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Optimization of FSP parameters in fabricating AA5083/Coal composites using Taguchi method

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Abstract

This study investigates the optimization of Friction Stir Processing parameters to fabricate AA5083/Coal composites using the Taguchi method. The influence of key process parameters—tool tilt angle, tool rotation speed, and traverse speed—on the mechanical properties of the composites was evaluated, specifically focusing on ultimate tensile strength, microhardness, and elongation. Taguchi's L_9 orthogonal array was employed to minimize the number of experiments and maximize the efficiency of parameter selection. A Hounsfield tensile test machine was used to evaluate ultimate tensile strength, and Innova Test Falcon 500 hardness testing machine was used to determine microhardness. The highest ultimate tensile strength, microhardness and percentage elongation achieved with the orthogonal arrays were 242 MPa, 96.27 HV, and 22.43%, respectively. The optimal parameters were identified as a tool tilt angle of 2°, a tool rotation speed of 900 rpm, and a traverse speed of 60 mm min^{-1} based on signal-to-noise ratio. Furthermore, an analysis of variance was conducted to evaluate the parameter contributions. Analysis of Variance revealed that rotational speed had the most significant impact on microhardness and percentage elongation, while tilt angle most strongly influenced ultimate tensile strength. This study demonstrates the viability of coal particles as a cost-effective reinforcement material for AA5083 composites and provides a robust framework for optimizing friction stir processing parameters using statistical methods.

1. Introduction

Material selection is fundamental for the success of engineering products in diverse fields like marine, automotive, construction, and aerospace. Aluminium alloys have become the go-to choose because of their impressive properties: high strength-to-weight ratio (strong yet lightweight), excellent corrosion (durable) and wear resistance, and superior thermal and electrical conductivity (valuable for heat transfer or electrical applications) [1, 2]. Additionally, aluminium offers advantages over other metal matrix composites in terms of availability, cost-effectiveness, and lightweight nature, making it a practical and sustainable selection for a wide range of engineering applications.

Despite their excellent properties, aluminium alloys lack sufficient stiffness and strength. To address this, a focus has emerged on enhancing surface properties through various methods. The properties of aluminium alloys can be enhanced through heat treatments adding alloying elements and incorporating reinforcing particles to boost their performance in applications requiring strength wear resistance and structural applications [3]. Aluminium metal matrix composites (AMMCs) have become a popular solution, created by incorporating reinforcement particles into the alloy. AMMCs offer not only improved mechanical properties but also better electrical and thermal conductivity, making them suitable for demanding applications [4]. Friction Stir Processing (FSP) is now acknowledged as a cost eco promising method, for creating composites.

FSP is primarily a surface modification technique that refines the grain structure at the material's surface derived from Friction Stir Welding (FSW) [5] and has since been widely adopted as a novel technique for producing MMCs [6]. Unlike traditional methods such as powder metallurgy, squeeze casting, and stir casting for producing Metal Matrix Composites that can suffer from drawbacks, FSP offers a unique solution. It refines the grain structure at the surface and eliminates issues like porosity, defects, and weak bonding between particles. This localized modification process even allows for the creation of desirable micro or nanostructures within the material [6]. As a result, FSP significantly enhances AMMCs properties like tensile strength, hardness, wear resistance, and even resistance to harsh environments [7].

During the process of Friction Stir Processing (FSP), a localized section of a metal sheet is altered using a rotating tool equipped with both a pin and shoulder. The FSP tool is inserted into the designated area, as the pin plunges and rotates the material heat generated from friction softens the metal. The selected area and the tool move in relation, to each other allowing for the processing of the designated region. As a result, material is transferred from the leading edge towards the trailing face of the pin. Subsequently, the movement of the tool refines the microstructure and eliminates imperfections resulting in a quality layer [8]. This method significantly enhances the properties of Metal Matrix Composites (MMCs) such as resistance to corrosion, wear resistance, microhardness, fatigue endurance, and resistance to deformation over time.

Friction stir welding (FSP) relies on several critical parameters to achieve optimal results. These include tool geometry, traverse speed, tilt angle, tool rotation speed, and others [9]. Among these, traverse speed, tool geometry, and rotation speed have the biggest impact on heat generation, which significantly affects the quality of the welded joint. Many welding businesses traditionally employ a one-factor-at-a-time experimental approach, in which a single parameter is adjusted while others are kept constant. This trial-and-error method is time-consuming and inefficient [10, 11], especially for complex processes like Friction Stir Processing, which involves multiple interacting parameters. Researchers have explored alternative optimization methods to address these challenges, such as mathematical iterative search techniques, design of experiments (e.g., Response Surface Methodology, Taguchi), problem-specific heuristic approaches, and metaheuristic approaches (e.g., Genetic Algorithms, Tabu Search) [12].

While these advanced methods offer certain advantages, each comes with limitations that can hinder their practical application in FSP optimization. Mathematical iterative search techniques often concentrate on specific aspects of machining, such as cutting force, temperature, or tool wear. However, due to the numerous interdependent variables and their stochastic nature, these techniques may struggle to fully capture the complexities of the overall cutting process [13]. RSM techniques, relying on a series of experiments, may not be practical or cost-effective for many manufacturing scenarios [14]. Additionally, RSM requires a continuously differentiable objective function to determine optimal cutting conditions, which might not be the case in complex physical processes [12]. Metaheuristic methods offer a robust approach to optimization problems, bypassing the need for derivative information or explicit functional relationships. Genetic Algorithms (GAs), a popular metaheuristic technique, have demonstrated effectiveness in various applications. However, GAs are not without their limitations. Uncertain convergence, sensitivity to parameter settings, computational cost, and inconsistent results can hinder their performance. While GAs have proven valuable, it's essential to acknowledge these shortcomings and explore alternative metaheuristic techniques or hybridization strategies to address these limitations [12].

Given these limitations, the Taguchi method, with its orthogonal arrays, provides a robust alternative that optimizes FSP parameters with fewer experimental runs, offering a more practical and efficient approach for industrial applications. Taguchi's method employs Analysis of Variance (ANOVA) to identify the input parameters that significantly influence the quality or characteristics of the output. This is accomplished by looking for variations in the tested collections of items' average performance [15]. While extensive research exists on improving AA5083's surface properties with FSP, limited studies have explored how process parameters specifically impact surface quality during FSP of AA5083 [16–23].

Bauri *et al* [16] optimized FSP parameters for incorporating Nickel (Ni) particles into a metal-reinforced 5083 aluminium composite. Their focus was on identifying the ideal combination of traverse speeds, and tool rotation to achieve a defect-free nugget zone with uniform particle distribution. Experiments explored many parameters (tool rotation speeds: 1000–1800 rpm, traverse speeds: 6–24 mm min^{-1}) to optimize these goals. Using the optimized parameters, both coarse particles and finer particles from a ball mill were added to the Al matrix. The study revealed that a higher heat input [17], achieved through a lower traverse speed (15–12 mm min^{-1}), was necessary for effective dispersion of the coarser Ni particles (70 μm). However, this approach was unsuccessful, and even increasing the rotation speed did not improve the distribution of these coarse particles.

Taguchi's L_8 orthogonal array was utilized by Rahman *et al* [18] to assess the effects of FSP parameters on the surface characteristics and microstructure of AA5083 composites reinforced with Ti and SiC. Two levels were investigated for each of the following parameters: traverse speed, shoulder diameter, and tool rotation speed. The study revealed significant improvements in surface hardness after FSP, with a maximum recorded value of

90.4 HV. Interestingly, a strong correlation was observed between surface hardness and the processed zone (PZ) geometry. Specimens with a lower width-to-depth ratio exhibited superior hardness. The chosen parameters significantly impacted the PZ geometry, ranging from deep bowl shapes (smaller shoulder diameters) to shallow cups (larger diameters). Notably, specific parameter combinations—355 rpm, 63 mm min^{-1} traverse speed, 17 mm shoulder diameter, and 355 rpm, 80 mm min^{-1} traverse speed, 20 mm shoulder diameter—yielded exceptional tensile strengths of 292 and 294 MPa, respectively, which demonstrated remarkable stability even at elevated temperatures of 540 °C.

Rahman *et al* [19] investigated the use of FSP to create AA5083 surface composites reinforced with Ti and SiC. The main focus was identifying the optimal FSP parameters for achieving maximum surface hardness. Three parameters were studied: traverse speed, shoulder diameter, and tool rotation speed, using a Taguchi L_4 orthogonal array. The study found that the largest hardness (measured 2 mm below the processed surface) was achieved with a combination of 355 rpm tool rotational speed, 63 mm min^{-1} tool traverse speed, and 17 mm shoulder diameter. Interestingly, this parameter combination also resulted in the lowest width-to-depth ratio in the processed zone. The microstructure analysis revealed significant grain size variations within the processed region. The stir zone (SZ) exhibited the highest hardness resulting from dynamic grain refinement and a more homogeneous distribution of reinforcement particles.

Jain *et al* [20] investigated the use of Taguchi's method to optimize FSP parameters for enhancing the microhardness of AA5083/Al-Fe *in situ* composites. The focus was on three key parameters: shoulder diameter, traverse speed, and rotation speed, each with three different settings. Using Taguchi's design and Minitab software for analysis, the study identified the optimal parameter combination for maximizing microhardness with minimal experimentation. The experimental setup utilized a tool with a 21 mm shoulder diameter rotating at 900 rpm and traversing at a speed of 63 mm min^{-1}. With these parameters, the processed zone's microhardness significantly increased (to about 123.30 HV), which is an improvement of 50.6% over the base material.

Ghediya *et al* [21] introduced a novel method for creating AA5083 surface composites reinforced with both SiC and Gr particles using FSP. The research centered on enhancing the parameters of the FSP process to achieve the desired composite properties. To create a mathematical model that could forecast the performance of the hybrid composites, Response Surface Methodology was used. The model was created using a Box-Behnken design with four key factors having three different settings each. Statistical analysis (ANOVA) revealed that the number of FSP passes and the ratio of SiC to Gr reinforcement particles were the most significant factors influencing the composite's properties (p-value < 0.05). This research demonstrates the effectiveness of RSM for optimizing the FSP process to create new hybrid metal matrix composites.

Similar to Ghetiya *et al* [21], Bharti *et al* [22] investigated optimizing the FSP process for AA5083 surface composites reinforced with a hybrid mixture of SiC and Gr particles. The focus was on maximizing the hardness of the resulting composite. Using RSM, a mathematical model to predict the composite's hardness based on various FSP parameters was developed. The study optimized factors such as the number of FSP passes, traverse speed, the SiC to Gr reinforcement ratio, and tool rotation speed. The analysis revealed that the optimal parameter combination for achieving the highest hardness (32.6 HRB) was 1000 rpm tool speed, traversing at a speed of 80 mm min^{-1}, 3 FSP passes, and a 75:25 ratio of SiC to Gr reinforcement.

Kaya [23] studied how the properties of FSP affect the surface, strength, and wear resistance of aluminium alloy (AA5083) surface composites that are strengthened with silicon carbide particles. The study used a single-pass FSP process on pre-treated AA5083-H111 alloy and investigated the influence of two key parameters: tool rotation speed and axial load. Different combinations of axial load (6000N, 8000n, and 10000 N) and rotation speed (560 rpm, 710 rpm, and 900 rpm) were tested. The optimal results were achieved with a combination of 900 rpm rotation speed and 8000 N axial load (sample N8). This sample exhibited significant improvements in both hardness (38% increase) and wear resistance (42% increase under 15 N load) compared to the parental material. Furthermore, sample N8 displayed tensile strength performance that remained close to the base metal, reaching 97% of its original strength.

Extensive research shows that Metal Matrix Composites (MMCs) are often reinforced with materials like nickel [16, 17], silicon carbide [18, 19, 21–23], titanium [18, 19], iron [20], or graphene [21, 22] which improve strength and wear resistance but can be costly. As far as AA5083 composites reinforced with coal particles developed via Friction Stir Processing (FSP) are concerned, no published research has investigated the impact of process parameters on their mechanical properties. This study explores coal as an alternative reinforcement material, given its abundant availability, low cost, and carbon-rich structure, which contribute to hardness and wear resistance. Although unconventional, coal has the potential to offer similar benefits to traditional reinforcements, making it a sustainable choice for MMCs. By optimizing FSP parameters—such as tool rotational speed, traverse speed, and tilt angle—using Taguchi's method and ANOVA, this study aims to maximize the mechanical performance of AA5083/coal composites. Unlike previous studies focused on traditional reinforcements, this work fills a gap in the literature by examining the effect of coal particles

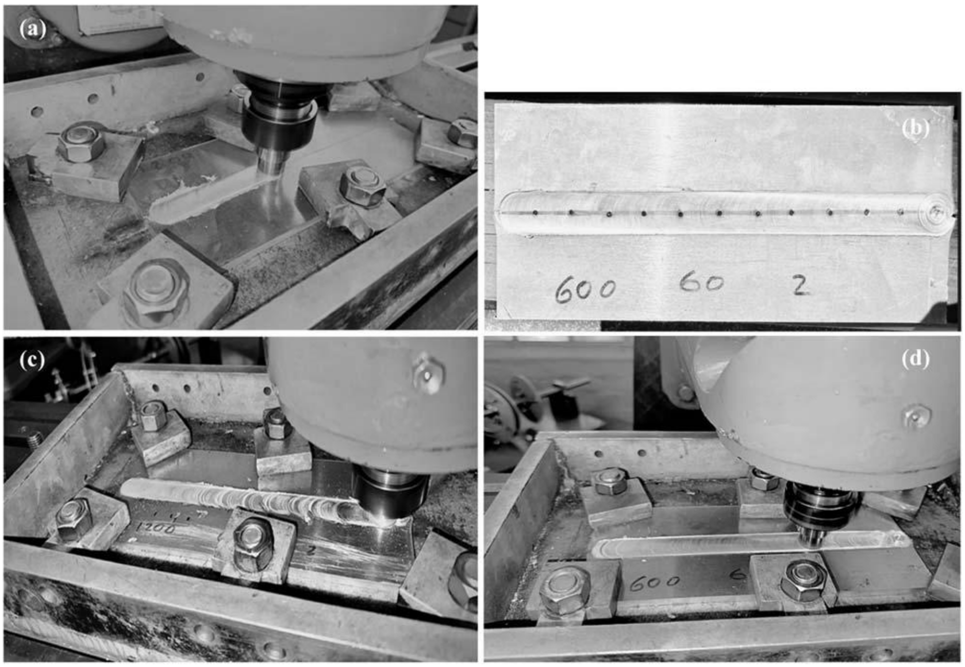

Figure 1. (a) FSW process; (b) Hole drilling and filling with reinforcement particles; (c) Closing of hole with pin less tool; (d) FSP single pass process.

Table 1. Mechanical properties of AA5083 alloy.

Mechanical properties	
Ultimate tensile strength	311 MPa
Microhardness	93.07 HV

combined with optimized FSP parameters on AA5083, contributing novel insights into sustainable, cost-effective reinforcement options for MMCs.

2. Experimental procedure

In this study, a 6 mm thick AA5083 alloy plate served as the base material for producing aluminium metal matrix composites (AMMCs). Coal particles were incorporated as reinforcement material, constituting 5% of the composite's volume. The AA5083 alloy, widely used in marine and automotive applications, was chosen for its high strength-to-weight ratio and excellent corrosion resistance [24, 25]. Its composition includes 4.03% magnesium, 0.01% zinc, 0.02% titanium, 0.05% chromium, 0.15% silicon, 0.69% manganese, 0.16% iron, and 0.02% copper [26]. Coal particles were selected as the reinforcement material based on their low cost, abundant availability, and properties conducive to enhancing hardness and tensile strength. These characteristics make coal a promising, sustainable alternative to more traditional reinforcement materials like silicon carbide (SiC) or titanium (Ti), contributing to the composite's improved mechanical properties while reducing production costs. The mechanical properties of the AA5083 alloy are summarized in table 1.

To fabricate the AA5083/coal composite, two AA5083 plates (measuring 55 mm in width and 250 mm in length each) were first friction stir welded (FSWed) to create a joint, as illustrated in figure 1(a). The FSW process employed a high-strength AISI 4140 steel tool with a 20 mm shoulder diameter, a 5.7 mm triangular pin, and a 7 mm probe diameter. The experimental procedure for fabricating the Coal-AA5083 composite was adapted from established methods in Friction Stir Processing (FSP) commonly used for particle-reinforced composites. Similar techniques were used in particle reinforcement and FSP composite fabrication in earlier research, which supports the experimental design and validates the parameter choices [26–33].

Following the welding, multiple holes with a depth of 4 mm and a diameter of 2.5 mm were drilled into the joint and filled with coal particles to serve as reinforcement, as shown in figure 1(b). The choice of hole dimensions was guided by previous studies [26, 27, 32–36], which emphasized the importance of optimizing

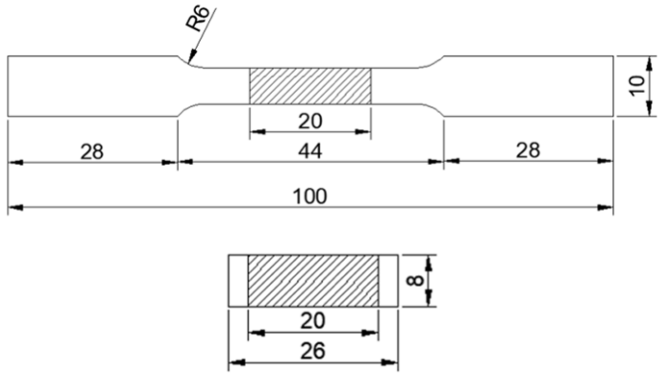

Figure 2. Tensile and hardness specimen size and configuration.

Table 2. Process variables and their corresponding values.

Parameters	Units	Level		
		1	2	3
Rotational speed (RS)	[rpm]	600	900	1200
Tilt angle (TA)	[°]	1	1.75	2
Traverse speed (TS)	[mm/min]	30	45	60

Table 3. Taguchi L_9 orthogonal design matrix.

No of experiments	Rotational speed [rpm]	Traverse speed [mm/min]	Tilt angle [°]
1.	600	30	1
2.	600	45	1.75
3.	600	60	2
4.	900	30	1.75
5.	900	45	2
6.	900	60	1
7.	1200	30	2
8.	1200	45	1
9.	1200	60	1.75

these parameters to ensure uniform particle dispersion and adequate reinforcement volume within the stir zone. These dimensions were also selected to accommodate the coal particle size while preserving the structural integrity of the material during processing. To secure the coal particles within the matrix during processing, a pin-less FSP tool was used to seal the holes, as depicted in figure 1(c). Finally, the composite underwent a finishing FSP pass at room temperature, as illustrated in figure 1(d).

Nine experiments were designed using Taguchi's L_9 orthogonal array, a statistical approach for optimizing parameters with a minimal number of tests. Minitab-18 software was employed to analyze the data obtained from these experiments. The study investigated three critical FSP process parameters—tool tilt angle, tool rotation speed, and traverse speed—each set at three different levels. These parameters were selected based on prior research, which indicates their significant influence on heat input, material flow, and the uniform distribution of reinforcement particles within the matrix [37, 38]. Tables 2 and 3 outline the specific parameter settings, their ranges, and the complete experimental layout.

The experimental procedure for fabricating the Coal-AA5083 composite was adapted from established methods in Friction Stir Processing (FSP) commonly used for particle-reinforced composites. The process involved drilling holes with a diameter of 2.5 mm and a depth of 4 mm into the base material, which were then filled with coal particles to ensure effective reinforcement. The choice of hole dimensions was guided by previous studies that demonstrated the importance of optimizing these parameters for uniform particle dispersion and adequate reinforcement volume within the stir zone. These dimensions were also selected to

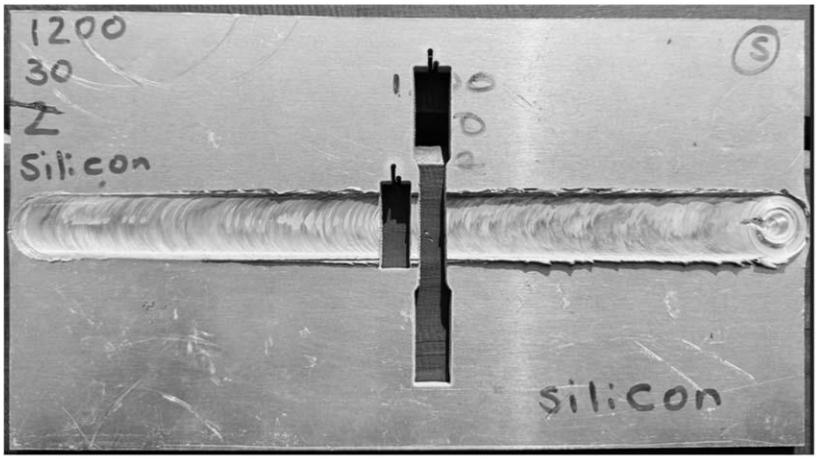

Figure 3. Sample of the plate with cut tensile and hardness specimens.

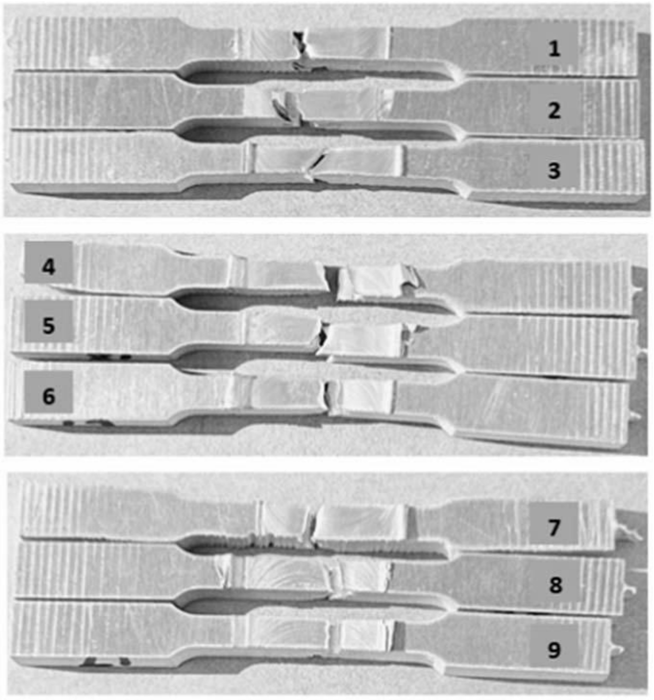

Figure 4. Post-tensile test specimens.

accommodate the particle size of coal while preserving the structural integrity of the base material during processing. References to similar methodologies in FSP composite fabrication and particle reinforcement methods support the experimental design and validate the chosen parameters.

Following the fabrication of AA5083/coal composites, waterjet cutting technology was used to precisely cut specimens perpendicular to the FSP direction for mechanical testing. Tensile specimens were prepared according to ASTM E8M-04 standards to assess the tensile strength of the composite joint, ensuring consistent dimensions across all samples for accurate comparison. Additional specimens were prepared for microhardness evaluation in line with ASTME384 standard, with testing conducted using a load of 300 gf and a dwell time of 10 s. Indentations were made along the cross-section of the stir zone at regular intervals to evaluate the uniformity of hardness distribution. All tensile and microhardness tests were performed at room temperature in a controlled environment to maintain consistent testing conditions, with no preheating or post-processing treatments applied to the specimens.

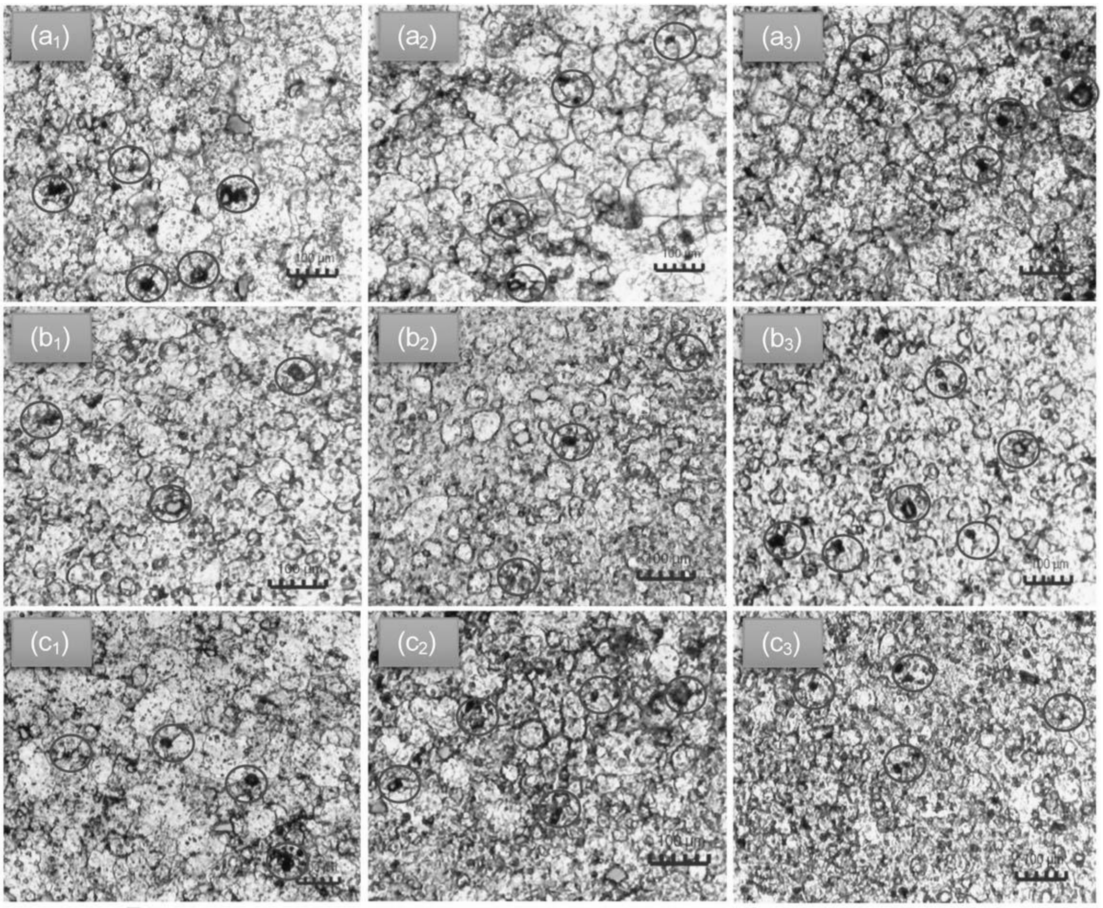

Figure 5. AA5083/Coal composites (Optical microstructures 20x): a_1 Exp.1, a_2 Exp. 2, a_3 Exp. 3, b_1 Exp. 4, b_2 Exp. 5, b_3 Exp. 6, c_1 Exp. 7, c_2 Exp. 8 and c_3 Exp. 9.

Table 4. Mechanical properties of AA5083/coal composites.

Experiment no.	UTS (MPa)	PE (%)	MH (HV)
1.	167	11.95	93.62
2.	109	7.000	88.34
3.	224	**22.43**	92.65
4.	134	12.18	**96.27**
5.	**242**	20.73	90.65
6.	161	21.18	92.43
7.	101	7.600	95.33
8.	181	12.75	93.09
9.	141	9.380	95.85
Base Material	311	58.65	93.07

Figure 2 illustrates the dimensions and configuration of the tensile specimens and microhardness indentation layout. Figure 3 shows the plate with cut tensile and microhardness specimens, while figure 4 displays the sample after tensile testing.

3. Results and discussion

3.1. Microstructure

Figure 5 illustrates the optical microstructures of each surface composite tested. Figures 4(a_1), (a_2), and (a_3) showcase the microstructure for the AA5083/Coal composite at 600 rpm, 30 mm min^{-1}, and a 1° tilt; 600 rpm, 45 mm min^{-1}, and a 1.75° tilt; and 600 rpm, 60 mm min^{-1}, and a 2° tilt, respectively. Similarly, figures 4(b_1),

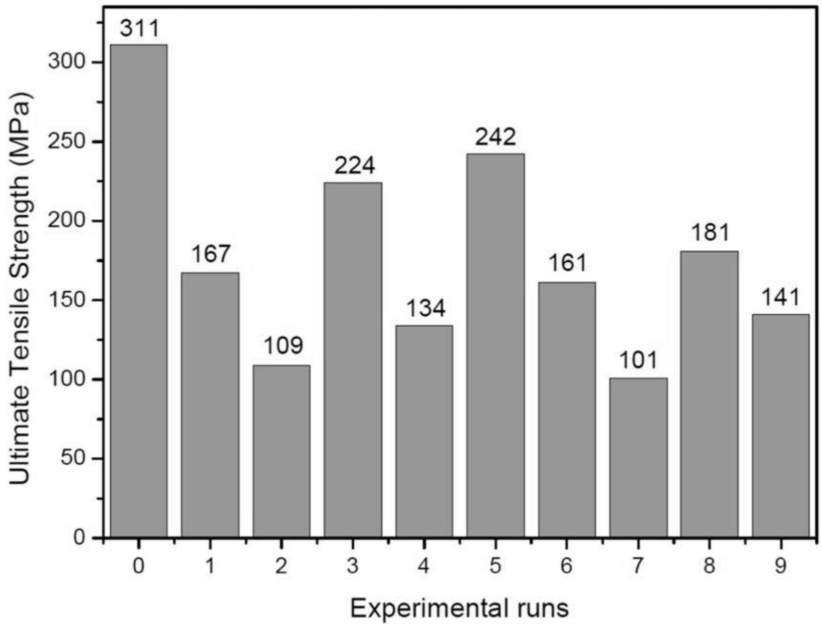

Figure 6. Ultimate tensile strength bar graph.

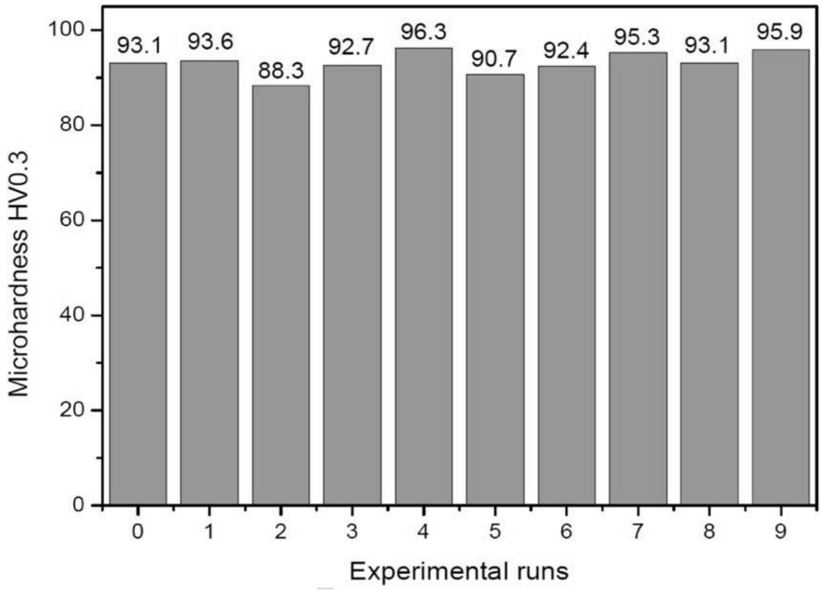

Figure 7. Hardness bar graph.

(b_2), and (b_3) present the microstructure for another set of composites at 900 rpm, with tilt angles of 1.75°, 2°, and 1° for traverse speeds of 30 mm min^{-1}, 45 mm min^{-1}, and 60 mm min^{-1}, respectively. Lastly, figures 4(c_1), (c_2), and (c_3) detail the microstructure at 1200 rpm, with corresponding tilt angles and traverse speeds as 2° at 30 mm min^{-1}, 1° at 45 mm min^{-1}, and 1.75° at 60 mm min^{-1}.

The microstructural images provide insights into the distribution of coal reinforcement particles within the AA5083 matrix, highlighting how varying FSP parameters affect particle dispersion and bonding within the composites. The microstructure images reveal that the coal particles are dispersed within the stir zone, but there is a low-particle-percentage bond, likely due to limited vertical material mobility. Similar findings were reported by [32], who observed that non-uniform particle dispersion significantly affects the failure properties and plastic deformation behavior of metal-based composites. These observations clarify the differences in mechanical properties, which are influenced by both the reinforcement material and processing conditions. The results

Table 5. AA5083/Coal composite experimental results with relevant S/N ratio.

RS (rpm)	TS (mm/min)	TA (°)	UTS (MPa)	PE (%)	MH (HV)	S/N ratio For UTS	S/N ratio For PE	S/N ratio For HV
600	30	1	167	11.95	93.62	44.4543	21.5474	38.6606
600	45	1.75	109	7.000	88.34	40.7485	16.9020	38.9231
600	60	2	224	22.43	92.65	47.0050	27.0166	39.3369
900	30	1.75	134	12.18	96.27	42.5421	21.7129	39.6698
900	45	2	242	20.73	90.65	47.6763	26.3320	39.1474
900	60	1	161	21.18	92.43	44.1365	26.5185	39.3163
1200	30	2	101	7.600	95.33	40.0864	17.6163	39.4190
1200	45	1	181	12.75	93.09	45.1536	22.1102	39.3781
1200	60	1.75	141	9.380	95.85	42.9844	19.4441	39.2833

Table 6. Signal to Noise ratio response for ultimate tensile strength.

Level	Rotational speed(rpm)	Traverse speed (mm/min)	Tilt angle (°)
1	44.07	42.36	44.58
2	**44.78**	44.53	42.09
3	42.74	**44.71**	**44.92**
Delta	2.04	2.35	2.83
Rank	3	2	1

Table 7. Signal to Noise ratio response for percentage elongation.

Level	Rotational speed(rpm)	Traverse speed (mm/min)	Tilt angle (°)
1	21.82	20.29	23.39
2	**24.85**	21.78	19.35
3	19.72	**24.33**	**23.65**
Delta	5.13	4.03	4.30
Rank	1	3	2

suggest that incomplete bonding between the reinforcement particles and the matrix can negatively impact mechanical properties, including hardness, tensile strength, and ductility.

3.2. Mechanical properties

Table 4 presents the mechanical properties of the AA5083/coal composites. The study achieved the highest tensile strength of 242 MPa with a tool tilt angle of 2°, a rotational speed of 900 rpm, and a traverse speed of 45 mm min^{-1}. Additionally, the highest percentage elongation achieved was 22.43%, obtained with a tool tilt angle of 2°, a tool rotational speed of 600 rpm, and a traverse speed of 60 mm min^{-1}. The highest microhardness measured was 96.27 HV, achieved with a tool tilt angle of 1.75°, a tool rotational speed of 900 rpm, and a traverse speed of 30 mm min^{-1}. The AA5083/coal composites showed lower ultimate tensile strength values compared to the base material. A similar trend, with reduced tensile strengths observed in single-pass composites compared to the base material, has been reported by Ayvaz *et al* [39], Yuvaraj *et al* [40], and Srivastava *et al* [41, 42]. Srivastava *et al* attributed the lower tensile strength to the agglomeration of reinforcement particles in single-pass specimens.

The addition of reinforcements increased hardness, with the highest values generally surpassing those of the base material, although some regions exhibited lower hardness. This variation can be attributed to dynamic recrystallization, differences in grain size, particle distribution [43], and fragmentation or redistribution of intermetallic particles [44]. The higher hardness is largely due to a more homogeneous distribution of the coal reinforcement on the surface and the ultra-refinement of grains [23]. Similar studies have reported compatible microhardness results, consistent with this study's findings [45]. Figure 6 presents the ultimate tensile strength bar graph, while figure 7 displays the hardness bar graph.

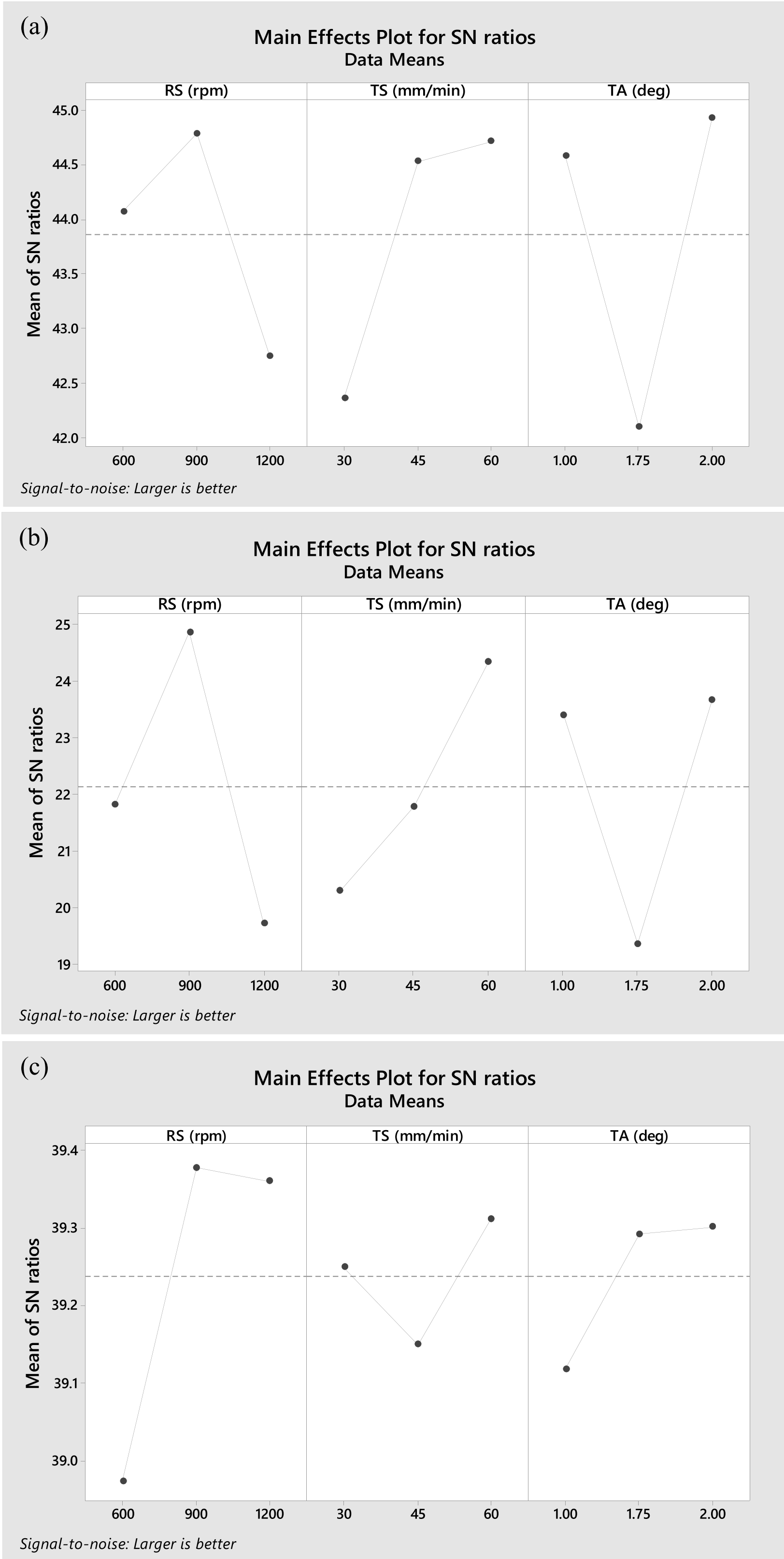

Figure 8. AA5083/Coal composite S/N ratio plot (a) UTS; (b) PE; (c) HV.

3.3. Signal-to-noise ratio analysis

Taguchi's method was utilized to optimize the AMMC parameters based on the fabricated AA5083/Coal composite joints. This approach involved analysing three key response factors: ultimate tensile strength, microhardness, and percent elongation. Taguchi's signal-to-noise ratio was utilized to assess the influence of each process parameter on these response factors using the experimental data. Higher S/N ratios indicate better

Table 8. Signal to noise ratio response for microhardness.

Level	Rotational speed(rpm)	Traverse speed (mm/min)	Tilt angle (°)
1	38.97	39.25	39.12
2	**39.38**	39.15	39.29
3	39.36	**39.31**	**39.30**
Delta	0.40	0.16	0.18
Rank	1	3	2

Table 9. Factors that impact/contribute to the variation of ultimate tensile strength.

Source	Degree of freedom (DF)	F-value	P-value	% Contribution
RS (rpm)	2	0.29	0.773	12.18
TS (mm/min)	2	0.47	0.682	19.31
TA (°)	2	0.65	0.605	**27.05**
Error	2			41.47
Total	8			

Table 10. Factors that impact/contribute to the variation of percentage elongation.

Source	Degree of freedom (DF)	F-value	P-value	% Contribution
RS (rpm)	2	2.43	0.292	**34.35**
TS (mm/min)	2	1.52	0.397	21.48
TA (°)	2	2.12	0.320	30.02
Error	2			14.14
Total	8			

Table 11. Factors that impact/contribute to the variation of microhardness.

Source	Degree of freedom (DF)	F-value	P-value	% Contribution
RS (rpm)	2	1.12	0.472	**44.89**
TS (mm/min)	2	0.14	0.874	5.792
TA (°)	2	0.23	0.815	9.131
Error	2			40.18
Total	8			

process parameter settings, following the 'larger-the-better' approach. The objective in this case is to determine parameter combinations that maximize the composite joints' microhardness, percentage elongation, and UTS. The following formula can be used to compute the 'larger-the-better' criterion [46, 47]:

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i-1}^{3}\frac{1}{y^2}\right)$$

In the formula, n represents the number of recurrences of experiments, and y denotes the response factors, which in this study are UTS, microhardness, and percentage elongation. 'Noise (N)' denotes the unwanted value for the output characteristic, whereas 'Signal (S)' denotes the desired value. Table 5 presents the experimental results alongside their corresponding S/N ratios for every combination of FSP parameters used with the AA5083/Coal composite. These results are further visualized in graphical form in figure 8.

The maximum ultimate tensile strength, percentage elongation, and microhardness for the AA5083/Coal composite joints are achieved when the tilt angle and traverse speed are set to level 3, and the rotational speed is set to level 2 (see figures 8(a)–(c)). Analysis of the signal-to-noise ratio indicated that the optimal process parameters are a tilt angle of 2 degrees, a traverse speed of 60 mm min^{-1}, and a rotational speed of 900 rpm. The larger-the-better approach has been successfully utilized to optimize mechanical properties in metal matrix composites, as demonstrated in previous research [20, 48].

3.4. Ranking of contributing factors and determining optimum factor

Minitab 18 software was employed to analyses the S/N ratio data and identify the most significant factors influencing each response variable ultimate tensile strength, elongation, microhardness) for the AA5083/Coal

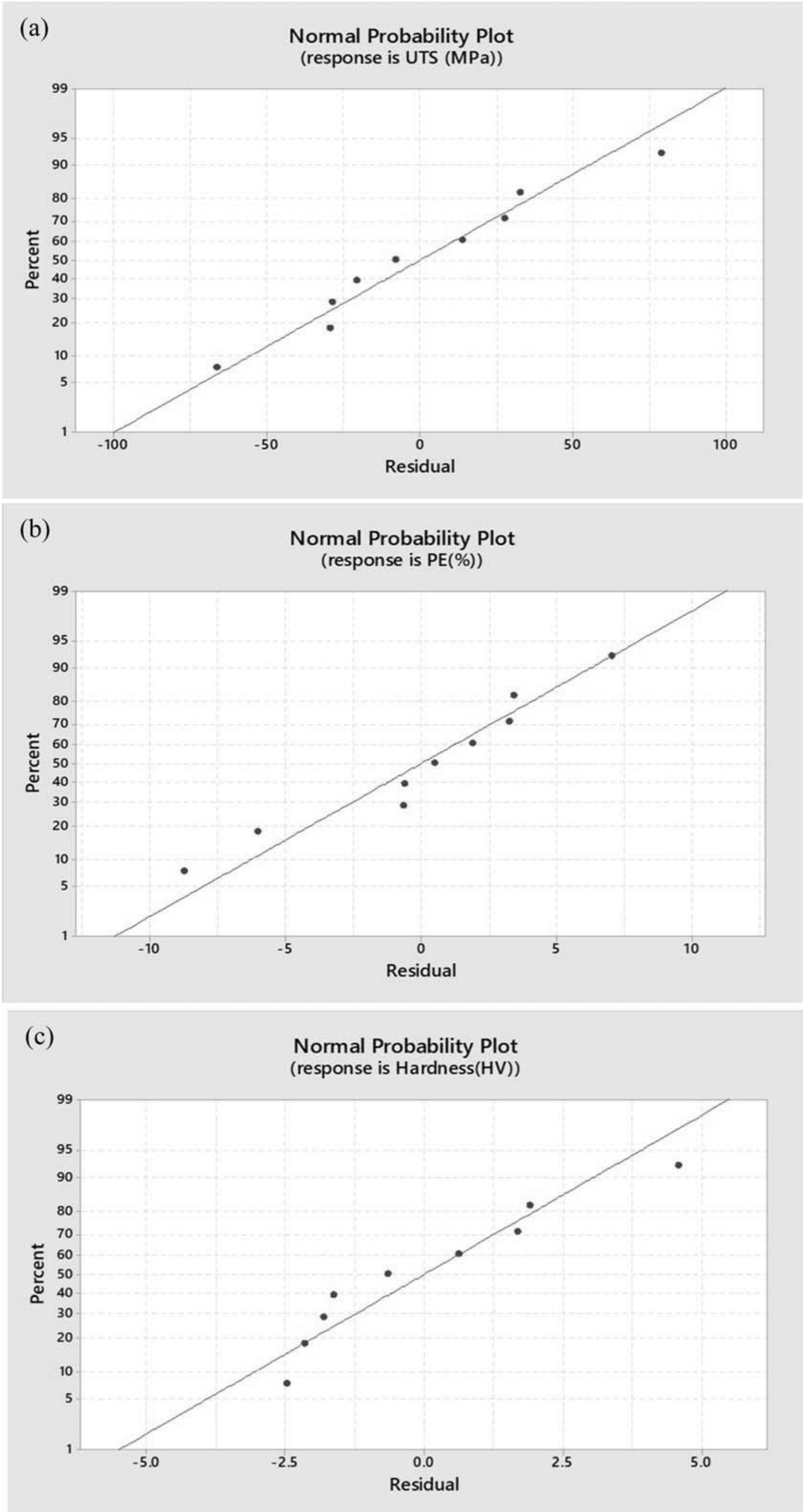

Figure 9. Normal probability plots of residuals; (a) Ultimate Tensile Strength, (b) Percentage Elongation, and (c) Microhardness, illustrating the alignment of residuals with the straight line to assess normality.

composite joints. This analysis utilized a delta ranking system within Minitab. For all three levels, the mean S/N ratio was computed across the three FSP process parameters (tilt angle, traverse speed, and rotational speed). Tables 6–8 summarize these findings. Table 6 indicates that tilt angle exerts the most significant influence on the ultimate tensile strength of the composite joint at rank 1, followed by traverse speed at rank 2 and rotational speed at rank 3. Tables 7 and 8 revealed that the percentage elongation and microhardness are primarily influenced by the rotational speed (rank 1), the tilt angle at rank 2, and lastly the traverse speed at rank 3. The study reveals that the optimal traversal speed, rotational speed, and tilt angle for maximizing ultimate tensile strength, percentage elongation, and tilt angle in AA5083/Coal composite joints are at level 3, level 2, and level 3 as see in tables 6–8. The S/N ratio mean response table was used to determine the ideal settings for each response. Optimal values for UTS, PE, and HV were achieved using a tool rotational speed of 900 rpm, a tool traverse speed of 60 mm min^{-1}, and a tool tilt angle of 2 degrees.

3.5. Analysis of variance

To statistically evaluate the significance of each FSP parameter on the response variables (ultimate tensile strength, elongation, microhardness), a frequency test was employed [49]. This approach helps determine the percent contribution of each factor and its impact on the desired properties. Tables 9–11 summarize the ANOVA results for the S/N ratio of ultimate tensile strength, percentage elongation, and microhardness. Table 9 reveals that tilt angle is the most dominant factor influencing ultimate tensile strength, contributing 27.05% according to the ANOVA analysis. This aligns with the ranking in table 6. The tilt angle's influence on ultimate tensile strength can be explained by its role in controlling material flow and tool penetration into the workpiece. Higher tilt angles can lead to larger grain and particle sizes, potentially affecting the mechanical properties. Conversely, lower tilt angles may result in defects in the processed zone [50].

Similarly, the findings for elongation (table 10) and microhardness (table 11) support the rankings in tables 7 and 8, respectively. Table 10 indicates that rotational speed is the most influential factor affecting percentage elongation (PE), contributing 34.35% to the variation. Similarly, table 11 shows that rotational speed is the primary factor influencing microhardness, contributing 44.89%. The significant effect of rotational speed on microhardness aligns with previous research (e.g., Chanakyan *et al* [51], Syed *et al* [52], and Butola *et al* [53]). The rotational speed is a dominant process variable in FSP, significantly influencing the even distribution of reinforcement particles, grain refinement, and heat input during the process [54–57], all of which contribute to increased hardness.

3.5.1. Residual analysis using normal probability plot

The normality of residuals was assessed using Normal Probability Plots for the responses—Ultimate Tensile Strength, Percentage Elongation, and Microhardness as shown in figure 9. These plots serve as a graphical method to evaluate whether the residuals follow a normal distribution, which is a key assumption for the validity of ANOVA. The Normal Probability Plot for UTS showed that the residuals aligned closely with the straight line, indicating an approximate normal distribution and validating the ANOVA assumptions for this response. Similarly, the residuals for Microhardness exhibited a strong linear trend, confirming their normality.

For Percentage Elongation, the residuals displayed slight deviations from the straight line, suggesting minor departures from normality. However, these deviations were not severe enough to undermine the reliability of the ANOVA results. These findings align with previous studies [5, 58–61] that advocate for the use of Normal Probability Plots in residual analysis to ensure the validity of statistical models.

Overall, the Normal Probability Plots demonstrate that the residuals for UTS, PE, and MH are approximately normally distributed, ensuring the reliability of the ANOVA results. While the graphical analysis supports the normality assumption, minor deviations in PE suggest that additional quantitative tests, such as the Kolmogorov-Smirnov test, may be conducted in future studies to confirm the findings further.

4. Conclusion

The Taguchi L9 factorial method and Analysis of Variance were employed to optimize FSP parameters for fabricating AA5083/Coal composites. The Taguchi L9 orthogonal array efficiently examined three critical FSP parameters: tool rotational speed, tool tilt angle, and traverse speed. Key findings are summarized below:

- The maximum UTS, PE and HV obtained were 242 MPa, 22.43 and 96.27 HV respectively.
- Based on S/N ratio analysis, the optimal processing conditions for achieving the highest tensile strength, elongation, and microhardness in AA5083/Coal composites were identified as a rotational speed of level 2, traverse speed of level 3, and tilt angle of level 3. Using the S/N ratio approach, the study determined statistically validated optimal parameters: a tool tilt angle of 2°, a tool rotation speed of 900 rpm, and a traverse speed of 60 mm min^{-1}. By selecting parameters that maximized the S/N ratio for UTS, microhardness, and elongation, the study ensured consistent and reproducible results, enhancing the reliability of the results and their practical application.
- ANOVA results indicate that tilt angle significantly influences ultimate tensile strength, while rotational speed has the most significant impact on percentage elongation and microhardness. The tilt angle's role in controlling material flow and tool penetration, which are crucial for avoiding defects and ensuring good

bonding, explains its influence on ultimate tensile strength. Rotational speed's high contribution to microhardness highlights the importance of heat generation in grain refinement and particle distribution. This methodical approach of using ANOVA provides a clear understanding of parameter influence on mechanical properties and ensures the reproducibility and reliability of the findings.

- The Taguchi method provided a systematic approach to optimizing FSP parameters, ensuring statistical robustness. This guarantees the accuracy of the mechanical improvements observed. The results suggest that coal particles can be a viable, cost-effective, and sustainable reinforcement material for AA5083 composites.

5. Future work

The findings suggest that coal particles can be a cost-effective and sustainable reinforcement material. Future research should focus on the long-term durability of coal-reinforced composites and the scalability of the FSP process for industrial applications. Additionally, exploring other statistical methods like Response Surface Methodology (RSM) could further refine the process and assess the long-term performance of these composites under various service conditions.

The ANOVA results revealed high p-values, indicating that none of the individual FSP parameters significantly influenced the response variables within the tested parameter range. This suggests that the mechanical properties may depend more on the interactions between parameters than on their independent effects. Future research should include a broader parameter range and additional experimental repetitions to reduce variability, explore interaction effects, and refine the statistical significance of the factors and their contributions to optimizing mechanical properties.

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Conflict of interest

The paper in question has no possible conflicts of interest, according to the authors.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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