Proceedings of the
International Conference on Mechanical Engineering 2009
(ICME2009) 26- 28 December 2009, Dhaka, Bangladesh

ICME09-RT-24

PARAMETRIC OPTIMIZATION OF CNC WIRE CUT EDM USING GREY RELATIONAL ANALYSIS

B. C. Routara, B.K. Nanda, D.R.Patra

Department of Mechanical Engineering, KIIT University, Bhubaneswar, India

ABSTRACT

In this present study a multi response optimization method using Taguchi's robust design approach is proposed for wire electrical discharge machining (WEDM) operations. Experimentation was planned as per Taguchi's L9 orthogonal array. Each experiment has been performed under different cutting conditions of gap current (I), gap voltage (V), wire feed rate (W) and duty factor (D). Two responses namely material removal rate and surface roughness have been considered for each experiment. The machining parameters are optimized with the multi response characteristics of the material removal rate and surface roughness, using the grey relational analysis. Multi response S/N (MRSN) ratio was applied to measure the performance characteristics deviating from the actual value. Analysis of variance (ANOVA) is employed to identify the level of importance of the machining parameters on the multiple performance characteristics considered. Finally experimental confirmation was carried out to identify the effectiveness of this proposed method. A good improvement was obtained.

Keywords: CNC WEDM, Optimization, Surface Roughness, MRR, ANOVA.

1. INTRODUCTION

Wire cut EDM (electrical discharge machining) is an exceptionally precise, efficient and economical manufacturing route in many applications, allowing customers to design parts for optimum function, without the many restrictions of other metalworking processes. Wire cut EDM produces exceptionally precise, parallel sidewalls, allowing stacking when machining multiple parts from sheet material. Usually, the desired machining parameters are determined based on experience or handbook values. However, it does not ensure that the selected machining parameters result in optimal or near optimal machining performance for that particular electrical discharge machine and environment.

Lot of works is going on to increase the efficiency and the cost effectiveness of the WEDM process. As the process depends of different parameters it is very tedious task to analyze the effectiveness of all the parameter for the process. So, different techniques are used to analyze the parameters for better utilization of the process. The material removal rate (MRR) is an important indicator of the efficiency and cost-effectiveness of the process. Several experiments are conducted to consider effects of power, time-off, voltage, wire speed, wire tension, and rotational speed on the MRR (response). A Taguchi standard orthogonal array is chosen for the design of experiments. Analyses of variance (ANOVA) as well as regression analysis are performed on experimental data. The signal-to-noise (S/N) ratio analysis is employed to find the optimal condition [1].

The study of surface roughness (R_a), roundness and material removal rate (MRR) on the cylindrical wire electrical discharge turning (CWEDT) has been carried out on AISI D3 tool steel due to its growing range of applications in the field of manufacturing tools, dies and molds as punch, tapping, reaming and so on in cylindrical forms. This study was made only for the finishing stages and has been carried out on the influence of four design factors: power, voltage, pulse -off time and spindle rotational speed, over the three previous mentioned response variables. For MRR, Ra and roundness regression models have been developed by using the response surface methodology [2].

One of the main challenges in wire electrical discharge machining (WEDM) is avoiding wire breakage and unstable situations as both phenomena reduce process performance and can cause low quality components. The proposed methodology establishes the procedures to following in order to understand the causes of wire breakage and instability. In order to quantify the trend to instability of a given machining situation, a set of indicators related to discharge energy, ignition delay time, and peak current has been defined. Wire breakage risk associated to each situation is evaluated comparing the evolution of those indicators with some previously defined threshold values. The results of work used to develop a real-time control strategy for increasing the performance of the WEDM process [3-5].

A closed-loop wire tension control system for Micro-Wire-EDM is presented to guarantee a smooth wire transport and a constant tension value. In order to keep smooth wire transportation and avoid wire breakage during feeding, the reel roller is modified and the clip reel is removed from the wire transport mechanism. A genetic algorithm-based fuzzy logic controller is proposed to investigate the dynamic performance of the closed-loop wire tension control system [6].

The surface integrity generated in AISI 01 tool steel by wire electro-discharge machining, hard turning and production grinding is studied and compared. Production grinding generates compressive stresses at the surface, and a slight tensile peak, accompanied by a decreased in hardness beneath it. No structural changes are noticeable. Hard turning generates slight tensile stress in the surface, accompanied by an increase in hardness and in the amount of retained austenite [7].

The issues of machining speed and machined surface quality are interlinked in WEDM with respect to the fundamental mechanism of material removal at the scale of a single discharge. The removal of molten workpiece material is presently understood to be due to the implosion of the plasma channel, and it is estimated that indeed only about 10% of the molten material is actually removed from the parent material, due to inadequate ejection forces. Near dry EDM shows advantages over the dry EDM in higher material removal rate (MRR), sharper cutting edge, and less debris deposition. Compared to wet EDM, near dry EDM has higher material removal rate at low discharge energy and generates a smaller gap distance [8-10].

In order to obtain good surface roughness, the traditional circuit using low power for ignition is modified for machining as well. With the assistance of Taguchi quality design, ANOVA and F-test, machining voltage, current-limiting resistance, type of pulse-generating circuit and capacitance are identified as the significant parameters affecting the surface roughness in finishing process. In addition, it is found that a low conductivity of dielectric should be incorporated for the discharge spark to take place. The performance characteristics of the turning operations such as tool life, cutting force and surface roughness are improved together by using Taguchi method and grey relational analysis [11].

The present study aims at consideration of two response variable such as material removal rate and surface roughness in the machining of die steel on WEDM.

2. ANALYSIS OF TAGUCHI METHOD

According to the name of the developer, this method is called as Taguchi Method [12-13]. This method has been utilized widely in engineering analysis to optimize performance characteristics within the combination of design parameters. Taguchi technique is also a powerful tool for design of high quality systems. It introduces an integrated approach that is simple and efficient to find the best range of designs for quality, performance and computational cost. In this optimization technique, the process or product should be carried out in a three -stage approach such as system design, parameter design and tolerance design. System design reveals the usages of scientific and engineering information required for producing a part. This design includes the product design stage and process design stage. The parameter design is used to obtain the optimum levels of process parameters for developing the quality characteristics and to determine the product parameters values depending optimum process parameter values. In addition, it is expected that the optimal process parameter values obtained from parameter design are insensitive to variation in the environmental conditions and other noise factors. Therefore, the parameter design has the key role in the Taguchi method to achieve high quality without increasing the cost factor. Lastly, the tolerance design is employed to determine and to analyze tolerances about the optimum combinations suggested by parameter design. Tolerance design is required if the reduced variation obtained by the parameter design does not reach the required performance.

The experimental design methods, which were developed by Fisher having some complexity and not easy to use and another important thing is that, whenever the number of process parameters increases, a large number of experiments have to be carried out. To eliminate such problems, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. After obtaining the experimental results, these values transformed into a signal - to- noise ratio.

Taguchi offers the use of the signal-to-noise (S/N) ratio to identify the quality characteristics applied for engineering design problems. The S/N ratio characteristics can be divided into three categories such as the smaller- the- better; nominal –the- better and larger the better. The S/N ratio for each level of process parameter is calculated based on the S/N analysis. Irrespective of the category of quality characteristic, a greater S/N ratio seems to be better quality characteristics. Here, it is suggested that the optimal level of process parameters is the level with the greatest S/N ratio. A statistical analysis of variance (ANOVA) can be utilized to verify the influences of the process parameters on surface roughness. With S/N ratio and ANOVA analysis the optimal combinations of process parameters are predicted. Lastly, a verification test is conducted to verify the optimal process parameters obtained from the parameter design.

3. EXPERIMENTAL DETAILS

3.1 Selection Of Process Parameters

In the present study the following parameters are selected as the control factors in the WCEDM machining: Gap current (I),Gap voltage (V),Wire feed rate (W) and Duty factor (D) is the ratio of pulse on time (T_{on}) and pulse off time (T_{off})

3.2 Design of Experiment

In this study, an L_9 orthogonal array has been used. The experimental layout for the four cutting parameters using L_9 orthogonal array is shown in Table .1

Table1: Experimental layout using L $_9$ OA

Expt. No	Gap Volt (V)	Wire feed Rate (W)	Gap Current (I)	Duty factor (D)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The process variables with their values on different levels are listed in the Table 2. The selection of the values of the variables is limited by the capacity of the machine used in the experimentation as well as recommended specification. The experimental results along with process variables levels are shown in Table 3.

Table 2: Process variable values with different levels

Machining parameter	**Level1**	**Level 2**	**Level 3**
Gap current (amp)	10	15	18
Gap voltage (volt)	20	30	40
Wire feed Rate (mm/min)	90	100	130
Duty factor	4	6	9

Table 3: Experimental results for material removal rate (MRR) and Surface roughness (SR)

Expt. No	**(V)**	**(W)**	**(I)**	**(D)**	**MRR**	**SR**
1	20	90	10	4	3.26	1.13
2	20	100	15	6	3.50	1.87
3	20	130	18	9	4.06	0.73
4	30	90	15	9	3.60	0.83
5	30	100	18	4	4.80	1.90
6	30	130	10	6	4.16	2.25
7	40	90	18	6	4.93	1.06
8	40	100	10	9	5.60	2.39
9	40	130	15	4	5.94	2.56

3.2 Wedm Machined Used

All the experiments are conducted in a CNC Wire cut EDM (AGIECUT 220) of Switzerland make. The schematic diagram of WEDM is given in the Fig.1.

3.3 Workpiece Used

High carbon medium chromium die steel (AISI A7) is used as work piece material for experimentation. The hardness of work piece material was measured on "Rockwell hardness tester" and found to be 56.4 HRC. Composition of work piece material: C 2.8%, Cr 5.25%, Mo1.1%, Si 0.3%, V 4.5%, Mn 0.7% and balance Fe 85.35%.

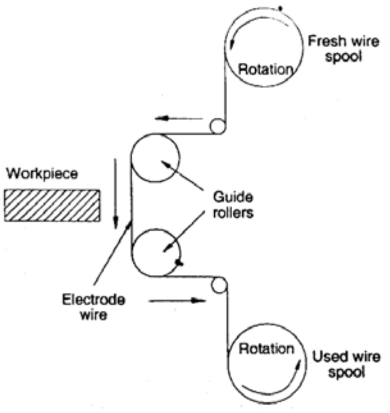

Fig 1. Schematic diagram of WEDM machine

3.4 Tool Electrode Used

A wire electrode is required to have a sufficient tensile strength and should be of uniform diameter of 0.25 mm. The electrode wire material is brass with tensile strength more than 45 Kgf / mm^2.

3.5 Surface Roughness Measurement

Surface roughness measurement was done using a portable stylus-type profilometer (Taylor Hobson, Surtronic- 25). The profilometer was set to a cut-off length of 0.8 mm and 4mm evaluation length. The least count of the profilometer is 0.01 micron.

3.6 Material Removal Rate (Mrr) Measurement

The material removal rate of the workpiece can be calculated by using the following relations and listed in the Table 3.The width of cut calculated from the relation,

$b= 2W_g+d$

where W_g is spark gap, d is diameter of wire and
b is width of cut
The material removal rate calculated by using the equation (1)
$MRR= Vc \times b \times h$ mm^3/min
Where Vc = cutting speed, b= width of cut mm
h=height of work-piece 10mm for all 9 experiments
Here the wire diameter is taken as 0.25mm

3.7 Grey Relational Analysis For The Experimental Results

In the grey relational analysis, the experimental results are first normalized in the range between zero and unity. This process of normalization is called the grey relational generation. After then, the grey relational coefficient is calculated from the normalized experimental data to express the relationship between the desired and actual experimental data. Then, the overall grey relational grade is calculated by averaging the grey relational coefficient corresponding to each selected process response. The overall evaluation of the multiple process responses is based on the grey relational grade.

This method converts a multiple response process optimization problem into a single response optimization problem with the objective function of overall grey relational grade. The corresponding level of parametric combination with highest grey relational grade is considered as the optimum process parameter [11].

In this grey relational analysis, the normalized data processing for surface roughness corresponding to lower- the-better criterion can be expressed as

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \qquad (1)$$

Similarly, the normalized data processing for MRR corresponding to larger-the-better criterion can be expressed as

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \qquad (2)$$

where $x_i(k)$ is the value after the grey relational generation, min $y_i(k)$ is the smallest value of $y_i(k)$ for the kth response, and the max $y_i(k)$ is the largest value of the $y_i(k)$ for the *kth* response. The normalized data processing, after grey relational generation is tabulated in the Table. 4. An ideal sequence is $x_0(k)$ where (k=1 & 2 for surface roughness and MRR). The definition of grey relational grade in the course of grey relational analysis is to reveal the relational degree between the nine sequences [$x_0(k)$ and $x_i(k)$, i=1,2,….9].The grey relational coefficient $\xi_i(k)$ can be calculated as

$$\xi_i(k) = \frac{\Delta_{\min} + \xi\,\Delta_{\max}}{\Delta_{oi}(k) + \xi\,\Delta_{\max}} \qquad (3)$$

where Δ_{0i} = $\|x_o(k) - x_i(k)\|$ =difference of the absolute value between $x_0(k)$ and $x_i(k)$; ξ =distinguishing coefficient in between zero and one.

$\Delta_{\min} = \forall j^{\min} \in i \forall k^{\min} \|x_o(k) - xj(k)\|$ = the smallest value of Δ_{0i} ;

and $\Delta_{\max} = \forall j^{\max} \in i \forall k^{\max} \|x_o(k) - xj(k)\|$ =largest value of Δ_{0i} .The grey relational coefficient results for the experimental data are shown in the Table 5.

After averaging the grey relational coefficients, the grey relational grade γ_i can be calculated as follows

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k)$$

where n = number of process responses. Table 6 shows the experimental results for the grey relational grade. The higher the value of grey relational grade considered as the stronger relational degree between the ideal sequence $x_0(k)$ and the given sequence $x_i(k)$. Earlier it has mentioned, the ideal sequence $x_0(k)$ is the best process response in the experimental layout. Here, it may conclude, the higher relational grade means that the corresponding parameter combination is closer to the optimal.

Table 4: Data processing of each performance characteristic (Grey relational generation)

Exp. No	MRR	SR
Ideal Sequence	1	1
1	0.000000	0.781421
2	0.089552	0.377049
3	0.298507	1.000000
4	0.126866	0.945355
5	0.574627	0.360656
6	0.335821	0.169399
7	0.623134	0.819672
8	0.873134	0.092896
9	1.000000	0.000000

Table 5: Grey relational coefficient of each performance characteristics (with ψ= 0.5)

Exp. No	MRR	SR
Ideal Sequence	1	1
1	0.333333	0.695817
2	0.354497	0.445255
3	0.416149	1.000000
4	0.364130	0.901478
5	0.540323	0.438849
6	0.429487	0.375770
7	0.570213	0.734940
8	0.797619	0.355340
9	1.000000	0.333333

Then, the grey relational grade that is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the grey relational grade. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. In other words, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. The grey relational grade is shown in the Table 6.

Table 6: Grey relational grade of performance characteristic

Exp. No	Grade
1	0.514575
2	0.399876
3	0.708075
4	0.232804
5	0.489586
6	0.402629
7	0.652576
8	0.576479
9	0.666667

3.8. Analysis of Variance

The purpose of the analysis of variance (ANOVA) is to investigate which machining parameters significantly affect the performance characteristic. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each machining parameter and the error. First, the total sum of the squared deviations SS_T from the total mean of the grey relational grade γ_m can be calculated as:

$$SS_T = \sum_{j=1}^{p} (\gamma_j - \gamma_m)^2 \tag{4}$$

Where p is the number of experiments in the orthogonal array and γ_j is the mean of the grey relational grade for j_{th} experiment.

The total sum of the squared deviations SS_T is decomposed into two sources: the sum of the squared deviations SS_d due to each machining parameter and the sum of the squared error SS_e. The percentage contribution by each of the machining parameter in the total sum of the squared deviations SS_T can be used to evaluate the importance of the machining parameter change on the performance characteristic. In addition, the Fisher's *F*-test can also be used to determine which machining parameters have a significant effect on the performance characteristic. Usually, the change of the machining parameter has a significant effect on the performance characteristic when *F* is large is shown in Table 8. It is found that gap voltage and current are the significant one where as the wire feed rate is not significant as the *P* value for wire feed rate is more than 0.05.

Table 7: Mean response table of grey relational grade

Level	V	W	I	D
1	0.540	0.466	0.497	0.556
2	0.375	0.488	0.433	0.485
3	0.631	0.592	0.616	0.505
Max -min	0.256	0.125	0.183	0.071
Rank	1	3	2	4

In the grey relational grade graph, it is clearly mentioned that third level voltage, third level wire feed rate, third level of current and first level of duty factor($V_3W_3I_3D_1$) are the optimal combination of process parameters for multiple performance characteristics.

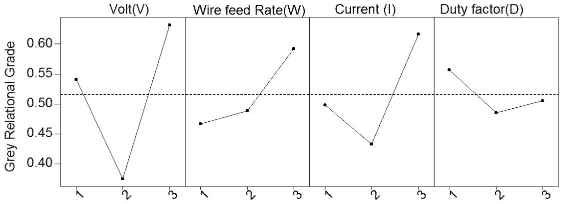

Fig 2 Grey relational grade graph of multiple performance characteristics

4. CONFIRMATION TESTS

Once the optimal level of the machining parameters is selected, the final step is to predict and verify the improvement of the performance characteristic using the optimal level of the machining parameters.

Table 8: ANOVA for grey relational grade

Source	DF	Adj SS	Adj MS	F	P
Volt(V)	2	0.101	0.050	12.38	0.025
Current	2	0.052	0.026	6.33	0.046
Wire feed rate	2	0.027	0.013	3.3	0.233
Error	2	0.008	0.004		
Total	8				

Table 9: Results of the confirmation experiment

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Setting Level	$V_1W_1I_1D_1$	$V_3W_3I_3D_1$	$V_3W_3I_3D_1$
Surface roughness	1.13		1.11
Material removal rate	3.26		4.96
Grey relational grade	0.5145	0.5524	0.6420

Improvement of grey relational grade =0.1275

The estimated grey relational grade $\hat{\gamma}$ using the optimal level of the machining parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\bar{\gamma} - \gamma_m) \tag{5}$$

where γ_m is the total mean of the grey relational grade, j_i is the mean of the grey relational grade at the optimal level, and q is the number of the machining parameters that significantly affects the multiple performance characteristics.

Table 9 shows the comparison of the predicted grey relational grade with the experimented grey relational grade using the optimal process parameter combinations and found that a good agreement between the predicted and actual grey relational grade. The increase of grey relational grade from initial factor setting to the optimal process parameter setting is of 0.1275. Here, it may conclude that the multiple performance characteristic of the WEDM process such as material removal rate and surface finish are improved together by using this approach.

5. CONCLUSION

The use of the orthogonal array with grey relational analysis to optimize the WEDM process with the multiple performance characteristics has been reported here. A grey relational analysis of the experimental results of material removal rate and surface roughness can convert optimization of a single performance characteristic called the grey relational grade. As a result, optimization of the complicated multiple performance characteristics can be greatly simplified through this approach. It is shown that the performance characteristics of the WEDM process such as material removal rate, surface roughness are improved together by using this study.

6. REFERENCES

1. Mohammadi, A, Tehrani, A.F., Emanian, E. and Karimi, D., 2008, “Statistical analysis of wire electrical discharge turning on material removal rate”, Journal of materials processing Technology, 205:283-289.
2. Haddad, M.J, and Tehrani, A.F., 2008, “Investigation of cylindrical wire electrical discharge turning (CWEDT) of AISI D3 tool steel based on statistical analysis”, Journal of materials processing Technology, 198:77-85.
3. . Haddad, M. J, and Tehrani, A.F., 2008, “Material Removal rate (MRR) study in the cylindrical wire electrical discharge turning (CWEDT) process”, Journal of Materials Processing Technology, 199:369-378.
4. Cabanes, I., Portillo, E., Marcos’s, M. and Sanchez, J.A., 2008, “An industrial application for on-line detection of instability and wire breakage in wire EDM”, Journal of Materials Processing Technology, 195:101-109.
5. Shinji I., Kushiya, M., Nakashima, T. and Sugihara, K., 2008, “Generation of cutter paths for hard material in wire EDM”, Journal of Materials processing technology, 206:453-461.
6. Yan, M.T, and Fang, C., 2008, “Application of genetic algorithm-based fuzzy logic control in wire transport system of wire-EDM machine”, Journal of Materials Processing Technology, 205:128-137.
7. Lauwers, B., Brans, K., Liu, W., Vleugels, J., Salehi, S. and K. Vanmeensel, 2008, “Influence of the type and grain size of the electro-conductive phase on the Wire-EDM performance of ZrO_2 Ceramic Composites”, CIRP Annals- Manufacturing Technology, 57:191-194.
8. K. H. Ho, Newman, S.T., Rahimifard, S., Allen, R.D., 2004, “State of the art in wire electrical discharge machining (WEDM)” Int. J. Machine Tools Manuf., 44:1247-1259.
9. Kao, C. C., Jia Tao and Shih, A.J., 2007, “Near dry electrical discharge machining”. International Journal of Machine Tools & Manufacture, 47:2273-2281.
10. Liao, Y.S., Huang, J.T. and Chen, Y.H., 2004, “A Study to achieve a fine surface finish in Wire –EDM”. Journal of materials processing Technology, 149:165-171.
11. Lin, J.L. and Lin, C.L., 2002, “The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics”, International Journal of machine Tools & Manufacture 42, pp.237-244.
12. Phadke, M. S., 1989, “Quality Engineering using Robust Design”, Prentice Hall international, Inc.
13. Montegomery. D. C., 1991, Design and Analysis of experiments, Wiley, India.

7. MAILING ADDRESS

B. C. Routara
Department of Mechanical Engineering,
KIIT University, Bhubaneswar-751024
E-mail: bharat_routray@rediffmail.com