scientific reports

OPEN

# Investigation mechanical properties and on surface roughness during WEDM machining of nano $Cr_2C_3$-$MoS_2$ hybrid metal matrix composites

Ramesh Vellaichamy[1], Pugazhenthi Rajagopal[1]✉, A. Geetha Selvarani[2], Itha Veeranjaneyulu[3], J. Immanuel Durai Raj[4], E. Balaji[5], Mamdooh Alwetaishi[8], S. Baskar[6], Krishna Moorthy Sivalingam[7]✉ & P. V. Elumalai[3]

**The study aims to identify a suitable machining parameter during Wire Cut Electrical Discharge Machining (WEDM) of duralumin reinforced with varying amounts of particulates. The nano chromium carbide ($Cr_2C_3$) at 3%, 4%, and 5% and Molybdenum diSulphide ($MoS_2$) at 2%, 3%, and 4% are chosen as reinforcements. In WEDM, machining parameters such as Pulse ON time, Pulse OFF time, and Wire Feed rate were considered, while surface roughness was measured as the response parameter. The Taguchi method of experimental design was employed to optimize the process parameters. To investigate the impact of process parameters on the surface roughness of Duralumin/$Cr_2C_3$/$MoS_2$ composites, an analysis of variance (ANOVA) table and regression equation were constructed. The findings indicated that the weight% of $Cr_2C_3$ had the most significant influence on the machining of hybrid metal matrix composites. The optimal combination for achieving better surface roughness was determined to be 3% of $Cr_2C_3$, 2% of $MoS_2$ a Pulse ON time of 100 µs, a Pulse OFF time of 100 µs, and a Wire Feed rate of 65 mm/sec, as determined by experimental values.**

**Keywords** Duralumin, Nano $Cr_2C_3$, Molybdenum disulphide, WEDM

The use of aluminum and aluminum alloys are rapidly increasing in the various fields and manufacturing industries because of their lightweight properties and high strength-to-weight ratio with good corrosion resistance. In aerospace and defense, they are essential for aircraft fuselages, satellite components, and armor plating. The automotive sector relies on these alloys for engine blocks, pistons, and electric vehicle battery housings to improve fuel efficiency and thermal management, while aluminum-matrix composites enhance wear resistance in high-stress parts like brake systems. Additionally, their superior thermal and electrical conductivity makes them ideal for electronics, such as heat sinks, and their formability supports advanced manufacturing techniques like additive manufacturing[1–3]. Metal Matrix Composites (MMC) owe their unique appeal as a lightweight material it is used in many industries and their greater modulus ratio, strength, fatigue, and fracture toughness, even at high temperatures, so it is used as a major structural material[4,5]. Due to its high strength complicated shaped profiles, more accurate surface characteristics, high levels of precision, reduction, reduced waste and additional processes, and larger production times are all issues that have been solved by modern manufacturing processes[6,7]. Strength, hardness, and wear resistance are the improved properties provided by the

[1]Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies, Chennai 600 117, Tamil Nadu, India. [2]Department of Civil Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai 600 062, Tamil Nadu, India. [3]Department of Mechanical Engineering, Aditya University, Surampalem, India. [4]Department of Mechanical Engineering, St. Joseph's Institute of Technology, OMR, Chennai 600 119, Tamil Nadu, India. [5]Department of Mechanical Engineering, Vel Tech Multi Tech Dr Rangarajan Dr Sakunthala Engineering College, Chennai 600 062, Tamil Nadu, India. [6]Research Faculty, School of Engineering, Vels Institute of Science, Technology & Advanced Studies, Chennai 600 117, Tamil Nadu, India. [7]College of Natural and Computational Sciences, Wolaita Sodo University, Post Box No.: 138, Wolaita Sodo, Ethiopia. [8]Department of Civil Engineering, College of Engineering, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia. ✉email: pugal4@gmail.com; drkrishna.micro@wsu.edu.et

Aluminum composites whereas machinability is decreased and tool wear rate is increased due to the presence of hard reinforcing elements[8]. To address the aforementioned issue, researchers have concentrated on non-traditional machining techniques in recent years as a machining element[9]. Thus, it is necessary to do modern machining on hybrid composite materials like WJM, WEDM, and LBM, among others; the WEDM is a more advantageous choice for cutting composite materials among various unconventional machining methods[10].

WEDM is a productive cutting technique that is frequently used to create intricately shaped and profiled medical, automotive, nuclear, and aircraft components. The Wire Electrical Discharge Machining (WEDM), works by removing material by the use of spark erosion, in which pulses of electrical discharges between the workpiece and the wire electrode produce localized heat, melting / vaporizing the metal[11]. Finding the ideal input settings had proven to be a significant obstacle when utilizing EDM to machine the composites. The EDM method removes material from the workpiece by creating a spark between the tool and the workpiece through a dielectric medium. The workpiece material's phase transition from a solid to a plasma state and the removal of material caused by the flowing dielectric both play crucial roles in the correct material removal process for the final component's surface roughness. As a result, the material removal process is extremely complex. The likelihood of a white layer forming on the workpiece's surface is decreased when materials are appropriately removed from it as a result of sparks.

A succession of isolated sparks between the tool and the workpiece causes a very small amount of work materials to melt and evaporate out. Also, proper input parameters are very much necessary to achieve a good surface finish and increased a higher material removal rate[12]. These response parameters of WEDM are mainly dependent on the various input parameters like peak current, spark voltage, Pulse-ON time, Pulse-OFF time and Wire Feed rate[13]. The base matrix and the reinforcement also greatly depend upon the input parameters for the particular applications. A large portion of aircraft constructions uses duralumin ($Al_20_{24}$) because of its superior machining properties, high tensile strength, and good fatigue resistance[14]. Chromium carbide despite their characteristics, are utilized as protective coatings in corrosive circumstances and may ultimately take the place of traditional coatings like hard chromium for the protection of the material surface. There are three different crystallographic structures of chromium carbides such, as cubic $Cr_{23}C_6$, hexagonal $Cr_7C_3$, and orthorhombic $Cr_3C_2$, all the crystallographic structures have the finest mechanical characteristics[15]. Self-lubricating materials can be created by coating the substrate material with the self-lubricant or by adding solid lubricants into the matrix of a base metal[16]. The effects of WEDM process factors such as gap voltage, Pulse-ON and Pulse-OFF times, and current. Liquid-state stir casting is used to create Al 7075 reinforced with nano-silicon carbide, which has an average particle size of 50 nm. Design of experiments is also used for machining in the WEDM. Surface roughness (Ra) and material removal rate (MRR) were examined for different experimental groups. It was investigated how MRR and Ra were affected by the weight content of the nanoparticle reinforcement. It has been observed that as Ra and the weight% of nano-reinforcement rise, MRR falls. When compared to materials made using the coating approach, adding solid lubricants to aluminum alloys to create AMMCs often results in material with superior corrosion resistance, exceptional tribological properties, and stronger resilience to wear resistance. Since it is a solid lubricant, a tribo-layer develops as the proportion of self-lubricating components like Gr and $MoS_2$ added in the matrix material increases; these materials have higher durability against wear properties. Brass wire was used in the WEDM process of AA7075, which showed that the rate of wear improved when high electric current was applied[17]. Additionally, the authors claimed that the cavities on the machined surface were enhanced by the increased current voltage and increased Pulse ON-time. The impact of WEDM parametric settings on the Al/SiC metal matrix composite's surface roughness was analyzed. A regression model was created using the obtained results, and the process parameters for surface roughness were optimized. The results of the experimental study showed that peak current, wire tension, and Pulse ON time have the greatest influence on surface roughness[18]. One of the ideal characteristics for smoothly mating or aligning two surfaces on an assembly line in the industry is surface roughness. A surface roughness tester was used to measure the surface roughness in a brief amount of time[19]. The machine vibration, the kind of tool and material, and coolant supply can all affect the surface roughness. Furthermore, it has been found that a very important factor in surface finish and fracture propagation is the agglomeration of reinforcing particles in the molten material[20].

One of the primary limitations of this machining operation is choosing the appropriate parameters for machining and their combinations in order to produce the highest surface integrity, which goes against the benefits of WEDM procedures[21]. The machinist will not be satisfied with the supplier's information if it does not allow them to select the appropriate parameter combination while taking into account variations in the output responses, such as surface roughness, material removal rate, heat-affected zone, etc., based on the materials. According to the machinist's demands on output response, a few WEDM process parameters that must be watched over include discharge current, voltage, Pulse ON time (P ON), Pulse OFF time (P OFF), wire material, wire tension, Wire Feed Rate (WFR), dielectric fluid, and its flushing under pressure[22].

Under various parametric conditions, the constructed regression model proved successful in predicting the surface roughness of the Al/SiC metal matrix composite. In this study, the Taguchi coupled desirability function analysis was used to determine the ideal machining parameters for the WEDM process of the Al7075-10 wt% TiO2 composite. ANOVA was also used to assess the parameters' significance in relation to the MRR and SR multiple response variables[23]. Finally, the confirmation test is employed to confirm and verify the optimal values. To compare the results of the input and output parameters, they used Taguchi's L27 orthogonal array and a backpropagation feedforward neural network in their design. A 70% correlation was found between the created model and the experimental results[24]. Conductive materials of any hardness that are challenging or impossible to cut using conventional techniques can be cut with WEDM. WEDM specializes in cutting delicate geometries or intricate curves. A high rate of material removal and a smooth surface completion cannot be attained in one go. Numerous scholars from all over the world are working tirelessly to solve this significant issue[25]. Using 0.25 mm diameter brass wire as the electrode, this research project aims to create an acceptable machining technique for WEDM of hybrid AMCs. The material removal rate is the output parameter, while the five crucial process parameters Wire Feed, % reinforcement, gap voltage, Pulse ON time, and Pulse OFF time are taken as input parameters[26].

A comprehensive review of existing literature indicated that there is a lack of research on the development of duralumin with higher concentrations of nano-sized $Cr_2C_3$ particles in their machinability characteristics[27,28]. The characteristics of these newly developed alloys and composites remain unexplored, necessitating an in-depth investigation. So this research focuses on using Wire Electrical Discharge Machining (WEDM) to assess the machinability of the material, analyze the effects of various parameters on surface roughness (Ra) values, and optimize the input parameters to achieve the lowest possible surface roughness. The WEDM is a precision cutting process applied to the complicated shapes of aerospace, medical, and automotive fields. In the WEDM process, surface finish and material removal rate (MRR) depend upon the Pulse ON/OFF times, particularly in hybrid composite materials. Although WEDM is highly versatile in hard materials, it is hard enough to produce good MRR at the same time that surfaces are smooth, resulting in optimization through Taguchi approaches and ANOVA. In this work, deficiencies pertaining to machining of the hybrid composite (e.g., nano $Cr_2C_3$, $MoS_2$) through the optimization of WEDM parameters aimed at reducing the surface roughness is achieved using orthogonal arrays.

The objective of this study is to investigate the mechanical properties and surface roughness of Nano $Cr_2C_3$ – $MoS_2$ hybrid metal matrix composites (HMMC) machined using WEDM. The composites will be fabricated using the stir casting method to ensure uniform dispersion of reinforcement particles. ANOVA (analysis of variance) will be employed to statistically analyze the influence of key WEDM parameters, such as Pulse ON-time, Pulse OFF-time, peak current, and Wire Feed rate, on surface roughness and mechanical properties. The study aims to optimize process parameters to achieve enhanced material performance, reduced surface irregularities, and improved machining efficiency for industrial applications.

## Experimentation

### Material used

The main matrix material used in these experimental studies is duralumin; the SEM image of duralumin is shown in Fig. 1. It is a combination of copper, manganese and magnesium. It consists of 91–95% AL, 3.8–4.9% CU, 1.2–1.8% Mg, 0.3–0.9% Mn, < 0.5% iron, < 0.5% Si, < 0.25% Zn, < 0.15% Ti, < 0.10% Cr[25–28]. The primary reinforcement is nano chromium carbide ($Cr_2C_3$) is a refractory ceramic compound chosen with varying weight% of (3, 4 & 5). Chromium carbide has high hardness, high strength and good corrosion resistance[29–32]. Molybdenum disulphide ($MoS_2$) has exceptional chemical and thermal stability with weight% of (2, 3 & 4). To develop the composites, we employ the novel bottom pouring stir casting method. The mixture was poured into the mould cavity with a die of size 40 × 40 × 10 mm under room temperature. In accordance with ASTM standards, we machined the specimens on their surface to achieve a uniform shape. Figure 2 shows the SEM micrograph of developed composites. It is generally utilized as a solid lubricant due to its reduced abrasion and resilience owing to the nature of $MoS_2$ it is used as a secondary reinforcement. The composition of developed composites is exhibited through EDAX as shown in Fig. 3.

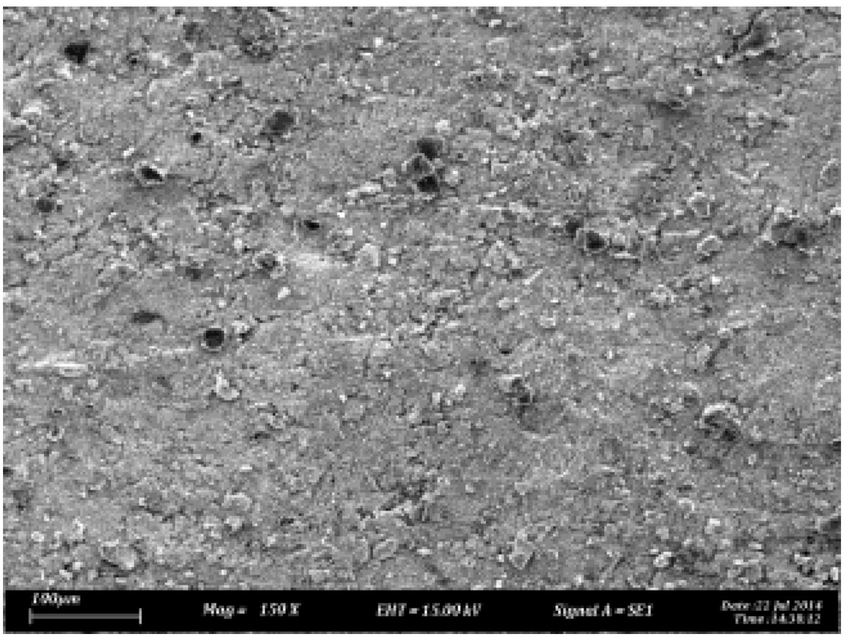


**Fig. 1**. Duralumin base alloy.

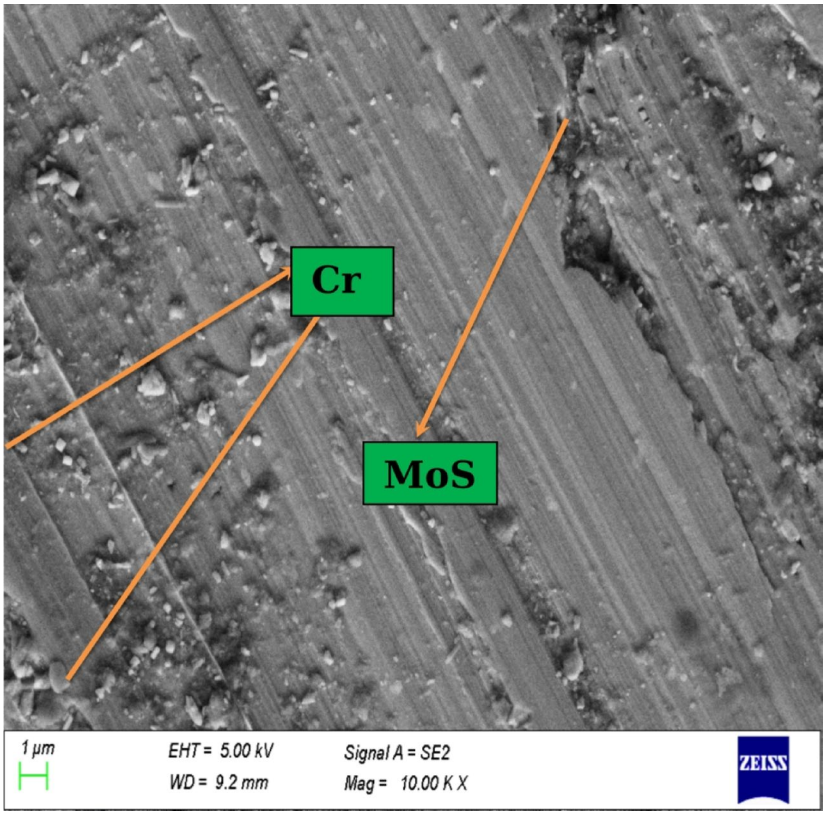


**Fig. 2**. SEM micrograph of developed composites.

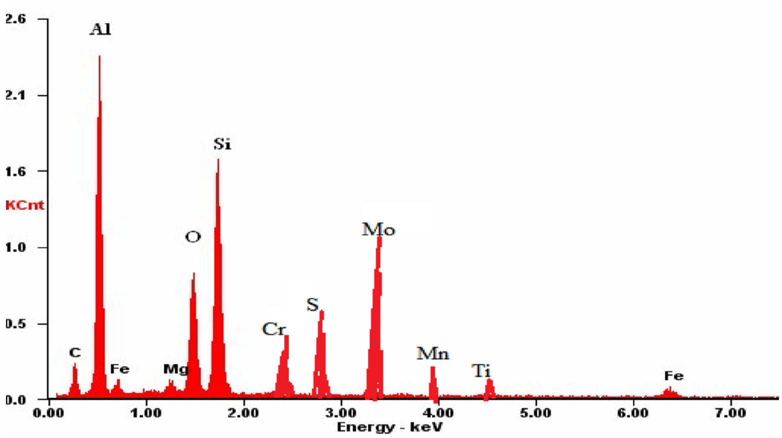


**Fig. 3**. EDAX of $Cr_2C_3$and $MoS_2$.

## Design of experiment

By using stir casting processes, the Duralumin / $Cr_2C_3$ / $MoS_2$ hybrid composite was created. The reinforcement is heated for 20 min at 450 °C before casting. Preheating the reinforcement was followed by melting the Duralumin at 650 °C in a graphite crucible. The Duralumin matrix is then combined with the reinforcement, and magnesium is added at 2%[33] with Duralumin to prevent explosions. The combination of matrix and reinforcement is then stirred for 6 min at 700 rpm. This experimental study used an electronic sprint cut WEDM machine for the machining process. The workpiece of the composite specimen with measurements of 40 × 40 × 10 mm was employed. It was decided to use deionized water as the dielectric medium and to deploy a tool electrode made of 0.20 mm diameter brass wire. To ensure sufficient removal of the particles from the gap zone, a jet flushing system was used. Table 1 shows the input process parameters taken into account in this experimental investigation, including Pulse ON/OFF and Wire Feed to examine the surface roughness as a response parameter. The Brinell hardness tester was used to find the hardness of the developed composites, which is shown in Table 2. Using a

| Levels | Level-1 | Level-2 | Level-3 |
|---|---|---|---|
| 1. $Cr_3C_2$ (%) | 3 | 4 | 5 |
| 2. $MoS_2$ (%) | 2 | 3 | 4 |
| 3. Pulse ON (μs) | 100 | 125 | 150 |
| 4. Pulse OFF (μs) | 50 | 60 | 70 |
| 5. Wire feed (mm/s) | 65 | 75 | 85 |

**Table 1**. Process parameters and their levels.

| $Cr_3C_2$ | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 |
|---|---|---|---|---|---|---|---|---|---|
| $MoS_2$ | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 | 4 |
| BHN | 71 | 79.2 | 73.7 | 78.4 | 80.1 | 79.8 | 83.6 | 89.3 | 84.1 |

**Table 2**. Hardness of the composites.

| S. No. | $Cr_2C_3$ (%) | $MoS_2$ (%) | Pulse ON (μs) | Pulse OFF (μs) | Wire feed (mm/sec) | Surface roughness (μm) |
|---|---|---|---|---|---|---|
| 1 | 3 | 2 | 100 | 50 | 65 | 0.422 |
| 2 | 3 | 2 | 100 | 50 | 75 | 0.441 |
| 3 | 3 | 2 | 100 | 50 | 85 | 0.434 |
| 4 | 3 | 3 | 125 | 60 | 65 | 0.431 |
| 5 | 3 | 3 | 125 | 60 | 75 | 0.451 |
| 6 | 3 | 3 | 125 | 60 | 85 | 0.423 |
| 7 | 3 | 4 | 150 | 70 | 65 | 0.602 |
| 8 | 3 | 4 | 150 | 70 | 75 | 0.618 |
| 9 | 3 | 4 | 150 | 70 | 85 | 0.591 |
| 10 | 4 | 2 | 125 | 70 | 65 | 0.521 |
| 11 | 4 | 2 | 125 | 70 | 75 | 0.542 |
| 12 | 4 | 2 | 125 | 70 | 85 | 0.532 |
| 13 | 4 | 3 | 150 | 50 | 65 | 0.549 |
| 14 | 4 | 3 | 150 | 50 | 75 | 0.57 |
| 15 | 4 | 3 | 150 | 50 | 85 | 0.553 |
| 16 | 4 | 4 | 100 | 60 | 65 | 0.504 |
| 17 | 4 | 4 | 100 | 60 | 75 | 0.532 |
| 18 | 4 | 4 | 100 | 60 | 85 | 0.495 |
| 19 | 5 | 2 | 150 | 60 | 65 | 0.412 |
| 20 | 5 | 2 | 150 | 60 | 75 | 0.43 |
| 21 | 5 | 2 | 150 | 60 | 85 | 0.415 |
| 22 | 5 | 3 | 100 | 70 | 65 | 0.503 |
| 23 | 5 | 3 | 100 | 70 | 75 | 0.62 |
| 24 | 5 | 3 | 100 | 70 | 85 | 0.505 |
| 25 | 5 | 4 | 125 | 50 | 65 | 0.638 |
| 26 | 5 | 4 | 125 | 50 | 75 | 0.552 |
| 27 | 5 | 4 | 125 | 50 | 85 | 0.732 |

**Table 3**. Main effects plot and response table.

portable surface roughness tester (Mitutoyo SJ-210), the surface roughness Ra of a Duralumin composites was measured. In Table 3 shows the main effects plot and response table.

## Design of experiments

Based on the trial and error and previous literature, five factors with three levels were chosen as the design of experiments. The L27 orthogonal array was chosen to conduct the experiments of developed composites. The experimental design matrix is provided in Table 1 and it includes the factors (i.e., the process parameters such as Pulse ON, Pulse OFF, wire feed rate, etc.) and the variation levels of the factors that were optimized according to Taguchi methods to reduce the variation. In Table 2, hardness values of the composites are shown; they allow one to see the impact of a reinforcement type (e.g., $Cr_2C_3$, $MoS_2$) and concentration on the mechanical properties.

## Results and discussion

The Taguchi technique stands out as a widely recognized approach for achieving optimal process parameters while performing the experiments. The current approach selects an L27 orthogonal array for conducting the experiments. The core of this methodology hinges on the concept of Signal-to-Noise (S/N) ratios. Depending on the nature of the optimization conditions, S/N ratios fall into three categories, i.e. : lower the better, nominal the better, and higher the better[13]. For this experimental data, the surface roughness is chosen as the response parameter. Here the objective is to minimize the surface roughness; hence smaller is better S/N ratio is chosen to find the optimum parameters.

Figure 4 shows the main effect plot for surface roughness; it shows that the percentage of $MoS_2$ is the most influential parameter that affects the surface roughness, followed by the Pulse OFF time. The primary effects plot for S/N ratios and the impact of Wire Feed, Pulse ON, and Pulse OFF on surface roughness are shown in (Fig. 4). The plotted data showed a relationship between surface roughness on the input parameters. It shows that the percentage of $MoS_2$ is the most influencing parameter which affects the surface roughness followed by Pulse OFF time. The experimental results revealed that the addition of particulates into the matrix reduces the MRR and increases SR. The optimum combination for better surface roughness is 3% of $Cr_2C_3$, 2% of $MoS_2$, 100 µs of Pulse ON time, 100 µs of Pulse OFF time and 65 mm/sec. This condition is caused by the lower weight% of the composites. The hardness value is very low due to this; the composites are very easily machined. When the hardness of a material is reduced, it becomes more susceptible to surface deformations under mechanical stresses, including those applied during machining, grinding, or polishing processes[34]. Softer materials may not hold as fine a finish because they can more easily undergo plastic deformation. This can result in a higher surface roughness, as the material may tear, plough, or deform instead of cutting cleanly[35] (Fig. 5).

Figures 6 and 7 are showing the interaction plot between chromium carbide and molybdenum disulphide and Pulse OFF time. It is observed that when the percentage of $Cr_2C_3$ and $MoS_2$ increases the surface roughness value increases, the Figs. 8 and 9 shows the interaction plot between Molybdenum disulphide and Pulse ON time and Pulse Off time. The increase in percentage of $MoS_2$ shows the increase in surface roughness and that time the machining is increased for a longer period of time, which causes high velocity of cutting difficulties and high discharge energy, which deteriorates the surface quality[36]. Energy from discharge will grow as igniting pulse current increases. This raises the material removal rate while degrading the surface roughness and lengthening the Pulse OFF time discharge crater. For improved surface finish, a lower ignition Pulse OFF current is preferred[37].

Figure 9 shows the interaction plot between Pulse ON and Pulse OFF time. The plot depicts how the parameters Pulse ON and Pulse OFF time influence surface roughness, helping to explain the connection between surface roughness and the interval between pulses. The delay period affects the applied voltage between electrodes. The decrease in gap voltage is caused by a reduction in the number of discharges in a particular amount of time when the delay time is increased[38,39]. Figure 10 dissipates the 3D surface plot of surface roughness for Pulse OFF time with Wire Feed; the surface plot confirms that as the increase of Pulse OFF time and Wire Feed increases, then the surface roughness linearly increases; they were relatively connected. Consequently, for the same power input and discharge, the discharge current increases, which results in increases in surface roughness. The relationship between wire speed and the roughness of the surface is that the higher wire speeds cause wire to cross over

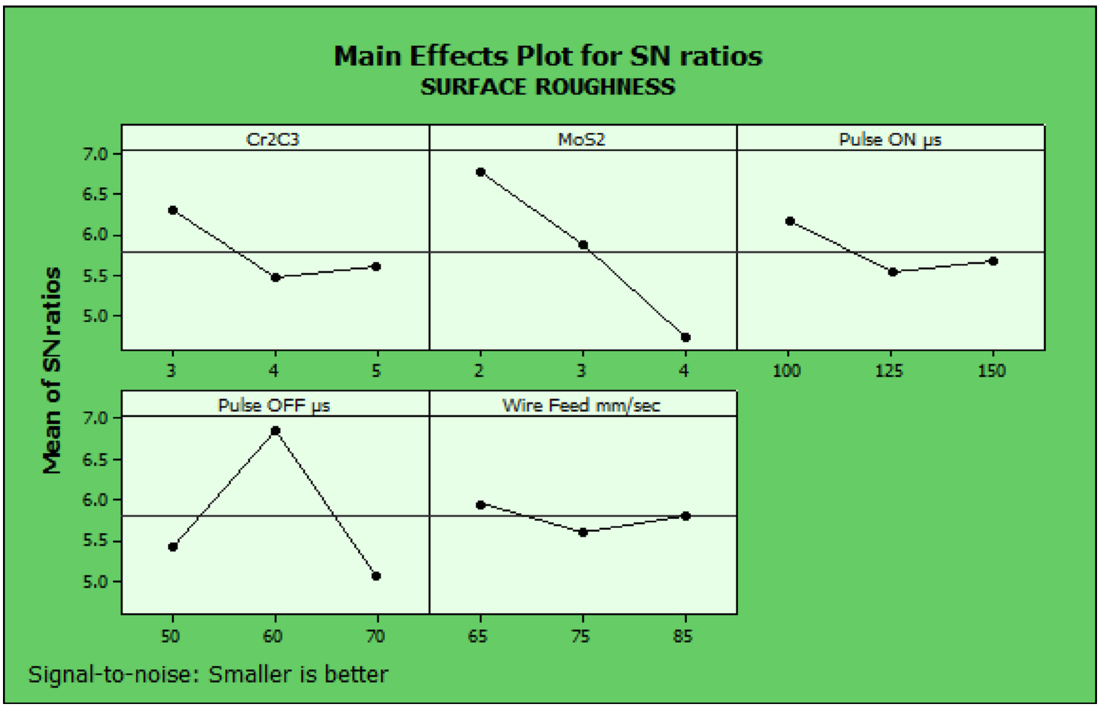


**Fig. 4**. Signal to noise ratio for surface roughness.

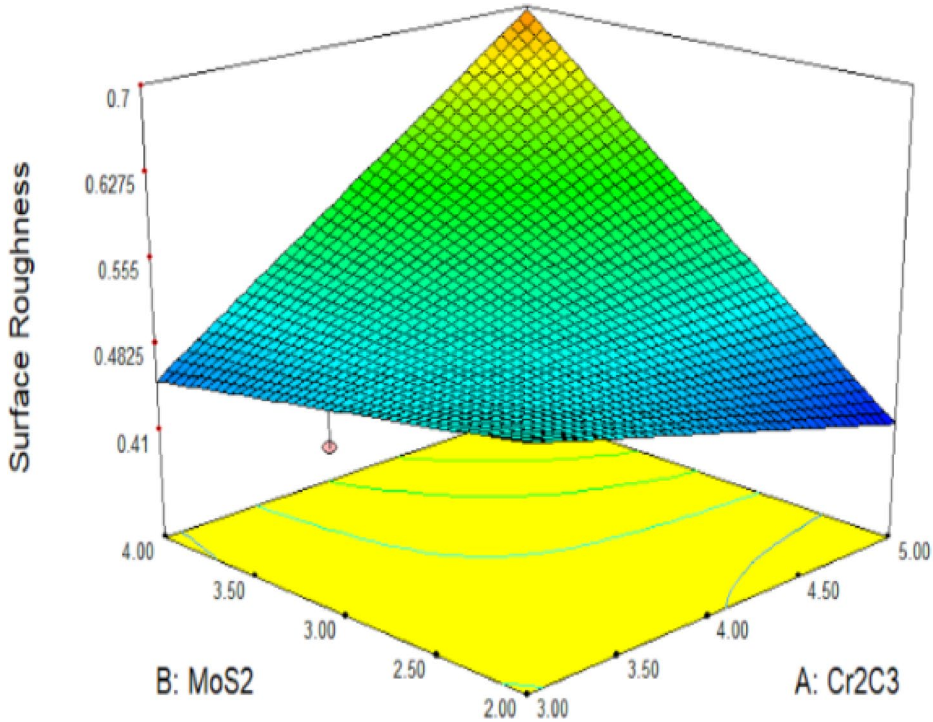


**Fig. 5**. 3D surface plot of surface roughness for $MoS_2$ with $Cr_2C_3$.

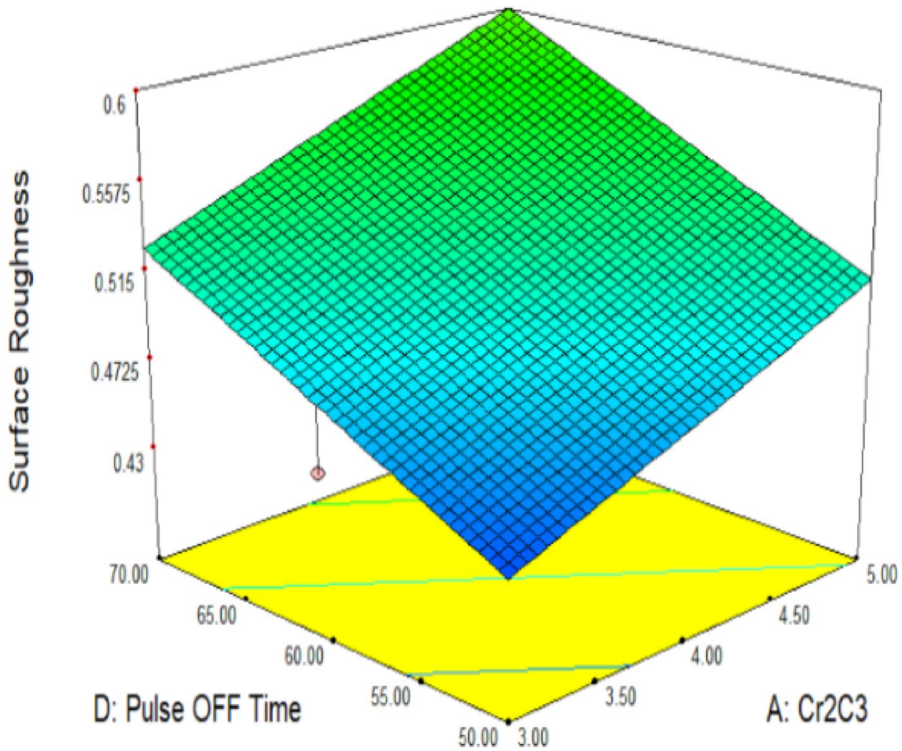


**Fig. 6**. 3D surface plot of surface roughness for Pulse OFF time with $Cr_2C_3$.

quickly on the workpiece. In which reduces the amount of energy available to cut the material; due to the considerable energy required for material removal at lower wire speeds, the surface finish is lowered[40].

The results of an experimental analysis that looked at the effects of various factors—$Cr_2C_3$, $MoS_2$, Pulse ON, Pulse OFF, and Wire Feed—on a response variable that was probably connected to a machining or materials

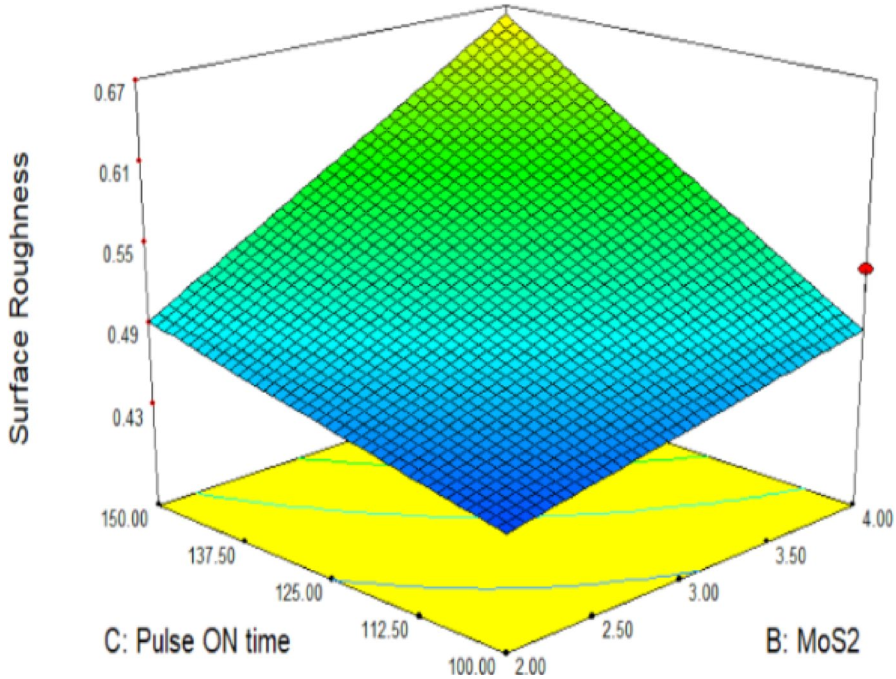


**Fig. 7**. 3D surface plot of surface roughness for Pulse ON time with $MoS_2$.

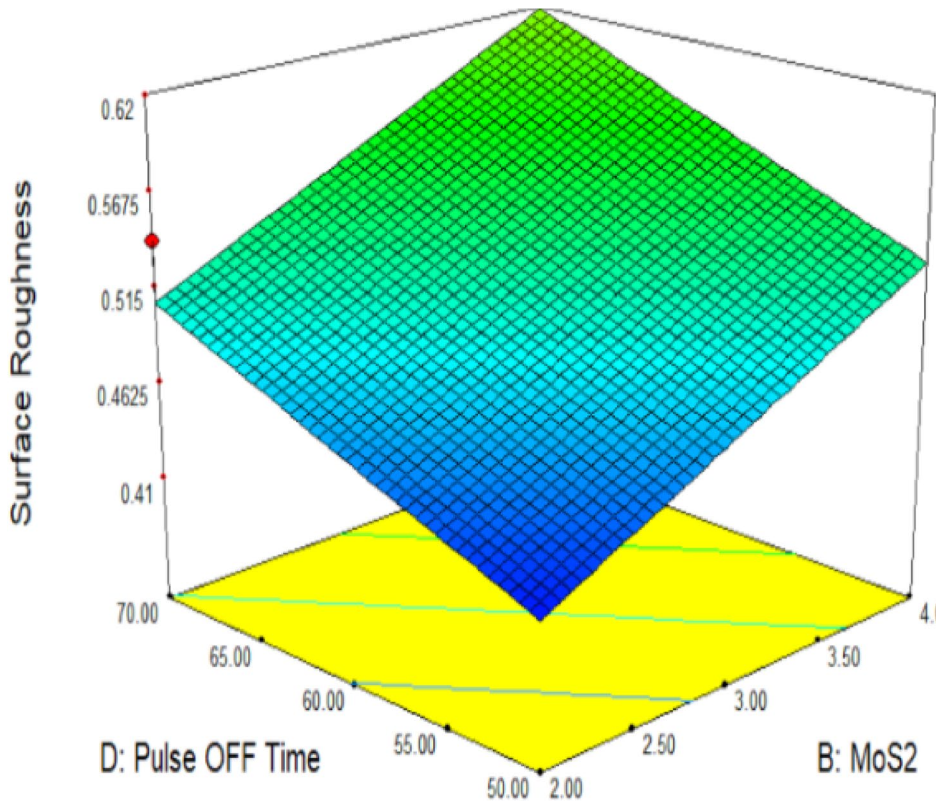


**Fig. 8**. 3D surface plot of surface roughness for Pulse OFF time with $MoS_2$.

science process are shown in the ANOVA Table 4. With p-values of 0.000, the research shows that $MoS_2$ and Pulse OFF are the most statistically significant factors, meaning that there is almost little chance that their effects are the result of chance. $MoS_2$ accounts for the largest percentage (40.14%) of the overall response variation, with Pulse OFF coming in second (32.85%). This implies that these two elements are crucial to the process and ought

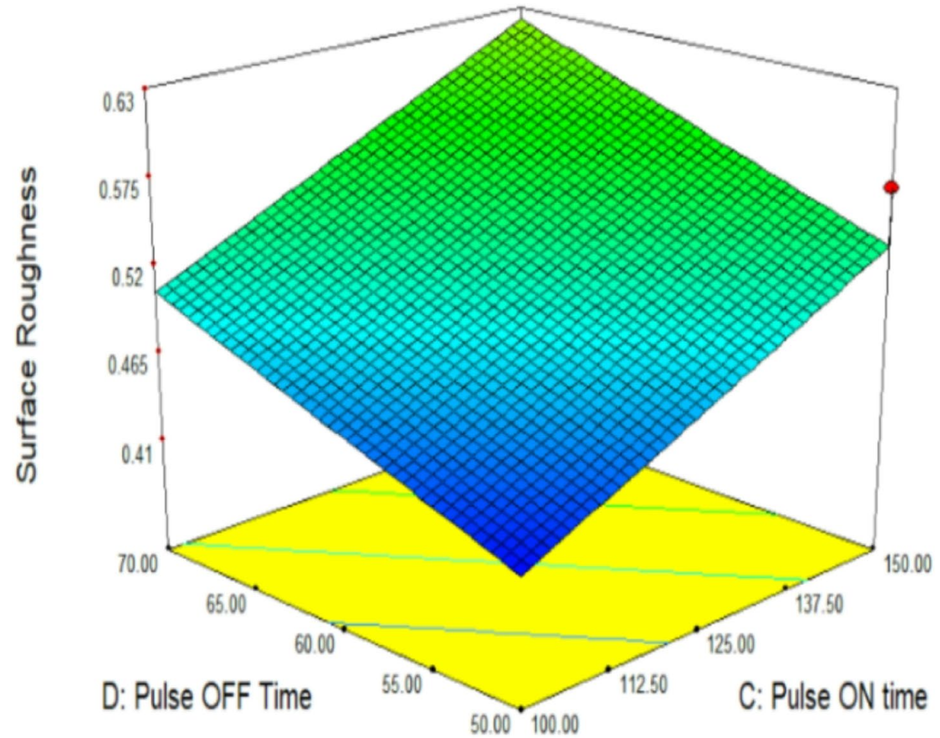


**Fig. 9**. 3D surface plot of surface roughness for Pulse OFF time with Pulse ON time.

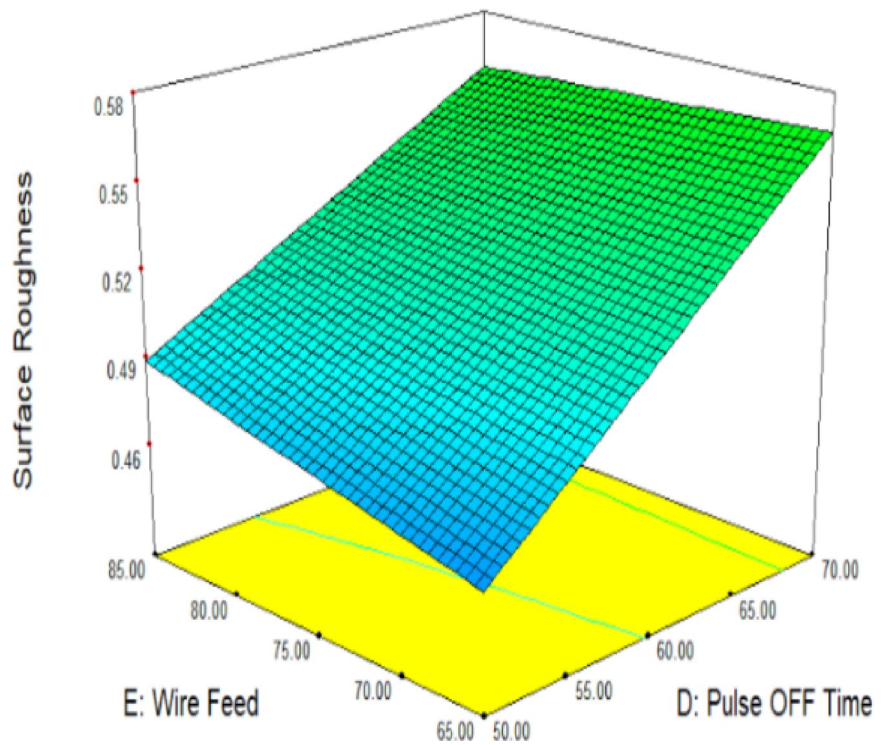


**Fig. 10**. 3D surface plot of surface roughness for Pulse OFF time with wife feed.

| Source | DF | Seq SS | Adj SS | Adj MS | F | *P* | % of contribution |
|---|---|---|---|---|---|---|---|
| Cr2 C3 | 2 | 0.011242 | 0.011242 | 0.005621 | 3.48 | 0.056 | 6.46 |
| MoS2 | 2 | 0.069831 | 0.069831 | 0.034916 | 21.6 | 0 | 40.14 |
| Pulse ON | 2 | 0.008198 | 0.008198 | 0.004099 | 2.54 | 0.111 | 4.71 |
| Pulse OFF | 2 | 0.057138 | 0.057138 | 0.028569 | 17.68 | 0 | 32.85 |
| Wire feed | 2 | 0.001691 | 0.001691 | 0.000845 | 0.52 | 0.602 | 0.97 |
| Error | 16 | 0.025862 | 0.025862 | 0.001616 | | | 14.87 |
| Total | 26 | 0.173962 | | | | | 100 |

**Table 4**. Analysis of variance table.

to be given top priority for optimization. With a marginal significance ($p=0.056$) and a contribution of 6.46% to the variation, $Cr_2C_3$ may have a small but significant impact that merits further investigation. Under the studied conditions, however, Wire Feed ($p=0.602$, 0.97% contribution) and Pulse ON ($p=0.111$, 4.71% contribution) are not statistically significant, suggesting they have little effect on the response variable. 14.87% of the variation is explained by the error term, which stands for experimental noise or unexplained variability.

Based on these experimental results, the concentrating of $MoS_2$ and Pulse OFF would result in the most process gains, however $Cr_2C_3$ might be looked into for possible enhancements. Process control is made simpler by the ability to set parameters like Wire Feed and Pulse ON at ideal levels without additional modification. To improve performance and deepen comprehension, further experiments or a more thorough statistical analysis (such as regression modeling or interaction effects) may be necessary.

## Regression equation

To establish the reliability and accuracy of the regression model for predicting surface roughness, a goodness-of-fit analysis and validation results should be provided. The surface roughness is predicted using a mathematical framework in the current work. Surface Roughness is postulated in the equation to be a function of $Cr_2C_3$%, $MoS_2$, Pulse ON time, Pulse OFF time and Wire Feed. The following model describes the link between surface roughness and other input variables:

$$\begin{aligned}\text{Surface Roughness} = 0.0784074 + 0.0218889\ \text{Cr}_2\text{C}_3 + 0.0619444\ \text{MoS}_2 + 0.000631111\ \text{Pulse ON}\mu\text{s} \\ + 0.000794444\ \text{Pulse OFF}\mu\text{s} + 0.000544444\ \text{Wire Feed mm/s}\end{aligned} \quad (1)$$

## Microstructure analysis

Based on the RSM analysis the two values are very good surface roughness they were tabulated in the (Table 3). The recommended values Pulse ON, Pulse OFF and Wire Feed were used for the two combinations of $Cr_2C_3$ at 3 wt% with $MoS_2$ 2wt.% and 3 wt% WEDM machining is processed and the particular samples morphological analysis confirms the Surface roughness the figures are confirmed by SEM images (Figs. 11 and 12). The Fig. 12 shows 2% of $MoS_2$, 100µs Pulse ON and 50 µs Pulse OFF time and 65 mm/sec Wire Feed time. Lower Pulse ON and Pulse OFF times contribute to better surface integrity by minimizing the thermal effects and associated material alterations. This can lead to finer surface textures with fewer defects, including groove, pits, or cracks[41,42]. Moreover, shorter pulse duration are essential for preserving the dimensional accuracy and integrity of machined components. Figure 11 illustrates that with 2% $MoS_2$, a Pulse ON time of 125 µs, a Pulse OFF time of 60 µs, and a Wire Feed rate of 85 mm/sec, the maximum surface roughness is observed. Extended pulse durations and elevated Wire Feed rates result in increased heat input during the machining process. This excessive heat can lead to material melting, the formation of recast layers, and surface defects such as deep grooves[43].

The prolonged exposure to electrical discharges and the higher rate of material removal can exacerbate thermal effects, resulting in deeper grooves on the machined surface[44]. The observations from the SEM analysis confirm that optimized Pulse ON and OFF times, along with appropriate Wire Feed rates, play a crucial role in achieving superior surface quality by controlling thermal effects and minimizing machining-induced defects. This research is highly relevant for industries that manufacture high-precision, high-performance components, where surface finish is critical, such as in the aerospace and defense sectors. Table 5 shows that recommended process parameters for the Surface roughness.

## Conclusion

The present study shows the significant information about the effects of input parameters has been obtained from the study of surface roughness optimization in Wire Electrical Discharge Machining (WEDM) of duralumin composites using the Taguchi design approach. Through experimental validation, the ideal parameter combination—3% $Cr_2C_3$, 2% $MoS_2$, a 100 µs Pulse ON duration, a 100 µs Pulse OFF time, and a 65 mm/sec Wire Feed rate—was identified, resulting in improved surface polish. The findings of the analysis of variance (ANOVA) show that the percentage of $MoS_2$ ($P=0.1975$) and the Pulse OFF time ($P=0.0321$) have a significant impact on surface roughness and are statistically significant in controlling the machining process. By reducing heat cracking and debris deposition, the use of 2% $MoS_2$ helps to minimize surface imperfections. Moreover, SEM analysis confirms that optimal machining conditions yield minimal surface defects, such as microcracks and recast layers, particularly with a 100 µs Pulse ON time, 50 µs Pulse OFF time, and a 65 mm/sec Wire Feed

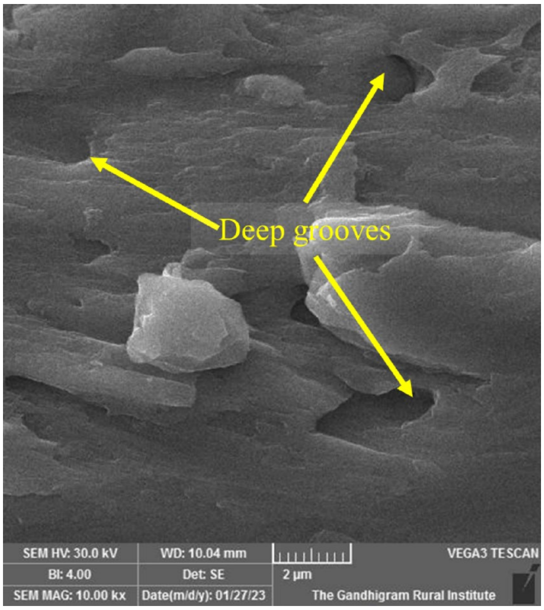


**Fig. 11**. SEM image of C1 combination.

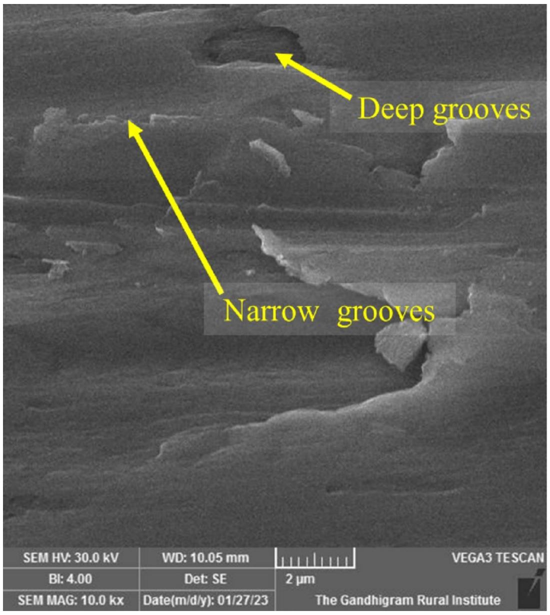


**Fig. 12**. SEM image of C2 combination.

| Combination | $Cr_2C_3$ | $MoS_2$ | Pulse ON (μs) | Pulse OFF (μs) | Wire feed (mm/s) | Surface roughness |
|---|---|---|---|---|---|---|
| C1 | 3 | 2 | 100 | 50 | 65 | 0.412 |
| C2 | 3 | 3 | 125 | 60 | 85 | 0.423 |

**Table 5**. Recommended process parameters for the surface roughness.

rate. These findings establish a scientific basis for refining WEDM parameters to enhance the surface integrity of duralumin composites, ensuring improved functional performance and extended component lifespan.

## Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Received: 20 December 2024; Accepted: 20 June 2025
Published online: 02 August 2025

## References

1. Bulei, C., Stojanovic, B. & Utu, D. Developments of discontinuously reinforced aluminium matrix composites: Solving the needs for the matrix. In Journal of Physics: Conference Series, vol. 2212, no. 1, p. 012029. IOP Publishing, (2022).
2. Tenali, N., Ganesan, G. & Babu, P. R. An investigation on the mechanical and tribological properties of an ultrasonic-assisted stir casting Al-Cu-Mg matrix-based composite reinforced with agro waste Ash particles. *Appl. Eng. Lett.* **9** (1), 46–63 (2024).
3. Sharma, S. et al. Ivan Miletić, and Blaža Stojanović. Progress in Aluminum-Based Composites Prepared by Stir Casting: Mechanical and Tribological Properties for Automotive, Aerospace, and Military Applications. Lubricants 12, no. 12 : 421. (2024).
4. Milojević, S. & Stojanović, B. Determination of tribological properties of aluminum cylinder by application of Taguchi method and ANN-based model. *J. Brazilian Soc. Mech. Sci. Eng.* **40** (12), 571 (2018).
5. Krstić, J. et al. *Application of Metal Matrix Nanocomposites in Engineering* (Advanced Engineering Letters, 2024).
6. Hussain, I. & Immanuel, R. J. Composite materials and its advancements for a cleaner engine of the future. In Advances in Engine Tribology, 169–191. Singapore: Springer Singapore, (2021).
7. Soni, R., Verma, R., Garg, R. K. & Sharma, V. A critical review of recent advances in aerospace materials. Materials Today: Proceedings (2023).
8. Nturanabo, F., Masu, L. & John Baptist Kirabira. and. *Novel Appl. Aluminium Metal Matrix Compos. Aluminium Alloys Compos.* (2019).
9. Manohar, M., Selvaraj, T., Sivakumar, D., Gopinath, S. & Koshy, M. George. Experimental study to assess the effect of electrode bottom profiles while machining inconel 718 through EDM process. *Procedia Mater. Sci.* **6**, 92–104 (2014).
10. Mohamed, O. A., Syed, H., Masood & Bhowmik, J. L. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. *Adv. Manuf.* **3**, 42–53 (2015).
11. Strength hardness, and wear resistance are the improved properties provided by the aluminum composites whereas machinability is decreased and tool wear rate is increased due to the presence of hard reinforcing elements.
12. Khandekar, A. V. Application of fuzzy axiomatic design principles for selection of non-traditional machining processes. *Int. J. Adv. Manuf. Technol.* **83**, 529–543 (2016).
13. Alagarsamy, S. V. et al. A Taguchi coupled desirability function analysis of wire cut EDM behaviour of titanium dioxide filled aluminium matrix composite. Materials Today: Proceedings 27 : 853–858. (2020).
14. Jayappa, K., Kumar, V. & Purushotham, G. G. Effect of reinforcements on mechanical properties of nickel alloy hybrid metal matrix composites processed by sand mold technique. *Appl. Sci. Eng. Progress*. **14** (1), 44–51 (2021). Jan.–Mar.
15. Kumaraswamy, J., Kumar, V. & Purushotham, G. Thermal analysis of nickel alloy/$Al_2O_3$/$TiO_2$ hybrid metal matrix composite in automotive engine exhaust valve using FEA method. *J. Therm. Eng.* **7** (3), 415–428. https://doi.org/10.18186/thermal.882965 (March, 2021).
16. Thirumurugan, R. Study on the quality and tooth root load carrying capacity of the high contact ratio asymmetrical gear tooth machined using WCEDM process. *Mater. Manuf. Processes*. **35** (12), 1352–1361 (2020).
17. Assarzadeh, S. and Majid Ghoreishi. Electro-thermal-based finite element simulation and experimental validation of material removal in static gap single-spark die-sinking electro-discharge machining process. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 231, no. 1 : 28–47. (2017).
18. Prasanna, R., Gopal, P. M., Uthayakumar, M. & Aravind, S. Multicriteria optimization of machining parameters in WEDM of titanium alloy 6242. In Advances in Manufacturing Technology: Select Proceedings of ICAMT 2018, pp. 65–75. Springer Singapore, (2019).
19. Karthik, B. M., Sharma, S., Gowrishankar, M. C., Hegde, A. & Srinivas, D. Effect of weight of reinforcement and coating thickness on the hardness of stir cast AL7075-nickel coated Duralumin powder Mmc. *J. Appl. Eng. Sci.* **20** (3), 900–907 (2022).
20. Anil, K. C., Kumarswamy, J., Reddy, M. & Prakash, B. Mechanical behaviour and fractured surface analysis of bauxite residue & graphite reinforced aluminium hybrid composites, frattura ed integritàstrutturale, **62** 168–179. (2022). https://doi.org/10.3221/IGF-ESIS.62.12
21. Houdková, Š., Zahálka, F. & Kašparová, M. Berger. Comparative study of thermally sprayed coatings under different types of wear conditions for hard chromium replacement. *Tribol. Lett.* **43**, 139–154 (2011).
22. Kandlikar, S. G., Schmitt, D. & Carrano, A. L. Taylor. Characterization of surface roughness effects on pressure drop in single-phase flow in minichannels. *Phys. Fluids*. **17**, 10 (2005).
23. Murugan, S. & Thyla, P. R. Mechanical and dynamic properties of alternate materials for machine tool structures: A review. *J. Reinf. Plast. Compos.* **37** (24), 1456–1467 (2018).
24. Aspinwall, D. K., Soo, S. L., Berrisford, A. E. & Walder, G. Workpiece surface roughness and integrity after WEDM of Ti–6Al–4V and inconel 718 using minimum damage generator technology. CIRP annals 57, 1 : 187–190. (2008).
25. Ishfaq, K. et al. Mustafa saleh, and Bashir salah. Optimization of WEDM for precise machining of novel developed Al6061-7.5% SiC squeeze-casted composite. *Int. J. Adv. Manuf. Technol.* **111**, 2031–2049 (2020).
26. Zhao, Y. et al. Microstructure and tribological properties of laser cladded self-lubricating nickel-base composite coatings containing nano-Cu and h-BN solid lubricants. *Surf. Coat. Technol.* **359**, 485–494 (2019).
27. Ebenezer Abishek, B., Raaza, A. & Rajendran, V. Simulation analysis of circular and linearly polarized patch antenna for vehicular SATCOM, Journal of Advanced Research in Dynamical and Control Systems, 12-Special Issue, pp. 800–803, (2018).
28. Saravanan, R., Asokan, P. & Sachidanandam, M. A multi-objective genetic algorithm (GA) approach for optimization of surface grinding operations. *Int. J. Mach. Tools Manuf.* **42** (12), 1327–1334 (2002).
29. Kumar, K. Multi-objective parametric optimization on machining with wire electric discharge machining. *Int. J. Adv. Manuf. Technol.* **62**, 617–633 (2012).
30. Khatoon, U. et al. Comparative study of antifungal activity of silver and gold nanoparticles synthesized by facile chemical approach. *J. Environ. Chem. Eng.* **6** (5), 5837–5844 (2018).
31. Khatoon, U., Thahira, G. V. S. & Nageswara Rao Krishna Mohan mantravadi, and Yasemin oztekin. Strategies to synthesize various nanostructures of silver and their applications–a review. *RSC Adv.* **8** (35), 19739–19753 (2018).
32. Haghighat-Shishavan, B. & Haghighat-Shishavan, R. A. K. S. Masoud Nazarian-Samani, and Naghi Parvini-Ahmadi. Improving wear and corrosion properties of alumina coating on AA7075 aluminum by plasma electrolytic oxidation: effects of graphite absorption. *Appl. Surf. Sci.* **481**, 108–119 (2019).
33. Garg, R. K., Singh, K. K., Sachdeva, A. & Sharma, V. S. Kuldeep ojha, and Sharanjit singh. Review of research work in sinking EDM and WEDM on metal matrix composite materials. *Int. J. Adv. Manuf. Technol.* **50**, 611–624 (2010).
34. Chalisgaonkar, R., Kumar, J. & Pant, P. Prediction of machining characteristics of finish cut WEDM process for pure titanium using feed forward back propagation neural network. Materials Today: Proceedings 25 : 592–601. (2020).

35. Kumaraswamy, J. et al. Thermal Analysis of Ni-Cu Alloy Nanocomposites Processed by Sand Mold Casting, Advances in Materials Science and Engineering, vol. Article ID 2530707, 11 pages, 2022. (2022).
36. Kumaraswamy, J., Kumar, V. & Purushotham, G. A review on mechanical and wear properties of ASTM a 494 M gradenickel-based alloy metal matrix composites, Materials Today: Proceedings, Vol 37, pp 2027–2032, (2021). https://doi.org/10.1016/j.matpr.2020.07.499
37. Daniel, S., Ajith Arul, Gopal, P. M. & Sudhagar, S. Study on tribological behaviour of al/sic/mos 2 hybrid metal matrix composites in high temperature environmental condition. *Silicon* **10**, 2129–2139 (2018).
38. Wu, F-C. & Chyu, C-C. A comparative study on taguchi's SN ratio, minimising MSD and variance for nominal-the-best characteristic experiment. *Int. J. Adv. Manuf. Technol.* **20**, 655–659 (2002).
39. Zhong, Z. W. Advanced polishing, grinding and finishing processes for various manufacturing applications: a review. *Mater. Manuf. Processes*. **35** (12), 1279–1303 (2020).
40. Hiremath, S. S. Effect of surface roughness and surface topography on wettability of machined biomaterials using flexible viscoelastic polymer abrasive media. *Surf. Topogr. Metrol. Prop.* **7** (1), 015004 (2019).
41. Sankar, M., Ravi, V. K., Jain & Ramkumar, J. Rotational abrasive flow finishing (R-AFF) process and its effects on finished surface topography. *Int. J. Mach. Tools Manuf.* **50** (7), 637–650 (2010).
42. Goswami, A. Optimization in wire-cut EDM of Nimonic-80A using taguchi's approach and utility concept. *Eng. Sci. Technol. Int. J.* **17** (4), 236–246 (2014).
43. Hewidy, M. S., El-Taweel, T. A. & El-Safty, M. F. Modelling the machining parameters of wire electrical discharge machining of inconel 601 using RSM. *J. Mater. Process. Technol.* **169** (2), 328–336 (2005).
44. Hashmi, A., Wahab, H. S., Mali & Anoj Meena. and. Improving the surface characteristics of additively manufactured parts: A review. Materials Today: Proceedings 81 : 723–738. (2023).

## Acknowledgements
The authors extend their appreciation to Taif University, Saudi Arabia, for supporting this work through project number (TU-DSPP-2024-32).

## Author contributions
R.V, P.R, A.G.S, I.V developed the idea and conducted the experiments, J.I.D.R, B.E wrote the manuscript, S.B, K.M.S, E.P.V edited the manuscript, all authors reviewed the manuscript.

## Declarations

## Competing interests
The authors declare no competing interests.

## Additional information
**Correspondence** and requests for materials should be addressed to P.R. or K.M.S.