

Sustainable Environmental Optimization of Abrasive Water Jet Machining Parameters of AZ31D/B₄C Composite Using TOPSIS Technique

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Abstract: MMCs are well known for their superior mechanical properties but are difficult to machine using traditional machining techniques because of hardness and brittleness. Among the non-traditional machining processes, AWJM was favoured as a cutting technique for hard and brittle materials. It is extremely beneficial in industries where finish quality and precision are the major concerns. Magnesium alloys possess an exceptionally high strength-to-weight ratio and find more application in structural use, especially in the automotive industry, as they are lightweight and have high performance. The research study comprises an investigation of the AWJM potentiality to cut B₄C and AZ31D composites produced based on the application of the Stir Casting process. The microstructure of composite material is observed with care so that Boron Carbide is uniformly dispersed in the magnesium matrix. Two crucial factors that affect machining precision and quality are used to evaluate the AWJM process. The settings are tuned using the Topsis technique to maximize composite material machining efficiency.

Keywords: Metal Matrix Composites (MMCs); Abrasive Water Jet Machining (AWJM); Magnesium Alloy (AZ31D); Stir Casting; Topsis Technique; Boron Carbide (B₄C); Composite Material; Magnesium Alloys.

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1. Introduction

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Composite materials are crafted materials composed of two or more component materials with radically different physical or chemical natures, each of which exists in its individual, separate, and distinct form in a macroscopic manner in the final product. These elements are blended to give the composite properties different from the materials. Still, single materials in the composite can be easily recognized since they do not dissolve or blend into one another, as seen in the work done by Masoud et al. [4]. Magnesium alloys, which could withstand high strength even under light weights, have gained the most popularity in automobiles and buildings based on the yield-cost-benefit and weight reduction benefit they provided over material and processes employed by Das et al., [1]. The Metal Matrix Composites employed here in this research project are the matrix metal to be AZ31 magnesium alloy with Boron Carbide (B_4C) reinforcing material, done by Perec et al. [8]. This research is concerned with the production, mechanical and metallurgical properties testing, and parameter optimization in the Abrasive Water Jet Machining (AWJM) process, which was explored by Ramalingam et al. [10]. Two-phase composite materials comprise two phases: the first phase is the matrix material, and the second is the reinforcement material, as explored by Saurabh et al. [13]. The matrix material contributes to the bulk shape of the composite, is generally weaker than the reinforcement material, and passes on induced stresses to the secondary phase, which is generally the stronger, dispersed material that increases the composite's mechanical properties, heat resistance, and conduction, according to the study of [3]. Composites may be divided by their matrix or reinforcement material, as used by Kiran Kumar et al. [12]. Composites that are classified based on the material used for the matrix are known as Metal Matrix Composites (MMC), Ceramic Matrix Composites (CMC), or Polymer Matrix Composites (PMC), as stated in [5].

Metal Matrix Composites consist of a metal matrix such as aluminium, magnesium, or copper reinforced with a dispersed phase such as ceramic oxides or carbides, such as those used by Solomon [2]. Ceramic Matrix Composites are made up of a ceramic matrix and dispersed ceramic fibres like Al_2O_3 or SiC , and Polymer Matrix Composites are made up of a polymer matrix, thermoset or thermoplastic, reinforced with glass, carbon, or kevlar fibres, as per [9]. Composites also vary with the reinforcing phase and are further divided into fibres, fillers, whiskers, flakes, and particulates, as per the research [11]. Benefits include being light, very strong, excess vibration absorption, heat control, and thermal stability at lower costs, as revealed by work done by Perec et al. [7]. Composites are used in numerous applications ranging from the components of aircraft and missiles to car parts such as the engine block and transmission case, sports equipment such as bicycles, and even on health devices such as those employed by Perec et al., [6]. Casting is a process of manufacture where a liquid material is poured into a mould with a cavity with the desired shape and then left to solidify, as researched by Aich et al. [14]. Materials used in casting are metals and other time-setting materials such as epoxy, concrete, and plaster, as researched by El-Hofy et al. [15].

Casting processes are divided into expendable mould casting, in which moulds are not reusable and short-lived, and non-expendable mould casting, in which the mould is reusable, as illustrated by work done by El-Hofy et al. [15]. Stir casting, a liquid metal process used for the production of MMCs entails the addition of the dispersion phase to molten matrix metal and then the provision of solidification of the mixture, and the phases must possess good interfacial wetting (bonding) so that high mechanical properties are obtained, as noted by Saurabh et al., [13]. Abrasive Water Jet Machining (AWJM) is a common non-conventional machining process used in machining hard and low-machinability materials such as titanium alloys, ceramics, and metal-matrix composites. AWJM uses the combined action of the high-pressure water jet and the abrasive particles to enhance machinability and thus is suitable for hard materials such as composites, kevlar polymer, and certain ceramics, as used by Masoud et al. [4]. AWJM process has a reciprocating pump that supplies pure water with a pressure between 4000 and 6000 bars. The abrasive grains are then supplied from a hopper within the mixing chamber to the waterjet, and abrasives and waterjet interaction affect the cutting or machining of abrasive materials, as carried out by Perec et al., [8]. Casting is a general process of manufacture in which a liquid material, often metal or setting time compound, is poured into a mould with the cavity of the final shape. The material is cooled and set in the mould to take on the product's final shape. Casting has widespread application in forming metals, plastics, and other composite materials. Materials to be moulded may vary from metals like aluminium, steel, and bronze to non-metallics like epoxy, concrete, and plaster, which harden or cure upon the mixture, as has been proven in prior work [15]. Properties of the application, i.e., strength, durability, thermal resistance, and expense, are primarily the basis for material selection.

The casting process has been classified as a general type into two broad categories: expendable mould casting and non-expendable mould casting. Expendable mould casting uses temporary and reusable moulds that are destroyed after casting. The practice has widespread application in the mass production of products with intricate shapes that would otherwise be too expensive or inconvenient to acquire. Some examples of expendable mould casting include investment casting, shell moulding, and sand casting. Non-expendable mould casting, however, involves repeated production runs using reusable moulds. The materials used to create the moulds include metal, repeat-stress durable permanent moulds, or graphite, into which the molten metal is poured repeatedly. Among the non-spending castings are permanent mould and die casting, which are frequently employed in mass manufacture due to their capacity to generate products with high reproducibility and accuracy. One of the expert processes in metal manufacture is Metal Matrix Composites (MMCs). This is done by incorporating a dispersed phase, i.e., ceramic particles or fibres, into molten matrix metal and mixing to distribute the dispersion phase within the matrix. The molten mixture is cast in a mould, and upon solidification, the reinforcement material gets trapped in the matrix effectively to

produce a composite material. The success of stir casting relies on creating a solidly established interfacial bond (or wetting) between the dispersed phase and the matrix metal. Interfacial bonding is key to the MMC's mechanical properties, and poor interfacial bonding can lead to the development of weak regions in the material, which compromise its strength and performance.

Stir casting is commonly used in MMC production since it is economical, convenient to apply, and enables the difference in concentration of reinforcements in the metal matrix, as per research studies [13]. Though casting is a relatively efficient and flexible process for the shaping of material, there are some applications where conventional casting operations may not be the best option, particularly when working with hard-to-machine or low-machinability material. These materials are machined using non-conventional machining operations like Abrasive Water Jet Machining (AWJM) successfully machined and cut. AWJM is used primarily on machine-hard materials like titanium alloys, ceramics, and metal-matrix composites that are largely hard to machined using conventional machining operations. In the AWJM process, a high-pressure water jet pressurizes a jet of abrasive-infused water onto the material. It is generally between 4000 and 6000 bar. The abrasive particles help enhance machinability within the material by making the waterjet cutting capability more potent so that the material can be machined or cut accurately. Combining the abrasive with the high-pressure water pressure makes AWJM very effective on hard and brittle materials like composite materials and ceramics, which otherwise need specialized cutting tools or processes to machine.

A reciprocating pump enables AWJM to generate the high-pressure water jet. Abrasion is supplied to the water jet by feeding through a hopper mounted in the mixing chamber and mixed with the water before being sprayed over the material. The abrasion-water synergetic effect allows for the processing of even low-machinability workpieces. AWJM becomes an important asset in the precision machining of hard materials used in aerospace, automotive, and medical industries, as illustrated in previous research work [8]; with these techniques, casting and AWJM as a hybrid produce efficient processes that can produce and optimize complex materials with optimal mechanical properties.

2. Literature Review

The effect of Abrasive Water Jet Machining (AWJM) on the surface properties and characteristics of various materials, primarily magnesium alloys and metal matrix composites (MMCs), has been widely studied. Abrasive flow rate and jet feed have been shown to play a major role in machining AZ91D casting magnesium alloy, primarily surface roughness, as performed by Das et al. [1]. 2D and 3D roughness parameters have been utilized in the literature to analyze the irregularities developed on the machined workpiece edge surface after machining and valuable information regarding surface quality was obtained [2]. Artificial neural networks have simulated a selected set of 2D surface roughness parameters to forecast future machining necessities after the AWJM process, as applied by Shetty and Hegde [3]. In addition, process parameter variables such as water pressure, traverse speed, and abrasive mass flow rate on penetration depth and AZ91 magnesium alloy surface topography have been studied, as done by Masoud et al. [4]. Analysis of variance (ANOVA) established that water pressure significantly influences penetration depth compared to traverse speed, as explained by work done by Szatkiewicz et al. [5]. Microstructural morphology and nature of the machined surface were also analyzed using scanning electron microscopy (SEM), where all the parameters are optimized to the extent of the impact on the machining process, as carried out by Perec et al. [6]. The surface integrity of MMCs, i.e., magnesium-based nanocomposites, was also controlled effectively with the jet traverse speed, as carried out by Perec et al. [7]. Experiments confirmed that higher surface quality can be achieved by employing slower traverse rates, which is of utmost significance for operations with high surface finish requirements, as disclosed in [8]. The second paper studied the optimization of AWJM process parameters in Al7075 TiB2 particle-reinforced composite.

Parameters such as water jet pressure, traverse speed, and standoff distance were considered to study the material removal rate, surface roughness, and taper angle used by Ravi Kumar et al. [9]. Taguchi-DEAR was employed for performing optimization and provided optimum parameters for minimizing surface roughness and taper angle used by Ramalingam et al. [10]. The ideal parameters were 280 MPa water jet pressure, 345 mm/min traverse rate, and 4 mm standoff distance, according to [11]. The parameters enabled the optimal performance in material removal and surface quality, and this shows just how important it is to possess the correct controlled AWJM process for composite materials, as researched by Kiran Kumar et al. [12]. Optimization of the AWJM process parameters for different alloys has also been addressed by research, i.e., for alloys like Inconel 625. The pressure of the water jet, abrasive flow rate, and standoff distance are modified, and research to minimize the kerf taper angle, as performed by Saurabh et al. [13].

Taguchi technique is commonly understood to be applied to optimize machining operation parameters, i.e., Abrasive Water Jet Machining (AWJM). Taguchi's method, in this regard, is utilized to determine optimal machining parameter values with an effort towards better cutting performance. With this strategy, the analysis of variance (ANOVA) is employed to examine the contribution percentage of each parameter to the kerf angle, which is among the important outcomes of the AWJM process. With this strategy, there exists a more structured way of assessing the influence of each parameter on cut quality, as examined in research studies by Aich et al. [14].

Experimental results reveal that water jet pressure influences kerf angle when machining is conducted, followed by abrasive flow and nozzle distances. They are very sensitive parameters governing the whole output of the AWJM process in such a manner that high-pressure water facilitates effective abrasive direction to the workpiece and leads to better cutting along with accuracy. The abrasive flow rate, however, determines the amount of abrasive material conveyed by the water jet and influences the material removal rate and the cut's finish. Likewise, the standoff distance, or how far the nozzle is from the workpiece, influences the accuracy of the cutting operation. As demonstrated by El-Hofy et al. [15], the water jet pressure was the most significant parameter in minimizing the kerf angle to a minimum, once again proving to be at the forefront in obtaining accurate cuts in the AWJM process.

The results affirm controlling the water pressure to attain the desired cutting quality, particularly in cutting hard materials like Inconel alloys. Inconel alloys possess a very high strength rating and are highly resistant to hostile environments; hence, such alloys are hard to cut with normal tools. One has to reduce the taper angle during cuts in such materials using AWJM so that cuts made through such materials are as precise as possible and to levels of desired use for application at high-performance rates. As concluded by Szatkiewicz et al. [5], reducing the taper angle improves accuracy in components' dimensions as well as the machinability quality of machined parts, a factor vital to precision sectors like the aviation and automobile industries. The generalized observation from the above studies offers general insight into how the parameters of AWJM can be optimized and controlled to improve the machining quality of different materials to the highest level.

From magnesium alloys, most widely used in automotive manufacturing, to metal matrix composites (MMCs) and high-performance alloys, precision fine-tuning of the AWJM parameters ensures that the machining is optimized to the surface finish, material removal rate, and dimensional accuracy requirements. This is especially important in uses such as aerospace, automotive, and manufacturing, where machining variability may result in catastrophic loss of function or product failure, even by a few per cent. By being subject to control by parameters such as water pressure, traverse rate, abrasive flow rate, and standoff distance in the optimal sense, AWJM can be tailored for the varied needs of various materials and uses. Balance of these parameters to the optimal facilitates achieving the ideal surface finish and maximum material removal rate without affecting the dimensional precision of the machined parts. They are significant parameters in the most precise applications and finest surfaces, as reflected by Perec et al. [6]. AWJM's capability of delivering in such areas makes it a highly worthwhile process in contemporary manufacturing.

3. Methodology

The research methodology used in this study is a set of elementary steps, from selecting materials to optimizing machining processes. Correct selection of materials, i.e., magnesium alloys and boron carbide (B₄C), is the first step in this context. Magnesium alloys, i.e., AZ31D, are chosen because they have low density, a high strength-to-weight ratio, and potential applications in aerospace, automobile, and medical areas. Aluminium, zinc, manganese, and copper are alloyed with magnesium, the lightest of all the structural metals, to improve its mechanical properties. The AZ31D alloy has been chosen for its good mechanical properties and resistance to tensile stress; therefore, it is suitable for use where strength and weight reduction are critical.

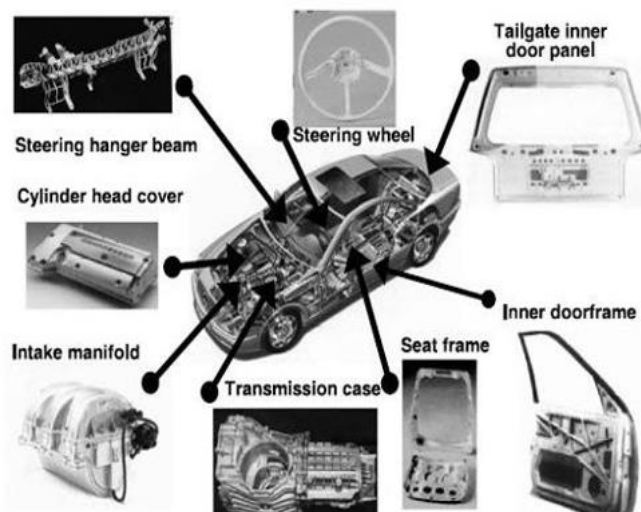


Figure 1: Extensive use of magnesium alloys in various automotive components

Some of the car parts produced with magnesium alloys are taken into account here in Figure 1. They are chosen because they are lighter and have a better weight-to-strength ratio. For use in parts like the steering hanger beam, cylinder head cover, intake manifold, transmission case, seat frame, inner doorframe, and tailgate inner door panel, the use of magnesium alloys is envisaged in the plan. Applying magnesium alloys on the same components goes a long way in keeping the vehicle weight at a minimum overall and, by extension, enhancing fuel use and performance. With optimum machining conditions such as water jet pressure, traverse speed, and abrasive flow rate, there is an assurance that such components are machined to specifications and still offer strength and minimum weight. The usage of materials such as magnesium alloys in such automobile systems is an indication of the automobile trend towards the production of environment-friendly and fuel-efficient automobiles. It also acts as a filler-strengthening composite material owing to its hardness and resistance to abrasion. Boron carbide is among the hardest materials, other than cubic boron nitride and diamond, with Vickers' hardness greater than 30 GPa. Its combination of high hardness and low density makes it an extremely suitable material for high-level performance applications like armour for armoured personnel carriers, bulletproof vests, and aerospace parts. Wear resistance and low oxidation temperature are also useful for wear applications.

The use of boron carbide on composite materials makes them wear-resistant and robust, as well as a light yet robust alternative to other traditional materials. The use of Abrasive Water Jet Machining (AWJM) in the machining of the composite materials is the second step in the methodology. AWJM is utilized as it can effectively machine hard-to-machine materials like magnesium alloys and composites. AWJM utilizes abrasives along its high-pressure water jet for high-accuracy material machining. The desired surface finish, material removal rate, and dimensional accuracy are obtained by properly controlling the water pressure, traverse speed, abrasive flow rate, and standoff distance. Particularly when used in aerospace and automotive applications, accuracy is highly important. The accuracy of cutting and control of kerf angle are two of the most important machining challenges for magnesium alloys and boron carbide-reinforced composites. The study uses the Taguchi method to optimize machining parameters. The Taguchi method is a method by which significant parameters on kerf angle, i.e., water pressure, abrasive flow rate, and standoff distance, may be identified. The influence of each factor on kerf angle variation is ascertained through Analysis of Variance (ANOVA). The critical factor on kerf angle is water pressure, followed by abrasive flow rate and standoff distance. These crucial facts establish machining optimization for minimum taper angle and proper cuts.

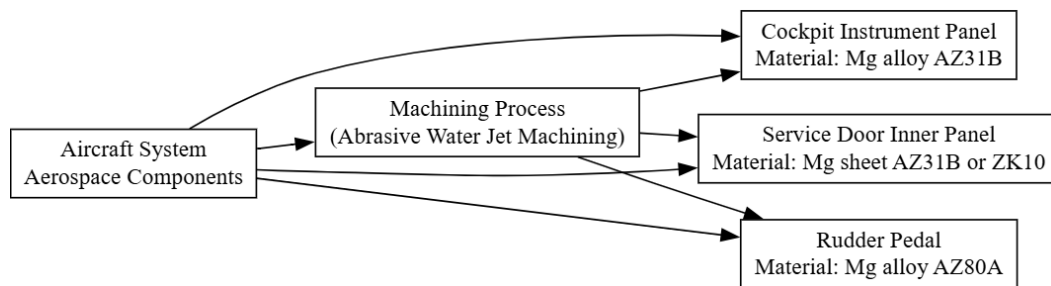


Figure 2: Role of magnesium alloys, particularly AZ31B and AZ80A, in the aerospace industry

Figure 2 focuses on using magnesium alloys such as AZ31B and AZ80A to develop aeroplane structural parts such as the cockpit instrument panel, service door inner panel, and pedal rudder. They are selected since they have a high strength-to-weight ratio, which is a factor of overriding exceptional importance in the case of aerospace commodities, where weight reduction goes hand in hand with maximization of performance and fuel consumption efficiency. The research process is a method that logically validates manufacturing processes, such as Abrasive Water Jet Machining (AWJM), to achieve the highest possible precision in the parts. Their application in such areas of the aerospace sector plays a crucial role in fulfilling the demands of the industry by providing strength and performance with less weight for the plane. The choice of magnesium alloys depends on their resistance to aerospace applications, mechanical and environmental loads, and weight-saving benefits to achieve more effective and efficient aircraft design.

In addition to optimizing machining parameters, the research addresses the health and safety concerns of materials like nickel. Nickel has been found to lead to chronic conditions ranging from respiratory conditions to cancer when exposed over a long period. The strategy in this case thus aims at safe handling and storage of nickel-containing materials, particularly in manufacturing settings where exposure to the materials is inevitable. The research also examines the economic constraints in using specific materials, i.e., Titanium Diboride (TiB₂) composites. As enhanced in performance, TiB₂ composites are uneconomical since the high material compaction cost of high melting point materials is involved. Hence, research is needed on cost-effective alternatives with comparable high-performance attributes of TiB₂ composites but without such high production costs. Fundamentally, the research process integrates material selection, optimization of machining parameters, and safety to efficiently machine magnesium alloys and boron carbide-reinforced composites. With the application of AWJM and optimization techniques like the Taguchi method and ANOVA, the research aims to maximize the precision of cuts and quality

of machined components, particularly for aerospace, automotive, and biomedical industry applications. Second, the research focuses on economic viability and the application of health security in the advanced use of materials where recycled materials work and are cost-effective to apply at scale, and safe to apply at scale.

4. Results and Discussions

Materials employed in the present work are AZ31D Magnesium alloy and Boron Carbide (B₄C) by weight fractions of earlier research studies. Specifically, Set I consists of 90% matrix material AZ31D and 10% reinforcing material, boron carbide, which have been used to make the composite material. A stir casting process based on mass production and low cost has been employed to make the composite. Stir casting employs a mechanical stirrer, forming a vortex to facilitate the effective reinforcement mixing into the matrix. Stir casting equipment employs a furnace, reinforcement feeder, and a mechanical stirrer. The material is heated and melted in a furnace, and a mechanical stirrer mounted on a variable-speed motor is used to mix the molten reinforcement and matrix effectively. The operation is carried out at precise temperatures, and the AZ31D magnesium alloy is pre-heated to 850°C and the Boron Carbide particles to 480°C. The stirring process is carried out at 450 rpm for 10 minutes, and the molten mixture is cast into a mould to create the composite. Objective Function for Surface Roughness (Ra) Minimization is given as:

Table 1: Out of roundness and kerf taper angle comparison for different abrasives

No.	Abrasive Type	Out of Roundness	Kerf Taper Angle
1	Garnet	1.254	0.288°
2	SiC	1.021	0.245°
3	Hybrid (Garnet + SiC)	1.033	0.146°
4	Garnet	0.6535	0.7105
5	SiC	0.5321	0.6044
6	Hybrid (Garnet + SiC)	0.5383	0.3602
7	Garnet	0.3267	0.3552
8	SiC	0.26605	0.3022
9	Hybrid (Garnet + SiC)	0.2691	0.1801

$$f_1(x) = \sum_{i=1}^n \left(\frac{s_i^{\text{measured}} - s_i^{\text{target}}}{s_i^{\text{target}}} \right) \quad (1)$$

Table 1 compares the fundamental parameters—Out of Roundness and Kerf Taper Angle—of various abrasives (Garnet, SiC, and Hybrid). Three measurement data sets have variations on different conditions. Roundness values reflect the degree of deviation from the perfect circularity of the cut, and such representation is required to conclude the accuracy of abrasive cutting processes. Kerf Taper Angle, however, is an angular misalignment of the cut that influences the width of the cut as it cuts. Garnet abrasive is comparatively higher in out-of-roundness than SiC, with 1.254 in set one and a reduction to 0.3267 in set three. The SiC category, on the other hand, possesses the minimum out-of-roundness values for all sets, 1.021 for set one and 0.26605 for the final set. The Hybrid (Garnet + SiC) category is also mid-range in performance with out-of-roundness of 1.033, 0.5383, and 0.2691 for the respective sets. For the Kerf Taper Angle, the Hybrid will see the least taper angles, especially in the third set of 0.1801°, which is much smaller than other abrasives. Overall, the table indicates how abrasive type impacts cutting quality and precision and how Hybrid abrasives produce the best compromise between minimum out-of-roundness and kerf taper angle.

The objective function for Material Removal Rate (MRR) maximization is:

$$f_2(x) = \sum_{i=1}^n \left(\frac{MRR_i^{\text{target}} - MRR_i^{\text{measured}}}{MRR_i^{\text{target}}} \right) \quad (2)$$

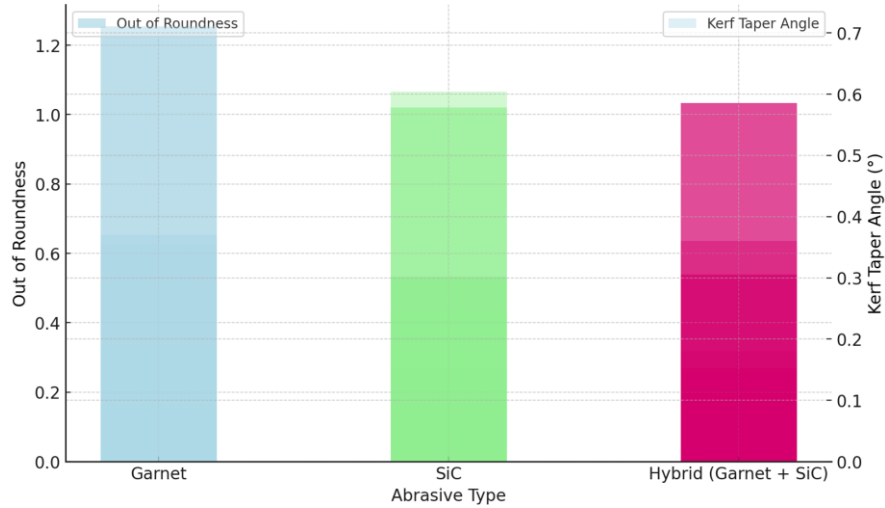


Figure 3: Comparison of out-of-roundness and Kerf Taper angle for different abrasive types

Figure 3 shows the comparison of “Out of Roundness” and “Kerf Taper Angle” for three abrasives: Garnet, SiC (Silicon Carbide), and Hybrid (Garnet + SiC). The data is depicted graphically by two sets of bars, in which each of the three abrasives is represented by bars of different colours: light blue for Garnet, light green for SiC, and dark pink for Hybrid (Garnet + SiC). The left y-axis is “Out of Roundness,” ranging from Garnet to Hybrid, with the highest and lowest values for Garnet. The right y-axis is the “Kerf Taper Angle” in degrees with the lowest values for Hybrid but tighter angles for Garnet and SiC. The chart uses thinner bars so they do not disappear, and a comparative bar chart of the two parameters by abrasive types is plotted. The two-axis bar chart enables the reader to understand the interaction of abrasive type with the two performance measures (Out of Roundness and Kerf Taper Angle). Typically, the graph shows Hybrid abrasives deliver better performance on both parameters with smaller out-of-roundness. Kerf taper angles were compared to single Garnet and SiC abrasives, the latter with larger values, particularly in “Out of Roundness.” The chart also illustrates how abrasive shape affects cutting accuracy and the geometry of the cut achieved. Therefore, it is a valuable graphical representation of abrasive performance under realistic conditions.

TOPSIS Technique (Positive and negative ideal solutions) is:

$$d_i^+ = \sqrt{\sum_{j=1}^m (x_{ij} - x_j^+)^2}, \quad d_i^- = \sqrt{\sum_{j=1}^m (x_{ij} - x_j^-)^2} \quad (3)$$

Table 2: Euclidean distance and performance score of different types of abrasives

No.	Abrasive Type	Out of Roundness	Kerf Taper Angle	Si+	Si-	Performance Score
1	Garnet	0.3267	0.3552	0.1853	0	0
2	SiC	0.26605	0.3022	0.1221	0.0805	0.3973
3	Hybrid (Garnet + SiC)	0.2691	0.1801	0.00305	0.1843	0.9837

Table 2 contains Euclidean Distance and Performance Score for three abrasives, namely Garnet, SiC, and Hybrid (Garnet + SiC), concerning their out-of-roundness and kerf taper angle. Computed values Si+ and Si- are positive and negative Euclidean distance, respectively, and the two are utilized for calculating the Performance Score that captures the performance in general for any abrasive being utilized for precision cutting and quality. While a standard abrasive, Garnet possesses the worst performance value of 0 with the maximum Euclidean distances and signifies worse cutting performance. SiC, albeit better than Garnet, has a performance value of 0.3973, indicating comparatively better out-of-roundness and kerf taper angle. The best of the three is Hybrid (Garnet + SiC), with a performance value of 0.9837 since it possesses the smallest Euclidean distances. It indicates that Hybrid abrasive possesses even lower out-of-roundness and kerf taper angle, i.e., better cutting accuracy and tapering. In general, the table indicates why the Hybrid abrasive using materials belong to improved performance and, therefore, is a better option for high-precision applications. Composite material strength optimization is:

$$\sigma_{comp} = \frac{F}{A} = \frac{P_{cut}}{d_{nozzle} h} \quad (4)$$

Optimization of process parameters using Response Surface Methodology (RSM) is given below:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \varepsilon \quad (5)$$

In the Optimization of Abrasive Water Jet Machining (AWJM) process parameters, the new process is a mixture of the Abrasive Jet Machining (AJM) and Water Jet Machining (WJM) processes with high-velocity abrasive particle streams and high-pressure water. AWJM is suitable for machine-hardened materials such as steel, titanium, and composites, with the benefit of a cold-cutting process that never shares heat transfer to the material. AWJM performance regarding productivity and surface finish can be controlled by control of critical parameters like jet traverse speed, standoff distance (SOD), and abrasive flow rate. Multi-objective optimization tools like Response Surface Methodology (RSM), Desirability Approach, etc., have also optimized AWJM performance.

Material testing in the current work is paramount, with the composites having to display the desired metallurgical, physical, and mechanical properties. The testing procedures include non-destructive testing and destructive testing. In the context of this research, there has been an emphasis on hardness testing by the Vickers test and microstructure testing by the optical microscope test. One of the main mechanical tests is the hardness test, which determines whether or not the materials are applicable. Vickers hardness test involves subjecting a load to a diamond indenter and measuring the resulting indentation to calculate the hardness. Unreinforced AZ31D, Set I, was 70.94 Vickers hardness, while the Set II Boron Carbide reinforced was 73.1. This is because of the introduction of Boron Carbide, the variation being small because of the porosity of the composite because of insufficient pre-heating of the die in stir casting.

Microstructure was also used as a criterion for attempting to quantify the homogeneity of reinforcement material distribution in the matrix. 200x optical micrographs revealed clear differences between the two sets. Set I revealed a wavy morphology of the magnesium alloy with no apparent sign of reinforcement material addition. Set II revealed more homogeneity of reinforcement material distribution and Boron Carbide deposits on the magnesium alloy matrix, showing highly high reinforcement-matrix interaction.

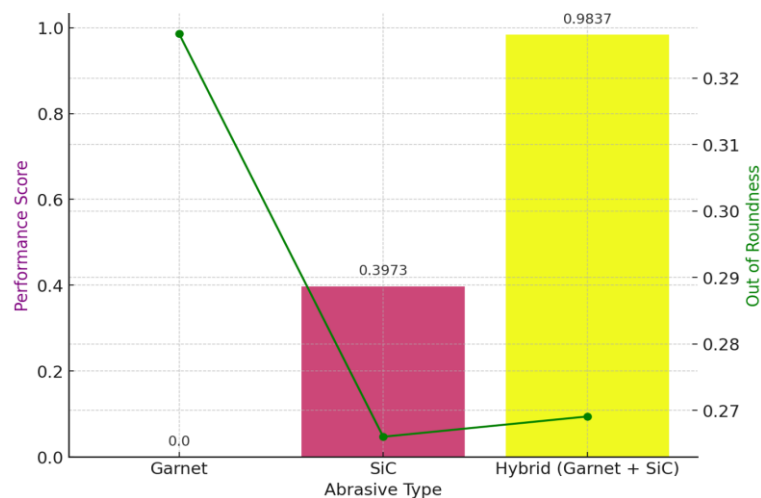


Figure 4: Performance score and out-of-roundness across abrasive types

Figure 4 shows the correlation between “Performance Score” and “Out of Roundness” for three abrasives: Garnet, SiC, and Hybrid (Garnet + SiC). The bars are shaded and differ in hue to represent their relative sizes. The worst performance score (0) is for Garnet at the bottom, and the best is Hybrid (Garnet + SiC) at the top with the best performance score (0.9837). Green is the “Out of Roundness” value represented by a secondary y-axis through graphing. It indicates SiC minimum out-of-roundness (0.26605), followed by Hybrid (0.2691) and Garnet (0.3267). The graphical proof in this work ensures that with a change of abrasive type from Garnet to Hybrid (Garnet + SiC), the performance rating is drastically raised, and out-of-roundness lowers slightly in Hybrid compared to SiC. In this case, the use of line and bar graphs gives an easy, side-by-side view of these two characteristics in an apparent manner and illustrates how precision and out-of-roundness are affected by abrasive type. The two-axis presentation offers a clear image of these features and makes it easy to read simply the relationship between precision and performance for any given type of abrasive. Employing a mixed graph with a line and a bar is a simple method of comparing the two related but different factors of roundness and performance for the different abrasives.

Circularity and kerf taper angle were also examined, which are significant post-machining variables in AWJM. Circularity is

the degree to which a particular object is a circle, and kerf taper angle is the deviation of kerf width with cutting depth. They were experimented upon samples by varying abrasive flow rate but maintaining SOD, hole diameter, traverse speed, and pressure as constant values. Different abrasives like Hybrid and silicon carbide (SiC) were employed. The results indicated that the minimum kerf taper angle was obtained by the hybrid type of abrasive in Set II and the minimum out-of-roundness by the SiC type in Set I. As the results were inconclusive, parameter optimization methods were employed to improve the results further.

The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) was used to determine the best process and optimize parameters. TOPSIS is a multi-criteria decision-making support tool that offers optimal solutions from the geometric distance of results between ideal and negative solutions. The approach enables the assessment of the best process parameter combination in terms of the global performance of the AWJM with compromises on different quality factors like surface finish, material removal rate, and dimensional accuracy.

Table 3: Optical Microscope Equipment Details

Name of the Equipment	Inverted Metallurgical Microscope
Model	FMI - 1
Magnification	100X – 2000X
Manufacturer	Fine Testing Instrument

Table 3 illustrates the equipment used to conduct composite material tests. Inverted metallurgical microscope model FMI-1 is used to examine the microstructure of the test specimen. The microscope has a range of magnifications from 100X to 2000X, and analyzing the composite at different magnifications is easy. Fine Testing Instrument manufactured the microscope and can be used for metallurgical testing of composite materials.

Table 4: Vickers Hardness of Composite

No.	Vickers Pyramid Number – HV (AZ31D) – Set I	Vickers Pyramid Number – HV (AZ31D + B ₄ C) – Set II
1	74.9	73.1
2	74.5	75.9
3	73.2	78.8
4	71.8	76.6
5	60.3	79.3
Mean	70.94	73.1

Table 4 indicates two sets of Vickers hardness (HV). Group I of AZ31D magnesium alloy is 60.3-74.9, and Group II of AZ31D alloy and B₄C composite is 73.1-79.3. The Mean of Set I is 70.94, and the mean of Set II is 73.1, which verifies that the hardening of the composite takes place due to the addition of B₄C.

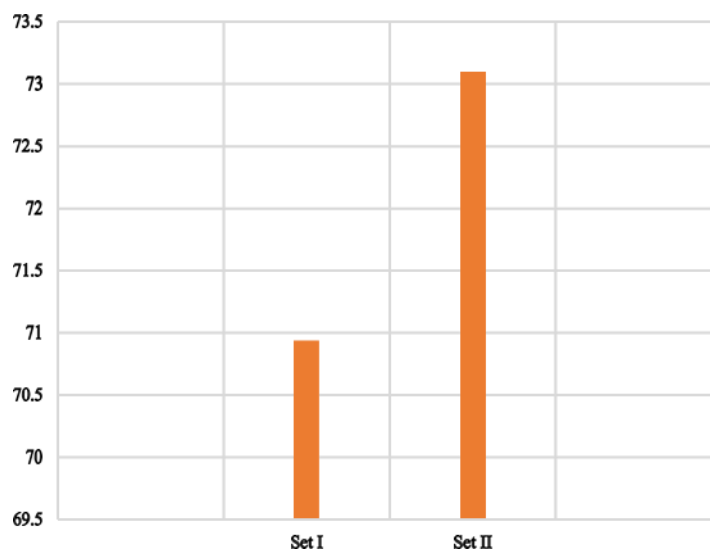


Figure 5: Comparison of Vickers hardness between Set I and Set II

Figure 5 represents Vickers hardness (HV) values of Set I (AZ31D magnesium alloy) and Set II (AZ31D + B₄C composite). One can easily see from this graph that the two sets contain different hardness values, with a mean of 70.94 for Set I and a greater mean of 73.1 for Set II. The graph shows two bars: one for Set I, a relatively shorter bar, for the lower value of hardness, and one for Set II, considerably larger, indicating a higher value of hardness as boron carbide (B₄C) has been added to the AZ31D magnesium alloy. The huge difference between the height of the two bars reflects the addition of boron carbide into the composite hardness. The information shows that incorporating B₄C in the AZ31D alloy increases the mechanical properties of the alloy, and the composite is wear-resistant and less deformed. This is significant where material of higher hardness is required, for instance, in manufacturing and engineering processes where wear-resistant material is required.

5. Conclusion

From the outcome, boron carbide (B₄C) is a perfect reinforcing material since there was a notable difference in the hardness of composite material. Improved hardness, as observed from Vickers hardness value of Set II (AZ31D + B₄C composite), ensures fine addition of B₄C to AZ31D magnesium alloy. This increase in hardness shows that boron carbide enhances the material's resistance to wear and deformation. Hence, it is a suitable material for applications with enhanced mechanical properties. The hybrid shape of abrasive particles also suits the machining process, reducing the error rate in the machined size of the end product. This means that hybrid abrasives are more precise when applied in the case of machining, thus resulting in higher-quality output. Moreover, the Kerf Taper Angle, one of the most important material processing characteristics, greatly influences the type of abrasive used. Specifically, Set I, and Set II established minimum Kerf Taper Angles when hybrid abrasives were utilized, proving that hybrid abrasives are evenly cut. Abrasiveness flow rate also, to a great extent, eliminates the roundness of the workpiece in case a low flow rate is employed. This is because abrasives' high flow rate may produce more deflections from the theoretical path and, therefore, cause more non-uniformity on the workpiece. The control over the abrasive flow rate is, therefore, a problem because it reduces the error in machining and increases the roundness of the product. Lastly, inferences made here dictate the excellence of using boron carbide as the reinforcement phase and the effectiveness of hybrid abrasives in providing enhanced machining accuracy and material characteristics.

5.1. Limitations

The Optimization of Abrasive Water Jet Machining (AWJM) Parameters of AZ31D/B₄C Composite Using the TOPSIS Technique is not limitation-free. To begin with, the research only retains the material AZ31D/B₄C, and hence, the application of the research is constrained to application on any other material or alloys. AZ31D's response in certain conditions, i.e., AZ31D's behaviour under different machining conditions, cannot be transferred to any other material and, therefore, limits generalizability. Second, the research is entirely dependent upon the TOPSIS technique, which is great for solving multi-criteria problems but sometimes neglects the very complex, non-linear relationship between the machining parameters, which otherwise can be achieved by using some other complex methods like machine learning. Moreover, the research overlooks the economic and environmental performance of machining's optimal parameters, i.e., material loss, energy efficiency, or cost machinability. Finally, the optimization is done on parameters such as pressure, abrasive flow rate, and cutting speed instead of other potential to-impact parameters such as nozzle design or cutting path that can provide other options for optimizing machining.

5.2. Future Scope

Future work done in Abrasive Water Jet Machining (AWJM) will improve the result of this research by using more materials. Higher numbers of alloys and composite materials undergoing tests will further drive the optimization towards more industrial applications. Moreover, combining machine learning techniques, i.e., artificial neural networks or genetic algorithms, with the model will improve the predictability and performance of optimization by detecting the non-linear relationships between the parameters and calculating optimal values. Most importantly, combining other machining parameters, i.e., nozzle profile, cutting direction, and even certain environmental characteristics, e.g., water conditions, will contribute to the reliability of models. The second approach would be economic and environmental analysis coupled with optimization, e.g., energy use efficiency, material waste reduction, and cost savings to enhance the eco-friendliness of the AWJM process. Last but not least, real-time feedback and monitoring devices via IoT can be utilized to offer dynamic optimization of the machining parameters to attain overall higher quality and efficiency of the machining process in real-time.

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References

1. O. Das, K. Babu, V. Shanmugam, K. Sykam, M. Tebyetekerwa, R. E. Neisiany, M. Forsyth, G. Sas, J. Gonzalez-Libreros, and A. J. Capezza, "Natural and industrial wastes for sustainable and renewable polymer composites," *Renew. Sustain. Energy Rev.*, vol. 158, no. 4, pp. 1-22, 2022.
2. D. G. Solomon, "Application of natural fibers in environmental friendly products," *Int. J. Environ. Sci. Nat. Resour.*, vol. 25, no. 2, pp. 147-153, 2020.
3. R. Shetty and A. Hegde, "Taguchi based fuzzy logic model for optimisation and prediction of surface roughness during AWJM of DRCUFP composites," *Manuf. Rev.*, vol. 9, no. 1, pp. 1-15, 2022.
4. F. Masoud, S. M. Sapuan, M. K. A. M. Ariffin, Y. Nukman, and E. Bayraktar, "Experimental analysis of kerf taper angle in cutting process of sugar palm fiber reinforced unsaturated polyester composites with laser beam and abrasive water jet cutting technologies," *Polymers*, vol. 13, no. 15, pp. 1-21, 2021.
5. T. Szatkiewicz, A. Perec, A. Radomska-Zalas, K. Banaszek, and B. Balasz, "Preliminary studies into cutting of a novel two-component 3D-printed stainless steel-polymer composite material by abrasive water jet," *Materials*, vol. 16, no. 3, pp. 1-14, 2023.
6. A. Perec, A. Radomska-Zalas, and A. Fajdek-Bieda, "Experimental research into marble cutting by abrasive water jet," *Facta Univ. Ser. Mech. Eng.*, vol. 20, no. 1, pp. 145-156, 2022.
7. A. Perec, A. Radomska-Zalas, A. Fajdek-Bieda, and E. Kawecka, "Efficiency of tool steel cutting by water jet with recycled abrasive materials," *Materials*, vol. 15, no. 11, pp. 1-16, 2022.
8. A. Perec, "Multiple response optimization of abrasive water jet cutting process using response surface methodology (RSM)," *Procedia Comput. Sci.*, vol. 192, no. 3, pp. 931-940, 2021.
9. K. Ravi Kumar, V. S. Sreebalaji, and T. Pridhar, "Characterization and optimization of abrasive water jet machining parameters of Alumin/Tungsten Carbide composites," *Measurement*, vol. 117, no. 3, pp. 57-66, 2018.
10. T. Ramalingam, S. Bhaskar, K. Seshumadhav, and K. Viswanath Allamraju, "Optimization of process parameters in bi-directional carbon fiber composite using AWJM," *Mater. Today Proc.*, vol. 5, no. 12, pp. 18933-18940, 2018.
11. M. Manoj, G. R. Jinu, and T. Muthuramalingam, "Multi-response optimization of AWJM process parameters on machining TiB2 particles reinforced Al7075 composite using Taguchi-DEAR methodology," *J. Manuf. Process.*, vol. 10, no. 6, pp. 2287-2293, 2018.
12. G. K. Kiran Kumar and C. Bhavani Sankar, "Optimization of abrasive water jet machining process parameters for Inconel-825 by using Grey Taguchi method," *Mater. Today Proc.*, vol. 4, no. 10, pp. 248-261, 2018.
13. S. Saurabh, T. Tiwari, A. Naga, A. R. Dixit, N. Mandal, A. K. Das, A. Mandal, and A. K. Srivastava, "Processing of alumina ceramics by abrasive waterjet—an experimental study," *Mater. Today Proc.*, vol. 5, no. 16, pp. 18061-18069, 2018.
14. U. Aich, S. Banerjee, A. Bandyopadhyay, and P. K. Das, "Abrasive water jet cutting of borosilicate glass," *Procedia Mater. Sci.*, vol. 6, no. 3, pp. 775-785, 2014.
15. M. El-Hofy, M. O. Helmy, G. Escobar-Palafox, K. Kerrigan, R. Scaife, and H. El-Hofy, "Abrasive water jet machining of multidirectional CFRP laminates," *Procedia CIRP*, vol. 68, no. 7, pp. 535-540, 2018.