400 rpm, the joint strength is optimal across all combinations considered, steadily increasing from approximately 2500 N at 1 min to about 3250 N at 2 min. Thus, it can be concluded that at 1400 rpm, an optimal balance between heat generation and polymer stability is achieved, resulting in improved bonding without excessive surface burning. On the contrary, at 1800 rpm, as welding time increases, the tensile shear force decreases, going from approximately 2650 N at 1 minute to about 1850 N at 2 minutes. Thus, it can be assumed that, as the thermal input at higher speeds becomes excessive and the process takes longer, some thermal changes will occur in the polyethylene, leading to weakening at the interface and possible formation of voids.

Thus, based on the interaction plot, there is a significant interaction effect between welding time and speed, which supports the observations from the contour plot (Figure 5) and the Pareto chart (Figure 6). Hence, it is evident that to achieve the best joint performance, both parameters must be adjusted; in this case, 1400 rpm and 2 minutes were found to be the best combination for the analysis.

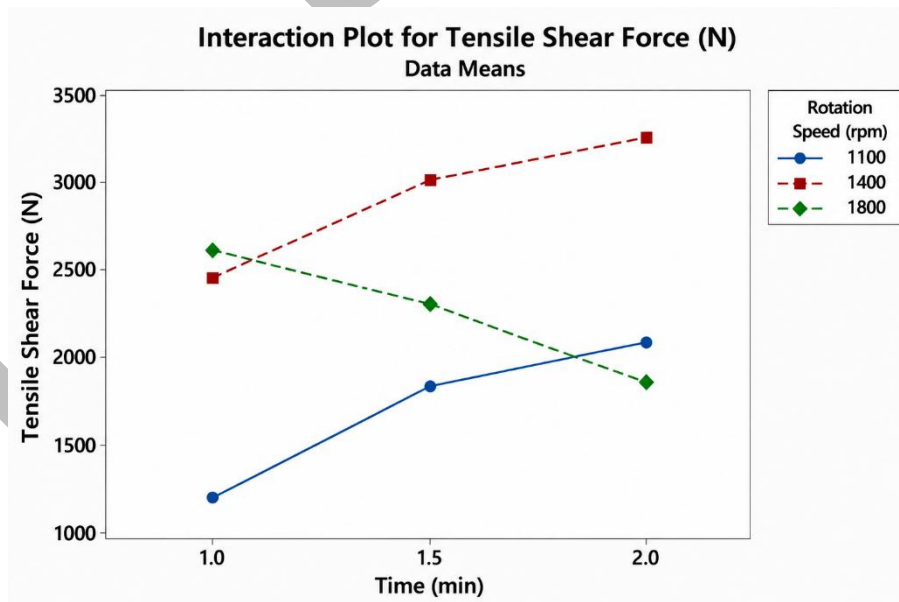


Figure 8. Interaction plot of the effects of process parameters on tensile shear force

Figure 9 illustrates a three-dimensional surface graph showing the interaction between welding time and rotation speed and the tensile shear load of copper-PE hybrid joints. The graph clearly illustrates the surface response, which helps determine the effect of process parameters.

From the surface response, it has been observed that low rotational speeds (~1100-1250 rpm) lead to low tensile shear values (~1200-1600 N), irrespective of the welding time, because little frictional heat is generated and insufficient polymer is distributed on the copper surface.

The tensile shear force reaches its peak value (about 3000-3250 N) when a moderate speed (of around 1400 rpm) is taken into account together with a long welding time (around 2 min), which proves that this is the optimum condition in terms of heat needed to achieve firm mechanical interlocking of the components without producing any significant thermal damage to the polymer.

When the rotation speed reaches around 1800 rpm, the tensile shear values are much lower than those obtained at 1400 rpm, particularly for longer welding durations. This demonstrates that polymer degradation occurs, resulting in weakened bonding.

From the surface plot, it can be determined that there is an ideal operating region where the rotational speed and time are around 1400 rpm and 2 minutes, respectively.

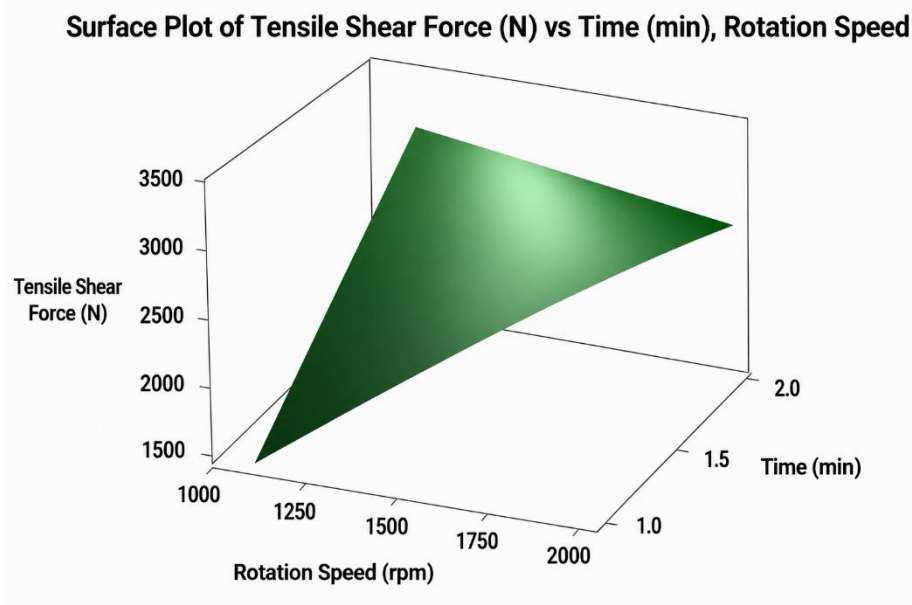


Figure 9. Surface plot of the effects of process parameters on tensile shear force

3.3 SEM

SEM studies were conducted on sample No. 6, which exhibited the highest shear force, to determine the interface between the two hybrid materials, copper C23000 and PE. The cross-section of the joint's microstructural zones, comprising the base materials and resolidified PE over the treated metal surface, is shown in Figure 10. SEM was performed to examine the continuity and morphology of the copper-to-PE (Cu-PE) interface and to determine the thickness of the interfacial region produced by FSW. The results showed that the copper alloy surface (C23000) contained interfacial layers with average thicknesses ranging from approximately 19 to 24 μm . The SEM images showed that there is a relatively continuous interfacial region between the metal and PE, as evidenced by the apparent adhesive properties and well-connected physical contacts at both interfaces. In conclusion, the overall morphology of the interfacial layer suggests that the primary mechanism involved in the joining process is the formation of an interfacial-bonding layer during polymer softening and the subsequent resolidification of the polymer. The morphology observed by SEM is consistent with the formation of mechanical interlocking. The interfacial layer thickness of approximately 19–24 μm is significant for load transfer across the Cu-PE interface. During the welding process, PE softens and flows into surface irregularities in the copper substrate and then solidifies, creating a mechanically interlocked structure. This interlocking under tensile shear loading increases the effective contact area and strengthens resistance to interfacial sliding, thus improving the load transfer between the two dissimilar materials. The higher tensile shear force of 3256 N obtained experimentally is consistent with the more continuous and better-developed interfacial morphology under the optimum welding conditions (1400 rpm and 2 min).

The thickness of the interfacial layer is approximately 19 to 24 μm at the copper/PE interface and is within the range of thicknesses reported for friction-based metal-polymer joining processes. Consistent with other studies documenting interfacial layer thicknesses ranging from several micrometres to tens of micrometres in association with effective bonding and load-bearing capacity, the interfacial thicknesses observed in this study indicate that a well-defined interfacial-bonding region is formed at the copper alloy-PE interface.

The SEM results indicate that the amount of heat generated by the FSW process during welding considerably affected bond formation between the C23000 alloy and the PE polymer in the hybrid joints. When the shoulder began rotating on the specimen surface, it generated a localized thermal energy zone at the joint interface, which led to softening of the PE layer and close contact between the joining surfaces. Furthermore, softening improved the mechanical interlocking and adhesive bonding between the copper alloy C23000 and the PE polymer layers in the welded joints.

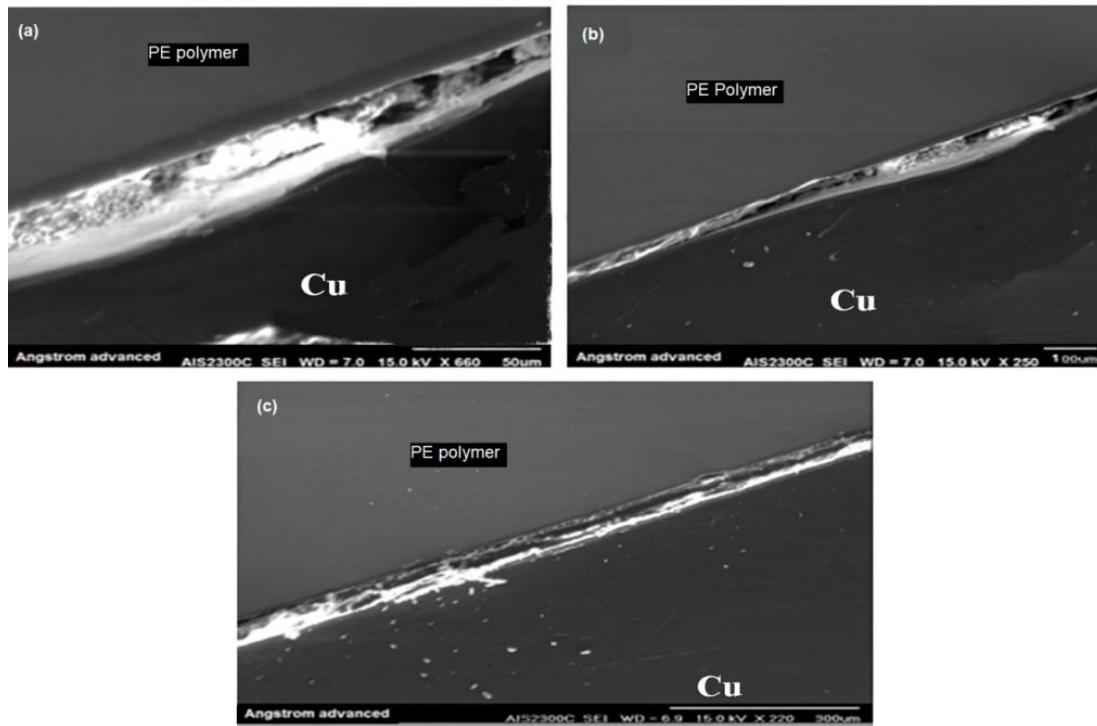


Figure 10. Scanning electron microscopy (SEM) images of the Cu alloy–polymer (C23000–PE) interface welded at a rotational speed of 1400 rpm for 2 minutes: (a) interface at $\times 660$ magnification, (b) interface at $\times 250$ magnification, and (c) interface at $\times 220$ magnification. The interface shows uniform bonding characteristics and improved interfacial continuity

Moreover, the SEM images indicate that the optimum welding parameters created a uniform interface, showing that the interfacial morphology and characteristics of mechanical interlocking were consistent with the tensile shear strength results obtained in this study for these samples. However, excessive thermal energy input (TEI), due to high rotational speed, resulted in localized thermal degradation and cavitation at the interface, which essentially reduced the bond shear tensile strength and mechanical performance of the hybrid-welded samples.

3.4 Sustainability Considerations

The proposed process, FSW, for joining copper C23000 to PE offers many potential environmental benefits compared with traditional methods of joining materials using adhesives, rivets, or other fasteners. Hybrid joints created through a frictional-heating process will require fewer additional materials during assembly and enable simpler assembly operations than traditional methods.

Using a pinless tool (pinless tooling) minimizes material removal and thus reduces the amount of waste produced by the process. In addition, because the heat generated by friction is localized, it is confined to the area around the joint, providing greater efficiency than fusion processes, which require excessive heating.

Although this study did not include a quantitative analysis of energy consumption, greenhouse gas emissions, or life cycle impacts associated with energy use and the overall environmental impacts of the process, the results obtained from this work suggest that FSW is an efficient method for joining metal/polymer structures. Future research should focus on implementing detailed energy monitoring and life cycle assessment methods to quantify the environmental performance of Cu–PE hybrid joints relative to existing joining technologies.

4. Conclusions

This study clearly demonstrated that using a pinless cylindrical tool design and FSW to join copper alloy C23000 to PE polymer is feasible. Our findings show that the highest tensile shear strength, 3256 N, was achieved under the optimal process conditions: a rotational speed of 1400 rpm and a welding time of 2 min. The DOE analysis showed that the effect of rotational speed on tensile shear performance was more pronounced than that of welding time within the studied parameter range. The observed trends suggest that both parameters affect the behaviour of the joint, but the ANOVA results did not indicate statistical significance at the 95% confidence level. An excessively high rotational speed of 1800 rpm can reduce strength by causing thermal degradation of the polymer.

A well-formed mechanical interlock with an interface width of 19 to 24 μm was observed at the copper–PE contact via SEM. This interlocking, together with localized heat softening of the polymer, enabled strong adhesion and resulted in few interfacial flaws.

The results demonstrate the potential of FSW as an effective and environmentally friendly method for producing hybrid metal–polymer joints without additional fasteners or adhesives. These joints show strong potential for applications in the electronics, automotive, and aerospace industries, where recyclability, mechanical reliability, and weight reduction

are critical. Future research should focus on environmental durability, fatigue performance, and process scaling for industrial manufacturing.

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Declaration of Competing Interests

The authors declare no relevant financial or non-financial conflicts of interest.

CRediT Author Contribution Statement

- Osamah Sabah Barrak: Methodology; Validation; Investigation; Resources; Software; Writing – review & editing; Project administration.
- Mahmood Mohammed Hamzah: Conceptualisation; Methodology; Formal analysis; Data curation; Visualisation; Writing – original draft.
- Sabah Khammass Hussein: Formal analysis; Project administration; Supervision
- Nabil Kadhim Taieh: Formal analysis; Visualisation; Writing – original draft.

Availability of Data and Materials

- **Available upon request:** The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

References

- [1] F. Lambiase, H. A. Derazkola, and A. Simchi, “Friction Stir Welding and Friction Spot Stir Welding Processes of Polymers—State of the Art,” *Materials*, vol. 13, no. 10, p. 2291, May 2020, doi: 10.3390/ma13102291.
- [2] Y. Wu *et al.*, “Joining copper to thermosetting polymer via ‘Mortise and Tenon’ interlocking and chemical-bonding both in-situ generated during friction stir spot welding,” *J. Manuf. Process.*, vol. 149, pp. 318–330, Sep. 2025, doi: 10.1016/j.jmapro.2025.05.057.
- [3] Z. Wei, H. Duan, G. Weng, and J. He, “Metals in polymers: hybridization enables new functions,” *J. Mater. Chem. C Mater.*, vol. 8, no. 45, pp. 15956–15980, 2020, doi: 10.1039/D0TC03810E.
- [4] K. Kumari, S. Pradhan, C. Samantra, M. Priyadarshini, A. Barua, and D. Dhupal, “Emerging Trends in Ultrasonic and Friction Stir Spot Welding of Polymers and Metal-Polymer Hybrids: A Review of Process Mechanics, Microstructure, and Joint Performance,” *Materials*, vol. 19, no. 8, p. 1602, Apr. 2026, doi: 10.3390/ma19081602.
- [5] S. Eslami, P. J. Tavares, and P. M. G. P. Moreira, “Friction stir welding tooling for polymers: review and prospects,” *The International Journal of Advanced Manufacturing Technology*, vol. 89, no. 5–8, pp. 1677–1690, Mar. 2017, doi: 10.1007/s00170-016-9205-0.
- [6] A. K. Hussein, O. S. Barrak, M. M. Hamzah, and S. K. Hussein, “Friction stir welding AA6061-T6 with multi-objective optimization of parameters,” *Advances in Science and Technology Research Journal*, vol. 19, no. 10, pp. 162–172, Oct. 2025, doi: 10.12913/22998624/207049.
- [7] M. A. R. Pereira, I. Galvão, J. D. M. Costa, A. M. Amaro, and R. M. Leal, “Production of Aluminium-Polymer Joints by Friction Stir Spot Welding,” *Journal of Manufacturing and Materials Processing*, vol. 8, no. 4, p. 179, Aug. 2024, doi: 10.3390/jmmp8040179.
- [8] C. Ding, X. Kang, N. Wu, J. Xiao, S. Gai, and S. Chen, “Improvement of aluminium alloy and polymer single sided coaxial resistance spot welded joint with steel cover plate,” *Welding in the World*, vol. 70, no. 7, pp. 2755–2767, Jul. 2026, doi: 10.1007/s40194-025-02151-x.
- [9] A. Mishra, “Friction Stir Welding of Dissimilar Metal: A Review,” *SSRN Electronic Journal*, 2018, doi: 10.2139/ssrn.3104223.
- [10] S. A. Hussein, A. J. Hashim, S. M. Khaleel, M. A. Al-Obaidi, and F. L. Rashid, “A Review of Recent Improvements, Developments, Influential Parameters and Challenges in the Friction Stir Welding Process,” *International Journal of Automotive and Mechanical Engineering*, vol. 21, no. 2, pp. 11438–11452, Jun. 2024, doi: 10.15282/ijame.21.2.2024.20.0883.
- [11] Hanaa Soliman *et al.*, “Multifunctional Superhydrophobic Coatings for Aluminum and Magnesium Alloys: Applications and Performance - Review,” *Journal of Techniques*, vol. 7, no. 2, pp. 83–100, Jun. 2025, doi: 10.51173/jt.v7i2.2697.
- [12] D. Bouha, A. Kaou, L. Gaidi, B. Moulai Ali, D. Benyerou, and A. K. Bouha, “Evaluation of Friction Stir Welding Process on Defective Polyethylene Pipes: Experimental Study,” *J. Pipeline Syst. Eng. Pract.*, vol. 16, no. 3, Aug. 2025, doi: 10.1061/JPSEA2.PSENG-1827.

- [13] O. S. Barrak, S. Ben-Elechi, and S. Chatti, "Parameters influence on mechanical properties of resistance spot welding: AISI304L/AISI1005," *Pollack Periodica*, vol. 20, no. 1, pp. 102–109, Mar. 2025, doi: 10.1556/606.2024.01142.
- [14] L. E. Melaku and J. Tomków, "Dissimilar friction stir welding of aluminum to polymer: a review," *The International Journal of Advanced Manufacturing Technology*, vol. 140, no. 5–6, pp. 2377–2396, Sep. 2025, doi: 10.1007/s00170-025-16393-y.
- [15] U. W. Gedde, M. S. Hedenqvist, M. Hakkarainen, F. Nilsson, and O. Das, "Processing of Polymeric Materials," in *Applied Polymer Science*, Cham: Springer International Publishing, 2021, pp. 453–487. doi: 10.1007/978-3-030-68472-3_8.
- [16] F. B. Darsono, A. Bahatmaka, M. Hilman, G. Syafei, S. B. Azara, and R. Ramadhani, "Quality of Friction Stir Welding on High-Density Polyethylene-Polypropylene Polymer," 2026, doi: 10.12962/j25481479.v11i2.
- [17] M. M. Hamzah, S. M. Shnain, O. S. Barrak, S. Chatti, and M. A. Al-Obaidi, "Sustainable Friction Stir Spot Joining Process for Aluminum Alloy AA 4045 Parameter Optimization and Mechanical Assessment," *Annals of Dunarea de Jos University of Galati Fascicle XII Welding Equipment and Technology*, vol. 36, pp. 67–72, Dec. 2025, doi: 10.35219/awet.2025.07.
- [18] R. N. Bulacu, M. Dhondt, Y. Demmouche, C. Bădulescu, E. L. Nițu, and D. M. Iordache, "A Review on Friction Stir Welding of Copper: Tool Geometry, Process Parameters, and Joint Properties," *Materials*, vol. 17, no. 21, p. 5374, Nov. 2024, doi: 10.3390/ma17215374.
- [19] Q. Chen *et al.*, "Ultrasonic Welding of Multi-layer PET-Al Composite Current Collector and Al Tab: Joining Mechanism and Resistance Analysis," *J. Mater. Eng. Perform.*, vol. 35, no. 23, pp. 23280–23291, Jun. 2026, doi: 10.1007/s11665-026-13318-y.
- [20] A. Kaştan, "Investigation of welding defects in friction stir spot welding of plastics," *Journal of Elastomers & Plastics*, vol. 55, no. 4, pp. 457–474, Jun. 2023, doi: 10.1177/00952443231158779.
- [21] A. H. Elsheikh, M. Elmiligy, and A. M. El-Kassas, "Optimization of joint strength in friction stir welded wood plastic composites using ANFIS and Cheetah Optimizer," *Journal of Materials Research and Technology*, vol. 34, pp. 2539–2552, Jan. 2025, doi: 10.1016/j.jmrt.2024.12.257.
- [22] Osamah Sabah Barrak *et al.*, "Joining of Polymer to Aluminum Alloy AA1050 By Friction Spot Welding," *Journal of Techniques*, vol. 5, no. 4, pp. 88–94, Dec. 2023, doi: 10.51173/jt.v5i4.1976.
- [23] M. M. Abdulatef *et al.*, "A comparative study of power and vibration signals for different tool pin sizes of friction stir welding," *International Journal of Automotive and Mechanical Engineering*, vol. 23, no. 1, pp. 13278–13294, Mar. 2026, doi: 10.15282/ijame.23.1.2026.9.1007.
- [24] M. A. Sanchez-Miranda, S. R. Vasquez-Garcia, J. J. Villalon-Lopez, N. Flores-Ramirez, M. A. Tamayo-Soto, and J. L. Rivera, "Effect of friction stir welding parameters on the mechanical performance of recycled HDPE plates," *Journal of Thermoplastic Composite Materials*, Jun. 2026, doi: 10.1177/08927057261461201.
- [25] P. K. Rakesh, "Direct joining of polymers to metals," in *Advanced Manufacturing and Joining Technologies for Composite Materials*, Elsevier, 2026, pp. 329–359. doi: 10.1016/B978-0-443-33364-4.00012-2.
- [26] M. A. R. Pereira, I. Galvão, J. D. M. Costa, A. M. Amaro, and R. M. Leal, "Metal-polymer friction stir spot welding enhanced by meso-mechanical interlocking," *The International Journal of Advanced Manufacturing Technology*, vol. 136, no. 10, pp. 4581–4593, Feb. 2025, doi: 10.1007/s00170-025-15105-w.
- [27] S. Bocchi and M. Negrozio, "Experimental Investigation and Finite Element Simulation of the Microstructural Evolution in AA6082 Friction Stir Welded Joints," *J. Mater. Eng. Perform.*, vol. 34, no. 12, pp. 11274–11291, Jun. 2025, doi: 10.1007/s11665-025-10752-2.
- [28] Y. Zhang, Y. Sun, C. Zhao, W. Li, and X. Yang, "Enhancing interfacial integrity in Al/CFRP friction stir welds: Microstructure control and shear strength improvement," *Journal of Thermoplastic Composite Materials*, vol. 39, no. 5, pp. 2148–2169, May 2026, doi: 10.1177/08927057251387075.
- [29] J.-W. Choi, R. Hino, K. Ushioda, H. Fujii, and S.-J. Lee, "Critical Review of Solid-State Welding for Al Alloys with High Joint Efficiency: Friction Stir Welding (FSW) vs. Linear Friction Welding (LFW)," *Metals and Materials International*, vol. 32, no. 1, pp. 139–163, Jan. 2026, doi: 10.1007/s12540-025-02007-5.
- [30] F. B. Darsono *et al.*, "Quality of friction stir welding joints on aluminum 1100 thin plates," *International Journal of Automotive and Mechanical Engineering*, vol. 23, no. 1, pp. 13190–13199, Mar. 2026, doi: 10.15282/ijame.23.1.2026.3.1001.
- [31] J. J. Silva, R. G. C. da Silva, C. L. Morelli, E. A. T. López, and T. F. A. Santos, "Trends and Future Projections in Ultrasonic Welding Research for Hybrid Materials," *Polymers (Basel)*, vol. 17, no. 8, p. 1124, Apr. 2025, doi: 10.3390/polym17081124.
- [32] Y. Zhang, S. Wang, Y. Sun, C. Zhao, and W. Li, "Friction Stir Welding of Dissimilar Materials: A Review on Joining Mechanism, Defects, and Process Optimization," *Materials*, vol. 19, no. 11, p. 2327, Jun. 2026, doi: 10.3390/ma19112327.