International Research Journal of Multidisciplinary Scope (IRJMS), 2024; 5(3):152-161

Original Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2024.v05i03.01188

Effects of Ceramic Volume Fraction and Cryogenic Treatment on Kerf Width in WEDM of Al/SiCp Metal Matrix Composites

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Abstract

Wire EDM is widely used to machine variety of materials including MMCs with highest precision. Cryogenic treatment is used to improve the material properties of materials. In this paper kerf width is studied for 6 hrs and 12 hrs cryogenically treated Al/SiCp with 10%, 20% and 30% volume of silicon carbide particle samples. The input parameters used are pulse on time, pulse off time and % volume fraction of reinforced particles. Design of experiment is done by Response Surface Methodology. Kerf width is one of the major response parameters deciding precision in machined parts. Results shows Pulse off-time, pulse on-time were found to be significant on kerf. Kerf is reduced by 3.42% in 12 hrs cryogenic compared to 6 hrs cryogenic samples.

Keywords: Al/SiC, Cryogenic treatment, Cutting rate, Kerf, RSM, Wire EDM.

Introduction

For composite materials, wire EDM machining has demonstrated its interest beyond its drawbacks as an unconventional machining technique (1). A class of sophisticated materials known as metal matrix composites (MMCs) are difficult to work with because they contain hard ceramic reinforcing particles randomly dispersed throughout a soft matrix material. These composites are suitable for many applications because of their strength and stability (2). Two different Al-6063 alloy-based MMCs were developed by Sarmah and Patowari (3) use additional silicon carbide material with a size between 220 and 600, accounting for nine weight percent. Pandiyan *et al.,* (4) The effects of three different techniques pulse-on time, pulse-off time, and peak current on the response of machining time, kerf width, and product removal rate investigated using the full test model. After testing, ANOVA analysis shows that for Al/SiC 22 and Al/SiC 600 MMCs, peak current is the main factor affecting machining time and material removal rate. For both MMCs, however, the most important factor affecting kerf width is timing. A central composite rotatable design based on Response Surface Methodology was used to conduct the studies. The impact of input factors on output parameters was investigated using analysis of variance. Through, the use of Desirability Function Analysis, the output was optimized to yield a lower surface roughness value and an improved MRR. Surface roughness and material removal rate increased with increased pulse on time and current, whereas material removal rate and surface removal rate fell with decreasing pulse off time. In a practical analysis, Modi *et al.,* (5) examined the effects of wire electric discharge machining machine feed rates on the kerf width, material removal rate, and surface roughness during the machining of Al/SiC composite. A graphic representation is obtained of the relationship between the machine's feed rates and the kerf width, material removal rate, and surface roughness. The wider kerf width, better surface polish, and slower rate of material removal are achieved at current 5 A, wire speed 5 m/minute, wire tension 1.3 kg, feed rate 3 m/minute, and voltage 60 volts with these settings. Mahamood and Khan (6) focuses on the utilization of single variable and multi variable optimization in the microchannel manufacturing of Al-10% SiC composite utilizing the Wire-EDM technique. The most important factor influencing both reduced surface roughness and increased material removal

(Received 30th May 2024; Accepted 12th July 2024; Published 30th July 2024)

rate was pulse on time. The results for the input process parameters, based on the single variable optimization technique, are Ton 125 µs for the maximum metal removal rate, 40 volts for the SV, 12 kgf for weight, and WFR6 mmin−1. Ton 125 µs, SV 10 volts, WT 12 kgf, and WFR 6 mmin−1 are the minimal surface roughness values. The least tool wear rate that may be achieved is Ton 105 µs, SV 25 volts, WT8 kgf, and WFR2mmin−1. Ton 105 µs, SV 10 volts, WT 12 kgf, and WFR4 mmin−1 are the ideal spark gap values. To examine the effects of silicon carbide (SiC), Phate and Toney (7) proposed a model based on Dimensional Analysis (DA) combined with the Taguchi method. The process parameters percentage silicon carbide 20, pulse on time 112, pulse off time 54, wire feed rate 4, peak current 1, wire tension 11, and flushing pressure 15 were shown to have the maximum MRR based on the Taguchi analysis. The process parameters of % silicon carbide 15, pulse on time 108, pulse off time 56, wire feed rate 6, peak current 3, wire tension 10, and flushing pressure 13 were found to yield the lowest surface roughness. Gore *et al.,* (8) created a mathematical model that predicts material removal rate, crater radius, and heat flux. The results of experiments, FEA simulations and theoretical models are contrasting. At lower Ton values, such as 0.2 µs and 0.4 µs, the anticipated MRR via FEA simulation differs by 2% from the experimental MRR. A semi-empirical model for material removal rate in WEDM is proposed by Patil and Brahmankar (9) It is based on the thermophysical characteristics of the workpiece and machining parameters such as average interval voltage and pulse on duration. Empirical and model predictions as well as experimental results agree well. Nevertheless, tuning was shown to be limited to low levels of pulse on time, 0.2 µs. A higher proportion of ceramic particles in MMC results in lower MRR. When ceramic reinforcements are increased by 10%, the MRR decreases by almost 12%. Using Taguchi techniques, Patil and Brahmankar (10) examined the effects of control parameters on cutting speed and surface finish in WEDM of Al/SiCp, including on time, off time, pulse current ignition, wire speed, wire tension and flushing pressure. There are mathematical models that relate machining parameters and performance. Additionally, the optimum parameters for each response were found. A comparative analysis of unreinforced materials revealed how the machining process is affected by percentage reinforcement and it was observed that, the cutting speed of unreinforced alloys was higher than that of unreinforced alloys. The wire breakage could limit the cutting speed of MMC. The impact of reinforcement volume fraction and wire electrode type on the EDM machining performance of 10%, 20% & 30% A359/SiCp composite wire was studied by Patil *et al.,* (11). The author done experimentations to observe the effects on kerf width and cutting speed of various combinations of voltage, current, pulse on and off time, wire speed, and wire tension (12, 13).

It was found that cutting speed and kerf width were significantly affected by voltage, current and operating time. To characterize the thermal and electrical properties of Al/SiC composites with a volume fraction of SiC particles greater than 60% as a function of a temperature ranging from 273K to 373K, Aydin (14) studied the differential thermal analysis approach. Electrical resistance has been shown to increase with sample temperature and volume fraction of SiC ceramic particles. On the other hand, it was found that as the sample temperature and volume percentage of SiC increased, the electrical conductivity decreased. When the volume percentage of SiC reaches 60%, the electrical conductivity drops to 2 x 106 1/ohm m. The tensile and compressive strength of an aluminium-silicon carbide-graphite hybrid composites were assessed by Arunkumar *et al.,* (15) both with and without cryogenic treatment. Al6061 is utilized as the matrix material in this composite, and the amounts of graphite and SiC vary from 1 weight percent to 10 weight percent. After cryogenic treatment, hybrid MMC's properties have improved as the amount of SiC has increased. The XRD result indicates that the hybrid MMC's crystalline structure is enhanced by cryogenic treatment. To investigate the impact of cryogenic treatment, Raghavendra *et al.* (16) produced composites that are subjected to cryogenic treatment and the mechanical and thermal properties are assessed. The tests consist of the Impact, Hardness, and Thermal Conductivity tests. The current study yielded better mechanical characteristics, such as increased hardness, and better thermal characteristics because of cryogenic treatment. Aluminium silicon composites with two distinct compositions (Al 2024_5%SiC and

10%SiC) were developed by Rasool *et al.,* (17) At -186ºC, the samples underwent a controlled cryogenic treatment. The samples that underwent treatment exhibited enhanced compressive strength. The microstructural modifications and the hardness survey complement the improvement.

According to studies, the proportion of reinforcement has a significant impact on the kerf width, cutting rate, and, ultimately, the surface roughness and rate of material removal. Additionally, the authors noted that reinforced particles loosened, displaced, and aggregated in the recast layer after cutting. Poor bonding between the matrix and the reinforced particles is the cause of this. This poor bonding may be improved by cryogenic treatment.

The kerf width directly affects the accuracy and quality of the machined workpiece. The uneven kerf width can cause the product to be defective as undersized or oversized, and thus deviates from design specification. A narrower kerf makes the surface smoother, better materials utilization, and maintains the integrity of the product. In addition, the narrow kerf can improve cutting speed and efficiency. Controlling kerf width is important for creating accurate product and minimizing thermal distortion. By controlling the width of the kerf, manufacturers achieve high precision, tight tolerances, and optimal use of materials.

To achieve the smooth surface and narrow kerf, optimum process parameter setting is very important in the manufacturing industry. Optimization of control parameters leads to overall saving of cost and time with lesser number of experiments.

The proposed study gives insights to determine optimal set of process parameters and respective responses pertinent to cryogenically treated MMCs and percentage of ceramic particles. Currently no researcher undertaking this type of work, which makes findings unique.

Material and Methods

Al/SiCp 10%, 20%, and 30% (DURALCAN™ MMCs) is the material employed. A class of aluminium matrix composites known as DURALCAN™ composites is made up of silicon carbide for gravity-casting and die-casting materials, and particulate aluminium oxide for wrought products. The AA 359/SiC/10, 20 and 30 composite was used for in plaster casts and permanent moulds in general foundries.

The cryogenic treatment cycle includes three main stages: the cooling period, which is the slow cooling rate stage that lowers the material to liquid nitrogen temperature; the soaking period, which keeps samples at liquid nitrogen temperature -196 °C for up to 12 hours; and the warming period, which gradually brings the samples back to room temperature. Liquid nitrogen tank, cryogenic processor, and cooling temperature regulator make up the arrangement. Cryogenic treatment parameters are shown in Table 1.

Table 1: Cryogenic Treatment Parameters

Sr. No.	Sample	Soaking Period Hrs
1	Al/SiC10%	6, 12
2	Al/SiC20%	6, 12
3	Al/SiC30%	6, 12

Table 2: Details of the Experiment (Fixed Parameters)

Machining parameters	Fixed level
Workpiece height	15 mm
Length of cut	10 mm
Angle of cut	Vertical
Location of the workpiece	Centre of the table
Work material*	A359/SiCp/10%, 20% and 30%
Wire electrode	Coated brass wire, 0.25mm diameter, CuZn50
Temporary reduction in frequency (FF)	100
Short pulse time (Tac)	0.4μs
Ignition pulse current (IAL)	16A
Servo reference voltage, (Aj)	40V

Open circuit voltage, (V)	-80 V
Injection pressure, (Inj)	4MPa
Strategy (ST)	1
Dielectric	Deionized water, 15 µs/cm
Dielectric temperature	22ºC

*DURALCAN MMCs

The wire electrical discharge machine (WEDM) used in the trials was a Robofil 300 model made by Charmilles Technology. CNC WEDM machine with five axes. An electrode consisting of 0.25 mm diameter zinc-coated brass wire (CuZn50) was utilized. Electrical conductivity was kept at 15 µS/cm while using deionized water as a dielectric. 22ºC was maintained as the dielectric temperature. Cutting rates and average values expressed in terms of mm^2/min were obtained from the machine display. 10 mm was chosen as the cut-off length. The work piece has a thickness of 15 mm. Table 2 presents the specifics of the experimental setup. Cutting rate is observed from machine display, kerf widths were measured by using Mitutoyo Toolmaker's microscope with an optical magnification of 100X (9-12).

Design of Experiment

The Response Surface Method is a set of mathematical and statistical techniques used in empirical modelling. The link between different input machining parameters and their outputs is determined using this method. Al/SiCp WEDM was created using the central composite design approach. Initial research and a review of the literature were used to determine the input parameters for twenty factorial experiments (9–12, 18).

The parameters that were selected for the input were pulse on-time (µs), pulse off-time (µs) and % volume fraction of SiC particles (19). The experimental parameters' range and levels are displayed in Table 3.

Table 3: Machining Factors and Their Levels

Levels	Pulse on-time	Pulse off-time	% Volume Fraction
	(µs)	(µs)	(%)
	Ton	Toff	% Vf
2	1	16	30
1	0.8	16	30
0	0.6	14	20
-1	0.4	12	10
-2	0.2	12	10

Table 4: Experimental Results of Kerf Width

Ex. No.	Process Parameters			6 Hrs Cryogenic	12 Hrs Cryogenic
	Pulse on-time (µs)	Pulse off-time (µs)	% Volume Fraction (%)	Kerf Width (mm)	Kerf Width (mm)
	Ton	Toff	%Vf	Kerf	Kerf
1	0.4	12	10	0.32	0.31
2	0.8	12	10	0.34	0.33
3	0.4	16	10	0.33	0.32
4	0.8	16	10	0.34	0.33
5	0.4	12	30	0.33	0.31
6	0.8	12	30	0.35	0.32
7	0.4	16	30	0.34	0.31
8	0.8	16	30	0.36	0.32

9	0.6	14	10	0.34	0.33
10	0.6	14	30	0.35	0.33
11	0.6	12	20	0.33	0.33
12	0.6	16	20	0.33	0.33
13	0.2	14	20	0.32	0.30
14	1	14	20	0.36	0.34
15	0.6	14	20	0.33	0.33
16	0.6	14	20	0.33	0.33
17	0.6	14	20	0.33	0.33
18	0.6	14	20	0.33	0.33
19	0.6	14	20	0.33	0.33
20	0.6	14	20	0.33	0.33

Experimental Design

As shown in Table 4, analysis was done on the cutting rate and width of cut (Kerf), as represented by CR and Kerf, respectively. The model's constants and coefficients were computed using the CCD experimentation findings.

Regression equations for 6 hrs cryogenic and 12 hrs cryogenic samples developed using experimental data for Kerf width, to determine the real factors influencing the output parameters.

Regression Equation in Uncoded Units for Kerf for 6 hrs cryogenic samples given in Eq. 1 as:

Kerf mm = 0.1625 + 0.0195 Ton + 0.02580 Toff - 0.003913 % Volume fraction + 0.02629 Ton*Ton - 0.000938 Toff*Toff + 0.000084 % Volume fraction*% Volume fraction - 0.000729 Ton*Toff + 0.000292 Ton*% Volume fraction + 0.000071 Toff*% Volume fraction [1]

Kerf mm = -0.1090 + 0.1633 Ton + 0.05299 Toff + 0.001009 % Volume fraction - 0.0846 Ton*Ton - 0.001856 Toff*Toff - 0.000018 % Volume fraction*% Volume fraction - 0.00073 Ton*Toff - 0.000625 Ton*% Volume fraction - 0.000012 Toff*% Volume fraction [2]

Results and Discussion

The determination coefficient (R2) for the width of cut models for cryogenic samples kept for six hours is 0.97. It shows that the model's predictions and the experiments fit and accord quite well.

Regression Equation in Uncoded Units for Kerf for 12 hrs cryogenic samples Eq. 2.

The determination coefficient (R2) for the width of cut models for 12-hour cryogenic samples is 0.97. It shows that the model's predictions and the experiments fit and accord quite well.

Analysis of Variance (ANOVA)

The purpose of the variance analysis for cutting rate and kerf was to examine the impact of the volume fraction, pulse on time, and pulse off time. Tables 5 and Table 6 present the ANOVA results for 6 hrs cryogenics and 12 hrs cryogenic, respectively for the width of cut (Kerf). This variance analysis was done at the 5% significant level, or 95% confidence level. All-important parameters, including the coefficients, are included in the final equations. The variance analysis (F-test) was another tool used to assess the suitability of the suggested models. The Kerf width models have R values of 99.54 for 6-hour cryogenic samples, and 97.41 for 12-hour cryogenic samples, respectively. R-sq indicates that the model explains 99.54% of the range in responses during a 6-hour cryogenic period. R-sq (adj) for Kerf shows the participation of 99.12% of significant terms in variation. In terms of linear terms, %V is the most significant term, followed by Ton and Toff. It is discovered that the square terms of %V are more significant than the other factors in the mode.

R-sq indicates that the model explains 94.41% of the range in responses for a 12-hour cryogenic period. R-sq (adj) for Kerf shows the contribution of 95.08% of significant terms in variation. In terms of linear terms, Toff is the most significant term, followed by Ton and %V. It is discovered that Toff's square terms are more relevant than the other factors in the model.

Table 5: Analysis of Variance for Kerf Width for 6 hrs Cryogenic

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.002074	0.000230	238.62	0.000
Linear	3	0.000137	0.000046	47.35	0.000
Ton	1	0.000002	0.000002	1.97	0.191
Toff	1	0.000042	0.000042	43.79	0.000
% Volume fraction	1	0.000124	0.000124	128.39	0.000
Square	3	0.000265	0.000088	91.53	0.000
Ton*Ton	1	0.000030	0.000030	31.14	0.000
Toff*Toff	1	0.000045	0.000045	46.59	0.000
% Volume fraction*% Volume fraction	1	0.000227	0.000227	234.70	0.000
2-Way Interaction	3	0.000019	0.000006	6.72	0.009
Ton*Toff	1	0.000001	0.000001	0.70	0.421
Ton*% Volume fraction	1	0.000003	0.000003	2.82	0.124
Toff*% Volume fraction	1	0.000016	0.000016	16.62	0.002
Error	10	0.000010	0.000001		
Lack-of-Fit	5	0.000010	0.000002	1.25	0.404
Pure Error	5	0.000000	0.000000		
Total	19	0.002084			

Table 6: Analysis of Variance for Kerf Width for 12 hrs Cryogenic

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.001757	0.000195	41.77	0.000
Linear	3	0.000319	0.000106	22.74	0.000
Ton	1	0.000133	0.000133	28.47	0.000
Toff	1	0.000178	0.000178	38.16	0.000
% Volume fraction	1	0.000008	0.000008	1.76	0.214
Square	3	0.000686	0.000229	48.90	0.000
Ton*Ton	1	0.000311	0.000311	66.60	0.000
Toff*Toff	1	0.000176	0.000176	37.73	0.000
% Volume fraction*% Volume fraction	1	0.000011	0.000011	2.32	0.159
2-Way Interaction	3	0.000014	0.000005	0.98	0.442
Ton*Toff	1	0.000001	0.000001	0.15	0.711
Ton*% Volume fraction	1	0.000013	0.000013	2.67	0.133
Toff*% Volume fraction	1	0.000000	0.000000	0.11	0.750
Error	10	0.000047	0.000005		
Lack-of-Fit	5	0.000047	0.000009	0.67	0.64
Pure Error	5	0.000000	0.000000		
Total	19	0.001804			

The following is the impact of input machining parameters on their response factors:
Because it directly impacts the accuracy and precision of the machined samples, width of cut, also known as Kerf, is very important. Greater precision is achieved with a smaller Kerf. The machined surface finish improves with decreasing Kerf width, whereas increased cut width can damage the surface finish though it might offer greater removal rates.
This is consistent with the literature; a rise in volume fraction yields good kerf width (10). The minimum kerf is seen for Ton=0.2 µs, Toff=12 µs, and %V=30%. Given Ton = 0.6 µs, Toff = 14 µs, and %V = 20%, shown in figure 1. The uneven distribution of particles in the matrix may be the

reason of the kerf widening (11). Cryogenic samples demonstrate improved kerf width during a 12-hour cryogenic period. This could be because cryogenic treatment has improved the mechanical qualities. Additionally, wire breakage was not detected in the 12-hour cryogenic samples, but it was considerable in the 6- hour cryogenic samples. Furthermore, a reinforced particles played a role in kerf width distortion (11). The kerf width is smaller for cryogenically treated samples. However, wire shifting was a noticeable in cryogenically treated samples; this could be because the matrix and reinforced particles had a better bond (13).

The dislocation and dislodging of reinforced particles resulting from poor bonding are the main causes of material removal in non-cryogenic samples (7-9). As in cryogenic treatment, this bonding may have improved, leading to wire continue to travel along the same cutting line rather than dislocation or dislodging of particles. Sparking also observed due to presence of reinforced particles. When wires and reinforced particles come into contact, a phenomenon known as sparking occurs. This also prevents wires travel and Surface finish eventually degrades as a result of this, as does kerf width. This wire shifting and wire bands may be reduced if pulse duration is increased with increase in % volume fraction of reinforced particles.

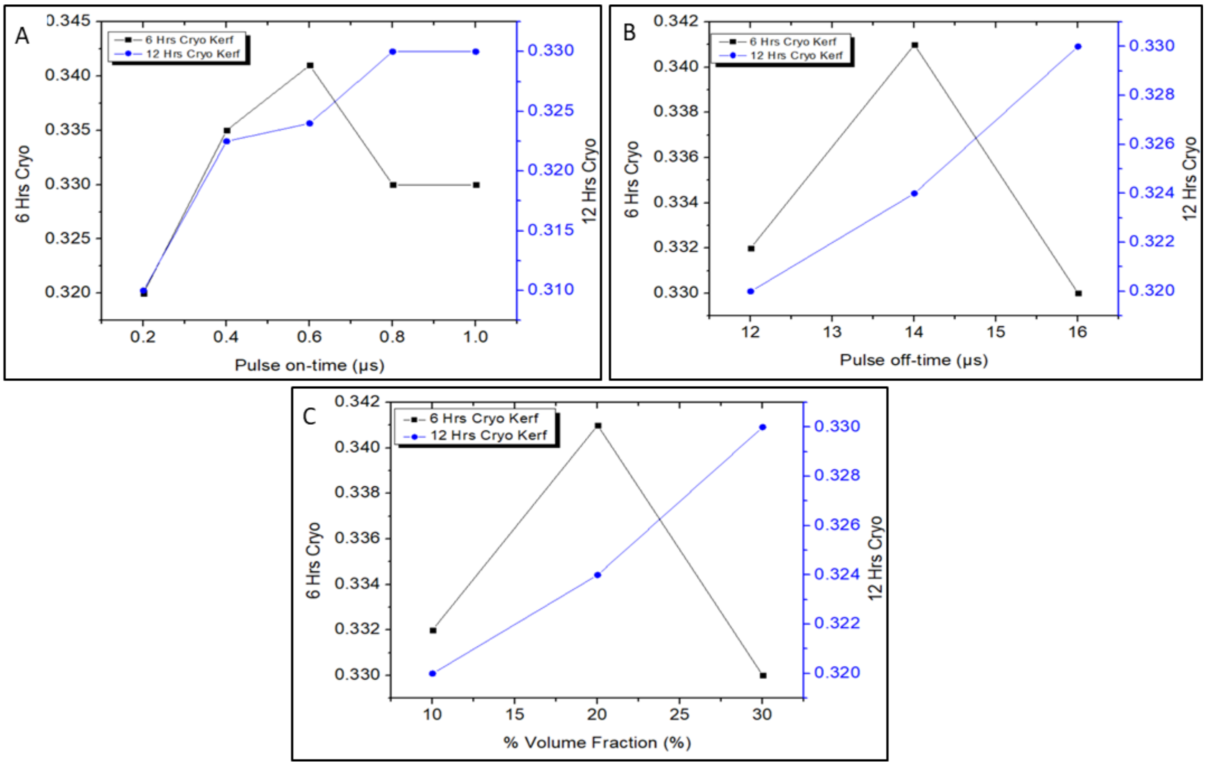

Figure 1. Effect of Process Parameters on Kerf (mm): A) Ton vs Kerf, B) Toff vs Kerf, C) %V vs Kerf

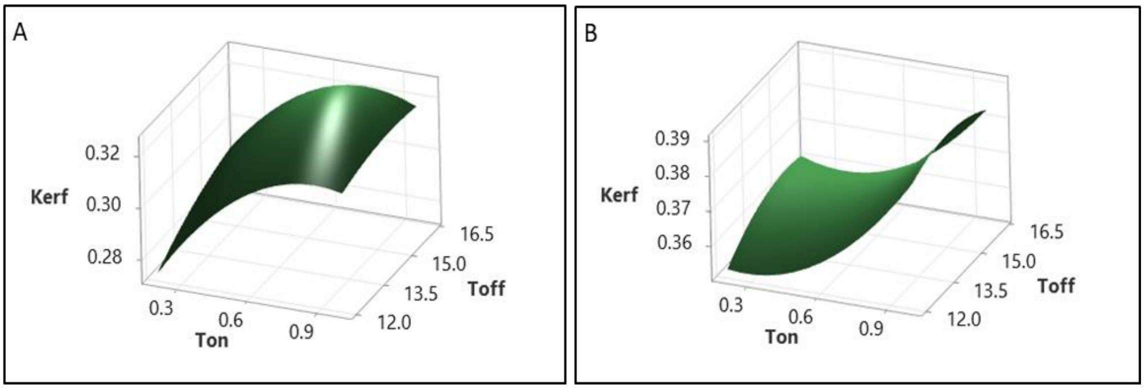

Figure 2. Surface Plots: A) 6 Hrs Cryogenic, B) 12 Hrs Cryogenic

Figure 2 shows various surface plots, kerf width fo 6-hour cryogenic more than that of 12 hrs cryogenically treated samples. Thus it is evident that cryogenic treatment may improve kerf width, and ultimately surface roughness.

Optimization and Cutting Condition

To minimize the width of cut (Kerf), the optimum machining settings for Al/SiCp wire EDM employing coated brass electrode are taken into consideration. Table 7 displays the objectives and range of input parameters for parametric optimization.

Optimized responses shown in Table 8, for 6 hrs cryogenic optimized responses are Kerf=0.3135 for Ton=0.2 µs, Toff=12 µs, %V=17.87 as shown in fog. 3 a), and for 12 hrs cryogenic optimized are Kerf=0.2926 at Ton=0.2 µs, Toff=12 µs, %V=30 as shown in Figure 3. These observations are in line to previous studies (7-12, 20).

Table 7: Goals and Factors for Optimization

Condition	Symbol	Goal	Lower limit	Upper limit
Pulse on time	Ton	In the range	0.2	1
Pulse off time	Toff	In the range	12	16
% volume fraction	%V	In the range	10	30

For optimization range of Ton 0.2-1, Toff 12-16, %V 10-30 are considered.

Table 8: Goals and Optimized Parameters of Responses

Responses	Symbol	Goal	6 hrs cryogenic	12 hrs cryogenic
Kerf width	Kerf	Minimize	0.3135	0.292649

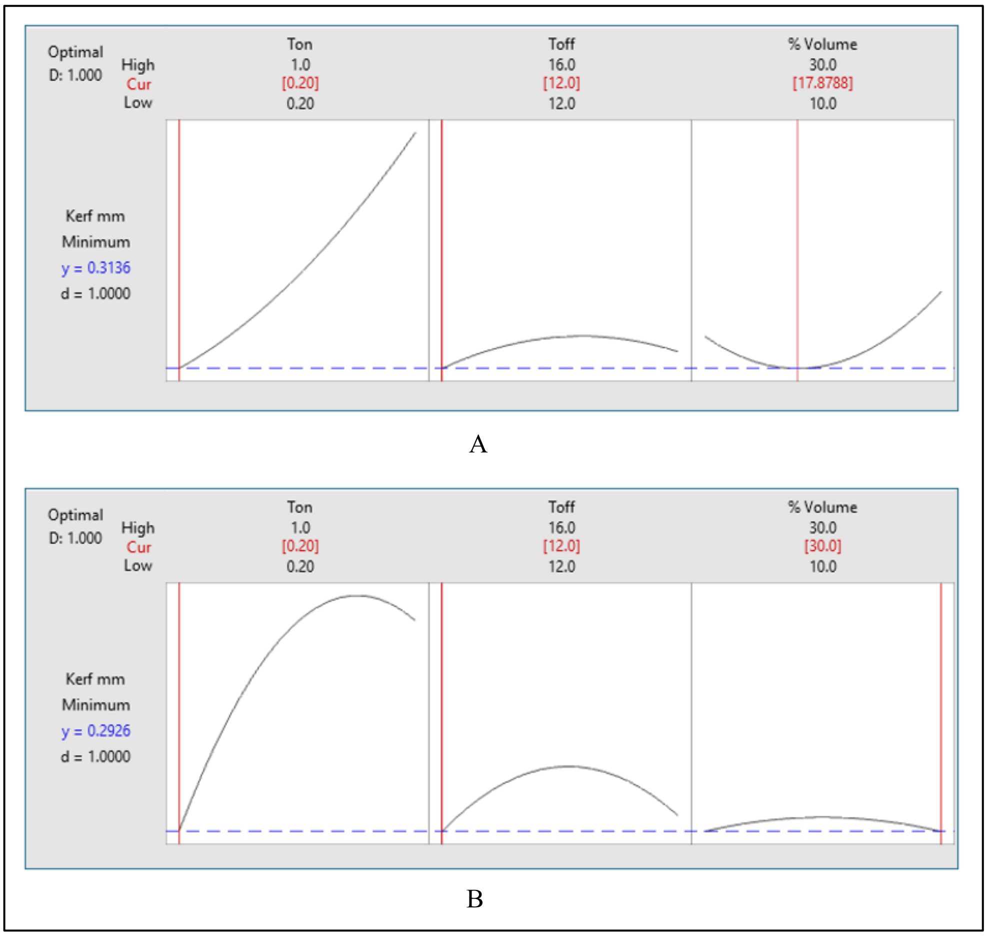

Figure 3. Various Optimization Plots: A) 6-hrs Cryogenic, B) 12-hrs Cryogenic

Kerf is reduced by 3.42% in 12 hrs cryogenic compared to 6 hrs cryogenic samples. This reduction in kerf is due to increase of volume fraction of reinforced particles and improved properties of material cryogenically (13-18)

Considering the limitation of the experimental set up, confirmatory tests were carried out for 6 hrs cryogenic Ton=0.2 μs, Toff=12 μs, %V=20 results Kerf=0.32mm. For 12 hrs cryogenic Ton=0.2 μs, Toff=12 μs, %V=30 delivered Kerf=0.3mm.

With an average error of around of 2.28%, Kerf for 6 hrs cryogenic 2.07%, for 12 hrs cryogenic 2.5% observed for predicted against confirmatory tests. Thus, developed models can be used to predict cutting rates and width of cut accurately for cryogenically treated Al/SiC 10% to 30% MMCs.

Conclusion

In this study Al/SiCp are machined by WEDM by varying Ton, Toff, %V considering cryogenically treated and untreated conditions. Pulse off-time, pulse on-time were found to be significant on kerf. Kerf is increased to 3.42 % in 12 hrs cryogenic compared to 6 hrs cryogenic samples. Kerf is minimum for short pulse duration. And widens for log pulse durations. Optimized results show RSM can predicts kerf up to 2.28%. Wire breakage was found to pose limitations on the Kerf in machining all samples. However, wire breakages could be reduced by employing appropriate pulse on-time, pulse off-times. Wire band marks are also observed in longer pulse durations and higher volume fraction reinforced particle samples. This can be eliminated by choosing appropriate pulse on-time, pulse off-times. Overall, 12 hrs cryogenic samples show good kerf width.

Abbreviations

Al-SiCp: Aluminium Silicon Carbide percentage
Ton: Pulse on time
Toff: Pulse off time
%V: Percentage volume fraction
Kerf: Kerf width
RSM:Response Surface Methodology
DOE: Design of Experiment

Acknowledgments

The authors are indebted to the MSME Technology Centre Indo-German Tool Room, Chh. Sambhajinagar, Maharashtra, India for the provision of machining facility.

Author Contributions

Abhay Gore conceptualized the study, methodology, machining, collected the data, analysed the data, and drafted manuscript. Nilesh Patil and Md. Naser Farooqui critically reviewed and supported the study.

Conflict of Interest

The authors declare no conflict of interest.

Ethics Approval

Not Applicable.

Funding

No funding received.

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