Multivariable Optimization in Micro WEDM of Al 7000 Alloy Using Grey Relational Analysis

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Abstract—**With advancement in technology, demand of materials having high tensile strength and high impact strength increases. Machining of these materials with the help of conventional methods, is rather difficult and non productive. To overcome this challenge, Non-conventional machining methods were discovered and wire electrical discharge machining (WEDM) is one of them. WEDM is one of the popular machining methods which is helpful in cutting complex geometries in hard to machine materials. Aluminium alloys are increasingly finding commercial usage in automotive and aerospace industries owing to light weight and high strength factors. Micro WEDM of Al 7000 series alloy which is widely used in commercial applications has been chosen as work piece material in the current study. Charge capacitance decides the energy input in a spark responsible for material erosion and machining accuracy in micro WEDM. Wire feed rate as a process parameter in micro WEDM has not been studied. Objective of present research is to study the effect of voltage, capacitance and wire feed rate on material removal rate and surface roughness while machining of Al 7000 series alloy. These two are important response parameters. Material removal rate tells us about the speed of machining process whereas surface roughness tells us about the finish of machined surface. Zinc coated brass wire of diameter 0.07mm is used on micro WEDM. Taguchi methodology has been chosen for design of experiment and L9 orthogonal array has been selected for present study. Replicates of experiment have been done to avoid any chances of random error. Analysis of variance and main effect plot have been used to find significant factors and their respective contribution on response variables. Multivariable optimization has been done using Grey Relational Analysis. Parametric levels are found at which both response parameters i.e. material removal rate and surface roughness have optimal values. The results obtained have been validated using conformational experiments.**

Index Terms—**WEDM, Grey Relational Analysis, Optimization, Al 7000 alloy**

I. INTRODUCTION

Many new materials/alloys have been developed for specific purposes. Some of these possess a very low machinablity. Producing complicated shapes in these with traditional/conventional machining methods is very difficult. In nonconventional machining there is no requirement of physical engagement between tool and work piece. It uses various types of energies for removal of material which includes mechanical, chemical, electrochemical, thermal etc. In recent years, the technology of Wire Electro Discharge Machining (WEDM) has been improved significantly to meet the requirements in various manufacturing needs, especially in precision mold and die industry. Wire EDM has greatly improved in terms of accuracy, quality, productivity and precision, thus immensely helped the tooling and manufacturing industry. Its chief applications are in the manufacture and reconditioning of press tool and forging dies as well as molds for injection moldings.

A significant amount of research has explored the different methodologies of achieving the ultimate WEDM goals of optimizing the numerous process parameters analytically with the total elimination of the wire breakages thereby also improving the overall machinability on a variety of materials. A brief chronological review is presented.

WEDM operation on SKD11 alloy steel with Brass wire as electrode was explored and influence of various machining parameters such as pulse-on time, pulse-off time, table feed-rate, flushing pressure, distance between wire periphery and work piece surface, and machining history has been observed in finish cutting operations. Pulse-on time and the distance between the wire periphery and the work piece surface are two factors which affect the machining performance significantly. Huang et al.[1]. Optimization of machining parameters namely cutting radius of work piece, on time of discharging, off time of discharging, arc on time of discharging, arc off time of discharging, servo voltage and wire feed with consideration of multiple performance characteristics too has been attempted in WEDM of Al_2O_3 particle reinforced aluminum 6061.Chiang and Chang [2].

Saha et al. [3] developed a second order multi-variable regression model and back-propagation neural network (BPNN) model for WEDM process. While studying

Manuscript received Nov 8, 2018; revised Feb 13, 2019.

doi: 10.18178/ijmerr.8.2.177-181

tungsten carbide-cobalt (WC-Co) composite Mohammadi et al. [4] investigated the effect of wire tension, wire speed along with rotational speed on surface roughness and roundness. Rakwal and Bamberg [5] performed experiments for machining of Germanium wafers using WEDM process. Molybdenum wires of two different diameters were used as electrode during the process study. Two different chemical etchants were used to measure thickness of recast layer and quality of cleaning of wafers was analyzed with the help of Raman spectroscopy. Kumar et al. [6] investigated machining of Inconel 800 super alloy. The variation of output responses with process parameters was mathematically modeled using non-linear regression analysis method and the model was checked for its adequacy results.

Islam et al. [7] investigated dimensional accuracy on Mild Steel 1040 in WEDM observing that wire tension is the only significant factor that leads to better dimensional accuracy. Sivaprakasam [8] investigated micro-WEDM on titanium alloy (Ti-6Al-4V) using response surface methodology with central composite design (CCD). Bobbili et al. [9] studied multi response optimization using Taguchi method coupled with Grey relational analysis in Wire EDM using ballistic grade Aluminium alloy as work piece in machining of Al 7017. Dongre et al. [10] used Wire EDM process for slicing Si ingots to Si wafers using Molybdenum wire. Minimization of kerf width is analyzed with the help of RSM methodology. Some studies have been undertaken in the investigation of micro WEDM with assisted vibration techniques. [11]. Distribution of discharge products in the narrow slit created while WEDM too has been examined. [12]. A high-density, super-high-aspect-ratio microprobe array realized by high-frequency vibration assisted inverse micro WEDM has been studied by Chun and Yang. [13]. Three kinds of high-density, super-high-aspect-ratio microprobe arrays comprising: (1) straight-type, (2) wave-type, and (3) spanning-type are verified successfully. Studies show that each probe has highly consistent dimensional and form accuracy with aspect-ratio realized at 104:1.

It has been observed that most of the work is carried on WEDM operation generally. Not much work has been reported in the domain of micro WEDM (μ-WEDM) operation. Micro WEDM uses an RC type of circuit in the present machines. In the domain of micro WEDM process capacitance, wire feed rate are important variables which need to be studied for the optimised performance of the process. In the present work, effect of the process variables namely Voltage, Capacitance and Wire Feed Rate on response variables namely Material Removal Rate (MRR) and Surface Roughness (SR) of Al 7075 alloy has been studied and optimised for better performance using Zinc coated brass wire of diameter 0.07mm.

Al 7075 aluminium alloy's composition roughly includes 5.6–6.1% zinc, 2.1–2.5% magnesium, 1.2– 1.6% copper, and less than half a percent of silicon, iron, manganese, titanium, chromium, and other metals. Al 7000 series alloys such as 7075 are often used in transport applications including marine, automotive and aviation, due to their high strength-to-density ratio.

II. METHODOLOGY

Work piece of the specifications Length 76mm, Breadth 12.5mm, Thickness 2mm as shown in Fig. 1. is machined for a micro cut of 6mm length, 0.5mm breath and 2mm thickness with the help of micro WEDM. Material removal rate has been found out using weight difference method while surface roughness has been found out with the help of Mitutoyo surftest SJ400.

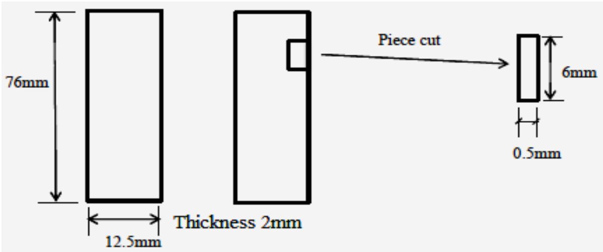

Figure 1. Machined work piece dimensions and schematics

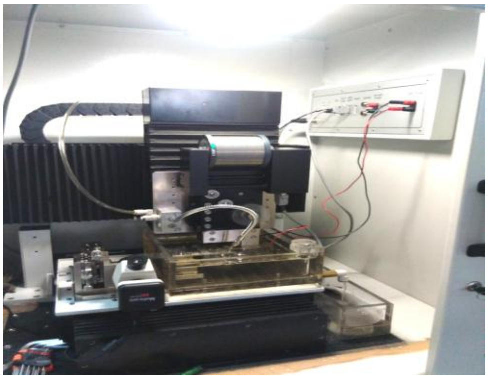

Plate 1 Micro WEDM of Al7075 work piece on DT 110 micro machine

A brief detail about various important process variables in micro WEDM is given below:

i. **Peak voltage:** It is an important input parameter. Preset voltage determines width of spark gap between work piece and edge of electrode. With increase in applied voltage, gap increases and hence machining as well as flushing. In our study voltage range selected is 100V - 120V.

ii. **Feed Rate:** Rate at which wire travels and fed towards wire guide path for continuous sparking is known as feed rate. In our study feed rate is in the range of 2 mm/min to 6 mm/min. With increase in feed rate MRR increases but due to breakage of wire we cannot increase it after a certain range.

iii. **Capacitance:** Resistance Capacitance (RC) relaxation circuit is present in micro WEDM machines. Capacitor is charged through variable resistance R and Voltage Vo. Capacitance vales are selectable in steps which vary from 1 to 6 giving a range 10pF to 400nF.

iv. Various process variables of micro WEDM on the selected machine with their respective range are given as under

Process Variables Range	Voltage (V) 80-130	Capacitance (steps) 1-6 (10pF-400nF)	Feed Rate (mm/min) Manual set

III. Experimental Design

Experimental work is performed on μ-WEDM machine using Aluminium 7075 alloy as work piece. Total three input parameters are selected namely Voltage, Capacitance and Wire Feed Rate to find optimized Material Removal Rate (MRR) and Surface Roughness (SR) as output parameters. Each input parameter is selected at three levels. L9 orthogonal array is used in which 9 experiments have to be performed. Two set of experiments have been done to minimise chances of random errors. Different levels of various input parameters are given in Table I and L9 orthogonal array is given in Table II along with process parameters.

TABLE I. Different Levels of Process Parameters

Input parameters	Level 1	Level 2	Level 3
Voltage (V)	100	110	120
Capacitance steps (Absolute value)	4 (10nF)	5 (100nF)	6 (400nF)
Wire Feed Rate (mm/min)	2	4	6

TABLE II. L9 Orthogonal Array Table (LEVELS)

Experiment No.	Voltage	Capacitance	Wire Feed Rate
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

IV. Results and Analysis

Taguchi method has been used for design of experiments. L9 orthogonal array has been used and experiments have been performed according to combinations given in L9 orthogonal array. Voltage, feed rate and capacitance have been selected as input parameters. Zinc coated brass wire of diameter 0.07mm is selected as electrode.

Analysis For Material Removal Rate (MRR) The results of all experiments for material removal rate (MRR) are given in Table III. Material Removal Rate (MRR) is calculated using weight difference. Difference of weight of work piece before (W_i) and after trial (W_f) is calculated and is then divided by time taken to calculate the desired material removal rate (MRR).

$$\text{MRR} = W_i - W_f$$

TABLE III. Results for MRR

Experiment No.	Voltage (V)	Capacitance step	Wire Feed Rate (mm/min)	MRR(μg/min)	
				Replicate I	Replicate II
1	100	4	2	24.34	26.2
2	100	5	4	61.76	47.63
3	100	6	6	47.06	52.31
4	110	4	2	10.00	8.3
5	110	5	4	70.00	74.82
6	110	6	6	135.71	103.9
7	120	4	2	32.03	30.1
8	120	5	4	225	192.7
9	120	6	6	71.33	93.31

Experimental results presented above for MRR were analyzed using ANOVA to find significant factors which are affecting response factor. ANOVA table for material removal rate is given in Table IV. ANOVA table is generated for 95% confidence interval. F-test is performed on data to find contribution of each factor. ANOVA table for material removal rate (MRR) shows that capacitance (F value 34.18), feed rate (F value 24.83) and voltage (F value 16.9) are the significant factors because F value of these factors are greater than F-value from standard table and P-value is less than 0.05 Further, Capacitance has the highest contribution to MRR whereas voltage has the lowest contribution to affect MRR. However all three significantly contribute to MRR. Respective contribution of various factors is given in Table IV along with the corresponding P value.

TABLE IV. Anova Table for MRR

	DOF	Seq SS	Adj SS	F Value	% Contribution	P Value
Voltage	2	12631	6351.7	16.9	22.26	0.00
Capacitance	2	25545	12772.4	34.18	45.03	0.00
Feed Rate	2	18560	9280	24.83	32.71	0.00
Error	11	411	373.7			
Total	17	60847				

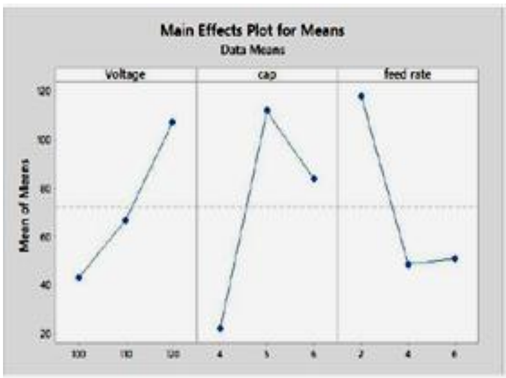

Figure 2. Main effects Plot for the means of MRR.

Analysis For Surface Roughness (SR): The results of all experiments for surface roughness are given in Table V. Responses of surface roughness have been calculated using Mitutoyo Surftest SJ 400 machine.

TABLE V. RESULTS FOR SURFACE ROUGHNESS

Experiment No.	Voltage (V)	Capacitance step	Wire Feed Rate (mm/min)	Surface Roughness (µm)	
				Replicate I	Replicate II
1	100	4	2	1.24	1.24
2	100	5	4	2.3	2.16
3	100	6	6	3.21	3.13
4	110	4	2	1.62	1.54
5	110	5	4	2.65	2.4
6	110	6	6	3.47	3.35
7	120	4	2	1.22	1.21
8	120	5	4	2.25	2.35
9	120	6	6	3.13	3.29

Results for SR were analyzed using ANOVA to find significant factors which are affecting response factors. ANOVA table for surface roughness is given in Table VI. ANOVA table is generated for 95% confidence interval. F- Test is performed on data to find contribution of each factor.

TABLE VI. ANOVA TABLE FOR SURFACE ROUGHNESS

	DOF	Seq SS	Adj SS	F Value	% Contri-bution	P Value
Voltage	2	0.310	0.155	20	2.66	0
Capacita-nce	2	11.049	5.524	729.79	97.3	0
Feed Rate	2	0.004	0.002	0.27	0.036	0.771
Error	11	0.083	0.007			
Total	17					

Figure 3. Main Effects Plot for the means of Surface Roughness

ANOVA table for surface roughness (SR) shows that capacitance (F value 729.79) and voltage (F value 20) are the two significant factors whereas feed rate (F value 0.27) is an insignificant factor. Capacitance has the highest contribution to SR whereas voltage has a lower contribution to affect SR. Contribution of Feed rate is insignificant in case of surface roughness. Respective contribution of various factors is given in Table VI along with P value.

Multivariable Optimization Using Grey Relational Analysis: Grey Relational Analysis is used for multivariable optimization. Table VII shows Grey Relational Grades for maximum material removal rate and minimum surface roughness. Larger the grey relational grade better is multi response output characteristic. With the help of Fig. 4 and Table VII we conclude that the optimal parameter combination is A3 (Voltage 120V), B1 (Capacitance step 4) and C3 (Feed Rate 6 mm/min). Response of Means of Grey Relational Grade [14] which shows ranks of various input parameters affecting Grey Relational Grade is shown in Fig. 4. Capacitance has highest rank which shows that it has highest significant contribution to Grey Relational Grade while Feed Rate has lowest rank which shows that Feed Rate has lowest contribution in affecting Grey Relational Grade.

TABLE VII. RESULTS FOR GREY RELATIONAL GRADE

Experiment No.	Voltage (V)	Capacitance step	Grey Relational Grade	Rank
1	100	4	0.382172	7
2	100	5	0.600897	3
3	100	6	0.296633	9
4	110	4	0.539262	4
5	110	5	0.44124	5
6	110	6	0.036600	6
7	120	4	0.72603	1
8	120	5	0.690734	2
9	120	6	0.340549	8

The confirmation tests for optimal parameters were conducted to check quality characteristics of microWEDM. The combination of the optimal levels of all three factors should produce the optimal magnitude of material removal rate and surface roughness. This result must be further supported through the confirmation runs.

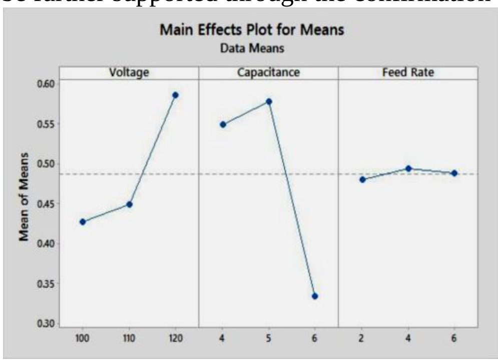

Figure 4. Main Effect Plot for means of Grey Relational Grade

TABLE VIII. SHOWING OPTIMAL PARAMETER SETTINGS BASED ON EXPERIMENTAL AND PREDICTED RESULTS

	Optimal Process Parameters		Error %
	Predicted	Experimental	
Level	A3B2C3	A3B2C3	
MRR (µg/min)	122.96	116.82	5.26%
SR(µm)	2.29	2.36	2.97%

From above Table VIII, it is seen that error obtained in experimental optimal value of material removal rate is 5.26% whereas error obtained in case of surface roughness is 2.97% as compared to predicted values. So the confirmation test also validates the results obtained by Grey Relational Analysis and found that error percentage is within limit i.e. in acceptable range. This shows a good agreement between experimental optimal values and predicted optimal values.

V. Conclusions

The main and important conclusions that can be drawn from this study are summarized. In case of material removal rate all the three process parameters voltage, capacitance and feed rate are found significant while in case of surface roughness only voltage and capacitance are significant parameters. Feed Rate has no significance in determining surface roughness. With increase in servo voltage MRR increases, surface roughness first increases then decreases. With increase in capacitance MRR first increases then decreases, however surface roughness increases with increase in capacitance. Both MRR and surface roughness are analyzed using Grey Relational Analysis to find a parametric level at which values of both MRR and surface roughness are optimum. A multi variable approach has been success fully implemented for optimized process performance based on material removal rate obtained and surface roughness generated in micro WEDM of Al 7075 material.

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