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Parametric Optimization of Aluminum Alloy 6061 Using Wire-EDM for Automotive Applications: A Taguchi-Based Approach

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Abstract

Machining hard materials with complex geometries presents numerous challenges, often requiring the use of non-traditional methods such as wire Electric Discharge Machining (EDM). However, wire EDM machines operate at slow speeds, and increasing the speed can negatively impact surface finish, making it a difficult task. The ongoing research investigates the machinability study of Aluminum Alloy 6061 using wire EDM, emphasizing the optimization of process parameters to enhance machining performance and surface quality. Experimental tests are conducted to assess the effects of key parameters like pulse-on time, pulse-off time, voltage, and feed rate on surface roughness. Through careful experimentation and statistical analysis, optimal parameters are identified to minimize surface roughness. The Taguchi method is applied to link process parameters with machining performance, identifying the optimized parameter combinations for superior results. The study revealed that Pulse on Time significantly impacts surface roughness and material removal rate in wire EDM machining of the aluminum alloy. This research enhances understanding of the process, offering critical insights for optimizing parameters in industrial applications. This study improves comprehension of the wire EDM machining process for Aluminum Alloy 6061 and provides valuable insights for optimizing the process parameters in industrial settings. Improved surface quality through this methodology may lead to significant advancements in the precision manufacturing of Aluminum Alloy 6061 components.

Keywords: Wire, EDM, Taguchi method, AA6061, Non-traditional machining

INTRODUCTION

In the evolving field of material science, numerous advanced materials are being developed, some of which are exceptionally hard and challenging to machine. These include materials like Inconel, aluminum 5454 alloys, VT 20 titanium alloy, Ni-Ti-Hf alloys, AA6061, EN31, and others. Their high hardness makes traditional machining methods difficult to apply, especially when intricate shapes are needed for specific applications. These challenges can be addressed through the wire EDM process [1].

Various process parameters involved are broadly divided into two categories input process parameters and output process parameters.

Input Process Parameters

The following are the important input process parameters to be considered during the wire EDM process,

a. *Pulse on time (µs):* It is a time interval in which current flows between wire electrode and material. Spark energy affects the material removal in EDM process. The unit of Pulse on time is 'µs'.

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b. *Pulse-off time (μs):* It is the time interval between two sparks. During this time the molten metal is flushed out, cooling of electrodes takes place, resolidifying of molten metal takes place and deionization of dielectric medium takes place, this improves the process stability.
c. *Spark gap (μm):* It refers to the distance between the wire electrode and the workpiece material.
d. *Peak current (A):* It is the maximum current required to melt material during the cutting process.
e. *Voltage*: It is the voltage required for the formation of plasma.
f. *Dielectric fluid*: This fluid is required for cooling. The dielectric in EDM must efficiently sustain a strong electric discharge while ensuring favorable conditions for spark initiation.
g. *Overcut*: After machining a clearance is observed per side between the tool and workpiece it is called overcut.
h. *Duty cycle*: It is the ratio of pulse on time to the sum of pulse on time and pulse off time.

Output Process Parameters

The following are the important output process parameters to be considered during the wire EDM process,

a. *Material removal rate (MRR):* The MRR for Wire Cut EDM, measured in mm^3/min, is determined using the following formula (1),

$$MRR = F \times (Dw + 2\,a) \times H \quad (1)$$

Where,
F is the machine feed rate (mm/min),
Dw is wire diameter (mm),
H is the thickness of the workpiece (mm) and
a is overcut.

b. *Surface roughness (Ra):* The surface finish achieved in Wire Electrical Discharge Machining (Wire EDM) typically ranges from 1 to 3 micrometers Ra (roughness average). This means that the surface of the machined part is relatively smooth, with minor imperfections. The precise surface finish can differ based on various factors.

Several research studies were carried out to study the machining characteristics of different engineering metals using wire EDM. Mandal et al. [1] examined the influence of various input parameters, including pulse-on time (T_{on}), pulse-off time (T_{off}), wire tension (WT), and servo voltage (SV), and the effect of various input parameters on kerf width (K_f) was evaluated. Pramanik et al. [2] examined the impact of Wire EDM machining parameters on the Material Removal Rate and Surface Roughness of Aluminum 6065 alloy. Experimental investigations were carried out based on response surface methodology (RSM). The optimized parameters can be applied to enhance productivity by boosting the Material Removal Rate during the machining of AA6061-8wt%SiC alloy composites in wire-EDM method. Likewise, conclusions were derived from the findings of the study [3], which examined the effects of parameters on kerf width and surface roughness during machining processes using Taguchi optimization. The research successfully achieved the desired outcomes in kerf width and surface roughness by optimizing the input machining parameters. These parameters were crucial in minimizing kerf width and enhancing surface quality during cutting processes. Taguchi optimization was employed to identify the best input parameters for achieving targeted machining outcomes, enhancing both efficiency and quality in manufacturing processes [3]. In wire electrical discharge machining (EDM), optimizing parameters such as T_{on}, T_{off}, SV, and WT is essential to achieve objectives like reducing kerf width and improving surface finish. Increased wire tension enhances machining stability, resulting in lower surface roughness, whereas extended pulse durations lead to greater wear on the wire electrode. [4]. On the contrary, the higher amount of tension decreases wear. As the wire electrode experiences wear over time, it results in the creation of tapered slots, with the taper becoming more pronounced as wear progresses. This demonstrates the intricate relationship between various parameters in wire EDM and underscores the need for meticulous parameter optimization to achieve the best machining performance [5]. This study investigated the optimization of wire-EDM parameters for machining SiC-reinforced Al6061 alloy, focusing on MRR enhancement. Significant influences of current, pulse parameters, wire speed, and voltage on MRR are noted, with optimum settings identified. Adding up to 8% SiC particles showed little effect on the material removal rate but led to changes in surface quality, such as the appearance of craters and recast layers. A statistical model with a 73.65% average R^2 was developed for MRR prediction within specified operating ranges. Additionally, the model demonstrated the minimum and average prediction errors of 4.45% and 20.46%, respectively. Future directions suggest exploring advanced optimization methods to further refine prediction accuracy in wire-EDM processes [6].

This research focuses on analyzing the impact of parameters like T_{on}, T_{off}, F, and V on the wire-EDM machining of AA6061 alloy. The study aims to optimize these parameters to achieve better surface quality. The statistical model developed is useful for predicting the R_a for different settings of the process parameters. Moreover, the Taguchi approach was employed to optimize the parameters.

MARERIALS & METHODOLOGY

The methodology employed in this study aims to optimize the Wire Electrical Discharge Machining process for machining intricate shapes in Aluminum Alloy 6061, a material that poses challenges with conventional machining methods. The process began with identifying the problem and research gap, surface roughness in non-conventional machining. Previous studies highlighted low machining speeds and trade-offs between MRR and surface finish, presenting an opportunity for optimization.

The objective was to optimize key Wire EDM parameters, including pulse-on time, pulse-off time, speed, and current, to improve surface roughness. The Taguchi method was chosen as the optimization tool for its effectiveness in handling multi-variable optimization through signal-to-noise (S/N) ratio analysis. A 2-level, 4-factor Design of Experiments (DOE) was developed using the Taguchi methodology, which allowed for a systematic exploration of parameter effects on the machining outcomes.

Aluminum Alloy 6061 was selected for its industrial importance and the difficulties it presents in conventional machining. Experiments were performed using a Wire EDM machine, with the parameter configurations determined according to the DOE matrix. Empirical data on surface roughness (Ra) were collected from the experiments, and preprocessing was performed to ensure the data's suitability for analysis. The Taguchi method's S/N ratio analysis was used to identify optimal parameter settings for achieving the best balance between surface roughness. Validation was performed by comparing predicted values with experimental results. The study concluded with significant improvements in both machining speed and surface quality, with future work aimed at employing advanced optimization techniques to further enhance the process.

Experimentation

Wire Electrical Discharge Machining (Wire EDM) is a precision machining process utilized for cutting conductive materials with high accuracy shown in Figure 1.

This approach utilizes a fine, electrically conductive wire serving as an electrode to achieve accurate cuts in the workpiece. The wire's movement follows a predefined path, typically directed by computer numerical control (CNC) systems. During machining, material is removed to create desired shapes by generating a series of electrical sparks between the wire electrode and the workpiece. Wire EDM is extensively utilized in industries that demand highly detailed and accurate components, such as aerospace, automotive, and medical device production. It provides benefits like exceptional precision, minimal tool degradation, and the capability to create intricate shapes without introducing mechanical stress [7]. Furthermore, the method can be applied to a variety of materials, such as metals, alloys, and certain non-conductive substances, when enhanced with techniques like wire threading or the use of dielectric fluid for flushing. Overall, Wire EDM stands as a versatile and efficient machining solution for producing intricate components with high precision.

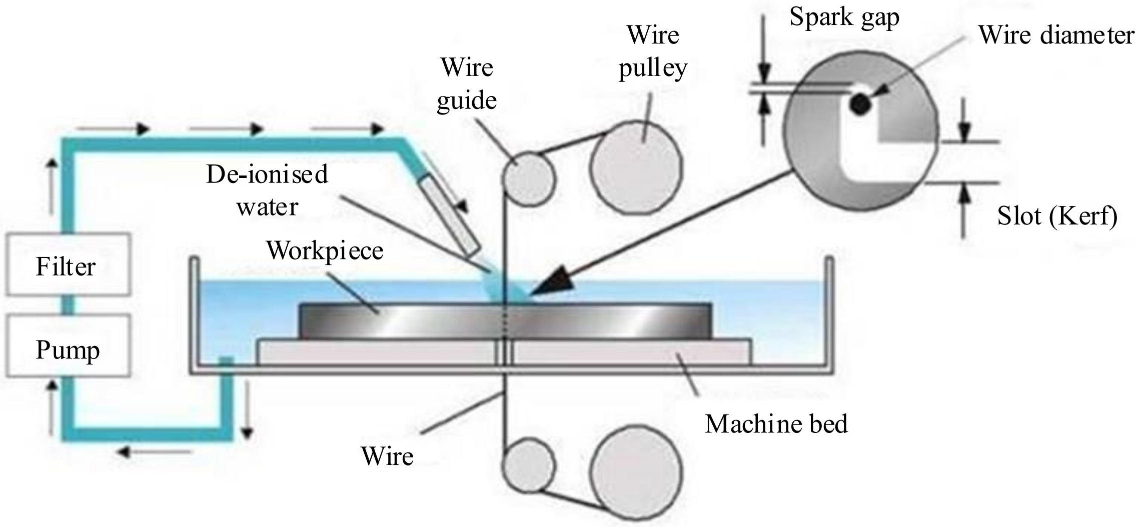

Figure 1. Schematic diagram of the experimental set-up of wire EDM.

Material Preparation

The material is tested in the laboratory for its chemical composition using an optical emission spectrometer as per ASTM E 1251:17 standard, which is presented in Table 1 below. The Brinell hardness test was also conducted on the aluminum alloy, the results of which are presented below as 100, 99.4, and 101 BHN. Similarly, the physical properties of Al6061 are presented in Table 2 below.

Experimentation was carried out by considering different readings for a combination of parameters as given in Table 3. Four factors were taken into consideration, and 2 levels for each factor were considered based on the machining operation study and interaction with operators.

Table 1. Chemical composition results of AA6061

Element	Result %
Silicon	1.09
Magnesium	1.1
Copper	0.06
Manganese	0.068
Chromium	0.05
Aluminum	Remainder

Table 2. Physical properties of AA6061.

Properties	Value
Density	2.70 g/cm³
Melting Point	630 °C
Thermal Conductivity	167 W/m·K
Young's Modulus of Elasticity	68 GPa
Ultimate Tensile Strength	305 MPa

Table 3. Factors and levels of input parameters.

Factors/ levels	T_{on}	T_{off}	Speed (F)	Ampere (A)
1	9	7	4	3
2	5	3	2	2

Table 4. Wire EDM set parameters for taguchi design.

SL.	T_{on}	T_{off}	Speed (F)	Ampere (A)
1	9	7	4	3
2	9	7	4	2
3	9	7	2	3
4	9	7	2	2
5	9	3	4	3
6	9	3	4	2
7	9	3	2	3
8	9	3	2	2
9	5	7	4	3
10	5	7	4	2
11	5	7	2	3
12	5	7	2	2
13	5	3	4	3
14	5	3	4	2
15	5	3	2	3
16	5	3	2	2

Table 5. Response table for means.

Level	T_{on}	T_{off}	Speed (F)	Ampere (A)
1	6.745	6.921	6.996	7.120
2	7.256	7.079	7.005	6.880
Delta	0.511	0.158	0.008	0.240
Rank	1	2	4	3

RESULTS AND DISCUSSION

Taguchi method is used for the analysis of the wire EDM parameters. The Response table for means (Table 5) indicates that the most influential parameter is Pulse on time (T_{on}), for which delta value is 0.511. The second influencing parameter is Pulse off time, delta is 0.158, third influencing parameter is Current, and delta is 0.24, and the least influencing parameter is Speed.

The Main effect plots for MRR are shown in Figure 2, which Plot indicates the best value of T_{on} is 9, T_{off} is 3, Speed is 4 and Ampere is 2. Similarly, Table 6 shows Response Table for Signal to Noise Ratios approach is Smaller is Better. The most influential parameter is Pulse on (T_{on}) for which delta value is 0.69. It is also observed that the second influencing parameter is Pulse off delta is 0.23 third influencing parameter is Current, and delta is 0.01, and the least influencing parameter is Speed. The material removal rate (MRR) rises as pulse on-time increases and falls with an increase in pulse off-time. This occurs because longer pulse on-time delivers greater spark-generated heat to the machining area, boosting MRR. The intense spark energy enhances the melting and vaporization of the alloy, leading to a higher MRR. Conversely, extending pulse off-time reduces available energy, diminishing thermal erosion processes such as melting, vaporization, and thermal spalling, resulting in a lower MRR. A briefer pulse-on duration lowers spark energy, causing reduced material erosion and smaller craters. As a result, the material removal rate drops, but this typically yields a smoother surface due to minimized thermal effects. Similarly, decreasing the pulse-off duration boosts spark frequency due to faster discharge cycles. This can improve the material removal rate (MRR) by enabling more material to be extracted within a specific timeframe. However, an overly brief pulse-off time may hinder effective debris clearance, potentially causing process instability or secondary sparking, which might adversely impact MRR and surface finish. Saha and Mondal [10] investigated multi-objective optimization of process parameters in the WEDM process for a hard-facing material. Their findings indicated that wire feed rate, pulse-on time, and servo voltage significantly affected the material removal rate (MRR). Moreover, Majumder et al. [11] employed to investigate the machining properties of titanium alloy using regression analysis and neural network techniques. Key process parameters, including wire feed rate, pulse-on duration, and pulse-off duration, served as input variables to evaluate material removal rate and surface roughness during the machining process. The general regression neural network model yielded superior outcomes for analyzing the alloy's machining characteristics.

Figure 3 represents the main effects Plot of surface roughness. Plot indicates the best value of T_{on} is 9, T_{off} is 3, Speed is 4 and Ampere is 3. Parameters and surface roughness correlation are given in Table 7 in which the Ra value of each sample is measured using the Mitutoyo surface tester. In the Wire Electrical Discharge Machining (WEDM) process, material removal occurs primarily due to localized heating from sparks, resulting in melting and crater formation. A portion of the material is ejected, while the remainder re-solidifies during the pulse-off period, collectively influencing surface roughness. A shorter pulse-on time (Ton) reduces spark energy, leading to less material removal and smaller craters, which results in a smoother surface finish with a lower Ra value.

Regression Analysis

A non-linear regression equation was developed to establish the relationship between Surface roughness and responses. The non-linear regression equation for surface roughness R_a is shown in eq (2), Regression Equation

$$R_a = 6.50 + 0.1277\ T_{on} + 0.0395\ T_{off} + 0.004\ F - 0.240\ A \quad (2)$$

Figure 2. Main effects plots for means for MRR.

Table 6. Table of Results for Signal-to-Noise Ratios (Smaller is Better).

Level	T_{on}	T_{off}	Speed (F)	Ampere (A)
1	-16.51	-16.74	-16.86	-17.02
2	-17.20	-16.97	-16.85	-16.69
Delta	0.69	0.23	0.01	0.32
Rank	1	2	4	3

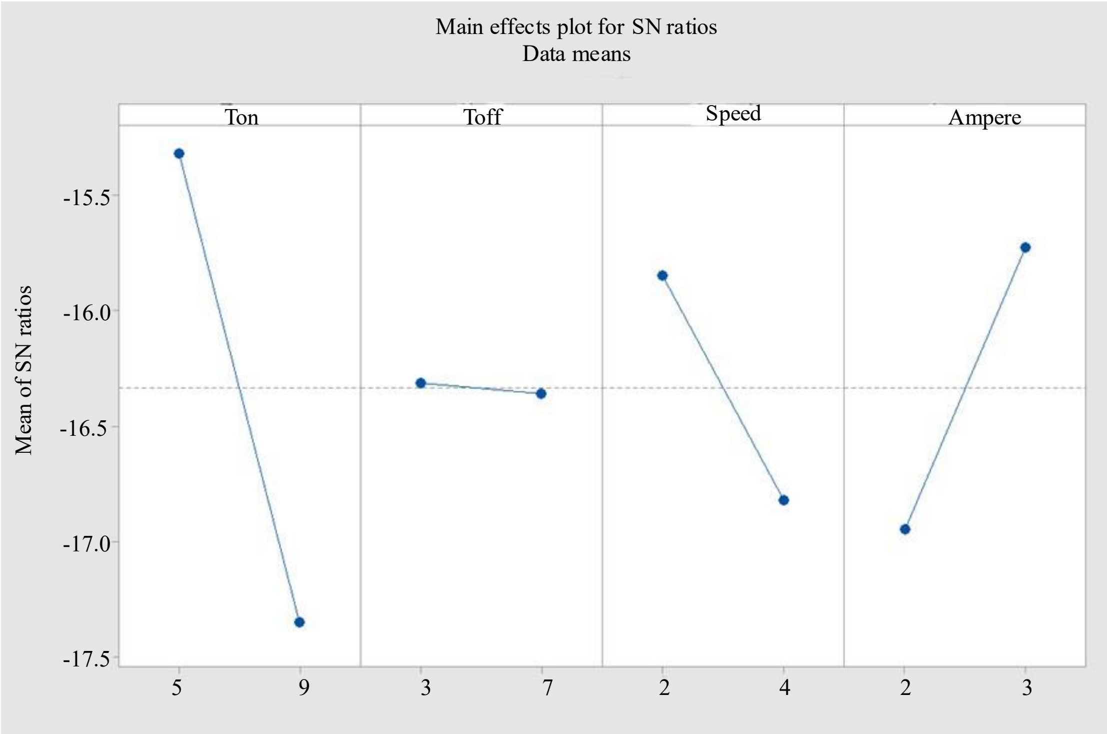

Figure 3. Main effects plot for surface roughness.

Table 7. Parameters and surface roughness correlation.

Sl.	T_{on}	T_{off}	F	A	R_a
1	9	7	4	3	6.423
2	9	7	4	2	7.06575
3	9	7	2	3	7.2225
4	9	7	2	2	7.34425
5	9	3	4	3	7.827
6	9	3	4	2	7.01375
7	9	3	2	3	7.6575
8	9	3	2	2	7.4925
9	5	7	4	3	7.7265
10	5	7	4	2	8.055
11	5	7	2	3	6.662
12	5	7	2	2	6.13675
13	5	3	4	3	5.6815
14	5	3	4	2	6.2435
15	5	3	2	3	5.843575
16	5	3	2	2	7.611

The positive coefficient of the variable suggests that the input parameter helped to enhance their effect, whereas the negative value of the coefficient indicates that the surface roughness of the material reduced with an increase in its associated variables. The magnitude associated with each term indicates the weightage of these variables. It has been noted that pulse on time and pulse off time play a significant role in influencing surface roughness. However, the influence of T_{off} is less significant than the T_{on}.

Figure 4 visualizes the response surface plots for surface roughness generated after machining. The above graphs predicted the optimized combination of parameters Ra value. In the Wire Electrical

Discharge Machining (WEDM) process, material removal primarily occurs due to localized heating caused by sparks, leading to melting and the formation of craters. During the pulse off-time, some of the removed material solidifies, contributing to surface roughness. When the pulse-on time is reduced, the lower spark energy results in minimal material removal and smaller craters, leading to an improved surface finish characterized by a lower roughness average (Ra) value [8].

Conversely, an increase in Ton elevates the spark energy, causing excessive material removal and producing a rougher machined surface. Similarly, a higher wire feed rate accelerates the occurrence of sparks, generating more heat on the workpiece. This increased thermal energy leads to the formation of larger craters, which deteriorate the surface finish [9].

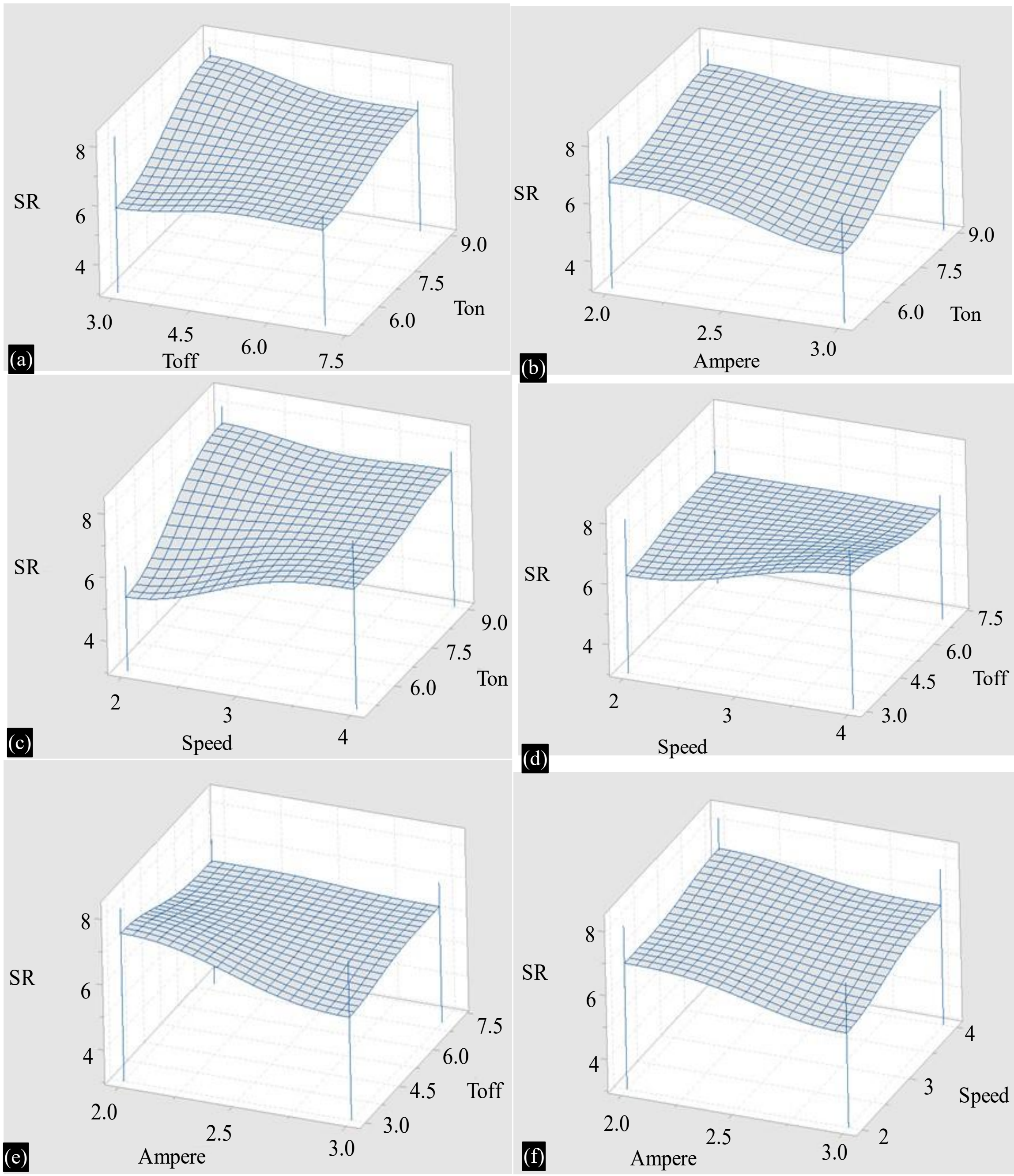

Figure 4. Response surface plot for surface roughness.

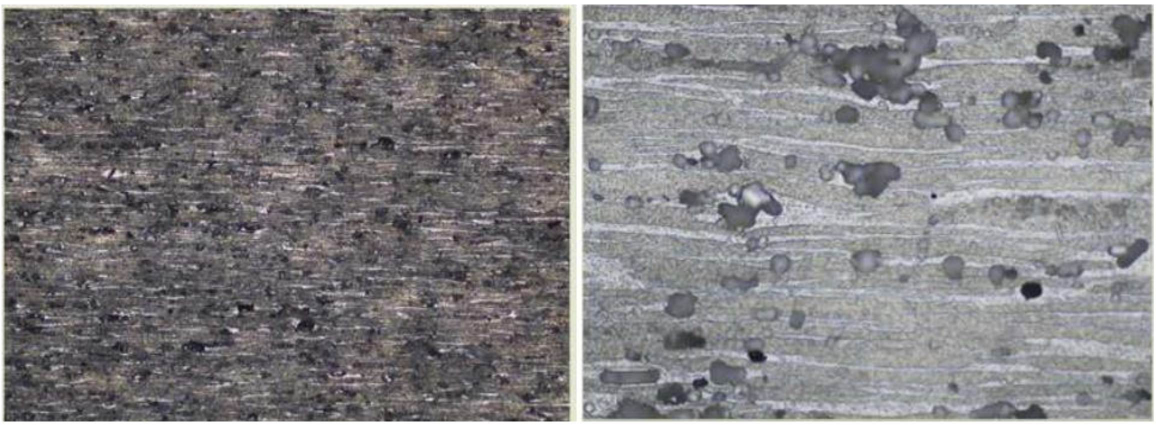

Figure 5. Microstructure examination with magnification a) 100X and b) 500X.

Microstructure Examination

Microstructure examination is done under a scanning electron microscope. Specimen orientation is kept longitudinal, whereas the magnification used a) 100X and b) 500X as shown in Figure 5.

FUTURE SCOPE

With the favorable machining characteristics, the future scope involves the fabrication of AA6061 aluminum composites to study their mechanical and machining behavior for potential industrial applications using the low-cost stir casting process. Through comprehensive analysis of their mechanical properties (such as strength, hardness, and wear resistance) and machining performance (including material removal rate, surface quality, and tool durability), researchers can tailor these materials for targeted applications.

CONCLUSION

In this study, the machining of Aluminum 6061 was successfully investigated, and the following conclusions were drawn from this study. In the statistical evaluation, the performance metrics MRR and SR of components machined via WEDM are examined to assess the alloy's machining properties. The parametric modeling results indicate that pulse on time, pulse off time, and peak current content significantly affect MRR and SR during the machining process. The Taguchi method for analysis was used, where the most influential parameter that affected the MRR and surface roughness was found to be T_{on}. The lowest value of Ra was achieved after measuring cut samples with Mitutoyo surface tester. Validation of the above results was analyzed after drawing surface plots for various combinations of input parameters. Drawing from the optimal surface roughness values and machining behavior, it is evident that Taguchi's design approach has been effectively applied to investigate the machining process.

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