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EXPERIMENTAL INVESTIGATION FOR THE OPTIMIZATION OF THE WEDM PROCESS PARAMETERS TO OBTAIN THE MINIMUM SURFACE ROUGHNESS OF THE Al 7075 ALUMINIUM ALLOY EMPLOYED WITH A ZINC-COATED WIRE USING RSM AND GA

EKSPERIMENTALNA RAZISKAVA OPTIMIZACIJE PROCESNIH PARAMETROV ŽIČNE EROZIJE S CINKOM OPLAŠČENE Cu ŽICE ZA ZAGOTOVITEV MINIMALNE POVRŠINSKE HRAPAVOSTI Al ZLITINE 7075 Z UPORABO POSTOPKOV RSM IN GA

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Wire Electrical Discharge Machining (WEDM) is widely used for machining conductive materials of intricate, complex and challenging shapes in the field of aerospace, die and mould making, automobile industries and the medical field. Proper selection of the WEDM process parameters can give good responses. Out of the various process responses, to achieve the minimum surface roughness is very difficult, due to arcing by the electrical discharge. The present investigation has been made to optimize the process parameters of WEDM during machining the Al 7075 aluminium alloy with zinc-coated copper wire using the Response Surface Methodology (RSM). Four input process parameters of WEDM, i.e., Pulse On Time, Pulse Off Time, Wire Feed and Wire Tension, were chosen as the process variables to study the process performance and to obtain the minimum surface roughness. An analysis of variance (ANOVA) was carried out to study the effect of the process parameters on the surface roughness and a mathematical model was developed. The model has been verified and checked for adequacy. The best fit surface roughness (R_a) value predicted is 1.048 µm for a Pulse On (T_{ON}) value of 120 µsec, a Pulse Off (T_{OFF}) value of 58 µsec, a Wire Feed (*WF*) of 3 m/min and a Wire Tension (*WT*) value of 9 gm. Furthermore, it is observed that with an increase in the pulse-on time the Surface Roughness also increases, and an increase in the pulse-off time and the wire tension, the Surface Roughness decreases. Wire Feed does not influence much on the Surface Roughness.

Keywords:WEDM (Wire Electrical Discharge Machining), optimisation, surface roughness, RSM, GA, Al 7075

Žična erozija (WEDM; angl.: Wire Electrical Discharge Machining) se pogosto uporablja za obdelavo in rezanje kompleksno oblikovanih izdelkov, modelov in orodij iz prevodnih materialov v letalski, orodjarski, modelarski in avtomobilski industriji ter v zdravstvu. Pri tem postopku je zelo pomembna izbira ustreznih procesnih parametrov WEDM. Doseganje minimalne površinske hrapavosti reza je zelo zahtevno zaradi nastajajočega talilnega obloka med razelektrevanjem. Avtorji so optimizirali procesne parametre WEDM, ki uporablja s cinkom oplaščeno bakreno žico med mehansko obdelavo Al zlitine 7075 z uporabo metodologije odgovora površine (RSM, angl.: Response Surface Methodology). Izbrali so štiri vhodne procesne parametre WEDM, in sicer: čas vklopa (T_{ON}) in izklopa (T_{OFF}) električnega impulza, hitrost dovajanja žice *WF* in napetost žice *WT* kot spremenljivke za študij vpliva procesa na zagotovitev minimalne hrapavosti. Z analizo variance (ANOVA) so raziskovali vpliv procesnih parametrov na površinsko hrapavost in na njeni osnovi razvili matematični model. Model so verificirali in preizkusili njegovo ustreznost. Najboljše ujemanje vrednosti za površinsko hrapavost (R_a) je bilo 1,048 µm pri T_{ON} vrednosti 120 µsec, T_{OFF} vrednosti 58 µsec, hitrosti dovajanja žice *WF* 3 m/min ter napetosti žice *WT* 9 mN/m. Avtorji ugotavljajo, da se je z nadaljnjim podaljševanjem časa T_{ON} povečevala površinska hrapavost. S podaljševanjem časa T_{OFF} in povečevanjem napetosti žice pa se je površinska hrapavost zmanjševala. Hitrost dovajanja žice ni pomembno vplivala na površinsko hrapavost.

Ključne besede: WEDM – žična erozija, optimizacija, površinska hrapavost, RSM, GA, Al zlitina 7075

1 INTRODUCTION

Several researchers investigated the different aspects of WEDM, but no comprehensive research work has been reported so far in the field of wire electrical discharge machining of this Al 7075 alloy using zinc-coated copper wire. Hence, an attempt was made to explore the influences of selected variable process parameters.

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G. E. Totten and D. S. Mackenzie[1] reported the machinability ratings of aluminium alloys span into five groups, with ratings of A, B, C, D and E, which are ordered in increasing order of chip length and decreasing order of surface quality. The Al 5083 aluminium alloy ranked D is an indicator for poor machinability. WEDM is one of the latest machining techniques to process the Al 5083 aluminium alloy to any complex intricate shapes with high accuracy and precision when comparing with diamond-based cutting tools. J. Prohaszka et al.[2] investigated the effect of electrode material coating with zinc, tin and magnesium on machinability in the WEDM process. These coating materials are required for improving the cutting efficiency because the existing wires do not fulfill all the requirements. R. Chalisgaonkar and J. Kumar[3] explored the characteristics of pure titanium during rough cut operation, and after the finish cut operation, they revealed the microstructure analysis of zinc-coated and in the uncoated wires the erosion during the rough cut operation was found to be more than the finish cut. B. Sivaraman et al.[4] stated that in the WEDM process the Taguchi method is most ideal and suitable, it simplifies the optimisation of multiple performance characteristics by avoiding complicated mathematical computations. G. Selvakumar et al.[5] presented an optimum input-parameter combination for the minimum Ra and the maximum MRR was obtained by an analysis of the signal-to-noise (S/N) ratio and the process was optimized by a Pareto-optimality approach by machining the Al 5083 aluminium alloy. D. Siva Prasad et al.[6] investigated the effect of different WEDM process parameters on the damping behavior of the A 356.2 aluminum alloy. The damping capacity of this alloy increases with an increase in the frequency and increasing Pulse On.

A. Dey et al.[7] examined the machinability of the cenosphere fly-ash reinforced Al 6061 aluminium alloys for various combinations of the input process parameters. The optimal combination of process parameters was arrived at for the maximum MRR, the minimum Tool Wear Rate and the minimum R_a. K. H. Ho et al.[8] carried out the WEDM process by understanding the interrelationship between the various factors affecting the process and identified the optimal machining condition from the infinite number of combinations. The adaptive monitoring and control systems were implemented to tame the transient WEDM behaviour without the risk of wire breakages. S. Kuriakose and M. S. Shunmugam[9] investigated the optimal parameters of the WEDM process for improving the cutting performance. There is no single optimal combination of cutting parameters, as their influences on the cutting velocity and the surface finish are quite the opposite. In the present work, a multiple regression model is used to represent the relationship between the input and output variables and a multi-objective optimization method based on a Non-Dominated Sorting Genetic Algorithm (NSGA) is used to optimize the WEDM process.

A. Sharma et al.[10] made an attempt to machine an Al 6063 / ZrSiO4(p) (5 %) metal-matrix composite using WEDM. The objective was to investigate the influence of the process parameters, i.e., T_{ON}, T_{OFF}, Peak Current and SV on the Cutting Rate and found experimentally that increasing the T_{ON} and Peak current, the cutting rate increases, whereas increasing the T_{OFF} and SV decreases the cutting rate. The higher discharge energy associated with the increased T_{ON}, Peak Current and lesser TOFF and SV leads to more powerful explosions, which increase the cutting rate. H. C. Tsai et al.[11] investigated the electrode performance and revealed that wires generally used are of brass or copper with a diameter of about 0.3–0.5 mm, but in recent times coated wires are widely used, usually zinc coated over brass wire. The impacts of coated wires were found to have a significant effect. The productivity and surface roughness were found to be better than uncoated wires. Several authors[12–14] also suggested that the concentration of electrical discharges at a certain point of the wire, which causes an increase in the localized temperature, resulting in the breakage of the wire. V. Chengal Reddy et al.[15] discussed the effects of the input control parameters, such as T_{ON}, T_{OFF}, Current, *WT*, upper flush and lower flush on the R_a, MRR and Kerf Width, while machining the aluminum HE 30 material and suggested the selection of the right combination of input parameters by Grey Relational Analysis (GRA).

Dain Thomas et al.[16], developed a second-order regression model using RSM and found that T_{ON} and *WT* play a major role in the surface roughness. V. R. Surya et al.[17] predicted the machining characteristics of an Al 7075-TiB2 composite using ANN for the maximum MRR, minimum Dimensional Error (DE) and better surface finish. In this study the control factors considered were T_{ON}, T_{OFF}, Current and Bed Speed based on Taguchi's L 27 orthogonal array. S. Prashantha et al.[18] investigated the Al 6061 aluminium alloy reinforced with SiC particles by varying the percentage of SiC from 3 %, 6 % and 9 % by weight. T_{ON}, T_{OFF} , Current (I) and Bed speed (BS) are varied to find their effects on the MRR. From the analysis, the average MRR for an unreinforced Al 6061 aluminium alloy is 9.2 mm^3/min and the average MRR is 9.15 mm^3/min, 9.13 mm^3/min and 9 mm^3/min, respectively for Al 6061 aluminium alloy MMCs with 3 %, 6 % and 9 % SiC, i.e., the MRR decreases with an increase of the silicon carbide particles. S. Prasad Arikatla et al.[19] executed a study on a titanium alloy using RSM in WEDM and registered the quality of the machined surface by T_{ON} & Input Power and *WT* & SV. In the I case Ra increases while in the II case Ra decreases. G. Amitesh and K. Jatinder[20] investigated the influence of machining parameters on the material removal rate and the cutting speed for the machining of Nimonic 80 A with Brass wire as the electrode in wire electrical discharge machining. From the observation, the cutting speed (CS) and MRR both increase with an increase in T_{ON} and the Peak Current (IP). Furthermore, it decreases with an increase in T_{OFF} and the spark gap set voltage. M. T. Antar et al.[21] explored the role of coated wire in the production and surface integrity, while machining aerospace alloys in WEDM. Coated wires are stated to protect the core from thermal shock and also from wire rupture. Its other effects were found on vibration, damping effect, heat transfer and resistance, which ultimately increased the machining speed. N. Kinoshita et al.[22] observed that wire breaks due to a rapid rise in the pulse frequency of the gap voltage. They developed a monitoring and control system that switches off the pulse generator and the servo system, preventing the wire from breaking, but it affects the machining efficiency.

The above literature review indicates that most of the researchers have considered the influence of a limited

Table 1: Al 7075 alloy composition in percentage by weight

Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	others
87.1–91.4	0.18–0.28	1.2–2.0	Max 0.5	2.1–2.9	Max 0.3	Max 0.4	Max 0.2	5.1–6.1	Max 0.15

number of control parameters on the performance measures of Wire Electric Discharge Machined parts. Furthermore, from the literature review it is understandable that the impact of coated wires was found to improve the productivity and surface finish, better than uncoated wires. Hence, it is intended to investigate the effect of the selected variable process parameters on the surface roughness, while machining with zinc-coated copper wire of diameter 0.25 mm. So far, no such investigation was carried out on the Al 7075 aluminium alloy. In this study an attempt has been made to optimize the various WEDM process parameters such as T_{ON}, T_{OFF}, *WF* and *WT* to find out the best fit to obtain minimum R_a.

2 EXPERIMENTAL PART

2.1 Work material

As the Al 7075 Aluminium alloy is a lightweight material, zinc-based alloy and possesses excellent corrosion resistant, it is widely used in marine, aerospace applications and in the medical field. Aluminium alloys have very good mechanical properties such as a high tensile strength, a very high yield strength, good fatigue strength, and superior corrosion resistance, and average machinability. However, these alloys were very difficult to fabricate as they are not ductile and have a low fracture toughness at room temperature. An unconventional machining process like WEDM is used intensively for a better process The response is to machine an aluminium alloy, due to its exceptional strength properties, whereas it is very difficult to machine in a conventional method. The analysis of the consequence of different process parameters is essential.

2.2 Machine tool

WEDM requires thin, single-strand conducting metal wire that is used as the electrode. There are several electrode materials available, but brass wire is commercially used. The wire can either be coated wire (zinc, brass, tin, magnesium etc.) or uncoated wire (copper, brass, molybdenum). This conducting wire is passed through the pre-drilled hole in the metal piece to be machined. The wire is fed from a spool and held between upper and lower guides tha are made of diamond, and in turn it is finally controlled by CNC and moved in the X-Y plane. This allows the wire-cut EDM to be programmed to cut very intricate, delicate and complex shapes. By using a pump, dielectric fluid (Deionised Water) is continuously passed over the work piece to remove, clear and flush out the debris that is cut from the work piece. When a D.C. supply is attached to the circuit, thousands of spark discharges occur across the gap between the wire and the work piece, which increases the temperature and causes the melting of material, erosion and even vaporizing and thus removing the metal from the work piece. The removed fine material particles are carried away by the dielectric fluid circulating around it.

Figure 1: WEDM machine set up

Table 2: Properties of Al 7075 Aluminium Alloy

Sl. No.	Property	Value
1	Density	2.81 g/cc
2	Ultimate Tensile strength	572 MPa
3	Tensile Yield strength	503 Mpa
4	Elongation at break	11 %
5	Modulus of Elasticity	71.7 GPa
6	Poisson Ratio	0.33
7	Hardness Brinell	150
8	Fatigue strength	159 MPa
9	Shear Modulus	26.9 GPa
10	Machinability	70 %
11	Thermal Conductivity	130 W/m k
12	Melting Point	477–635 °C
13	Electrical Resistivity	5.15 e^{-006} Ω cm

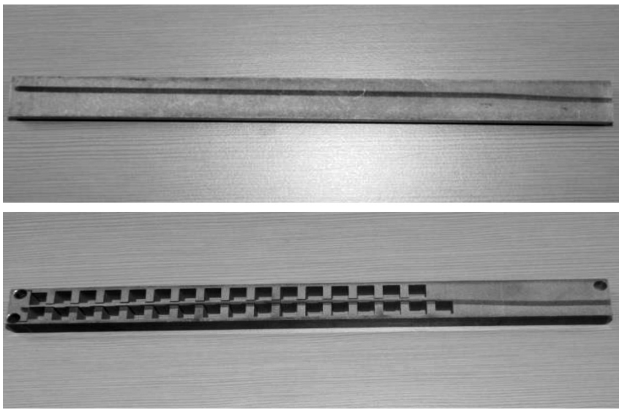

Figure 2: a) Work piece before machining and b) after machining

2.3 Specimen

An Al 7075 aluminum alloy rectangular block of length 200 mm, width 16 mm and thickness 10 mm was taken as the work material. The experiment was performed on a WEDM machine with zinc-coated copper wire (tool) of 0.25 mm diameter and deionized water is used as the dielectric fluid.

2.4 Parameters considered in this experiment

Table 3: Fixed parameters

Sl. No.	Parameter	Unit	value
1	Input Power	V	230
2	Dielectric fluid pressure	kg/cm^2	1 machine unit (low)
3	Pulse Peak Voltage	V	2 machine unit
4	Servo Voltage	V	20
5	Servo Frequency	cycles/s	2100

Table 4: Variable parameters and range

Sl. No.	Parameter	Unit	From	To
1	Pulse On (T_{ON})	µs	120	128
2	Pulse Off (T_{OFF})	µs	50	58
3	Wire Feed (*WF*)	m/min	1	3
4	Wire Tension (*WT*)	N	5	9

2.5 Experimental values

Table 5: Experimental results of R_a using *L*27 orthogonal array matrix

Sl. no.	Variable Process Parameters				Response R_a		Error	Remarks
	Pulse on	Pulse off	Wire Feed	Wire Tension	Experimental	RSM predicted		
	µs	µs	m/min	N	µm	µm	%	
1	128	54	2	5	1.84	2.08	11.62	
2	120	54	1	7	1.80	1.92	6.44	
3	124	58	2	9	1.36	1.39	1.88	WB
4	124	58	1	7	1.91	1.95	1.95	
5	124	50	2	5	1.79	2.19	18.12	
l6	124	54	2	7	1.94	2.15	9.94	
7	120	58	2	7	1.62	1.48	9.31	
8	128	54	3	7	1.91	2.22	13.96	
9	128	54	1	7	1.93	2.23	13.38	
10	124	54	3	5	1.87	2.02	7.61	
11	124	54	3	9	1.74	1.94	10.12	
12	120	54	2	5	1.73	1.69	2.37	
13	120	54	2	9	1.35	1.55	13.13	
14	124	54	2	7	1.93	2.15	10.40	
15	128	54	2	9	1.39	1.88	26.14	WB
16	128	50	2	7	1.98	2.47	19.97	
17	124	50	1	7	1.86	2.27	17.99	
18	124	50	3	7	2.11	2.52	16.14	
19	120	54	3	7	1.67	1.80	7.43	
20	128	58	2	7	1.62	1.62	0.12	
21	124	54	2	7	1.98	2.15	8.08	
22	124	54	1	5	2.02	2.17	6.83	
23	120	50	2	7	1.55	1.89	17.99	
24	124	54	1	9	1.73	1.92	9.90	
25	124	50	2	9	1.65	2.11	21.95	
26	124	58	2	5	1.70	1.65	3.03	WB
27	124	58	3	7	1.54	1.57	2.04	

2.6 Surface roughness

Roughness is a measure of the texture (quality) of the surface. It is quantified by the vertical deviations of the actual surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. The surface roughness R_a was measured with a Mitutoyo Surftest 211 Surface Roughness tester and the values are tabulated in **Table 5**.

2.7 Response Surface Methodology (RSM)

This is a collection of statistical and mathematical techniques useful for developing, improving and optimizing processes. RSM consists of an experimental approach to investigate the independent variables in the process, the experimental statistical model developed for an appropriate similar relationship between the yield and the process variables. Optimization methods for finding values of the process variables that produce desirable values of the responses. In order to investigate the effects of the WEDM parameters on the above-mentioned machining criteria, second-order polynomial response surface mathematical models can be developed. In the general case, the response surface is described by an equation of the form:

$$Y = \beta_0 + \Sigma\beta_j x_j + \Sigma\beta_{jj} x^2_j + \Sigma\Sigma\beta_{ij} x_i x_j \quad (1)$$

where Y is the response, in current research surface roughness, whereas the terms β_0, β_j, β_{ij} are second-order regression coefficients. The second term under the summation sign of this polynomial equation is attributable to a linear effect, whereas the third term corresponds to the higher-order effects and the fourth term of the equation includes the interactive effects of the process parameters. The above equation can be rewritten as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{11} X_{12} + \beta_{22} X_{22} + \beta_{33} X_{32} + \beta_{44} X_{42} + \ldots \quad (2)$$

The value of β, the regression coefficient, will be determined by the least-squares method.

2.8 Wire breakage

A wide variety of the control strategies preventing the wire from breaking are based on a knowledge of the characteristics of the wire. The breaking of the wire can be due to the excessive thermal load producing unwarranted heat on the wire. Most of the thermal energy generated during the WEDM process is transferred to the wire, while the rest is lost to the flushing fluid. However, when the instantaneous energy rate exceeds a certain limit depending on the thermal properties of the wire material, the wire will break. The WB in the **Table 5** indicates the occurrence of wire breakage while conducting the experiment, hence the corresponding set of parameters to be avoided for better performance.

3 RESULTS

3.1 Response Surface Methodology (RSM)

The relationship between the selected variable process parameters and the response R_a was obtained by a quadratic regression equation using RSM in Minitab. This regression equation is useful in predicting the response surface roughness with respect to the variable process parameters Pulse on Time (A), Pulse off Time (B), Wire Feed (C) and Wire Tension (D).

$$R_a = -231.114 + 2.903\,A + 1.773\,B + 0.866\,C + 1.162\,D - 0.01\,A^2 - 0.008\,B^2 + 0.05\,C^2 - 0.048\,D^2 - 0.007\,A{\cdot}B + 0.007\,A{\cdot}C - 0.002\,A{\cdot}D - 0.039\,B{\cdot}C - 0.006\,B{\cdot}D - 0.02\,C{\cdot}D$$

Figure 3 shows the difference between the experimental and predicted R_a. The error percentage was calculated based on the input variable process parameters and the predicted value, and tabulated in **Table 5**, and found to be reasonable.

3.2 Analysis of variance for R_a

Table 6: ANOVA result for R_a

Source	DF	Seq SS	Adj MS	F	% Contribution
Regression	14	1.02098	0.072927	15.96	
Linear	4	0.45663	0.057484	12.58	
Pulse on	1	0.07521	0.175001	38.31	6.99
Pulse off	1	0.11801	0.132032	28.90	10.97
Wire Feed	1	0.01401	0.002568	0.56	1.30
Wire Tension	1	0.24941	0.018231	3.99	23.18
Square	4	0.40138	0.100344	21.97	
Pulse on* Pulse on	1	0.07993	0.140833	30.83	7.43
Pulse off* Pulse off	1	0.05184	0.083333	18.24	4.82
Wire Feed* Wire Feed	1	0.07707	0.133333	2.92	7.16
Wire Tension* Wire Tension	1	0.19253	0.192533	42.15	17.90
Interaction	6	0.16297	0.027162	5.95	
Pulse on* Pulse off	1	0.04623	0.027162	10.12	4.30
Pulse on* Wire Feed	1	0.00302	0.046225	0.66	0.28
Pulse on* Wire Tension	1	0.00122	0.003025	0.27	0.11
Pulse off* Wire Feed	1	0.09610	0.001225	21.04	8.93
Pulse off* Wire Tension	1	0.01000	0.096100	2.19	0.93
Wire Feed* Wire Tension	1	0.00640	0.010000	1.40	0.59
Residual Error	12	0.05482	0.006400		
Lack-of-Fit	10	0.05342	0.004568	7.63	
Pure Error	2	0.00140	0.005342		
Total	26	1.07580	0.000700		

3.3 Contribution of the process variable parameter during machining

Table 6 shows the results of the ANOVA for a 95 % confidence level of R_a. It is observed from the table that foremost variable that affects R_a is linear *WT* with a contribution of 23.18 %. The second important factor is squared *WT* with a contribution of 17.90 %, then linear T_{OFF} with 10.97 %, interaction of $T_{OFF} \times WF$, squared T_{ON}, squared *WF*, linear T_{ON}, squared T_{OFF}, interaction of $T_{ON} \times T_{OFF}$ and linear *WF*, with a contribution of (8.93, 7.43, 7.16, 6.99, 4.82, 4.30 and 1.30) % respectively. In addition to the above, it is found that interaction of $T_{OFF} \times WT$, $WF \times WT$, $T_{ON} \times WF$, $T_{ON} \times WT$ contribution values are less than 1 %, which states that these interactions do not affect R_a. Further, from **Table 5,** it is observed that the predicted values from RSM are close to the experimental values of R_a. The higher correlation coefficient (R^2) of more than 90 % confirms the fitness of the model.

Figure 4a shows the fitness of the experimental R_a obtained to the predicted R_a. It is observed that there is not much deviation found between the experimental value and the predicted value obtained from RSM. **Fig-**

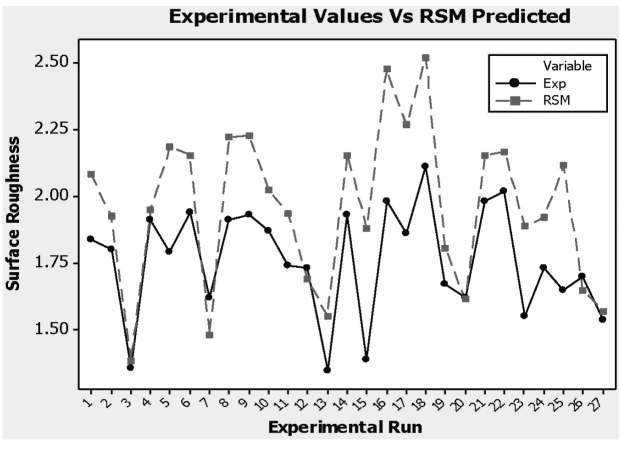

Figure 3: Experimental vs. predicted values of R_a

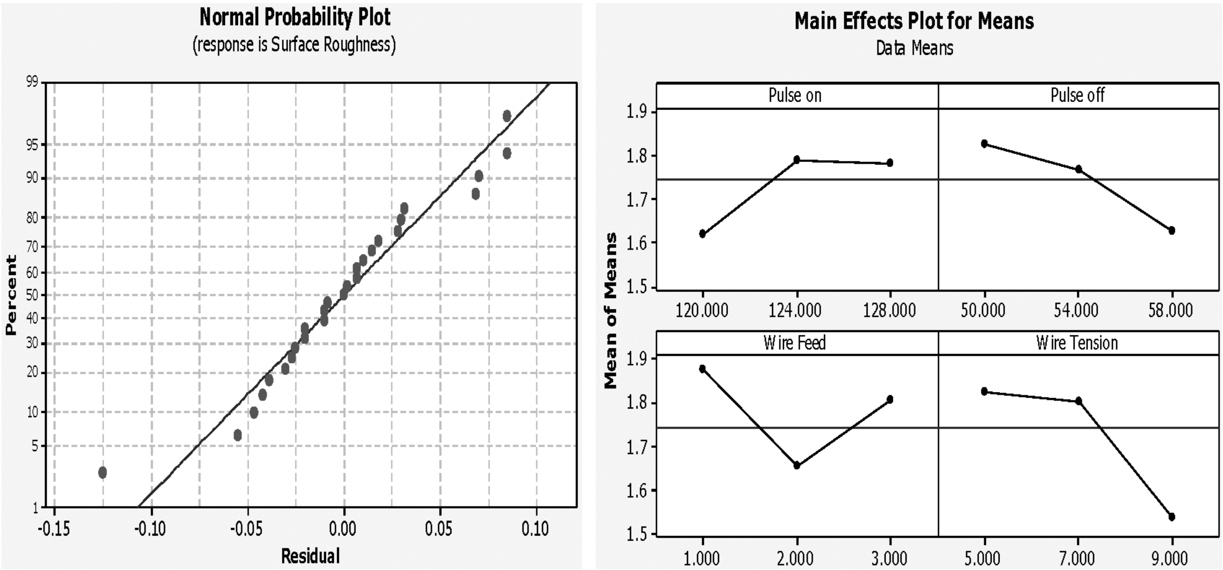

Figure 4: a) Fitness of the experiment, b) effect of *SN* ratios

ure 4b shows the effect plot for the SN ratios of the data mean of R_a, R_a is the minimum for the minimum T_{ON}, maximum T_{OFF}, moderate *WF* & maximum *WT*. R_a is the maximum for mid-value T_{ON}, minimum T_{OFF}, minimum *WF* and *WT*.

3.4 Contour and surface plots of RSM

4 DISCUSSION

4.1 Discussion of contour plot and surface plot obtained from RSM

Figure 5a depicts the effect of T_{ON} and T_{OFF} on R_a when *WF* and *WT* are held constant, for the T_{ON} value ranging from 123.5 µs to 128 µs and T_{OFF} rate from 50 µs

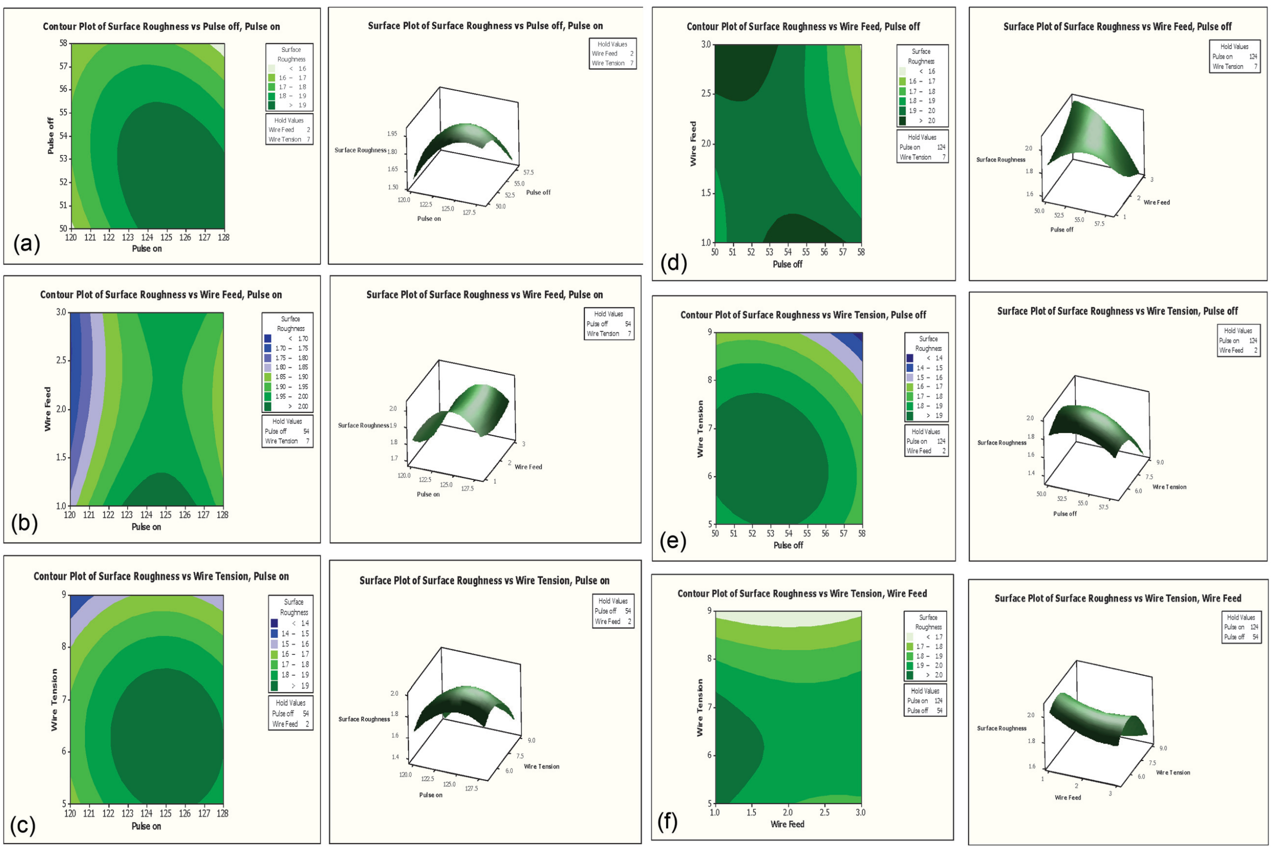

Figure 5: Contour plot and surface plot of surface roughness: a) R_a versus T_{OFF}, T_{ON}, b) R_a versus *WF*, T_{ON}, c) R_a versus *WT*, T_{ON}, d) R_a versus *WF*, T_{OFF}, e) R_a versus *WT*, T_{OFF}, f) R_a versus *WT*, *WF*

to 54.5 µs, the R_a value is a maximum (>1.90 µm). There is a gradual increase in the R_a for the intermediate T_{OFF} value and lower for higher and lower T_{OFF} value, as the T_{ON} value decreases the R_a value also decreases. And for the T_{ON} value ranging from 120 µs and T_{OFF} value 50 µs, the R_a value is a minimum (<1.60 µm).

Figure 5b depicts the effect of T_{ON} and *WF* on R_a when T_{OFF} and *WT* are held constant, for the T_{ON} value ranging from 122.5 µs to 126.5 µs and for the *WF* value ranging between 1 m/min and 1.25 m/min, the R_a value is a maximum (>2.00 µm), hence this condition should be avoided. As the T_{ON} value decreases and *WF* increases simultaneously the R_a value decreases. For the T_{ON} value of 120 µs and the *WF* range from 2.5 m/min to 3.0 m/min, the R_a value is a minimum (<1.7 µm). This is the ideal condition.

Figure 5c depicts the effect of T_{ON} and *WT* on R_a when T_{OFF} and *WF* are held constant, for the value of T_{ON} ranging from 122.5 µs to 128 µs and for *WT* value 5 N to 7 N, the R_a value is a maximum (>1.9 µm), for the T_{ON} rate 120 µs to 121.5 µs and *WT* values from 8.5 N to 9 N, the R_a value is a minimum (<1.4 µm). As the T_{ON} value decreases and *WT* value increases simultaneously, the R_a values decreases further for selected low T_{ON} value and high *WT* value the R_a value is found to be a minimum.

Figure 5d depicts the effect of T_{OFF} and *WF* on R_a when T_{ON} and *WT* are held constant, the R_a value is a maximum (>2.0 µm) for a T_{OFF} value of 50 µs to 53 µs and *WF* value above 2.5 m/min, i.e., in general it is clear that for minimum T_{OFF} value and maximum *WF* value the R_a is a maximum. For a T_{OFF} of more than 58 µs and *WF* value of 3.0 m/min, the R_a is minimum (<1.6 µm) and for the other values of T_{OFF} &*WF*, the R_a value is medium.

Figure 5e depicts the effect of T_{OFF} and *WT* on R_a when T_{ON} and *WF* are held constant, it is observed that for the T_{OFF} value ranging from 50 µs to 56 µs and *WT* value ranging from 5.5 N to 7.5 N, the R_a value is a maximum (>1.9 µm), the Surface Roughness will be in the extreme condition, and for T_{OFF} value exceeding 57.5 µs and *WT* value exceeding 8.7 N, the R_a value is a minimum (<1.4 µm). As the T_{OFF} and *WT* increases simultaneously the R_a value decreases.

Figure 5f depicts the effect of *WF* and *WT* on R_a when T_{ON} and T_{OFF} are held constant. When the *WF* ranges from 1 m/min to 1.75 m/min and *WT* values ranges from 5 N to 7.3 N, the R_a value is a maximum (>2.0 µm) the Surface Roughness will be in the excessive, which is an adverse condition. For the all values of *WF* and *WT* the value exceeding 8.8 N R_a is a minimum (<1.7 µm), as *WT* increases R_a decreases.

4.2 Simulation results obtained from the genetic algorithm

The equation obtained from RSM, i.e., Equation (3), is used for the minimization of R_a by using GA in MATLAB software to find the optimal selected variable process parameters for the best fit R_a values. Where T_{ON}, T_{OFF}, *WF* and *WT* are 4 variables, the population size selected for this simulation is 100, the Rank is set as the Fitness Scaling Function, Stochastic uniform is set as the Selection Function, the Reproduction elite count is 2, the Cross over probability is 0.8, the Cross over function is scattered, the Mutation probability is 0.05, the Initial penalty is 10, the Iteration is 100, the Number of generations is 100, and the Stopping criteria is Best Fitness.

The optimization function is formulated as

Minimize R_a (T_{ON}, T_{OFF}, *WF*, *WT*)

Subject to the following condition:

120 µs $\leq T_{ON} \geq$ 128 µs

50 µs $\leq T_{OFF} \geq$58 µs

1 m/min $\leq WF \geq$ 3 m/min

5 N $\leq WT \geq$ 9 N

Figure 6 depicts the best optimal solution for the Surface Roughness obtained in the simulation, for the input value of T_{ON} – 120 µs, T_{OFF}-58 µs, *WF*-3 m/min, *WT*-9 N the best fit Predicted R_a Value is 1.048 µm.

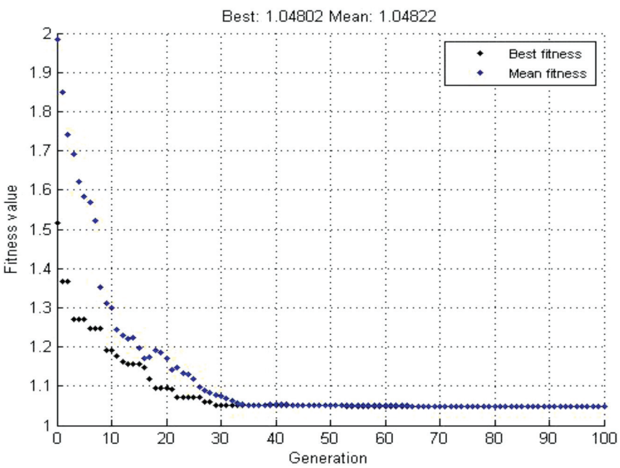

Figure 6: Predicted optimal solution of R_a using GA

4.3 Confirmation experiment

Confirmatory experiments carried out for the input value of T_{ON} 120 µs, T_{OFF} 58 µs, *WF* 3 m/min, *WT* 9 N and the experimental R_a value obtained is 1.08 µm and the error percentage between the predicted and experimental value is calculated as 3.05, which is less than 5 %. It confirms the excellent reproducibility of the results. **Table 7** indicates the error obtained.

Table 7: Comparison of the Optimized Process Parameter and its best fit R_a value

Sl. no.	Parameter	Values
1	Pulse On (T_{ON})	120 µs
2	Pulse Off (T_{OFF})	58 µs
3	Wire Feed (*WF*)	3 m/min
4	Wire Tension (*WT*)	9 N
Best Fit R_a Value (Predicted) µm	1.048	
Actual R_a Value (Experimental) µm	1.08	
Error %	3.05	

5 CONCLUSIONS

The present work elucidates the effect of variable WEDM process parameters while machining an Al 7075 alloy is investigated by using zinc-coated copper wire, a quadratic model for the Surface Roughness was developed, using RSM, to correlate the effects of the process parameters and the same is used in GA to establish the best fit R_a. Based on the results obtained the following conclusions were furnished for machining of an Al 7075 alloy using zinc-coated copper wire.

The best fit Surface Roughness value predicted is 1.048 μm for Pulse On (T_{ON}) value 120 μs, Pulse Off (T_{OFF}) value 58 μs, Wire Feed (*WF*) 3 m/min and for Wire Tension (*WT*) value 9 gm.

It is observed that for the increase in the Pulse On time, the Surface Roughness also increases.

The Surface Roughness decreases as the Pulse Off time increases.

The increase in the Wire Tension leads to a decrease of the Surface Roughness.

Wire Feed does not influence much on the Surface Roughness.

For the maximum value of Pulse Off (T_{OFF}), Wire Feed (*WF*), the Wire Tension (*WT*) and minimum Pulse On (T_{ON}) the Surface Roughness predicted is a minimum, which is the ideal condition for improving the quality of machined parts.

Furthermore, WEDM can be employed for machining an Al 7075 alloy with other coated and uncoated wires in order to compare the machined surfaces.

6 REFERENCES

[1] G. E. Totten, D. S. Mackenzie, Handbook of Aluminium [M]//Vol 1, Physical metallurgy and processes, Marcel Dekker, New York and Basel 2003

[2] J. Prohaszka, A. G. Mamalis, N. M. Vaxevanidis, The effect of electrode material on machinability in wire electro-discharge machining, J Mater Process Technol, 69 (**1997**) 233–237, doi:10.1007/s00170-016-9598-9

[3] R. Chalisgaonkar, J. Kumar, Investigation of the machining parameters and integrity of the work and wire surfaces after finish cut WEDM of commercially pure titanium, Brazilian Society Mechanical Science and Engineering (**2015**), doi:10.1007/s40430-015-0335-3

[4] B. Sivaraman, C. Eswaramoorthy, E. P. Shanmugham, Optimal control parameters of machining in CNC Wire-Cut EDM for Titanium, Int. Journal of Applied Sciences and Engineering Research, 4 (**2015**) 1, doi:10.6088/ijaser.04011

[5] G. Selvakumar, G. Sornalatha, S. Sarkar, S. Mitra, Experimental investigation and multi-objective optimization of wire electrical discharge machining (WEDM) of 5083 aluminum Alloy, Transaction of Nonferrous Metals Society of China 24 (**2014**) 373–379, doi:org/10.1016/S1003-6326(14)63071-5

[6] D. Siva Prasad, C. Shoba, K. Rahul Varma, A. Khurshid, Influence of wire EDM parameters on the damping behaviour of A 356.2 aluminum Alloy, Journal of Alloys and Compounds (**2015**), doi:10.1016/j.jallcom.2015.06.050

[7] A. Dey, S. Debnath, K. M. Pandey, Optimization of electrical discharge machining process parameters for Al6061/Cenosphere composite using grey-based hybrid approach, Transaction of Nonferrous Metals Society of China, 27 (**2017**), 998–1010, doi:10.1016/S1003-6326(17)60117-1

[8] K. H. Ho, S. T. Newman, S. Rahimifard, R. D. Allen, State of the art in wire electrical discharge machining (WEDM), International Journal of Machine Tools & Manufacture, 44 (**2004**), 1247–1259, doi:10.1016/j.ijmachtools.2004.04.017

[9] Shajan Kuriakose, M. S. Shunmugam, Multi-objective optimization of wire-electro discharge machining process by Non-Dominated Sorting Genetic Algorithm, Journal of Materials Processing Technology, 170 (**2005**), 133–141, doi:10.1016/j.jmatprotec.2005.04.105

[10] A. Sharma, M. Pal Garg, K. Kumar Goyal, Prediction of optimal conditions for WEDM of Al 6063/ ZrSiO4 (p) MMC, Procedia Materials Science, 6 (**2014**), 1024–1033, doi:10.1016/j.mspro.2014.07.173

[11] H. C. Tsai, B. H. Yan, F. H. Huang, EDM performance of Cr/Cu based composite electrodes, International Journal of Machine Tools & Manufacturing, 43 (**2003**) 3, 245–252, doi:10.1016/j.matpr.2015.07.328

[12] K. Shoda, Y. Kaneko, H. Nishimura, M. Kunieda, M. X. Fan, Adaptive control of WEDM with on-line detection of spark locations, Proc. of the Tenth International Symp. for Electro-Machining (ISEM-10), Magdeburg 1992

[13] M. Kunieda, H. Kojima, N. Kinoshita, On-line detection of EDM spark location by multiple connection of branched electric wires, Ann. CIRP 39 (1) (**1990**) 171–174, doi:10.1016/S0007-8506(07)61028-2

[14] T. Tanimura, C. J. Heuvelman, P. C. Vennstra, The properties of the servo gap sensor with wire spark-erosion machining, Ann. CIRP 26 (1) (**1977**) 59–63

[15] V. Chengal Reddy, N. Deepthi, N. Jayakrishna, Multiple response optimization of wire EDM on aluminium HE30 by using grey relational analysis, Materials Today: Proc. 2, 2015, 2548–2554, doi:10.1016/j.matpr.2015.07.201

[16] D. Thomas, R. Kumar, G. K. Singh, P. Sinha, S. Mishra, Modelling of surface roughness in coated wire electric discharge machining through response surface methodology, Materials Today: Proc. 2, 2015, 3520–3526, doi:10.1016/j.matpr.2015.07.091

[17] V. R. Surya, K. M. Vinay Kumar, R. Keshavamurthy, G. Ugrasen, H. V. Ravindra, Prediction of machining characteristics using artificial neural network in wire EDM of Al 7075 based in-situ composite, Materials Today: Proc. 4 (**2017**), 203–212, doi:10.1016/j.matpr.2017.01.014

[18] S. Prashantha, R. B. Veeresha, S. M. Shashidhara, U. S. Mallikarjun, A. G. Shivasiddaramaiah, A study on machining characteristics of Al 6061-Sic metal matrix composite through wire – cut electro discharge machining, Materials Today: Proc. 4 (**2017**), 10779–10785, doi:10.1016/j.matpr.2017.08.027

[19] S. Prasad Arikatla, K. TamilMannan, Arkanti Krishnaiah, Parametric optimization in wire electrical discharge machining of titanium alloy using response surface methodology, Materials Today: Proc. 4, (**2017**), 1434–1441, doi:10.1016/j matpr 2241-7853

[20] G. Amitesh & K. Jatinder, An investigation into the machining characteristics of NIMONIC 80A using CNC wire EDM, International Journal of Advanced Engineering Technology, 3 (**2012**) 1, 170–174

[21] M. T. Antar, S. L. Loo, D. K. Aspinwall, Productivity and work piece surface integrity when WEDM aerospace alloys using coated wires, Journal of Procedia engineering (**2011**)

[22] N. Kinoshita, M. Fukui, G. Gamo, Control of wire-EDM preventing electrode from breaking, Ann. CIRP 31 1 (**1982**), 111–114, doi:10.20965/ijat.2014.p0468