Correlation of Base Metal Properties, Process Parameters and Weld Quality in Friction Welding of SiC-Reinforced LM25 Aluminium Matrix

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Abstract—**Friction welding is a solid-state joining process in which the selection of process parameters plays a critical role in producing defect-free and high-strength weld joints. In this investigation, the influence of spindle rotational speed, forging pressure/time, and friction pressure/time on weld quality was examined in relation to the mechanical properties of the base metals. It was observed that yield strength, ductility, and hardness govern the extent of plastic deformation during welding, thereby determining the feasibility of achieving sound joints. Materials with lower yield strength, reduced hardness, and higher ductility exhibited superior weldability compared to those with higher strength and hardness. The study specifically focused on LM25 aluminium alloy reinforced with SiC particles (0–20 wt%), aiming to establish empirical relationships linking base metal properties, reinforcement levels and optimized process parameters. The developed relationships enable prediction of suitable welding conditions for achieving defect-free joints across varying reinforcement levels.**

Index Terms—**Friction welding, LM25 aluminium alloy, SiC reinforcement, Tensile Properties**

I. INTRODUCTION

Friction welding (FW) has emerged as a reliable and energy-efficient solid-state joining technique for similar and dissimilar metals, as well as advanced composites. Unlike conventional fusion welding, FW does not involve melting, which eliminates issues such as porosity, hot cracking and solidification defects, thereby ensuring superior metallurgical integrity [1], [2]. This makes it highly suitable for joining aluminium and its alloys, which are otherwise challenging to weld using fusion-based methods due to their high thermal conductivity and tendency to form refractory oxide films [3], [4]. Aluminium and its alloys are extensively employed in aerospace, automotive, and marine applications because of their high strength-to-weight ratio and corrosion resistance [5], [6]. However, joining aluminium alloys requires strict control of welding parameters to ensure defect-free welds. FW has proven effective in overcoming these challenges by optimizing spindle speed, forging pressure, and friction time, thereby producing high-quality joints [7]. Several investigations have emphasized that the mechanical properties of base materials—particularly yield strength, ductility, and hardness—govern the extent of plastic deformation during welding and thus directly influence joint integrity [8], [9]. Recent advancements have also extended FW to aluminium matrix composites (AMCs), which are reinforced with ceramics such as Silicon Carbide (SiC), to improve strength, hardness, and wear resistance, although the presence of reinforcements complicates weldability [10] – [12].

Aluminium Matrix Composites (AMCs) have received significant attention in recent decades because of their excellent combination of low density, high stiffness, improved wear resistance and better mechanical properties compared to unreinforced alloys [13]. SiC-reinforced aluminium alloys, such as LM25, are widely utilized in aerospace and automotive industries for applications requiring high specific strength and durability [14]. However, incorporating ceramic reinforcements introduces challenges during welding. The difference in thermal expansion between the ceramic and metallic phases often leads to residual stresses, void formation, or particle clustering at the interface [15]. Traditional welding techniques are typically ineffective for AMCs due to cracking and poor wettability between the matrix and reinforcement particles [16]. FW addresses many of these limitations by providing a solid-state joining process that minimizes reinforcement degradation and avoids reinforcement–matrix reaction layers, provided that the welding parameters are optimized [17]. Studies have shown that the successful welding of AMCs depends heavily on the balance between heat generation and plastic deformation, which is influenced by both the base metal properties and the reinforcement content [18]. This creates the need for empirical models that relate reinforcement percentage, base alloy properties, and FW parameters to achieve defect-free and mechanically reliable joints [19], [20].

The role of process parameters in FW has been investigated extensively, as these determine the heat input, extent of plastic deformation, and resultant bond strength. Parameters such as spindle rotational speed, friction pressure, forging pressure and dwell time significantly influence microstructure evolution, flash formation and mechanical properties of welded joints [21], [22]. However, achieving defect-free welds across varying welding conditions remains challenging, especially when the base materials have distinct mechanical properties [23]. For instance, materials with low yield strength and hardness but higher ductility undergo plastic deformation more easily, making them more weldable compared to harder and brittle alloys [24]. In AMCs, the addition of SiC increases hardness and decreases ductility, thereby complicating weldability [25]. Optimizing parameters becomes critical not only to ensure metallurgical bonding but also to avoid defects such as voids, incomplete bonding, or reinforcement clustering [26]. Several researchers have attempted to develop predictive models and empirical equations that link base metal properties and reinforcement levels with optimized welding parameters [27], [28]. These models help establish guidelines for selecting welding conditions suitable for different material systems, offering a pathway toward consistent and reliable production of AMC-based components [29].

Given the industrial importance of LM25 aluminium alloy and its composites, the present study focuses on establishing empirical relationships between FW parameters, base alloy mechanical properties and reinforcement content. Specifically, the study investigates LM25 reinforced with varying amounts of SiC particles (0–20 wt.%) to identify the optimized parameter windows for producing defect-free and mechanically sound joints. The approach highlights the influence of yield strength and hardness of the matrix alloy on weldability and establishes a correlation between reinforcement percentage and welding parameters. The developed empirical models provide a predictive capability to determine optimized FW conditions for a given reinforcement content, ensuring high-strength and defect-free welds. These relationships are expected to serve as a practical tool for engineers and manufacturers working with AMC components in high-performance sectors such as aerospace, automotive and defence. Furthermore, the insights gained contribute to advancing the fundamental understanding of solid-state joining of particle-reinforced composites, thereby bridging the gap between material design and process optimization [30] – [32].

II. EXPERIMENTAL WORK

The experimental work originated with the fabrication of LM25 aluminium alloy-based composites reinforced with varying weight percentages of Silicon Carbide (SiC) particulates. Three different castings were prepared corresponding to 0 wt.%, 10 wt.% and 20 wt.% of SiC reinforcement in the LM25 alloy matrix. The composites were fabricated by adopting the stir casting technique, which is recognized as one of the most effective and economical methods for producing particulate-reinforced aluminium matrix composites.

The preparation started with the preheating of LM25 aluminium alloy ingots at 575 °C for four hours to remove moisture and ensure uniform temperature distribution prior to melting. In parallel, SiC powders were preheated separately at 450 °C to eliminate surface impurities and improve wettability during incorporation into the molten matrix. The LM25 alloy was melted in a graphite crucible placed within a resistance furnace and the temperature was raised to 830 °C. Once a fully molten state was achieved, the preheated SiC powders were gradually introduced into the melt. To facilitate homogeneous dispersion of reinforcement particles, the molten alloy-reinforcement mixture was stirred dynamically for 15 minutes using a mechanical stirrer operating at 500 rpm. This vigorous stirring promoted the uniform distribution of SiC particles throughout the matrix, reducing the possibility of agglomeration or settling. The molten composite was then poured into preheated metallic moulds and allowed to solidify under controlled conditions. The resulting castings were sectioned for subsequent testing and evaluation. Figure 1 shows the working schema of experimental setup made for stir casting process. Figure 2 shows the steps involved in the Stir Casting of LM25+SiC AMC.

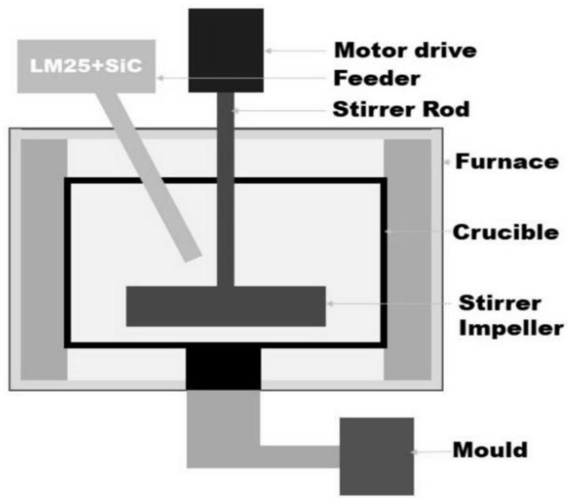


Figure 1 Schematic of the Stir Casting process

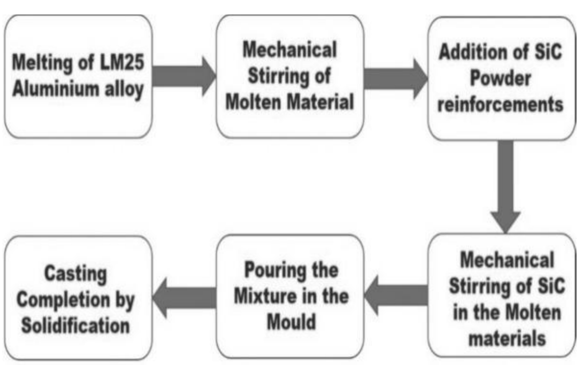


Figure 2 Steps involved in the Stir Casting of LM25+SiC AMC

Cylindrical rods of LM25 aluminium alloy and its composites (reinforced with 10 wt.% and 20 wt.% SiC) were machined to a diameter of 12 mm and a length of 75 mm using a power hacksaw and lathe machine to obtain precise surface finishing. The prepared specimens were then subjected to friction welding using a hydraulically controlled, continuous-drive friction welding machine (capacity: 15 Hp; 3000 rpm; 20 kN). The welding process parameters, such as spindle speed, friction pressure/time, and forging pressure/time, were varied according to the design matrix developed for this investigation. The same welding procedure was adopted for both unreinforced LM25 alloy and SiC-reinforced AMC specimens to maintain consistency in experimental methodology.

III. OPTIMIZATION

In addition to experimental trials, optimization studies were conducted to determine the most suitable friction welding process parameters for achieving defect-free, high-strength joints. The optimization framework employed Response Surface Methodology (RSM), which has been widely used in manufacturing process design owing to its efficiency in modelling nonlinear relationships and capturing interaction effects among multiple variables [6], [27]. In the present investigation, three critical process parameters were selected as input variables: spindle rotational speed (N), forging pressure/time (F), and friction pressure/time (P). These factors were chosen based on prior studies and preliminary experiments that identified them as the dominant parameters influencing weld quality and mechanical performance [8], [15], [22].

A three-factor, three-level Central Composite Design (CCD) was adopted to construct the experimental matrix. This design was chosen because it provides sufficient data points to estimate both linear and quadratic terms, while minimizing the number of required experimental runs. The three levels for each factor corresponded to low, medium, and high values, determined through trial runs and literature data for similar AMC systems. The design thus enabled the development of second-order polynomial equations for predicting the responses under varying combinations of process parameters.

The optimization was carried out separately for each material system namely, as-cast LM25, LM25 + 10 wt.% SiC, and LM25 + 20 wt.% SiC. This material-specific approach was necessary because the mechanical properties (yield strength, hardness and ductility) and reinforcement levels significantly alter the plastic flow behaviour during welding, thereby shifting the optimum parameter windows [9], [18]. For each case, the responses considered were weld strength, hardness at the joint interface and absence of macroscopic defects. The experimental data were analysed using statistical software, and the adequacy of the models was validated through analysis of variance (ANOVA).

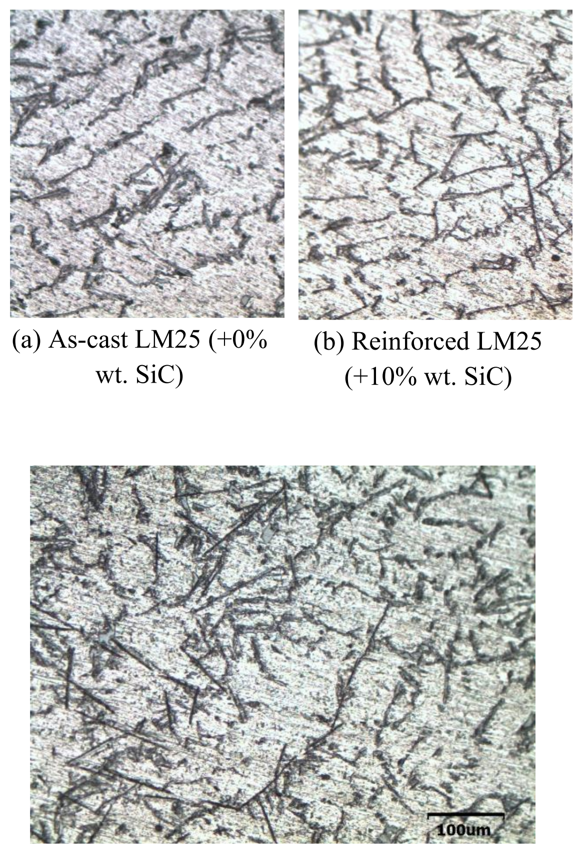
The optimization results indicated distinct process windows for each reinforcement level. While the as-cast LM25 alloy exhibited optimum weld quality at lower rotational speeds and moderate pressures, the SiC-reinforced composites required progressively higher spindle speeds and forging pressures to achieve defect-free joints. These results are consistent with the observed strengthening effect of SiC and the associated increase in resistance to plastic deformation [13], [19], [21]. The optimum parameters and the mechanical properties of the base metals of various combination of SiC percentages in AMC before welding are shown in the Table 1 and Table 2 respectively. The RSM-based models thus provide a predictive framework that complements the empirical relationships developed in this study, offering enhanced reliability in selecting parameter ranges for industrial applications. Figure 3 shows the microstructures of stir casted AMC of various SiC percentages.

Table 1 Mechanical Properties of Base metals

Material	Yield Strength MPa	UTS MPa	Vickers Hardness HV
As Cast LM25 Aluminium Alloy	90	140	72
LM25 + 10% wt. SiC AMC	115	156	83
LM25 + 20% wt. SiC AMC	131	172	97

Table 2 Optimized Friction Welding Process Parameters

Sl. No.	Friction Welding Process Parameters	Optimized Values		
		As Cast LM25 Aluminium Alloy Joints	LM25 + 10% wt. SiC AMC Joints	LM25 + 20% wt. SiC AMC Joints
1.	Spindle Rotational Speed, N (rpm)	1195.04	1242.22	1499.99
2.	Forging Pressure/ time, F (MPa/s)	11.06	22.92	29.11
3.	Friction Pressure/ time, P (MPa/s)	19.88	15.00	20.00



(a) As-cast LM25 (+0% wt. SiC)

(b) Reinforced LM25 (+10% wt. SiC)

(c) Reinforced LM25 (+20% wt. SiC)

Figure 3 Optical microstructure of the base material

IV. RESULTS & DISCUSSION

4.1 Relationship between Base Metal Yield Strength and Optimized Friction Welding Parameters

The criteria considered for establishing relationship are optimized friction welding parameters and the base metal properties. Table 1 shows the base metal properties namely yield strength and hardness. The values of optimized parameters viz., spindle rotational speed, forging pressure/time and friction pressure/time are shown in Table 2. Fig. 4(a) – (c) shows the relationship existing between the base metal yield strength and optimized friction welding process parameters. The relationship existing between the base metal yield strength and optimized spindle rotational speed, optimized forging pressure/time and optimized friction pressure/time is given by the equation below:

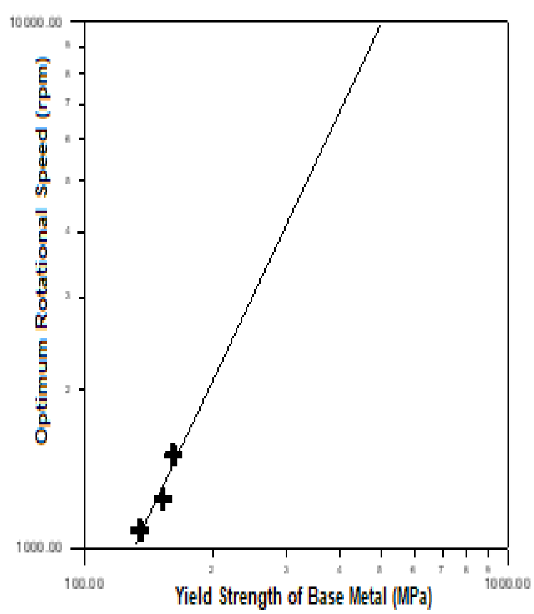
Optimized rotational speed $(N)_{opt} = 0.245\,(YS)^{1.8505}$ (1)

Optimized forging pressure/time $(F)_{opt} = 4.8541 \times 10^{-9}\,(YS)^{4.746}$ (2)

Optimized friction pressure/time $(P)_{opt} = 0.1522\,(YS)^{1.062}$ (3)

From Fig. 4 (a)-(c), it is found that, the welding parameters is having a direct proportional relationship with the base metal yield strength. Hence material with lower yield strength welded at lower friction welding parameters will result in defect-free welded joints.

(a)



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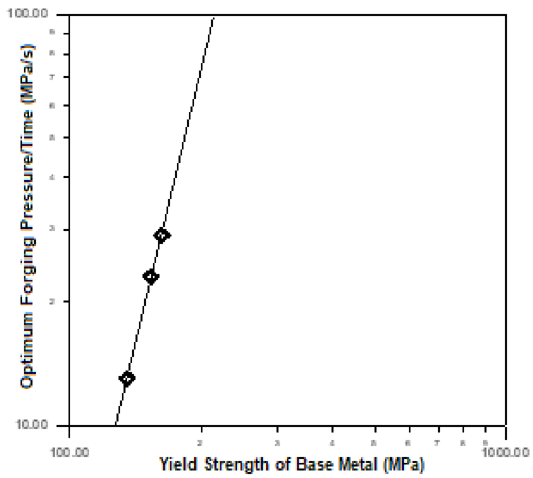


(c)

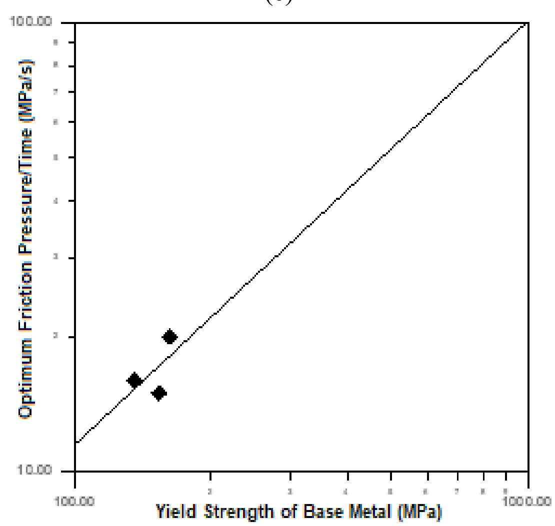


Figure 4 Relationship between Base Metal Yield Strength and Optimized Friction Welding Parameters

4.2 Relationship between Base Metal Hardness and Optimized Friction Welding Parameters

The relationship between base metal hardness and the optimized spindle rotational speed, friction pressure and forging pressure are shown in Fig. 5 (a), (b) and (c).

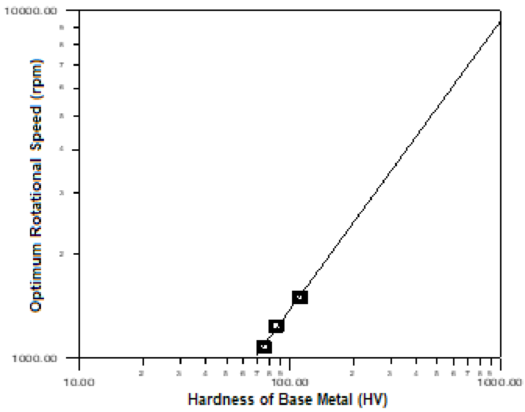
The equations of their relationship is expressed as given below:

Optimized Spindle Rotational speed $(N)_{Opt} = 30.0454 \times (H)^{0.849}$ (4)

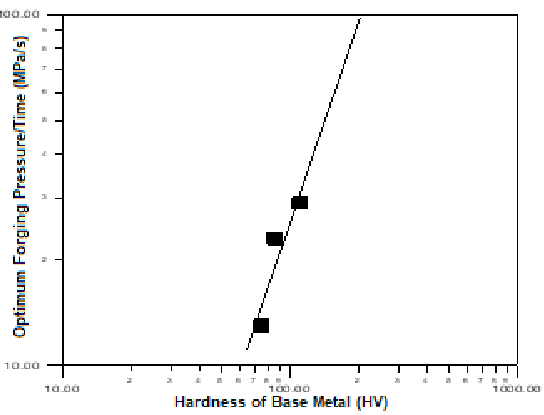
Optimized forging pressure/time $(F)_{Opt} = 0.0039 \times (H)^{1.843}$ (5)

Optimized friction pressure/time $(P)_{Opt} = 0.00399 \times (H)^{1.964}$ (6)

(a)



(b)



(c)

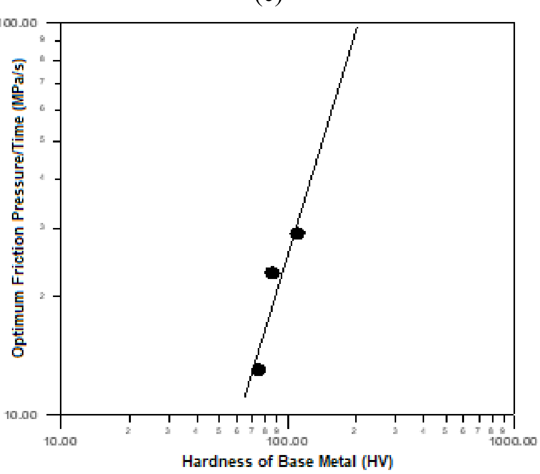
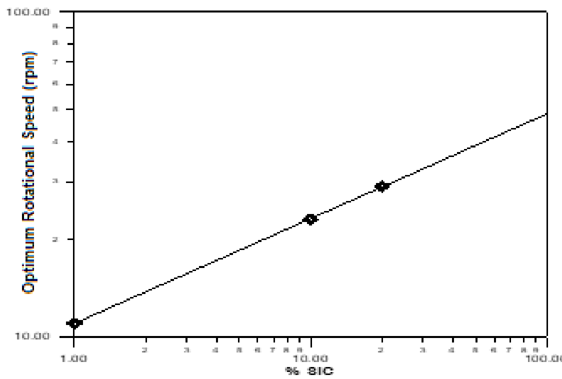


Figure 5 Relationship between Base Metal Hardness and Optimized Friction Welding Parameters

It is clearly evident from Fig. 5 (a)-(c) that; the welding parameters have a directly proportional relationship with the hardness. At lower friction welding parameters, lower hardness material can be welded without defects and vice versa.

4.3 Relationship between %wt. SiC reinforcement and Optimized Friction Welding Parameters

(a)



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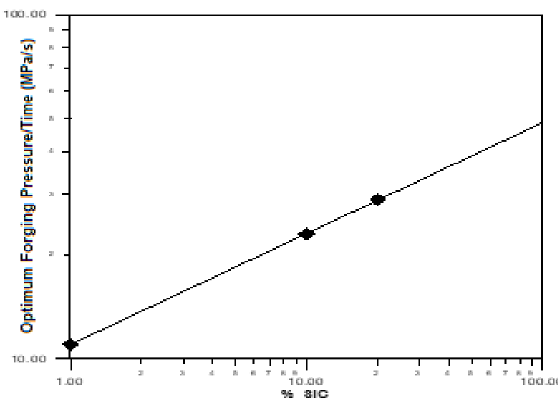

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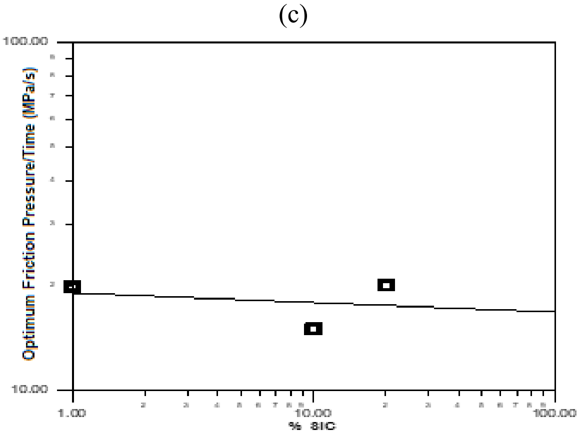

Figure 6 Relationship between % SiC and Optimized Friction Welding Parameters

Fig. 6(a)-(c) shows the relationship between % wt. SiC reinforcement and the optimized friction welding parameters. The equations providing the empirical relationships are given below:

Optimized Spindle Rotational speed $(N)_{Opt} = 1172.41 \times (\%\ wt.\ SiC)^{0.0609}$ (7)

Optimized forging pressure/time $(F)_{Opt}$ = 10.9884 x (% wt. SiC) $^{0.3228}$ (8)

Optimized friction pressure/time $(P)_{Opt}$ = 19.027 x (% wt. SiC) $^{-0.02776}$ (9)

It is clearly evident from Fig. 6(a)-(c) that; the spindle rotational speed and the forging pressure/time have a directly proportional relationship with the %wt. SiC reinforcement, whereas friction pressure/time is having inversely proportional relationship with % wt. SiC reinforcement.

4.4 Validation of Developed Empirical Relationships

With the welding conditions in the developed empirical relationships discussed before, confirmation studies were carried out in order to validate the developed empirical relationships.

Table 3 Validation of Relationships – Results

Base Metal Properties (Yield Strength & Hardness)					
Material	Property	Process Parameters	Optimized Values	Predicted Values (from empirical relationships)	% Variations with respect to predicted values
Base Material As Cast LM 25 Aluminium Alloy	Yield Strength 90 MPa	N (rpm)	1195.04	1012.75	17.99
		F (MPa/s)	11.06	9.14	21.01
		P (MPa/s)	19.88	18.07	10.02
	Hardness 72 HV	N (rpm)	1195.04	1138.13	5.01
		F (MPa/s)	11.06	10.35	6.86
		P (MPa/s)	19.88	17.75	12.00

Composition of SiC Reinforcement (% wt. SiC)				
Material	Process Parameters	Optimized Values	Predicted Values (from empi-rical relationships)	% Variations with respect to predicted values
LM25 + 10% wt. SiC AMC Joints	N (rpm)	1242.22	1348.90	-7.91
	F (MPa/s)	22.92	23.11	-0.822
	P (MPa/s)	15.00	17.85	-15.97
LM25 + 20% wt. SiC AMC Joints	N (rpm)	1499.99	1407.06	6.53
	F (MPa/s)	29.11	28.90	0.727
	P (MPa/s)	20.00	17.51	14.22

4.5 Discussion

Validation experiments were carried out to compare optimized values obtained from welding trials with those predicted by the developed empirical relationships. As shown in Table 3, the variation between experimental and predicted values was minimal. For example, the as-cast LM25 alloy showed only a 5% variation between predicted and optimized spindle speed and 12% for friction pressure/time. For composites, the variation was similarly low, with the 10 wt.% SiC joints showing a deviation of –7.91% for spindle speed and -0.82% for forging pressure/time.

Such close agreement confirms the reliability of the developed models. Similar validation efforts have been reported in literature. Barcellona et al. [19] established parametric models for aluminium MMCs, while Mishra and Ma [6] developed generalized models for aluminium alloys in friction stir welding, both reporting predictive accuracies within 10–15%. The present study's results fall within comparable accuracy ranges, underscoring the robustness of the developed equations. Moreover, the predictive capability of these empirical models ensures significant savings in time and cost for industrial applications. Rather than relying on repeated experimental trials, engineers can use these models to pre-select approximate parameter ranges based on known material properties, thereby streamlining process design.

The findings of this investigation are highly relevant to the broader context of AMC fabrication for aerospace and automotive industries. LM25 reinforced with SiC is a promising candidate for structural components requiring both light weight and high strength [14]. However, successful integration of such materials into engineering systems depends on the ability to reliably join them with minimal defects. The empirical relationships developed herein serve as practical design tools for welding engineers, enabling the prediction of suitable process windows for different reinforcement levels.

V. CONCLUSIONS

(i) This study successfully established empirical relationships linking the base metal yield strength and hardness with the optimized friction welding process parameters namely spindle rotational speed, forging pressure/time, and friction pressure/time. It was found that both yield strength and hardness are directly proportional to spindle speed and forging pressure/time, reflecting the increased thermal and mechanical inputs required for materials of higher strength and hardness to undergo adequate plastic deformation during welding. These results demonstrate that base metal properties can serve as reliable predictors for determining suitable friction welding conditions.

(ii) The introduction of SiC reinforcement into the LM25 aluminium alloy matrix significantly altered the mechanical properties, leading to higher yield strength and hardness but reduced ductility. Consequently, the optimized spindle speed and forging pressure/time increased with reinforcement content, while friction pressure/time showed an inverse relationship. This trend highlights the dual effect of SiC enhancing the composite's strength while simultaneously complicating its weldability. By quantifying these relationships, the present study provides practical guidelines for adjusting welding parameters in response to reinforcement levels.

(iii) Using Response Surface Methodology (RSM) with a three-factor, three-level central composite design, process parameters were optimized separately for as-cast LM25, LM25 + 10 wt.% SiC, and LM25 + 20 wt.% SiC composites. The RSM models effectively captured both linear and quadratic effects, allowing precise prediction of parameter windows that yielded defect-free joints. The distinct optimization outcomes for each material combination confirm the necessity of tailoring welding conditions based on reinforcement content and base alloy properties. The close agreement between experimental and predicted values (typically within ±10%) validated the robustness of both empirical and statistical models.

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