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RESEARCH ARTICLE

Optimization of setting parameters for aluminium matrix composite reinforced with boron carbide using two-stage stir casting techniques

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Abstract - Stir casting is a widely used metallurgical technique for producing aluminum matrix composites. Many studies in this area have focused on fabricating these composites using fixed stir casting parameters, often overlooking the importance of an optimization approach. These parameters significantly influence the microstructure and overall performance of the composites. This investigation aims to refine stir-casting parameters to produce Al 6061 composites reinforced with B_4C microparticles, thereby improving their performance. The sample was prepared using the two-step stir-casting technique with a 2 wt% B_4C particle composition. The Taguchi method was utilized to optimize three critical parameters in stir casting, such as melting temperature (700-800 ºC), stirring speed (100-300 rpm), and stirring time (10-30 minutes), which were systematically adjusted. A systematic analysis using an L9 orthogonal array was conducted to determine how varying levels of process parameters affected hardness properties. The optimization of two-stage stirs casting parameters using the Taguchi method identified stirring speed as the most dominant factor, with an optimal combination of 700 ºC melting temperature, 200 rpm stirring speed, and 20 min stirring time producing the highest Brinell hardness in Al 6061–2 wt.% B_4C composites. Analysis of variance results indicated that all three stir casting parameters significantly influenced the property responses, with stirring speed being the most dominant factor in achieving the highest Brinell hardness (HB) in the composite material.

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1. Introduction

Metal matrix composites are a category of composite materials in which a metallic matrix is used, augmented by the incorporation of ceramic or organic reinforcements to enhance the composite's capabilities beyond those of the base metal. Aluminum matrix composites (AMCs), magnesium matrix composites, and copper matrix composites are significant examples of metal matrix composites presently in great demand across multiple sectors, including the automotive, aerospace, and electronics industries. Their extensive use is attributed to their advantageous characteristics and economical accessibility, rendering them suitable for many technical applications [1, 2]. Aluminum matrix composites are currently among the most widely used metal matrix composites owing to their superior properties and applicability across diverse technical contexts. These composites consist of aluminum or aluminum alloys as the matrix material, reinforced with non-metallic elements. The reinforcements can be incorporated as weight or volume percentages and are available in various forms, including particulates, whiskers, and fibres. Aluminum matrix composites, especially those reinforced with ceramic particles such as boron carbide (B_4C), have attracted significant interest across various engineering fields. This interest stems from their remarkable mechanical properties, encompassing a high strength-to-weight ratio, improved wear resistance, and outstanding thermal stability [3].

Stir casting is acknowledged as a cost-effective and versatile technique for producing these composites, as it enables the uniform dispersion of reinforcement particles within the aluminum matrix [4]. Achieving the best properties of stir-cast aluminum matrix composites requires careful control and precise adjustment of various process parameters such as stirring speed, melting temperature, reinforcement addition rate, and stirring time. These characteristics significantly influence the consistency of reinforcement particle distribution, the integrity of the interfacial bond between the matrix and reinforcement, and the overall porosity of the composite material [5]. The interaction of aluminum with ambient air and moisture during the melting process forms an aluminum oxide layer. This oxide layer acts as a protective barrier, preventing further reaction between the molten aluminum and the environment. The two-stage stir casting method is a widely adopted technique for enhancing the uniform distribution of reinforcement particles, especially boron carbide in an aluminum matrix [6]. In conventional single-stage stirring, particles often agglomerate or settle due to density differences, poor wettability, or insufficient dispersion forces. The two-stage process addresses these challenges more effectively. Sambathkumar et al. [7] investigated the mechanical and corrosion behaviour of Al7075-based hybrid composites reinforced with 0–15 vol% SiC and TiC, fabricated via a two-step stir casting process incorporating a proportional-integral-derivative controller. The melting was conducted in a furnace fitted with a fire-resistant stirring motor and a speed regulator to control the stirring speed. The resulting composites exhibited significantly higher tensile strength and hardness compared to the unreinforced Al7075 alloy. S Krishna Prasad et al. [8] produced Al7075 -TiB2

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alloy composite using a stir casting furnace and studied its mechanical properties along with microstructural characterization. The hardness, ultimate tensile strength, and yield strength of TiC-reinforced composites have improved, and their ductility has increased marginally. Many researchers have reported that the stir-casting process is widely adopted to enhance the properties of aluminium matrix composites [9].

The wettability between the aluminum matrix and boron carbide particles is a critical factor influencing interfacial bonding quality and the composite's overall strength. Insufficient wettability may result in problems such as particle agglomeration, porosity formation, and a consequent deterioration in mechanical performance [3]. Optimizing processes requires a comprehensive assessment of various elements, including the pre-treatment of boron carbide particles to enhance their wettability and the addition of wetting agents to the molten aluminum. A range of optimization strategies has been explored to improve the characteristics of aluminum matrix composites produced via stir casting. One approach involves applying a two-step mixing technique to enhance dispersion of the reinforcement phase [4]. This approach helps address the challenges of achieving a consistent distribution of reinforcement particles, particularly when reinforcements exhibit elevated surface energy or a tendency to clump. Boron carbide particles possess advantageous properties, including high strength, low density, remarkable hardness and wear resistance, excellent chemical stability, and effective neutron absorption capability [10]. The particles demonstrate a highly developed surface, which enhances wettability and ensures robust interfacial contact within the matrix alloy. Furthermore, accurate control of the mixing rate of the reinforcing phase is essential, as insufficient mixing may undermine the composite's intended characteristics.

The primary aim of optimizing the stir casting process is to produce a composite material with a consistent distribution of reinforcement particles, strong interfacial bonding, minimal porosity, and customized mechanical properties that meet specific application requirements. This optimization usually requires a blend of experimental investigations, numerical simulations, and statistical analyses to identify the optimal process parameters and their influence on the final composite properties. Furthermore, employing design of experiments methodologies, including the Taguchi method, enables a structured assessment of the connections between process parameters and the resulting composite attributes [11]. By applying these strategies, scientists and producers can fine-tune the stir-casting process and ensure the production of high-performance aluminum matrix composites reinforced with boron carbide. These cutting-edge composites are ideal for a range of applications across sectors such as defence, aerospace, and automotive. The study used the Taguchi method and Minitab software to examine how different factors affected the process. The Taguchi method is a powerful statistical method for determining the optimal process parameters. The tuning focused primarily on three key factors: stirring time (s), melting temperature (ºC), and stirring speed (rpm). A set of controlled experiments was planned and carried out to test how these parameters affected the desired results. The Taguchi method enables finding the best choices that improve process performance and efficiency while reducing variation.

2. Materials and Methods

2.1 Chemical Composition of Material

Al6061 is commonly utilized in the aerospace and automotive industries due to its excellent corrosion resistance and superior strength to other aluminum alloys. The chemical composition of the base alloy material expressed in weight percentage (wt%) is as shown in Table 1. The composition was determined using Spark Emission Spectroscopy (Model: WAS Foundry-Master, Oxford Instruments).

Table 1. Chemical composition of Al 6061

Element	Al	Si	Fe	Cu	Mn	Mg	Cr
Composition (wt%)	Balance	0.5	0.41	0.21	0.12	0.76	0.21

Table 2. Comparison of the reinforcement commonly used in an Al matrix composite

Properties	Type of reinforcement		
	B_4C	SiC	Al_2O_3
Density ($g \cdot cm^{-3}$)	2.50 – 2.52	3.20 – 3.22	3.90 – 3.98
Melting point (ºC)	~2450	~2700	~2072
Hardness (Vickers, HV)	3000 – 3800	2500 – 3000	1800 – 2200
Elastic modulus (GPa)	450 – 470	410 – 450	370 – 390

2.2 Reinforcement Material

In this study, high-purity boron carbide (B_4C, 99.95%) was selected as the primary reinforcement material owing to its favourable physical and mechanical properties, as summarized in Table 2. These properties include excellent corrosion and wear resistance, as well as superior mechanical characteristics such as tensile strength, hardness, and impact resistance. The detailed properties of B_4C are shown in Table 3. The reinforcement particles consisting of 2 wt% B_4C were encapsulated in aluminum foil before being introduced into the molten metal. This step facilitates the uniform incorporation of boron carbide into the aluminum matrix during the pouring process [12]. Before the casting process, the boron carbide particles were preheated to 300ºC to eliminate trapped gases and stabilize temperature fluctuations. The boron carbide reinforcement particles were procured from Yemate Ind, China.

Table 3. Properties of B_4C [13]

Properties of B_4C	Value
Hardness	2900–3580 (Knoop100g) kg/mm^2 38100–44100 MPa
Density	2.52 g/cm^3
Compressive strength	2583–5687 MPa
Fracture toughness	2.9–3.7 MPa.m^{½}
Youngs Modulus	450–470 GPa
Tensile Strength	261–569 MPa
Ductility	0.00058–0.00124
Thermal conductivity	17–42 W/mK
Coefficient of thermal expansion	3.2–9.4($\times 10^{-6}$ /K)
Melting Point	2645–2780 K
Thermal Neutron Cross-section capture	600 barn
Latent heat of fusion	1350–2030 KJ/Kg
Dielectric Constant	4.8–8
Maximum service temperature	1000–2000 K

2.3 Two-Stage Stir Casting

The two-stage stir-casting process is a more advanced version of the conventional stir-casting method commonly used for producing metal matrix composites. This approach aims to overcome several issues associated with the single-stage stir casting technique, such as non-uniform dispersion and weak interfacial bonding between the aluminum matrix and B_4C. Figure 1 presents a schematic representation of the stir casting apparatus

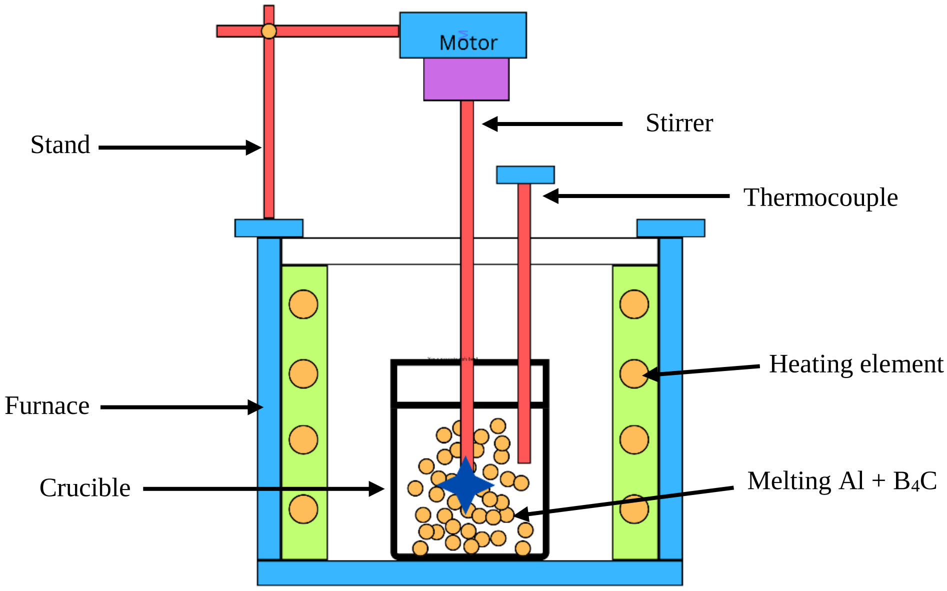

Figure 1. Schematic diagram of stir casting facilities

In the first stage, half of the initially weighed aluminum matrix is heated to a temperature above its melting point, specifically 700ºC. Once the aluminum is fully molten, an initial manual stirring process is performed. This preliminary stirring, conducted using a stirring blade, breaks the surface layer and ensures a smooth flow of the molten aluminum. Subsequently, the molten aluminum is cooled to a temperature close to its solidification point while remaining semi-liquid or semi-solid, estimated at approximately 600 ºC. In this condition, the viscosity of the aluminum melt increases, making it more effective at trapping B_4C particles and thereby enhancing their incorporation into the matrix. The B_4C reinforcement was then introduced into the semi-liquid aluminum melt. Continuous manual stirring was performed for 2 minutes to ensure a uniform mixture. The remaining aluminum matrix was added to the furnace and left for 10 minutes. In the second stage, the furnace temperature was increased beyond the melting point of aluminum to 700 ºC, 800 ºC, and 900 ºC, respectively. At this stage, the aluminum returned to a fully molten state, facilitating the improved dispersion of B_4C reinforcement within the aluminum matrix. Automated mechanical stirring was performed for 10, 20, and 30 minutes at 100, 200, and 300 rpm. This process was implemented to ensure uniform dispersion of B_4C within the aluminum matrix and to prevent particle agglomeration in specific regions. Upon completion of the stirring process, the aluminum melt reinforced with B_4C was poured into a separately preheated mould at 450 ºC. The produced samples were meticulously sectioned and thoroughly examined through detailed analysis.

2.4 Hardness Testing

The hardness test is widely used to evaluate a material's resistance to deformation under applied force or load. The Brinell hardness test determines material hardness by indenting the surface with a hardened steel or carbide ball. In this study, the Brinell hardness of a polished sample was measured using a Brevetti Affri Model 206 RSD hardness tester, in accordance with ASTM E10-18 for metallic materials. The test was conducted using a 2.5 mm diameter ball under a load of 62.5 kgf, applied for 10 seconds. The Brinell hardness value was determined based on the diameter of the indentation formed on the material's surface.

2.5 Design of Experiment

A Design of Experiments approach based on the Taguchi method was employed to optimize stir-casting parameters for fabricating Al 6061–B_4C composites. Three key process parameters, such as melting temperature, stirring speed, and stirring time, were selected as control factors due to their significant influence on melt fluidity, particle dispersion, and interfacial bonding during composite fabrication. Each parameter was investigated at three levels, selected based on preliminary trials and reported literature, to ensure stable processing conditions while minimizing defects such as particle agglomeration, oxidation, and porosity. In this study, the optimization of stir-casting process parameters was carried out using the Taguchi method in Minitab 20.2 (2021 LLC). The Taguchi approach is widely recognized for process optimization due to its ability to identify interaction effects between process parameters and achieve superior outcomes compared to other optimization techniques [11, 14]. Additionally, analysis of variance is frequently used to assess the significance of process parameters and to determine the contribution of input parameters to the response [15]. The stir casting process parameters examined in this study include melt temperature, stirring speed, and stirring time. Each parameter was evaluated at three distinct levels, as outlined in Table 4. The L9 orthogonal array, detailing the experimental parameter combinations, is shown in Table 5. The experimental design and L9 orthogonal array used in this study were generated in Minitab.

Table 4. Process parameters and level

Process parameters	Level 1	Level 2	Level 3
Melting temperature (ºC)	700	750	800
Stirring speed (rpm)	100	200	300
Stirring time (min)	10	20	30

Table 5. The L9 stir casting process parameters

No	wt% B_4C	Melting temperature (ºC)	Stirring speed (rpm)	Stirring time (min)
1	2	700	100	10
2	2	700	200	20
3	2	700	300	30
4	2	750	100	20
5	2	750	200	30
6	2	750	300	10
7	2	800	100	30
8	2	800	200	10
9	2	800	300	20

The signal-to-noise (S/N) ratio was determined using the average hardness values obtained from the measurements. The "larger-the-better" quality characteristic was adopted in this study. The performance was assessed based on the average hardness, which is desired to be as high as possible. This criterion is mathematically expressed in Eq. (1) [16].

$$\frac{S}{N} = -10\,log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{1}$$

where *n* represents the number of measurements, where *n* = 10, and y_i denotes the i^{th} response value of hardness for each noise repetition. The subscript *i* corresponds to the number of design parameters in the orthogonal array.

Statistical analysis was conducted using ANOVA to identify significant differences among the factors. This method assesses the significance of controlling factors by evaluating the F-ratio and the percentage contribution of each factor. The sum of squares (SS), degrees of freedom (DOF), mean square (MS), and the corresponding F-test at a 5% significance level were calculated using Equations (2)–(6) [16].

$$SS_T = \sum_{i=1}^{N}\left(\frac{S}{N_i}\right)^2 - \frac{T^2}{N} \tag{2}$$

where SS_T represents the sum of squares associated with total variation, while *N* denotes the total number of experiments.

$$SS_A = \sum_{i=1}^{Ka} \left(\frac{A_i^2}{n_A}\right) - \frac{T^2}{N} \tag{3}$$

where SS_A represents the sum of squares associated with factor A, while K_a denotes the number of levels for factor A. A_i refers to the total sum at a specific level of factor A. V_{total} corresponds to the variance of the degrees of freedom, V_{factor} represents the variance of the factors, and V_{errors} denotes the variance of errors. Additionally, SS_{factor} indicates the sum of squares for the factor, while F_{factor} represents the F-ratio of the factor, as shown in the following equations.

$$V_{total} = N - 1 \tag{4}$$

$$V_{factor} = \frac{SS_{factor}}{V_{factor}} \tag{5}$$

$$\mathrm{F_{factor}} = \frac{\mathrm{V_{factor}}}{\mathrm{V_{error}}} \tag{6}$$

3. Results and Discussion

3.1 Analysis of Reinforcement Boron Carbide

Figure 2 illustrates the morphology of boron carbide (B_4C) particles used as reinforcement in the aluminum matrix composite. The particles exhibit irregular shapes with sharp edges and angular corners, which are beneficial for mechanical interlocking with the matrix material. This irregular morphology can enhance load transfer efficiency at the particle-matrix interface, thereby improving the mechanical performance of the composite. Furthermore, the micrograph shows that the B_4C particles are well-dispersed and do not form large agglomerates. This is a desirable characteristic, as it suggests that the particles remain separated and uniformly distributed during the mixing and casting stages. Such behaviour is particularly important during the stir casting process, where uniform dispersion of reinforcement particles ensures consistent mechanical properties throughout the final product. A homogeneous microstructure reduces the risk of localized weaknesses and improves the composite's reliability. Additionally, the absence of significant particle clustering helps avoid regions of stress concentration, which are prone to crack initiation under mechanical loading. Overall, the favourable morphology and dispersion of B_4C particles are key to achieving a high-performance aluminum matrix composite.

Table 6. Percentage distribution of particle size by sample size

Percentage (%)	Particle Size (µm)			
	Sample 1	Sample 2	Sample 3	Average
10	7.15	7.28	7.12	7.18
20	9.11	9.28	9.07	9.15
30	11.14	11.36	11.10	11.20
40	13.28	13.54	13.23	13.35
50	15.45	15.75	15.39	15.53
60	17.69	18.03	17.62	17.78
70	20.25	20.64	20.171	20.35
80	23.67	24.13	23.58	23.79
90	29.92	30.50	29.80	30.07
95	38.21	38.95	38.06	38.41

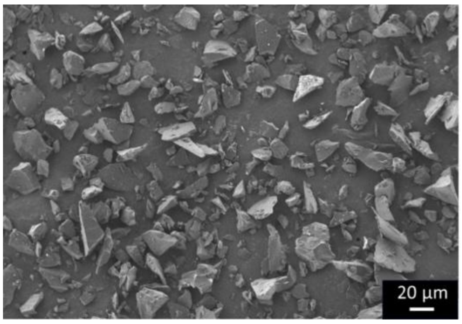

Figure 2. Microscope image of boron carbide

A total of three tests were conducted on micro-sized B_4C filler to obtain the average particle size, with each sample being randomly selected. Figure 3 and Table 6 present the percentage distribution of particle sizes, categorized based on particle size range. The percentiles are denoted by the letter *d* followed by a percentage value (%). For instance, *d10* indicates that 10% of the sample consists of particles smaller than 7.18 µm. The median particle size, represented by *d50*, signifies that 50% of the sample has a particle size smaller than 15.53 µm. Meanwhile, *d95* denotes that 95% of the sample comprises particles smaller than 38.41 µm. These findings indicate that the average particle size across all three samples is 15.53 µm. Monitoring these three parameters enables the identification of significant variations in the primary particle size and extreme points in the distribution, which may arise from the presence of fine particles or oversized particle agglomerates [17].

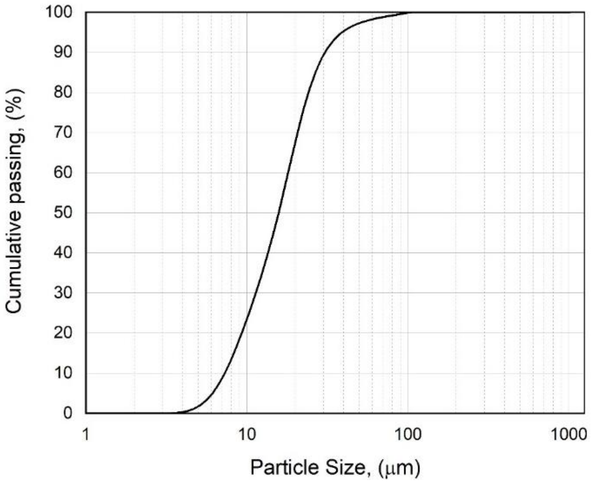

Figure 3. Result of particle size analysis of boron carbide for sample 1

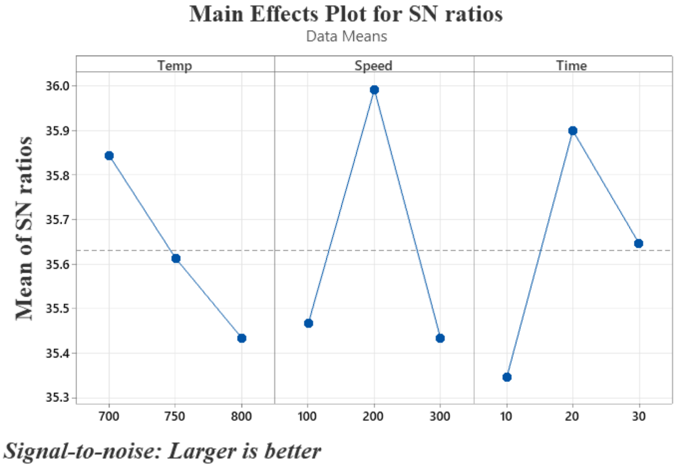

Figure 4. Main effects plot for the S/N ratio of hardness

Table 7. L9 Orthogonal array with design factors and S/N ratio for hardness

No. Exp	Melting temperature (°C); (A)	Stirring speed (rpm); (B)	Stirring time (min) (C)	Hardness value (HB); (D)	S/N Hardness
1	700	100	10	60.4	35.52
2	700	200	20	67.1	36.52
3	700	300	30	60.2	35.50
4	750	100	20	60.6	35.55
5	750	200	30	64.4	36.12
6	750	300	10	58.0	35.17
7	800	100	30	59.7	35.33
8	800	200	10	59.1	35.34
9	800	300	20	61.0	35.63

3.2 Optimization of Setting Parameters

Stir casting is a commonly used method for producing aluminum matrix composites due to its cost-effectiveness and simplicity. The quality of AMCs is primarily influenced by three key parameters: stirring speed, stirring time, and molten matrix temperature. Proper optimization of these factors is essential to ensure uniform dispersion of the reinforcement material, enhance mechanical properties such as hardness, and minimize porosity. In the stir-casting process, the quality of aluminum matrix composites is often evaluated based on mechanical properties, such as hardness. The distribution of hardness across the composite matrix provides valuable insights into the uniformity of reinforcement particle dispersion and the overall effectiveness of the process. Optimizing stir-casting parameters using hardness distribution as a key indicator ensures that the composite material achieves the desired mechanical properties while minimizing defects, such as reinforcement particle agglomeration, porosity, or uneven particle distribution. The L9 orthogonal array was used to fabricate AL6061/B_4C composites, which were analysed using the Brinell hardness test. The composite specimens were fabricated using a combination of stir-casting input process parameters arranged according to the L9 orthogonal array, as shown in Table 7. The influence of each stir casting input parameter was determined using optimization techniques. The optimization process was carried out using Minitab 20.2. The main effects plot for the signal-to-noise ratio of hardness is presented in Table 8 and Figure 4. The signal-to-noise ratio is a robustness measure used to identify optimal control factor settings that minimize the effect of noise on the response. Minitab calculates the signal-to-noise ratio separately for each combination of control factor levels in the design. The "larger-is-better" criterion was selected to optimize the stir-casting process parameters for hardness response [18]. The highest hardness value of 67.1 HB was obtained at a melt temperature of 700ºC, a stirring speed of 200 rpm, and a stirring time of 20 minutes. Increasing the melt temperature from 700ºC to 800ºC decreased hardness. The melt temperature of 700ºC recorded the highest S/N ratio value of 35.85. At this temperature, the aluminum matrix is fully melted and flows freely, allowing it to surround and adhere to the boron carbide (B_4C) particles. Optimizing this melt temperature contributes to a more uniform distribution of B_4C within the aluminum matrix. A uniform distribution of boron carbide reduces the formation of weak points and enhances mechanical properties, such as hardness, due to stronger interfacial bonding between aluminum and B_4C [19, 20].

Table 8. Response table for signal-to-noise ratio analysis using the "larger-is-better" criterion for hardness

Level	Stirring speed (rpm)	Stirring time (min)	Melting temperature (ºC)
1	35.47	35.35	35.85
2	35.99	35.90	35.61
3	35.43	35.65	35.43
Delta	0.56	0.55	0.41
Rank	1	2	3

3.3 Effect of Molten Temperature

Temperature plays a significant role in the behaviour of molten aluminum (Al) during the fabrication of aluminum matrix composites, particularly in viscosity. An increase in temperature typically reduces the viscosity of molten aluminum (Al), facilitating the uniform dispersion of B_4C particles within the matrix. Lower viscosity plays a critical role in enhancing particle distribution by allowing B_4C to move freely and settle more uniformly in the melt. While reduced viscosity aids dispersion, it also poses a potential drawback. Excessive temperature increases can result in an overly fluid melt, causing the relatively denser B_4C particles to settle more rapidly to the bottom of the crucible. However, excessive viscosity reduction can increase particle sedimentation at the bottom of the crucible [21]. This phenomenon occurs because lower viscosity diminishes the resistive forces that normally maintain particle suspension, thereby allowing gravitational forces to act more effectively on the B_4C particles [22]. As a result, particle sedimentation leads to an uneven distribution, creating regions with lower reinforcement content and areas with higher concentrations near the bottom [23]. Such non-uniform dispersion negatively impacts the composite’s mechanical properties, including tensile strength, hardness, and wear resistance.

3.4 Effect of Stirring Speed

Stirring speed is a critical process parameter influencing the uniform distribution of B_4C particles within the aluminum matrix. The composite's hardness increases from 100 to 200 rpm, then decreases at 300 rpm, with the highest hardness observed at 200 rpm. At a lower stirring speed of 100 rpm, the generated turbulence is insufficient to achieve effective dispersion of B_4C particles throughout the Al matrix. This inadequate mixing results in a non-uniform particle distribution, with some regions containing fewer B_4C particles. These particle-deficient areas create weak zones within the composite, leading to inconsistencies in hardness values [24]. Increasing the stirring speed to 200 rpm enhances turbulence to an optimal level, promoting the uniform dispersion of B_4C particles within the Al6061 matrix. At this speed, hardness improves due to better particle embedding, thereby strengthening interfacial bonding and enhancing the mechanical properties of the composite. This suggests that 200 rpm is the ideal stirring speed for achieving homogeneous particle distribution without excessive turbulence. However, at stirring speeds exceeding 200 rpm, such as 300 rpm, excessive turbulence can lead to particle agglomeration or uneven sedimentation of the reinforcing phase. As a result, the hardness decreases due to ineffective particle dispersion within the matrix, thereby reducing the overall reinforcement effectiveness and compromising the composite’s mechanical performance.

3.5 Effect of Stirring Time

The stirring time is a key process parameter that significantly influences the hardness of aluminum matrix composites. The Brinell hardness increases from 10 to 20 minutes of stirring, then decreases beyond 20 minutes, with the highest hardness at 20 minutes. This suggests that an optimal stirring time is essential for maximizing the hardness of AMCs. At

20 minutes and a stirring speed of Level 2, the material likely achieves an ideal particle dispersion and refined grain structure, contributing to enhanced hardness. However, prolonged stirring beyond this duration may lead to defects or particle agglomeration, which can negatively impact hardness. This phenomenon is attributed to the fact that, at optimal stirring time and speed, AMCs achieve uniform particle distribution and an ideal grain structure, thereby enhancing their mechanical properties [25]. The highest signal-to-noise ratio corresponds to the best process performance. Therefore, the optimal process parameters are determined based on the maximum S/N ratio. According to Table 8, which presents the response analysis, the ranking of the process parameters affecting the hardness of AMCs is as follows: stirring speed, then stirring time, and finally melt temperature. In summary, the optimized process parameters for achieving superior hardness in AMCs are a stirring speed of 200 rpm, a stirring time of 20 minutes, and a melt temperature of 700 ºC.

3.6 Analysis of Variance

ANOVA is utilized to assess the significance of individual process parameters in influencing hardness [26]. The ANOVA results provide a clear understanding of the effects of each parameter on hardness values, enabling identification of the most significant factors and their interactions that affect overall performance characteristics. Table 9 presents the percentage contribution of key process parameters, namely stirring speed, stirring time, and melt temperature, in determining the hardness of the composite. The F-value, P-value, and percentage contribution serve as critical indicators for distinguishing between controllable process factors and the influence of uncontrolled variables on achieving optimal hardness [27].

Table 9. Analysis of variance for hardness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F- Value	P-Value
Stirring Speed (rpm)	2	26.050	40.50%	26.050	13.025	3.90	0.204
Stirring Time (min)	2	21.266	33.06%	21.266	10.633	3.18	0.239
Melt Temp. (ºC)	2	10.332	16.06%	10.332	5.166	1.55	0.393
Error	2	6.678	10.38%	6.678	3.339		
Total	8	64.326					

As shown in Table 9, stirring speed contributes the most at most stirring times (33.06%), followed by melt temperature (16.06%) and an error contribution of 10.38%. These results demonstrate that stirring speed is the most dominant factor in achieving the highest Brinell hardness in the composite material. The associated *p*-values for stirring speed (0.204), stirring time (0.239), and melt temperature (0.393) indicate that none of the factors had a statistically significant effect at the 0.05 significance level. The error contribution is 10.38%, which is within an acceptable range (<15%), suggesting that the experimental design successfully captured the major factors influencing hardness. According to accepted principles of experimental design, an error contribution of less than 15% is often deemed acceptable, indicating that the principal variance in the response is adequately represented by the chosen process parameters [28-30]. Therefore, stirring speed is the most significant parameter in enhancing the hardness of the aluminium matrix composite.

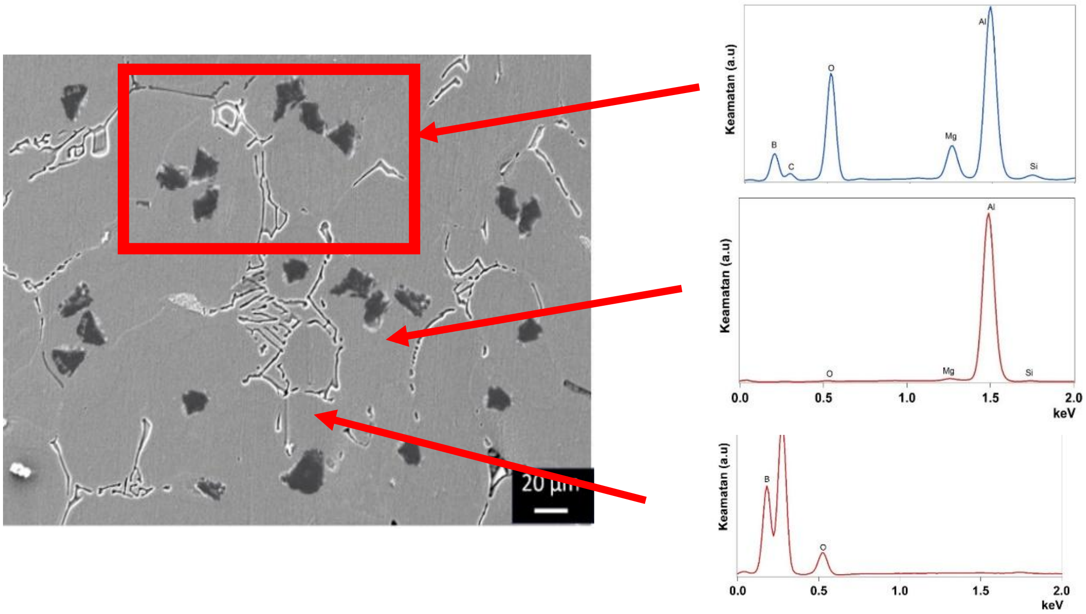

Figure 5. Microstructural image and EDX analysis of the developed Al-B4C composite at optimal setting parameters

3.7 Microstructure and XRD Analysis

Figure 5 presents the morphology of the developed composites under optimal stirring conditions of 700°C, 200 rpm, and 20 minutes for temperature, stirring speed, and time, respectively. The image illustrates a uniform distribution of particulates within the matrix, which contributes to improved properties compared to pure Al 6061. The composites were precisely fabricated using an advanced two-step stir-casting process. In the micrographs, the darker regions indicate the presence of boron carbide. Ensuring a uniform distribution of boron carbide within the aluminum matrix is essential for the successful development of aluminum matrix composites. X-ray Diffraction (XRD) analysis was performed on Al6061-based composites to confirm the presence of B_4C as a reinforcing phase and to identify any additional phases. These composites comprised 2 wt% B_4C particles uniformly distributed within the Al 6061 matrix, as depicted in Figure 6. The upper section of Figure 6 presents the XRD pattern and corresponding results for the Al 6061 alloy reinforced with 2 wt% B_4C at the optimal setting parameter. The middle section corresponds to the analysis of B_4C, while the lower section represents the analysis of Al 6061. The diffraction pattern showed seven distinct peaks over the 2θ range of 20° to 80°. Specifically, peaks at 2θ values of 23.50°, 34.92°, and 37.69° were associated with B_4C, whereas peaks at 38.51°, 44.82°, 65.18°, and 78.28° corresponded to pure aluminum. Additionally, minor peaks observed in the pattern were attributed to impurities. The reaction between B4C and Al produces no new elements. However, studies have confirmed that some reactions occur between B_4C and Al. The compositions Al_3BC, AlB_2, and AlB_{12} have been detected, with AlB_2 being more stable than the more complex phases due to its formation temperature exceeding 900°C [31].

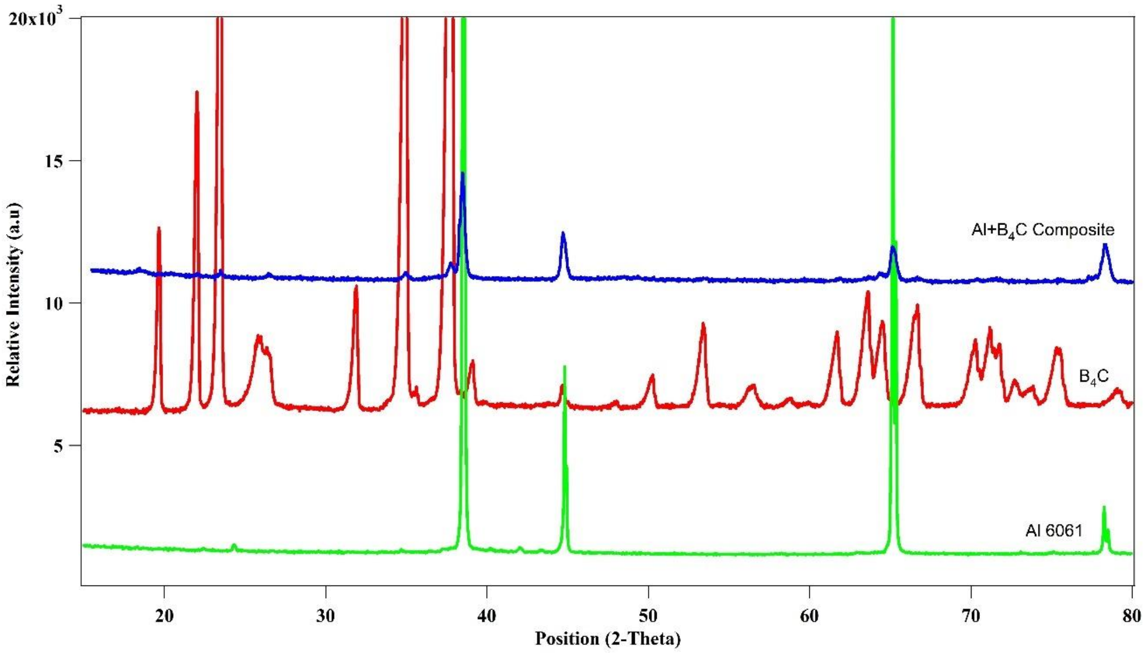

Figure 6 XRD analysis of Al-2%B_4C, B_4C and Al 6061

4. Conclusions

This work involved the fabrication of Al6061/B_4C matrix composites by the two-stage stir-casting method. Three process parameters, such as stirring speed, melt temperature, and stirring time, were chosen at three distinct levels. The mechanical properties, specifically hardness, were assessed using multiple tests employing the L9 orthogonal array according to the Taguchi methodology. Conclusions were derived from experimental data and optimization methodologies. The microhardness test is conducted on all Al6061-based composites to evaluate their hardness properties. The larger-is-better criterion is used for the S/N ratio of microhardness. The maximum hardness value recorded was 67.1 HB in experiment L2, which aligned with the optimized process parameters of a stirring speed of 200 rpm, a melting temperature of 700°C, and a stirring time of 20 minutes. The ANOVA results showed that stirring speed contributed the most at 40.5%, followed by stirring time at 33.06% and melt temperature at 16.06%. The results of microstructure and XRD showed a homogeneous distribution of B4C particles in the Al 606 matrix

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRediT Authorship Contribution Statement

Zaifol Samsu: Writing, Methodology, Experimental Investigation, Draft Preparation, Reviewing, and Editing
Norinsan Kamil Othman: Methodology, Data curation, Supervision, Review
Mohd Suzeren Md Jamil: Review and Editing, Validation, Methodology
Hafizal Yazid performed the experiments and analyzed the data
Mohd Sofian Alias: Analyzed the data

Availability of Data and Materials

The data supporting this study’s findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors stated that generative AI was not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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