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Prediction and Optimization of Machining Parameters for Cutting Al6061/MoS$_2$ MMC Material by WEDM Process

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Abstract: Wire cut Electric Discharge Machining (WEDM) is a vital technology which is required for high speed cutting and high precision machining to enhance productivity and accuracy for manufacturing of press tools, moulds, prototype parts and complicated contours etc. The machining system involves many input parameters effecting output. The main objective of this research is to determine the optimum values of machining parameters for attaining economical and competent performance for machining Al6061/MoS$_2$ Metal Matrix Composite (MMC). The MMC material was made by stir casting process and the specimen were prepared for machining as well as testing. The cutting operations were carried out on WEDM by varying the machining current on work pieces of thickness ranging from 5-80 mm. The surface roughness value was measured using Talysurf. The Material Removal Rate (MRR) was computed by measuring cutting width using profile projector. The optimal current value at which the machining is stable with high cutting speed is identified. Mathematical correlations are developed to determine the cutting parameters, the MRR and surface roughness by using Origin software. The same parameters were analyzed using RSM technique and the results were compared. The correlations developed are useful for evaluating the machining parameters for different machining situations arising out of customer requirements and machining time calculation in turn cost of machining.

Key words: WEDM, Al 6061/MoS$_2$ MMC, surface roughness, MRR, RSM origin, mathematical correlations

INTRODUCTION

The Wire cut Electrical Discharge Machining (WEDM) is a high precision machining process in the field of conducting and hard to machining materials. Electrical sparks have been produced between the wire electrode and work piece as another electrode. The electrodes are flushed with the de-ionized water as di-electric. The material will be cut and removed in the form of tiny particles by the way of melting and vaporization after freezing once the spark jumps between the electrodes. Figure 1 shows the schematic view of the WEDM process.

WEDM machining uses a thin single strand metal wire usually brass is fed through the work piece. The wire which is constantly fed from a spool isheld between upper and lower guides. The guides move in the X-Y plane. This gives the wire EDM the ability to be programmed to cut very intricate and delicate shapes.

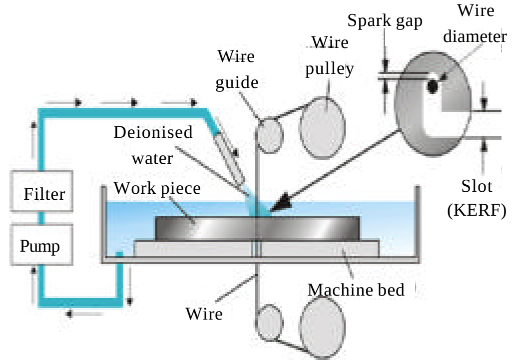

Fig.1: Machining in wire EDM

WEDM is considered as one of the most versatile process for machining intricate, complex shapes and difficult to machine materials. A number of research works has been carries out on different materials to study the

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influence of different process parameters. Al 6061 has the properties of high corrosion resistance and good machinability. Because of these properties it is commonly used for construction of air craft structures such as wings and fuselages. MMCs are the materials consisting of two or more constituent materials in which a metal is reinforced with high strength materials such as Sic, MoS_2, etc. in various proportions. This leads to MMCs with enhanced properties like high strength, high wear resistance. However, the reinforcement material in various forms (particulate, whiskers and continuous fibers) makes it difficult to machine using traditional machining methods due to its hardness.

In the present investigation, aluminium alloy 6061 was used as the matrix material. Among the various aluminium alloys, aluminium alloy 6061 is typically characterized by properties such as fluidity, corrosion resistance, castability and high strength weight ratio. When aluminium matrix is reinforced with the hard ceramics particles like MoS_2 its strength increases (Rani *et al*., 2017a, b).

Literature review: Garg *et al.* (2013) investigated the machining characteristics and the effect of wire EDM process parameters while machining of Al/ZrO_2 Particulate Reinforced Metal Matrix Composite (PRMMC). Central Composite Design (CCD) of Response Surface Methodology (RSM) considering full factorial approach was used to design the experiments. The input parameters for optimization were pulse width, time between pulses, short pulse time, servo control mean reference voltage, wire feed rate and wire tension. The response measures considered were surface roughness and cutting velocity. The multi optimization results obtained by initial input parameters setting, grey relational techniques and response surface methodology were compared and validated by confirmation experiments.

Sharma *et al.* (2014) experimentally investigated the influence of process parameters namely pulse on Time (T_{on}), pulse off Time (T_{off}), peak current (IP) and Servo Voltage (SV) on Cutting Rate (CR) using Wire Electric Discharge Machining (WEDM) on Al 6063+$ZrSiO_4$(p) (5%) metal matrix composite. A Box-Behnken design approach of Response Surface Methodology (RSM) was used to plan and analyze the experiments. To determine optimal values of cutting rate mathematically, the mathematical relationships between WEDM input process parameters and response parameter were established. The Analysis of Variance (ANOVA) and F test were performed to obtain statistically significant process parameters. The optimal process conditions were verified by conducting confirmation experiments and predicted results were found to be in good agreement with experimental findings. It was concluded that on increasing the pulse on time and peak current, the cutting rate increased whereas on increasing the pulse off time and servo voltage it decreased the cutting rate. Surface topography of the machined surface showed that large size craters and cracks were formed on the surface when pulse on time was increased to a high level and pulse off time was decreased at a lower level. It was found that the effect of production of crates was more pronounced on the surface of the machined work piece when peak current was increased to a high level and servo voltage was kept at lower level.

Roy *et al.* (2008) studied the factors influencing the behaviour of Al_2O_3/Al interpenetrating phase composite during wire electro discharge machining process. The responses which were compared under different machining conditions were Material Removal Rate (MRR) and Surface Roughness (SR). The machining variables used in the study were peak current, pulse on time and pulse off time. It was found that pulse current and pulse on time exert most considerable influence on MRR and SR. Pulse off time was least effective. MRR was found to be higher for larger current and pulse on time at the expense of SR.

Hemalatha *et al.* (2014) analyzed the surface integrity in wire-cut EDM of Al 6063/Al_2O_3 MMC. Response surface methodology was used to design the layout of experiment. The pulse on time, pulse off time and servo feed were selected as machining parameters. From results, it was observed that the kerf width decreased with respect to decrease in pulse on time and weight percentage of alumina. And the surface roughness decreased with increase in pulse on time and weight percentage of alumina.

Ramesh *et al.* (2014) carried out the experimental investigation of Al6061/SiCp/B4Cp hybrid MMCs in wire electrical discharge machine. In this study an attempt is made to study the effect of wire electric discharge machining parameters like pulse current and pulse on time on MRR and SR.

Shandilya *et al.* (2012) attempted to optimize the Kerf in machining of SiC/6061 Al MMC using Response Surface Methodology (RSM). Properties of the machined surface have been examined by using SEM and Mathematical model have been developed for response parameter.

Singh *et al.* (2004) investigated the effect of WEDM process parameters on Al-10% SiCP MMC with pulse on time, current and flushing pressure as process parameter and MRR, tool wear rate, taper, radial overcut and surface roughness as responses using brass wire electrode of diameter 0.27 mm. Taguchi L27 orthogonal array has been used for experimental design. Mathematical model has been developed by regression analysis and optimized using gray relational analysis technique. The results revealed that pulse on is the most significant factor.

MATERIALS AND METHODS

The experiments were designed by using Taguchi L_9 array with the machining parameters as shown in Table 1. Electronica-make 4-axis CNC SPRINTCUT wire electrical discharge machine shown in Fig. 2 is used for the experimentation. Deionized water is used as dielectric fluid and brass wire of 0.25 mm diameter as electrode. The following parameters selected as pre setting on the machine (Raouthor and Rao, 2014).

- Machine = Sprintcut
- Dielectric = De-ionized water
- Wire material = Brass
- Wire tension = 70 N
- Wire velocity = 3 m/min
- Gap voltage = 80 V
- Wire diameter = 0.25 mm
- Flushing pressure = 1 Bar

The Al6061/MoS_2specimens of 30 mm×60 mm size on thicknesses 5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 and 80 mm are prepared. The experiments are conducted on the work piece of every thickness by cutting L shape by varying the machining current as per the design of experiments. The cutting speed, spark gap and surface roughness values were measured, MRR was calculated for every experiment and tabulated. The surface roughness is measured on ‘L’ cut using Talysurf and the cutting width is measured by using profile projector. The spark gap is calculated from cutting width.

Cutting width:

$$W = d+2x\ Sg$$

Where:

d = The wire diameter

Sg = The Spark gap

The MRR is calculated as:

$$MRR = T x\ W x\ Cs$$

where, Cs is the cutting speed. The optimum values of machining current, cutting speed, spark gap and MRR for every thickness are used for plotting the curves and best fit curve is selected using software. The mathematical relation is generated for this best fit curve and statistical analysis is performed to find the fitness of the curve.

Table 1: Machining parameters and their factor levels used in the experiments

		Level		
Parameter	Units	L1	L2	L3
Pulse on time (T_{on})	µs	6	8	10
Pulse off time T_{on})	µs	4	5	6
Peak current (I_p)	A	4	3	2
Wire feed (W_F)	mm/min	1	2	3

Fig. 2: Photograph of experimental set up (Curtesy: Sri Purnodaya CNC , Hyderabad)

The results are plotted for work piece thickness and MRR as well as surface roughness using Origin software. The best fit curve was selected based on the results of ANOVA. Mathematical correlations were developed. The same results were analyzed for multi objective criteria optimization by using RSM technique.

RESULTS AND DISCUSSION

Figure 3 was drawn for the variation of MRR with thickness of work piece using origin. It is observed that the MRR is increasing with increase in work piece thickness up to 60 mm and then declining .The MRR is increasing with increase in work piece thickness and the input machining current. Beyond 60 mm thickness the cutting speed decreased drastically as the current can not be raised due to machine limitations. This may be the reason for decrement in MRR even though thickness is increasing beyond 60 mm. The best fit curve was selected based on regression quotient and standard deviation, shown in red colour. The mathematical correlation, Eq. 1 is developed for determining the MRR and is:

$$MRR = 22.87292-\{15.25477/[1+ \exp\left(T-22.17531\right)/11.75745]\} \quad (1)$$

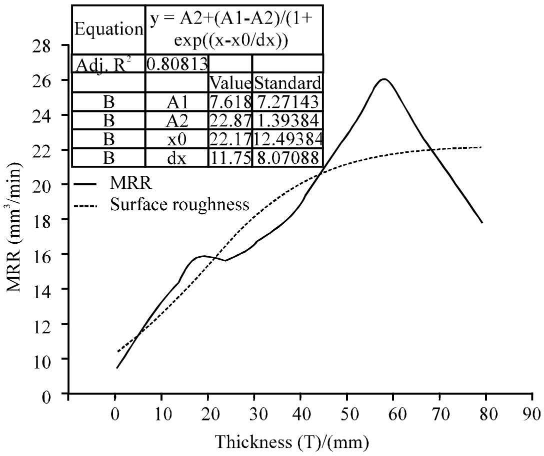

Fig. 3: Best fit curve for thickness versus MRR

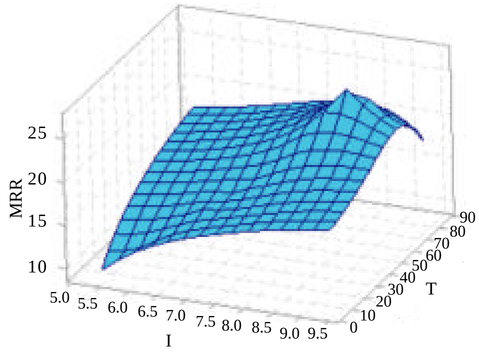

Fig. 4: Response surface regression: MRR versus T, I

Where:

MRR = Material Removal Rate in mm³/min

T = Work piece Thickness in mm

The variation of MRR with respect to current and work piece thickness as a multi objective criteria is drawn as shown in Fig. 4. The plot shows that the MRR was increased with increase in current and thickness. But beyond 60 mm thickness the current increment is less and MRR values fallen down. This trend may be due to machine limitations on maximum possible current. The maximum MRR 26.82 mm³/min. is observed at the current 8.61 A and thickness of 60 mm. The analysis of variance is as shown below and the mathematical correlation, equation 2 is developed for determining MRR in relation to current and thickness (Table 2):

$$MRR = -779-21.85T+295.6I-0.1301TT-27.58II+4.034TI \quad (2)$$

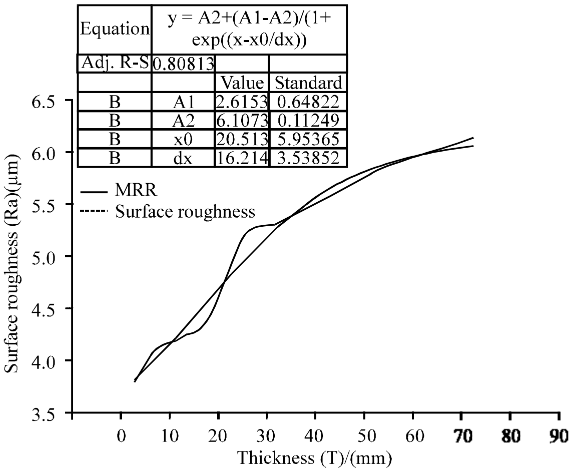

Fig.5 : Best fit curve for thickness versus SR

Table 2: Analysis of variance

Source	df	Adj SS	Adj MS	F-values	p-values
Model	5	451.577	90.3154	233.98	0.000
Linear	2	90.335	45.1673	117.01	0.000
T	1	34.286	34.2861	88.82	0.000
I	1	37.005	37.0053	95.87	0.000
Square	2	59.017	29.5086	76.45	0.000
T*T	1	21.671	21.6711	56.14	0.000
I*I	1	8.825	8.8247	22.86	0.00
2-Way Interaction	1	15.324	15.3239	39.70	0.000
T*I	1	15.324	15.3239	39.70	0.000
Error	13	5.018	0.3860		
Total	18	456.595			

S, R², R² (adj), R² (pred), 0.621287, 98.90%, 98.48%, 98.01%

The mathematical correlations developed are interpolated for 10 and 25 mm thickness and the values are found to be very near to the experimental values with a variation of 1.06% with Eq. 1 (origin) and 0.4% with Eq. 2 (RSM). Both the equations are valid as the variation is <2%. The analysis by RSM is giving better prediction than Origin.

Figure 5 was drawn for the variation of surface roughness with thickness of work piece using Origin. It is observed that the surface roughness increasing with increase in work piece thickness . The surface roughness is increasing in turn finish is decreasing with increase in thickness of work piece . This is due to higher material removal rate at higher current values demanded by the thickness of the work piece. At higher current values the spark will jump longer and causing more material removal in turn higher roughness. The best fit curve was selected based on regression quotient and standard deviation, shown in red colour using Origin software. The mathematical correlation, Eq. 3 is developed for determining the surface roughness and is:

$$R_a = 6.10731-\{3.49197/[1+\exp[(T-20.51324)/16.21468]]\} \quad (3)$$

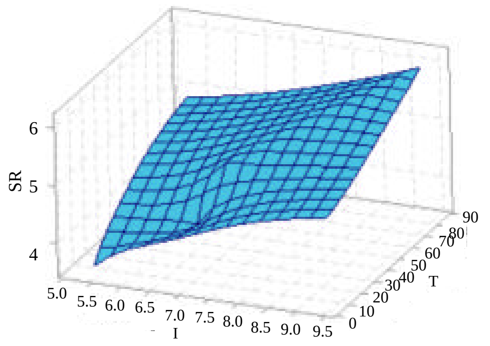

Fig. 6: Response Surface Regression: SR versus T, I

Table 3: Analysis of variance

Source	df	Adj SS	Adj MS	F-values	p-values
Model	5	14.0642	2.81284	490.38	0.000
Linear	2	4.4307	2.21536	386.22	0.000
T	1	0.0309	0.03095	5.40	0.037
I	1	0.0124	0.01237	2.16	0.166
Square	2	0.0145	0.00725	1.26	0.315
T*T	1	0.0016	0.00160	0.28	0.607
I*I	1	0.045	0.00452	0.79	0.391
2-Way Interaction	1	0.0016	0.00158	0.28	0.609
T*I	1	0.0016	0.00158	0.28	0.609
Error	13	0.0746	0.00574		
Total	18	14.1388			

S, R^2, R^2 (adj), R^2 (pred), 0.0757364, 99.47%, 99.27%, 99.11%

Where:
R_a = Surface roughness/(μm)
T = Work piece thickness/(mm)

The variation of surface roughness with respect to current and work piece thickness as a multi objective criteria is drawn as shown in Fig. 6 using RSM technology. The plot shows that the surface roughness was increased with increase in current and thickness. The minimum surface roughness obtained 3.5 μm is observed at the current 5.4 A and thickness of 5 mm, 6.1 μm at 9.5A. The analysis of variafdnce is as shown below and the mathematical correlation is developed for determining surface roughness in relation to current and thickness and depicted as Eq. 4 (Table 3):

$$SR = -13.5-0.118T+6.441-0.00112T * T-0.624I * I+0.0409T * I \tag{4}$$

The mathematical correlations developed are interpolated for 25 and 40 mm thickness and the values are found to be very near to the experimental values with a variation of 1.064% with Eq. 3 (Origin) and 0.9% with Eq. 2 (RSM). Both the equations are valid as the variation is <2%. The analysis by RSM is giving better prediction than origin.

CONCLUSION

In the present research the effect of machining current and Al6061/MoS_2 work piece thickness on MRR and surface roughness are evaluated and optimized using Origin software and RSM software. Mathematical correlations are developed as single objective criteria with origin and multi objective criteria with RSM Software. The results are indicating that RSM technique is predicting more nearer value to that of experimental. The industry or academia can utilize any of the correlation for setting up of the machining parameters. These results will be useful to make the wire EDM system to be efficiently utilized in the modern industrial applications like die and tool-manufacturing units for parametric setting, machining time and cost calculations and also for process planning.

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