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Parameter Optimization for Electrical Discharge Machining of Stir Casted AA6063/Nano-SiC with Graphite Hybrid Composite Materials by Using Response Surface Methodology

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Abstract

Study of machining characteristics is an important phenomenon of any material; the confirmation of good surface finish can justify the materials application and its usage conditions. The ultimate aim of the automobile industry is providing good mileage with highest safety. In this virtue, the material selected by light weight is very strong. This can be achieved by using the aluminum alloys materials and machined by Electrical Discharge Machines (EDM). In this research work the aluminum alloy 6063 is used as base material and 9 weight percentage of nano-SiC (Silicon carbide) powder is used as a reinforcement with 3 weight percentage of graphite (Gr) is used for the improvement of the aluminum hybrid composite material which is fabricated by using stir casting method. The mechanical properties and microstructures were studied; the machinability characteristics were studied in the EDM and optimized the process parameters by using Taguchi technique with usage of L9 orthogonal array.

Keywords

AA 6063, Nano-SiC, Electrical discharge machines, Taguchi, Graphite, Optimization process parameters

Introduction

Aluminum is smelted from its ore Bauxite. Aluminum is a lightweight and a soft metal. It is in silvery white colour. After iron it is the second most widely used metal in the world. Due to its lightweight and corrosion properties, it is a very important metal in this century. After gold, it is the second most malleable element and the sixth most ductile element. The weight of aluminum is 33% of steel and yet it offers high strength in its alloy form. Its density and the melting temperatures are lower values of 2.7 gm/cm^3 and 660 ˚C, respectively. It has the face centred cubic crystal structure. So, it is used to produce and fabricate the aluminum components. It is easily made with lower cost. The pure aluminum is a soft material having a tensile strength of 40 MPa to 50 MPa in the annealed conditions. Its strength is increased by adding various elements, cold working methods and by the method of heat treatments. In aluminum many elements are added to make aluminum alloys to increase its strength, corrosion resistance, formability, and thermal conductivity. Due to the aluminum alloys, wide range of capability and applicability having its many advantages it is used in automotive industries, aerospace industries, marine, railways, civil construction works and many more other industries.

The aluminum alloys are classified into wrought aluminum alloys and the

cast aluminum alloys. The American society for testing materials followed 4-digit systems for the wrought aluminum alloys and the 3-digit systems for the cast aluminum alloy. In the cast aluminum alloys system, the digits followed a decimal. In the wrought aluminum alloy, the number series ranges are from 1xxx to 9xxx and the cast aluminum alloys the number series ranges are 1xx.x to 9xx.x. The number series are classified on the basis of adding the major alloying element with the aluminum. In the growth of the manufacture of emerging industries in the twenty-seventh century, EDM is a well-established machining alternative. This research work is primarily focused on aspects of metal removal rates (MRR) with surface roughness (SR), which are two of the most critical characteristics to choose the best process conditions and economic aspects to involve the metal matrix composite applied in two different compositions, one of which is Al6063-SiC/Gr particulate composite reinforcement through the stir casting method to be suitable in EDM process. The research evaluated and compared the effect of SiC reinforcement of mechanical characterization and synthesis of aluminum alloy hybrid metal matrix composites. By adjusting parameter optimization under EDM pulse on and off circumstances, the challenge of discovering process factors such as response parameters like SR and MRR, tool wear rate surface morphology, and surface topography has been explored. Making use of an electrode and die steel. Response surface methodology (RSM) and analysis of variance (ANOVA) were used to create the output response model in the current work, which is utilized to estimate the rate of material removal and the roughness of the surface. The experimental result showed that the combination of reinforcement powder balanced in Al6063 with SiC + Gr considerably improved the MRR and reduced SR. As the MRR is high and the SR is not worsened, the improvement of SR is not obvious in this condition. The optimal parameter combination determined as the average flushing pressure of lower as 3 levels compared to EMWF of Al6063 with Nano-SiC + Gr was found to be 9% lower as compared to EMWF. The morphology analysis in SEM (Scanning electron microscope) had been utilized to analyse the structural characteristics of the machined surface in detail to observe the impact of a combination of graphite powder on the machining surface.

In light of their excellent performance, efficiency, dependability, and weight reduction qualities, low-density materials have seen a surge in demand for functional applications in recent years. Aside from that, these materials must be resistant to low and high temperatures, pressure, and corrosion [1]. As a result, metal matrix composites are appropriate for such applications. Aluminum alloys are commonly used in the manufacture of metal matrix composites because they not only have a reduced density, but also a high strength to weight ratio, great castability, and outstanding processability when compared to other metals and alloys. These materials' limited applicability in functional applications is due to their low melting temperature, low modulus, and low degree of elasticity. Suitable ceramic reinforcements can be added to the alloy matrix to increase performance [2]. When compared to nanoscale reinforcement, the incorporation of micron-sized ceramic reinforcement demonstrates lower ductility and hardness [3]. The results show that high weight percentage incorporation of these nano-scale ceramic reinforcing particles in the matrix alloy is not possible, and as a result of agglomeration, the microstructure displays an inhomogeneous microstructure with a poor mechanical strength [4]. They are also known as nano hybrid composites, and they may be used to get around this restriction by adding additional reinforcing particles to the basic material [5].

The processing technique also shows an increase in mechanical qualities. Both the solid phase approach and the liquid phase method are often used for the synthesis of metal matrix nanocomposites. Through solidification, which restricts those materials for extended manufacturing, the solid-state processing technique achieves the greater cost of metal powder, lower production volume, inexplicable on making complicated shaped mixtures, and inferior density. Liquid state processing techniques were therefore often used to examine the physical characteristics of created intermixtures [6]. The mechanical qualities of produced composites were limited by the liquid state processing method's porosity, wettability, and deteriorated intermetallic precipitates during processing [7]. Even though the liquid metallurgical process has such poor qualities, research on the production of metal matrix composites is continually centered on this goal [8]. One of the processing techniques that many researchers utilize the most frequently is the squeeze casting technique [9]. Utilizing measured vacuum pressure helps to remove the gas porosity inhibitors in the mixture, improving the grain structure, and greatly improving the characteristics of cast metal matrix composites [10]. Several studies on the reinforcement of various hard ceramic strengthening particles with soft solid lubricants, including as MoS_2, graphite, and boron nitride (BN), have been conducted [11].

Solid lubricants are included into the matrix alloy to improve the tribological and wear qualities by acting as secondary reinforcement in the alloy's ability to tolerate both high and low temperatures. All solid lubricants, however, cannot be used for frictional purposes due to the presence of heavy metals, carbon Gr, sulphur, and phosphorus since they hurt the environment and increase pollution [12]. Because of this, researchers have concentrated on boron powders with a nanoscale as solid lubricants. When sliding occurs in both dry and wet situations, they operate as extremely hard materials, forming layers on the surface that expose the mixture's low friction qualities.

In addition, BN has a relatively low density compared to aluminum alloys. This makes it impossible to enhance the density of growing composites, which is the main justification behind the selection of these particles as secondary reinforcement particulates in the current investigation. By adjusting the weight ratios of boron carbide and BN reinforced aluminum alloy hybrid composites, stir casting was used to create the composites' microstructure and mechanical characteristics. The BN serves as a heterogeneous nucleation site, enriching grain refinement and considerably enhancing the mechanical characteristics of hybrid composites [13]. Hybrid composites reinforced with SiC and WC are created via liquid metallurgy, and their physical properties are examined. The corrosion resistance, tensile strength, hardness, and compressive toughness

all greatly improved over the basis materials. As opposed to adding a solid lubricant as a secondary ceramic strengthening particle, it is observed that adding hard ceramic strengthening can enhance the mechanical qualities [14]. Using the vacuum sintering technique, the microstructure and mechanical behavior of aluminum-hybrid composites were examined, and their physical and microstructure features were analyzed. When such ceramic reinforcing particles are added to composites, their mechanical characteristics are improved in comparison to the base material, which lowers sintering temperatures [15]. The analysis of the literature showed that there have only been a few investigations on hybrid nano-SiC enhanced aluminum alloy nanocomposites, and their physical characteristics have not yet been investigated. Furthermore, it was claimed that one of the most significant drawbacks in the synthesis of nano composites is that using nano-sized ceramic particles and increasing the weight proportion tends to reduce the wettability between intermixtures.

Materials and Method

Using AA6063 alloys, which comprise Zn, Mg, and Cu as alloying components and have a high strength-to-weight ratio due to precipitation hardening, the current work is focused on producing aluminum alloy hybrid composites [16]. As a result, in maritime applications, these materials are employed to replace cast iron engine blocks. However, it is not suitable for low compressive strength and hardness, and these properties can be increased by adding nano ceramic strengthening particles. It can be overcome by adding ceramic strengthening particulates during solidification because these particulates exhibit nucleation sites and, as a result, they act as a good grain refiner and enhance the interface between the matrix and the strengthening particulates [17-18]. Nano-SiC is significantly tougher than aluminum alloys and has a very high density of 3.2 g/cm^3, which is highly dense. Regarding thermal conductivity, strength, and corrosion resistance, this substance has benefits over conventional ceramic strengthening particles [19, 20]. Furthermore, the wettability of the intermixtures is greatly improved by the addition of these ceramic strengthening nano particulates in matrix alloy. H-BN (White graphite) is employed as a supplementary reinforcement in the current investigation. It is a hexagonal crystal system-related solid lubricant that may be employed in high temperature applications. It has a density of 2.15 g/cc and a friction coefficient between 0.2 and 0.3. The process is like that of graphite and molybdenum disulphide, two other outstanding solid lubricants, in that lubrication is produced by shearing along the basal plane of a hexagonal crystalline structure [21-24]. When compared to unclean graphite or molybdenum disulphide, BN is thought of being clean in comparison to other solid lubricants. In the current experiment, BN is utilized as supplementary reinforcement while taking this element into consideration.

Aluminum nanocomposites made of the aluminum alloy AA6063 and Sigma Aldrich's nano-SiC 9 wt.% reinforcing material were created using a stir casting method. Squeeze casting involves using a ram to gently press molten metal into a preform with regulated pressure. The remaining shrinkage porosity that may develop when the liquid metal turns to solid is then removed by applying pressure to the solid metal. The outstanding mechanical capabilities of squeeze cast metal matrix composite materials are due to the quantity of consolidation and lack of porosity. The alloy was heated to 700 ˚C in a resistance furnace for 10 min to melt it. The stirring speed was kept at 400 rpm to ensure the molten slurry was fully melted. By preheating the reinforcement particles to 250 ˚C, the moisture is eliminated, improving the wettability between the matrix and reinforcement particles. The reinforcing particles were introduced to the melt using an external sprue after the melting temperature was increased to 750 ˚C. The viscosity of the molten metal is reduced by raising the temperature, which prevents particle agglomeration and allows the reinforcing particles to float throughout. The temperature was increased to 800 ˚C, and the stirring was done for 15 min at 600 rpm. The die cavity was warmed in order to liberate the trapped gas before the molten slurry was poured into it. As a result, the impact of matrix porosity was reduced. An EN24 die with a diameter of 22 mm and a length of 200 mm is used to cast the molten slurry, which is then allowed to cool at ambient temperature.

Results and Discussion

Microstructure

Using an optical microscope, the microstructure of hybrid nano composites of aluminum alloys was investigated. Figure 1 depicts the cast and etched examples of various weight proportions. The samples are ground using emery paper with a grit of 240 - 1200, then they are polished using alumina with a thickness of 0.5 mm, 1.0 mm, and 5.0 mm, respectively, using the standard polishing procedure. The etching agent is Keller's reagent. The inter-dendrite patterns of the nano-ceramic strengthening particle were seen to permeate through the grain boundaries of the matrix materials without leaving behind any leftover pores in the microstructure. Moreover, it is observed that nano ceramic particulate inclusions curtail the length of dendrites and that the new phase formed during solidification is due to homogeneous diffusion of ceramic particulates in the matrix. The inclusion of BN, which acts as heterogeneous nuclei and raises the dislocation density, causes a decrease in grain size in hybridized composites. According to the literature, the decrease in grain size prevents disruption, which improves the mechanical characteristics of aluminum alloy hybrid nanocomposites.

The SEM, as shown in figure 1, is used to investigate the reinforcement distribution and phase distribution in the inter-

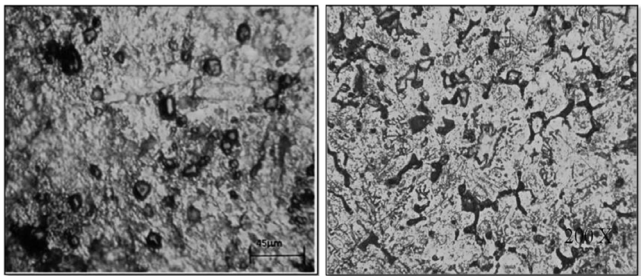


Figure 1: Microstructure of AA6063, 9 wt.% nano-SiC with 3% Gr hybrids composite.

mixture. In hybrid nanocomposites, the ceramic strengthening particles Nano-SiC are created within the alloy of the aluminum base medium because they cannot dissolve with an increase in temperature. Additionally, in an Al phase of synthetic aluminum hybrid composites, the main ceramic strengthening particles (Nano-SiC), which include the regions of grain borders and accompanying grains. The relevance of strengthening mechanisms to improve the physical characteristics of hybrid nanocomposites is highlighted by the subsequent combination of these ceramic particles with aluminum to create new phases. The largest full width half maximum, according to the computed crystallographic size, was found at 44.56° along the (200) plane. This composite is assumed to have a hexagonal unit cell structure with the following dimensions: c = 4.063460 and a = 4.063460. The hybrid composite material made of nano-SiC's mechanical properties are listed in table 1.

Table 1: Mechanical properties of nano-SiC based hybrid composite material.

Composites	Hardness	Tensile	Yield strength
AA6063, 9% nano-SiC, 3% Gr	65	150	152

Electrical discharge machining

Manufacturing of complicated machine components uses a variety of unconventional machining processes more often. EDM procedure, one of the non-traditional machining techniques, have attracted a lot of research interest because to their extensive industrial applications. High strength steel, tungsten carbide, and thermal conductivity are often machined with EDM. Due to its exceptional hardness and temperature resistance qualities, aluminum alloys enhanced with nano-SiC particles are often employed in a variety of automotive and aerospace applications. Metal matrix composites with strong ceramic fiber reinforcement can be processed using polycrystalline diamond cutting tools or an electroplated diamond grinding wheel for carbide. Due to this, particle reinforced metal matrix composites were increasingly being machined using non-traditional methods such as EDM, lasers, and other methods. To improve the process parameters in the EDM process, extensive research is required. From the perspective of machinability, the cutting force was determined during the shaping operation using a dynamometer and HSS cutting. This work also demonstrates that during the machining of Al-SiC composites, a large volume proportion of SiC reinforced particles results in discontinuous and advantageous chip production without any build up edge development. In the current inquiry, an effort was made to assess the impact of the composite's nano-SiC reinforcement on the MRR, SR, and wear ratio. Additionally, the impacts on machining parameters have been researched.

Mathematical models for the responses

The mathematical models for the replies are estimated using the uncoded data from the provided input trials. The regression equation for wear mass loss (Equation 1) reveals that the applied load influences more compared to reinforcement addition. Nano-SiC concentration has a significant impact on the COF (Equation 2). This occurrence demonstrates the distinction between COF and wear mass loss.

$$= 0.042034 - 0.006167 * + 0.0113 * + 0.002879 * 2 - 0.00362 * 2 - 0.00025 * * \quad (1)$$

$$= 0.341586 + 0.0395 * + 0.010167 * - 0.003052 * 2 + 0.003948 * 2 - 0.002 * * \quad (2)$$

Adequacy of model

The response adequacy is recorded in table 2 using R^2 and R^2 (adj) values. These results show that the model fits the data well, and R^2 agrees with R^2 (adj), indicating that the model can forecast. All of the models have R^2 (adj) values that are smaller than R^2, making them suitable for predicting solutions. The residual plots of wear mass loss and COF are depicted in figure 2, figure 3, figure 4, and figure 5.

ANOVA for MRR

All answers were analyzed using an ANOVA, and the results are shown in table 3, table 4, and table 5. All kinds of regression have P values smaller than the F values and 0.05, making them all significant at the 95% confidence level. The fact that the projected values are in good agreement with the measured data demonstrates the suitability of the proposed models.

Interactions of factors on wear mass loss and COF

The contour plots are developed to investigate the interactions of factors on responses. The applied load influences the wear mass loss in increasing trend, but COF remains the same. The reinforcement content influences the COF in increasing trend and the wear mass loss in decreasing trend.

Optimization

From figure 6, it was established that the input parame-

Table 2: EDM process parameter and MRR, SR, wear ratio of 9 wt.% of nano-SiC.

Run order	Discharge current	Pulse on time	Flushing pressure	MRR	SR	Wear ratio
1	10	50	3	0.709	0.773	1.178
2	15	100	6	0.816	0.801	1.27
3	20	150	9	0.885	0.744	1.572
4	15	100	3	0.756	0.803	1.121
5	20	150	6	0.884	0.744	1.572
6	10	50	9	0.71	0.773	1.181
7	20	150	3	0.881	0.743	1.57
8	10	50	6	0.709	0.792	1.178
9	15	100	9	0.752	0.798	1.19

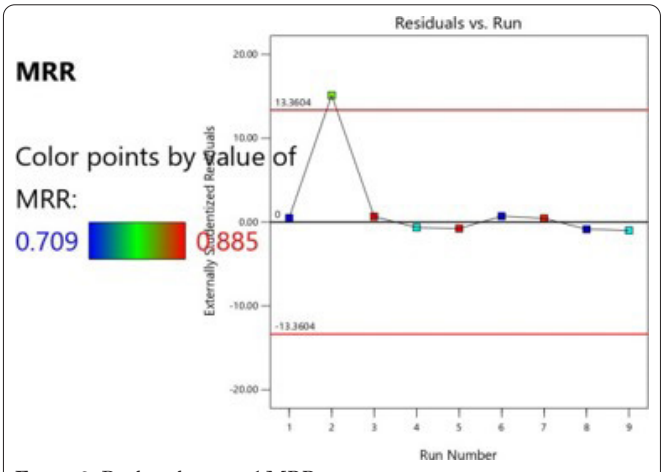


Figure 2: Predicted vs actual MRR.

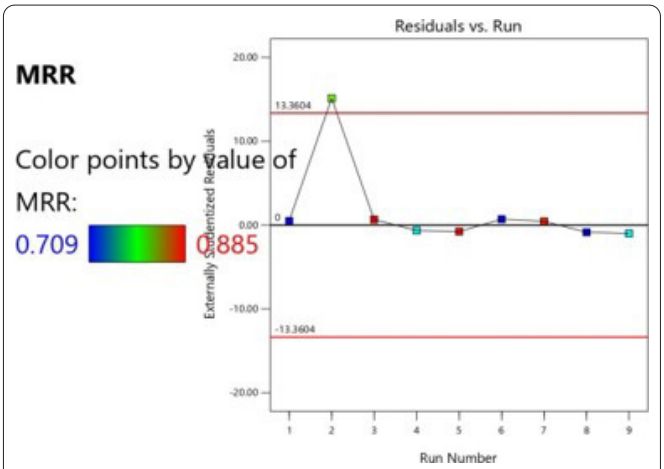


Figure 3: Residual plot for MRR.

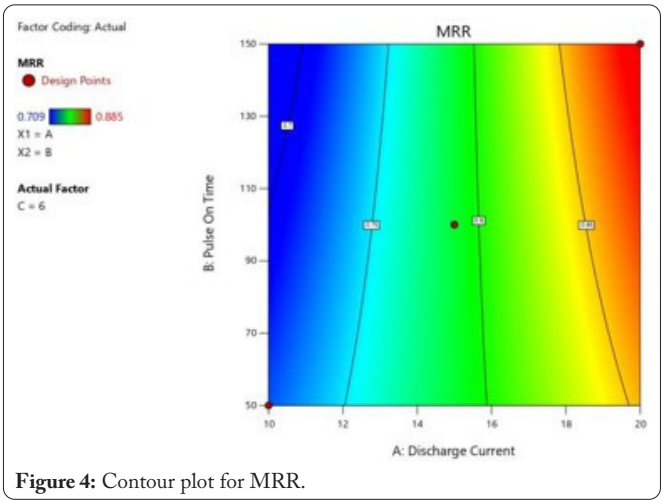


Figure 4: Contour plot for MRR.

ters were configured in the best way possible. The ideal combination of 5.88 weight percent SiC and 10 N applied stress yields a worldwide optimal result of 0.03 g wear mass loss and 0.31779 COF at the appropriate zone for the composite attractiveness of 90.7%.

AA6063/SiC/Gr composites exhibit better wear resistance and mechanical properties as compared to AA6063/Gr composite and base alloy. The wear behavior of AA6063/SiC/Gr composites is optimized using RSM and global solution is

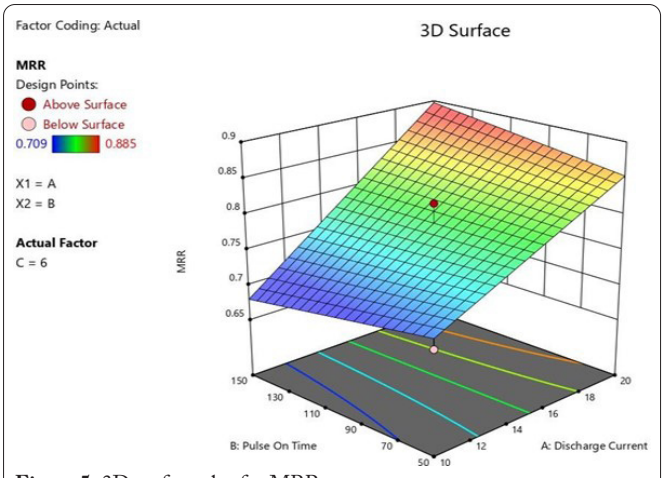


Figure 5: 3D surface plot for MRR.

obtained.

SEM morphology after EDM

The effect of reinforcement is visible for the Al/SiC composite, where it is shown that as reinforcement increases, the MRR increases as a result of severe abrasive particle damage, which is amply supported by figure 7. Figure 7 shows that the main MRR criterion was the impact of current. The MRR has significantly risen due to the increase in current from 5 to 15 A. Low current supplies cause the white layers to develop, which may be caused by oxidation from the environment. Less substantial alterations are seen despite the fact that the flushing pressure and pulse on time had little effect on the machining process. The effect of current is significantly more than the influence of these two components, therefore when these two factors grow, the MRR drops. The primary uses of flushing pressure and pulse on time are for the initial pitting and crack propagation, respectively, and simple delamination.

EDS after EDM

The EDS (Energy dispersive X-ray spectroscopy) analysis for the machined surface of Al/SiC composites reveals that the maximum tool material (Cu) is transferred from the tool to the work piece, which was due to the severe damage of tool material (Figure 8). It occurred for the 9 wt.% nano-SiC in aluminum metal composite at the current supply of 15 A with the flushing pressure of 3 kgf/cm^2 and the pulse on time of 50 µs. From figure 9, it is evident that the tool is damaged less since the Cu transfer is less from the tool.

Conclusions

The AA6063 nano-SiC particulate reinforcement with 3% of graphite aluminum alloy metal matrix composites were manufactured by using a stir-casting method. Thus, the mechanical properties such as hardness, tensile strength, compression strength, and flexural strength of the composites with different weight percentage of nano-SiC are determined and analysed. Further, a machinability evaluation study was made through the EDM process. The EDM carried out to understand the influence of nano-SiC 9 wt.%, and other factors on the responses. Taguchi and RSM techniques are

Table 3: ANOVA for MRR.

Model	0.0472	5	0.0094	16.57	0.0215	
A-Discharge current	0.0454	1	0.0454	79.70	0.0030	
B-Pulse on time	0.0000	0				
C-Flushing pressure	1.667E-07	1	1.667E-07	0.0003	0.9874	
AB	0.0009	1	0.0009	1.65	0.2894	Significant
AC	2.250E-06	1	2.250E-06	0.0039	0.9538	
C^2	0.0009	1	0.0009	1.52	0.3050	
Residual	0.0017	3	0.0006			
Cor Total	0.0489	8				

Table 4: ANOVA for SR.

Model	0.0051	5	0.0010	18.75	0.0180	
A-Discharge current	0.0019	1	0.0019	35.29	0.0095	
B-Pulse on time	0.0000	0				
C-Flushing pressure	2.667E-06	1	2.667E-06	0.0493	0.8385	
AB	0.0031	1	0.0031	56.75	0.0048	Significant
AC	2.500E-07	1	2.500E-07	0.0046	0.9501	
C^2	0.0001	1	0.0001	1.64	0.2899	
Residual	0.0002	3	0.0001			
Cor Total	0.0052	8				

Table 5: ANOVA for wear ratio.

Model	0.3006	5	0.0601	24.61	0.0122	
A-Discharge current	0.2309	1	0.2309	94.52	0.0023	
B-Pulse on time	0.0000	0				
C-Flushing pressure	0.0009	1	0.0009	0.3736	0.5842	
AB	0.0659	1	0.0659	26.97	0.0139	Significant
AC	2.500E-07	1	2.500E-07	0.0001	0.9926	
C^2	0.0029	1	0.0029	1.18	0.3565	
Residual	0.0073	3	0.0024			
Cor Total	0.3079	8				

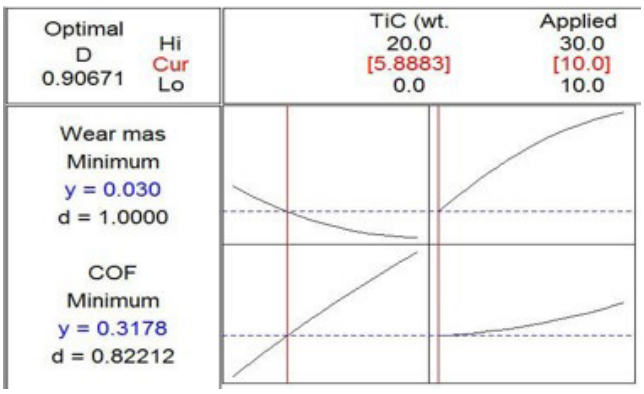


Figure 6: Optimization of wear behavior.

used to determine the optimal process parameters in order to optimize the EDM process.

- SEM showed that current was the main factor determining MRR, and EDS showed that greater current levels resulted in the greatest tool material transfer from the tool to the work piece.

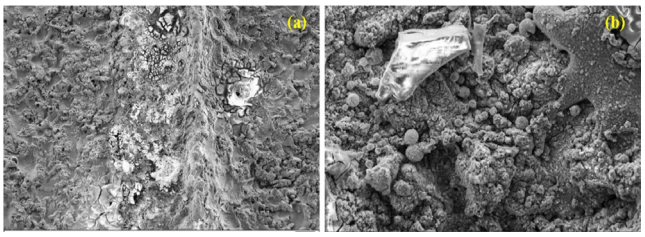


Figure 7: Effect of reinforcement on EDMed surface of aluminum alloy composites.

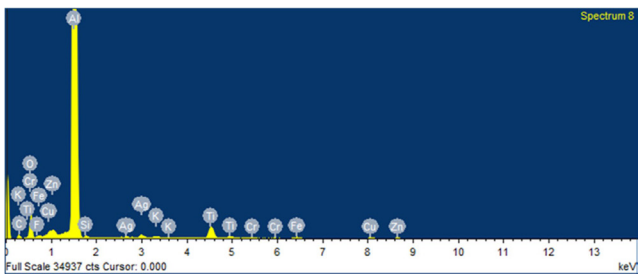


Figure 8: EDS of Al6063 alloy composites with minimum MRR.

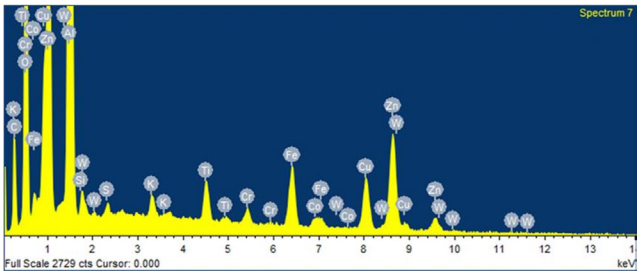


Figure 9: EDS of Al6063 alloy composites with maximum MRR.

- The RSM and Taguchi optimization procedures, the design tables L9 are chosen, respectively. Additionally, the MRR and SR mathematical models have been constructed with good adequacy above 80%, which improves fitness in forecasting more accurate results.
- The maximum MRR of 0.093 g/min and the lowest tool wear rate of 0.032 g/min were achieved at 10 A current, 50 s pulse on time, and 6 kgf/cm^2 flushing pressure, respectively, when EDM machining parameters for 9 wt.% of nano-SiC reinforcement were varied. The current is clear to see as the main influencing parameter on MRR in SEM morphology, which shows how parameters can affect MRR.

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None.

Conflict of Interest

None.

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