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OPTIMIZATION OF THE DIE-SINKING MICRO-EDM PROCESS FOR MULTIPLE PERFORMANCE CHARACTERISTICS USING THE TAGUCHI-BASED GREY RELATIONAL ANALYSIS

OPTIMIRANJE MIKRO-EDM-POSTOPKA POGREZANJA ORODJA ZA DOLOČANJE VEČ ZNAČILNOSTI Z UPORABO TAGUCHIJEVE SIVE RELACIJSKE ANALIZE

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In modern industries, the expectation is to manufacture high-quality products with a low cost within a short duration. In order to produce any product with a desired quality by machining, the influence of various parameters such as the material-removal rate (MRR), the tool-wear ratio (TWR) and the surface roughness (R_a) should be considered. This paper presents the methodology of the Taguchi method and grey relational analysis to find the optimum parameters for obtaining a higher MRR, a lower TWR and the minimum surface roughness in the die-sinking micro-EDM process. The experiments were carried out as per L_{16} orthogonal array with each experiment performed under different conditions of the gap voltage, capacitance, feed rate and threshold. Additionally, an analysis of variance (ANOVA) was also applied to identify the most significant factor. The capacitance and the gap voltage were found to be the most significant controlled factors influencing the performance of the machining process.

Keywords: micro-EDM, optimization, Taguchi method, ANOVA, grey relational analysis

Od moderne proizvodnje se pričakuje hitra izdelava kvalitetnih proizvodov z majhnimi stroški. Da bi s struženjem izdelali izdelek z želeno kvaliteto, je treba upoštevati vplive različnih parametrov, kot so hitrost odrezavanja materiala (MRR), hitrost obrabe orodja (TWR) in hrapavost površine (R_a). V tem članku je predstavljena metodologija Taguchijeve metode in sive relacijske analize za iskanje optimalnih parametrov za povečanje MRR, zmanjšanje TWR in minimalno hrapavost površine pri mikro-EDM-postopku pogrezanja orodja. Eksperimenti so bili izvršeni za pravokotno matriko L_{16}, pri čemer je bil vsak eksperiment izvršen pri različnih razmerah voltaže razmika, kapacitivnosti, hitrostih odvzemanja in mejnih vrednostih. Dodatno je bila uporabljena analiza variance (ANOVA) za ugotovitev najpomembnejšega faktorja. Ugotovljeno je bilo, da sta kapacitivnost in voltaža razmika najpomembnejša kontrolna faktorja, ki vplivata na uspešnost procesa obdelave.

Ključne besede: mikro-EDM, optimiranje, Taguchijeva metoda, ANOVA, siva relacijska analiza

1 INTRODUCTION

Several researchers focussed their efforts on producing micro-components and micro-systems to meet the industrial demand for miniaturisation. When producing micro-components, it is critical to achieve high form accuracy and precise dimensions. However, it is a challenge to produce complex micro-components such as micro-dies made of high-hardness materials using conventional machining methods such as micro-milling or micro-turning. This problem can be resolved with one of the methods, such as the micro-EDM. The advantage of this method is that the machining process is independent of the hardness of the workpiece. In fact, high-hardness materials are better candidates for electrical-discharge machining. Therefore, it has become one of the most important methods for machining micro- and sub-micro-components of hard, electrically conducting materials. In order to use the micro-EDM in the industries more effectively, many researchers all over the world have initiated research works to overcome all the parameters that influence the performance of the machining process.

The material-removal rate (MRR), the tool-wear ratio (TWR) and the surface roughness (SR) are the important parameters to be considered to obtain the desired machining-performance characteristics during the micro-EDM process. The gap voltage, capacitance, feed rate and threshold are the machining parameters affecting the performance measures. Among the other performance measures, the TWR and the surface roughness determining the dimensional accuracy of a machined part, the MRR determining the economics of machining and the rate of production are of the utmost importance.

The Taguchi method has been widely used in the engineering analysis, being a powerful tool to design a high-quality system. Moreover, the Taguchi method employs a special design of orthogonal array to investigate the effects of all the machining parameters through a small number of experiments. Recently, the Taguchi method was widely employed in several industrial fields and research works. Lin et al.[1] adapted the Taguchi method to obtain the optimum machining parameter of the electrical-discharge-machining process. Prihandana et al.[2] used the Taguchi method to identify the optimum process parameters to increase the material-removal rate of a dielectric fluid containing a micro-powder in the micro-EDM using the L_{18} orthogonal array. Tosun et al.[3] used the Taguchi method to explore the effects of the MRR and the kerf of the wire-electrical-discharge machining. Their works revealed that the Taguchi method was a powerful approach used in designing an experiment. However, the Taguchi method can be used to optimize only single performance characteristics. Hence, in order to optimize any multiple performance characteristics, the researchers found the grey relational analysis to be a suitable theory.

Somashekhar et al.[4] used a new approach for the optimization of the micro-WEDM process with multiple performance characteristics based on the statistical-based analysis of variance (ANOVA) with the grey relational analysis. Chiang and Chang[5] applied the grey relational analysis to optimize the WEDM process with multiple performance characteristics such as the MRR and the maximum surface roughness.

The Taguchi method coupled with the grey relational analysis has a wide area of application in manufacturing processes as it can solve multi-response optimization problems.[6,7] Natarajan and Arunachalam[8] presented the optimization of multiple performance characteristics using the Taguchi method and grey relational analysis. With this analysis, the optimum parameters in the EDM of the 304 stainless steel were identified and the improvements in the performance characteristics were found using the grey relational analysis. Vijay Kumar Meena and Man Singh Azad[9] studied the effect of the input and output parameters of a micro-EDMed Ti-6Al-V alloy with a tungsten carbide electrode. They employed the grey relational analysis of variance to optimize the levels of input parameters and found that the MRR, the TWR and the overcut can be improved. Rajyalakshmi and Venkata Ramaiah[10] utilized the grey-Taguchi technique as a multi-objective optimizer to identify the machining parameters of Inconel 825 in the WEDM process. It has been concluded that the grey-Taguchi method is suitable for a parametric optimization of multiple performance characteristics.

Jung and Kwon[11] also employed the Taguchi method and grey relational analysis to find the optimum machining parameters to satisfy the multiple characteristics of the EDM process. Shen et al.[12] determined the optimum combination of the process parameters during the EDM process of 1Cr17Ni7 using Cu as the electrode based on the performance characteristics such as the material-removal rate, the tool-wear rate and the surface roughness. Muthu Kumar et al.[13] identified the optimum levels of the parameters with the grey relational analysis and the percentage contribution of all the parameters with ANOVA to study the optimization of machining parameters. In this paper, to solve the multiple-performance-characteristics problem of the micro-EDMed EN-24 die steel, the Taguchi-based grey relational analysis was used.

2 EXPERIMENTAL PROCEDURE

Experiments were conducted on the CNC micro-electrical-discharge machine (die-sinking type) of a DT-110-model multi-process micro-machining tool. The workpiece material used in this study was EN-24 die steel, widely used in the tool and die industry. EN-24 die steel is a high-quality alloy steel. Silver tungsten (AgW) with the diameter of 300 µm was used as an electrode. The dielectric used in this study was the EDM oil3. A micro-electrical-discharge machine with an RC-type pulse generator was used to obtain a quality micro-hole in the EN-24 die steel.

Experiments were conducted using the L_{16} orthogonal array, in which the parameters such as the gap voltage, the capacitance, the threshold and the feed rate were varied at four levels, with the level four being the highest value of the process variable. The machining parameters and their levels are highlighted in **Table 1**.

Table 1: Machining parameters and their levels for die-sinking micro-EDM

Tabela 1: Parametri obdelave in njihove vrednosti pri mikro-EDM poglabljanju orodja

Parameters	Level1	Level2	Level 3	Level 4
Gap voltage (V)	80	100	120	140
Capacitance (nF)	0.1	1.0	10	100
Feed rate (µm/s)	2	4	6	8
Threshold (%)	20	40	60	80

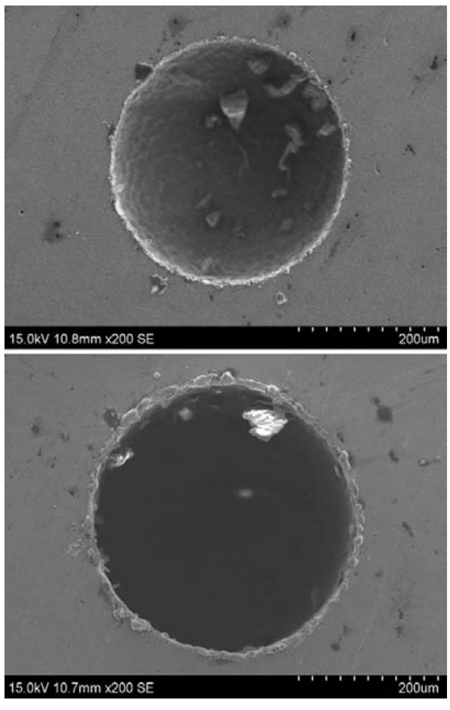

Figure 1: SEM image of a micro-hole on the workpiece

Slika 1: SEM-posnetek mikroluknje na obdelovancu

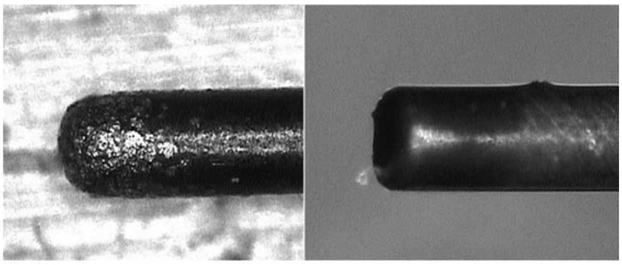

Figure 2: VMS image of the electrode after machining
Slika 2: VMS-posnetek elektrode po obdelovanju

The material-removal rate for the micro-EDM process can be calculated by dividing the total volume of the material removed by the total machining time. Assuming a nil diametral wear of the electrode, the MRR is calculated on the basis of the effective depth of the hole, divided by the respective time. The effective depth of the hole is calculated on the basis of the difference between the depth shown on the monitor of the machine and the difference between the electrode lengths before and after the machining, which can be measured using the video-measuring system (VMS). The wear ratio is defined as the ratio of the amount of the electrode to the amount of the workpiece removed. One of the most difficult output parameters to be calculated is the tool-wear ratio in the micro-EDM process. There are four methods used to measure the tool-wear ratio by means of measuring the weight, the length, the shape and the total volume, respectively.

In this study, the tool-wear ratio was calculated on the basis of the total volume. The average surface roughness (R_a) was measured using a non-contact Talysurf CCI 3000A. **Figure 1** shows a SEM (scanning electron microscope) image of a machined micro-hole and **Figure 2** shows a VMS image of the electrode after machining.

3 DESIGN AND PLAN OF THE EXPERIMENTS

To evaluate the effects of the machining parameters on the performance characteristics, a specially designed experimental procedure is required. Classical experimental-design methods are too complex and difficult to use. Additionally, a large number of experiments has to be carried out when the number of machining parameters increases.[14,15] In this study, the Taguchi method, a powerful tool for the parameter design of performance characteristics, was used to determine the optimum machining parameters for the maximum MRR, the minimum TWR and a lower surface roughness in the die-sinking micro-EDM. The methodology of Taguchi for four factors at four levels was used for the implementation of the plan of the experiments. According to the Taguchi quality-design concept, a L_{16} orthogonal-array table with 16 rows (corresponding to the number of experiments) was chosen for the experiments. The optimization of the observed values was then determined through a comparison with the Taguchi signal-to-noise (*S/N*) ratio. The calculation of the value of ANOVA with the use of the full factorial design (4 × 4 × 4 × 4) reduced the total of 256 sets of the experiments down to 16, thereby decreasing the cost, time and effort.

Data pre-processing is a process of transferring the original sequence to a comparable sequence. Hence, the experimental results are normalized in the range between zero and one. Based on the characteristics of the data sequence, various methodologies are available for data pre-processing.[16] Therefore, a linear normalization of the experimental results for the MRR, the TWR and the surface roughness were performed.

3.1 Analysis of the Taguchi method

The *S/N* ratio based on the larger-the-better criterion for the overall grey relational grade was calculated using the following equation:

$$\frac{S}{N} = -10 lg \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \tag{1}$$

The *S/N* ratio based on the smaller-the-better criterion for the overall grey relational grade was calculated by using the following equation:

$$\frac{S}{N} = -10 lg \frac{1}{n} \sum_{i=1}^{n} y_i^2 \tag{2}$$

Thus, the *S/N* ratio is considered to evaluate the effect of the machining parameters on the MRR, the TWR and the SR.

3.2 Grey relational analysis (GRA)

The grey relational analysis is a widely used analyzing system even when a model is uncertain or the information is incomplete. It provides an efficient solution to complicated interrelationships among multiple performance characteristics.[17] Based on the normalized experimental data, the grey relational coefficient is calculated representing the correlation between the desired and actual experimental data. Then, the overall grey relational grade is determined by averaging the grey relational coefficient corresponding to the selected responses. The overall performance characteristics of the multiple response process depends on the calculated grey relational grade.[18,19] In the grey relational analysis, the normalized MRR value corresponding to the larger-the-better (LB) criterion can be calculated using:

$$x_i\,(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{3}$$

and the normalized TWR and SR values corresponding to the smaller-the-better (SB) criterion can be calculated using:

$$x_i\,(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{4}$$

where x_i (k) is the value after the grey relational generation, min x_i (k) is the smallest value of x_i (k) for the k^{th} response, and max x_i (k) is the largest value of x_i (k) for the k^{th} response.

The grey relational coefficient ($\xi_i(k)$) for the normalized *S/N* ratio values is computed using:

$$\xi_i(k)=\frac{\Delta_{min}+\xi\Delta_{max}}{\Delta_{oi}(k)+\xi\Delta_{max}} \quad (5)$$

where Δ is the absolute difference, Δ_{oi} (k) = $\|x_o$ (k) – $i(k)\|$ is the difference in the absolute values between $x_o(k)$ and $x_i(k)$, ξ is the distinguishing coefficient (0–1), Δ_{min} is the smallest value of Δ_{oi} and Δ_{max} is the largest value of Δ_{oi}. After averaging the grey relational coefficients, the grey relational grade γ_i can be obtained:

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (6)$$

where n is the number of the process responses.

4 RESULTS AND DISCUSSION

The plan of the tests was developed with the aim of determining the effects of the gap voltage, the capacitance, the feed rate and the threshold. The values calculated using all the equations generated were compared with the experimental measurements to identify the optimum parameters. This study shows that the Taguchi method with the grey relational analysis can be extensively used to determine the optimum parameters in the micro-EDM process with multiple performance characteristics.

Initially, by using equations 1 and 2, the *S/N* ratio was calculated on the basis of the experimental data. **Table 2** lists the experimental results and the *S/N* ratios of the MRR, the TWR and the SR correlated with each experimental measurement for the die-sinking micro-EDM from the L_{16} orthogonal array based on the Taguchi method.

By using equations 3 and 4, the *S/N* ratio values were normalized to obtain the grey relational grade. The normalized data and derivative sequence Δ_{oi} for each of the responses are presented in **Table 3**. The grey relational coefficients, given in **Table 3**, for each response were calculated by using equation 5. **Table 3** also shows the overall grey relational grade calculated using equation 6. Thus, the multi-criteria optimization problem was transformed into a single equivalent objective-function-optimization problem using the combination of the Taguchi approach and grey relational analyses. It is maintained that the higher the value of the grey relational grade, the closer to the optimum is the corresponding factor combination.[20]

The higher GRG highlighted in **Table 3** shows that the corresponding experimental results are closer to the ideally normalized value. Experiment 5 has the best multiple performance characteristics among 16 experiments as it has the highest GRG. In this study, the optimization of the multiple performance characteristics of the micro-EDM of EN-24 die steel was converted into an optimization of the GRG. The mean of the GRG for each level of the machining parameters and also the total mean of the GRG for 16 experiments are calculated in **Table 4**. Usually, the larger is the GRG, the closer will the product quality be to the ideal value. Hence, a large GRG is desired for an optimum performance. Therefore, the optimum-parameter setting, highlighted in **Table 4**, for a better MRR and lower TWR and SR is $A_2B_1C_4D_3$. The optimum level of the process parameters is the level with the highest GRG. **Figure 3** shows the grey-rela-

Table 2: Experimental layout using the L_{16} orthogonal array and the performance results
Tabela 2: Eksperimentalna postavitev z L_{16} pravokotno matriko in uspešnost rezultatov

Exp. No	Level of parameter				Experimental result			*S/N* ratio (dB)		
	Gap voltage (V)	Capacitance (nF)	Feed rate (μm/s)	Threshold (%)	MRR (mm³/s)	TWR (%)	SR (μm)	MRR	TWR	SR
1	80	0.1	2	20	0.00025	13.42	0.087	–72.03	–22.55	21.21
2	80	1	4	40	0.000555	14.01	0.098	–65.11	–22.93	20.18
3	80	10	6	60	0.000555	18.29	0.113	–65.11	–25.24	18.94
4	80	100	8	80	0.000527	16.70	0.107	–65.57	–24.45	19.41
5	100	0.1	4	60	0.001271	14.06	0.094	–57.92	–22.96	20.54
6	100	1	2	80	0.000533	17.03	0.101	–65.47	–24.62	19.91
7	100	10	8	20	8.86E–05	18.31	0.126	–81.05	–25.25	17.99
8	100	100	6	40	0.000478	14.16	0.117	–66.42	–23.02	18.64
9	120	0.1	6	80	9.22E–05	16.36	0.102	–80.70	–24.27	19.83
10	120	1	8	60	0.000939	16.12	0.116	–60.55	–24.15	18.71
11	120	10	2	40	0.000202	21.50	0.132	–73.89	–26.65	17.59
12	120	100	4	20	0.000894	13.22	0.136	–60.97	–22.42	17.33
13	140	0.1	8	40	0.001335	15.81	0.112	–57.49	–23.98	19.02
14	140	1	6	20	0.001249	13.49	0.139	–58.07	–22.60	17.14
15	140	10	4	80	9.87E–05	16.97	0.163	–80.11	–24.59	15.76
16	140	100	2	60	0.000516	17.85	0.161	–65.75	–25.03	15.86

Table 3: Experimental results using the grey relational analysis
Tabela 3: Rezultati eksperimentov s sivo relacijsko analizo

Exp. No.	Normalized *S/N* ratio			Derivation sequence Δ_{oi}			Grey relational coefficient GC_{ij}			Grey relational grade γ_i
	MRR	TWR	SR	MRR	TWR	SR	MRR	TWR	SR	
1	0.3827	0.9697	1	0.6173	0.0303	0	0.4475	0.9429	1	0.7968
2	0.6765	0.8804	0.8104	0.3235	0.1196	0.1896	0.6071	0.8069	0.7250	0.7130
3	0.6765	0.3326	0.5835	0.3235	0.6674	0.4165	0.6071	0.4283	0.5456	0.5270
4	0.6571	0.5199	0.6704	0.3429	0.4801	0.3296	0.5932	0.5101	0.6027	0.5687
5	0.9818	0.8736	0.8767	0.0182	0.1264	0.1233	0.9649	0.7982	0.8022	0.8551
6	0.6612	0.4792	0.7623	0.3388	0.5208	0.2377	0.5961	0.4898	0.6778	0.5879
7	0.0000	0.3302	0.4101	1.0000	0.6698	0.5899	0.3333	0.4274	0.4588	0.4065
8	0.6210	0.8595	0.5281	0.3790	0.1405	0.4719	0.5689	0.7806	0.5145	0.6213
9	0.0148	0.5620	0.7466	0.9852	0.4380	0.2534	0.3366	0.5331	0.6637	0.5111
10	0.8703	0.5923	0.5418	0.1297	0.4077	0.4582	0.7940	0.5508	0.5218	0.6222
11	0.3039	0.0000	0.3360	0.6961	1.0000	0.6640	0.4180	0.3333	0.4295	0.3936
12	0.8523	1.0000	0.2884	0.1477	0.0000	0.7116	0.7720	1.0000	0.4127	0.7282
13	1.0000	0.6325	0.5977	0.0000	0.3675	0.4023	1.0000	0.5764	0.5541	0.7102
14	0.9754	0.9591	0.2537	0.0246	0.0409	0.7463	0.9530	0.9245	0.4012	0.7596
15	0.0397	0.4863	0	0.9603	0.5137	1	0.3424	0.4933	0.3333	0.3897
16	0.6494	0.3822	0.0197	0.3506	0.6178	0.9803	0.5878	0.4473	0.3378	0.4576

Table 4: Response table for the grey relational grade (GRG)
Tabela 4: Tabela odgovorov za sive relacijske stopnje (GRG)

	Grey relational grade					Rank (Max–Min)
Symbol	Parameter	Level 1	Level 2	Level 3	Level 4	
A	Gap voltage	0.6514	0.6177	0.5638	0.5793	4
B	Capacitance	0.7183	0.6707	0.4292	0.5940	1
C	Feed rate	0.5590	0.6715	0.6048	0.5769	3
D	Threshold	0.6728	0.6095	0.6155	0.5143	2

Total mean value of the GRG (γ_m) = 0.6030

tional-grade graph, where the dashed line is the value of the total mean of the grey relational grade. Basically, the larger the grey relational grade, the better are the multiple performance characteristics.

4.1 Analysis of variance (ANOVA)

ANOVA was used to investigate the design parameters that significantly affect the quality characteristics. Therefore, ANOVA was done by analyzing the influence of the gap voltage, capacitance, feed rate and threshold. The results of the analysis of variance (ANOVA) for the MRR, the TWR and the SR were calculated using the values of the grey relational coefficients and grey relational grades from **Table 3**. **Table 5** shows that the contribution of the capacitance and threshold were 47.44 % and 39.35 %, respectively. These two input parameters were found to be the most significant controlling parameters meaning that they controlled the MRR, TWR and SR simultaneously and very effectively.

4.2 Confirmation test

A confirmation test was carried out to predict and verify the enhancement of the quality characteristics using the optimum parametric combination. The esti-

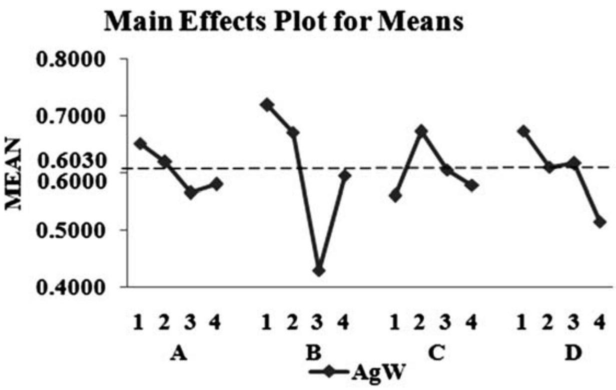

Figure 3: Main effects of the factors on the grey relational grade for AgW
Slika 3: Glavni vpliv faktorjev na razred pri sivi relaciji za AgW

Table 5: ANOVA table of grey relational analysis for AgW
Tabela 5: Tabela sive relacijske analize za AgW ANOVA

Source of variance	Sum of square	DOF	Mean square/ variance	Contri- bution (%)
Gap voltage (V)	4.66	3	1.55	6.38
Capacitance (nF)	48.17	3	16.06	65.92
Feed rate (μm/s)	7.31	3	2.44	10.01
Threshold (%)	12.93	3	4.31	17.69
Error	0	3	–	–
Total	73.06	15	4.87	100

mated grey relational grade using the optimum level of machining parameters can be calculated as:

$$\hat{\gamma}=\gamma_m+\sum_{i=1}^{p}\left(\bar{\gamma}_i-\gamma_m\right) \tag{7}$$

where γ_m is the total mean grey relational grade, $\bar{\gamma}_i$ is the mean grey relational grade at the optimum level, and p is the number of the main designed parameters that affect the quality characteristics. Based on equation 7, the predicted grey relational grade was calculated. **Table 6** shows a comparison of the experimental results using the initial A2B1C2D3 and the optimum grey-theory-prediction-design A1B1C2D1 machining parameters. It is found that the MRR increased from 0.001271 mm^3/min to 0.00132 mm^3/min. The TWR decreased from 14.0579 % to 13.4671 % and the SR also decreased from 0.094 µm to 0.0907 µm. The corresponding improvement in the material-removal rate is 3.86 %, while the tool-wear ratio and the surface roughness were 4.20 % and 3.51 %, respectively. Hence, it is concluded that the grey relational analysis based on the Taguchi method for optimizing multi performance characteristics is a very useful tool for predicting the MRR, TWR and SR of the die-sinking micro-EDM.

Table 6: Micro-EDM results of L_{16} using the initial and optimum process factors
Tabela 6: Mikro-EDM-rezultati L_{16} pri uporabi začetnih in optimalnih procesnih dejavnikov

	Initial condition	Optimal factor	
		Prediction	Experiment
Level	A2B1C2D3	A1B1C2D1	A1B1C2D1
MRR	0.001271		0.00132
TWR	14.0579		13.4671
SR	0.094		0.0907
Grey relational grade	0.8551	0.905	0.9346

Improvement of the grey relational grade: 0.0795

5 CONCLUSIONS

An orthogonal array with a grey relational analysis was used to optimize the multiple response characteristics of the die-sinking micro-EDM.

The performance characteristics such as the material-removal rate, the electrode wear and the surface roughness were improved using the method proposed in this study.

According to the Taguchi L_{16} mixed orthogonal table, only 16 experiments need to be conducted to find the significant machining parameters. On the basis of an integration of the grey relational analysis and the *S/N* ratio, it is concluded from **Tables 4** and **5** that the capacitance and the threshold are the main influencing parameters followed by the gap voltage and the feed rate. More precisely, the significant machining parameters for the whole machining performance were the gap voltage of 80 V, the capacitance of 0.1 nF, the feed rate of 4 µm/s and the threshold of 20 %.

On the basis of the confirmation test, the improvement in the performance characteristics was found to be as follows: MRR 3.86 %, TWR 4.20 % and SR 3.51 %.

6 REFERENCES

[1] J. L. Lin, K. S. Wang, B. H. Yan, Y. S. Tarng, J Mater Process Technol, 102 (**2000**), 48–55
[2] G. S. Prihandana, M. Mahardika, M. Hamdi, Y. S. Wong, K. Mitsui, Int J Machine Tools Manuf, 49 (**2009**), 1035–1041
[3] N. Tosun, C. Cogun, G. Tosun, J Mater Process Technol, 152 (**2004**), 316–322
[4] K. P. Somashekhar, N. Ramachandran, J. Mathew, Sixth international conference on Precision, Meso, Micro and Nano Engineering, COPEN6, 2009, C31–C36
[5] K. T. Chiang, F. P. Chang, J Mater Process Technol, 180 (**2006**), 96–101
[6] S. Datta, A. Bandyopadhyay, P. K. Pal, Int J Adv Manuf Technol, 39 (**2008**), 1136–1143
[7] U. Esme, Mater. Tehnol., 44 (**2010**) 3, 129–135
[8] N. Natarajan, R. M. Arunachalam, J Sci Ind Res, 70 (**2011**), 500–505
[9] V. K. Meena, M. S. Azad, Mat and Manuf Process, 27 (**2012**) 9, 973–977
[10] G. Rajyalakshmi, P. Venkata Ramaiah, Int. J of Adv. and Innov Res., 1 (**2012**) 3, 125–137
[11] J. H. Jung, W. J. Kwon, Journal of Mechanical Science and Technology, 24 (**2010**) 5, 1083–1090
[12] X. Shen, Z. Ning, M. Zhang, IEIT Journal of adaptive and Dynamic computing, 3 (**2012**), 26–30
[13] V. Muthu Kumar, A. Suresh Babu, R. Venkatasamy, M. Raajenthiren, CURIE, 3 (**2011**) 3–4, 79–88
[14] W. H. Yang, Y. S. Tarng, J Mater Process Technol, 84 (**1998**), 122–129
[15] T. R. Lin, Int Adv Manuf Technol, 19 (**2002**), 330–335
[16] K. Jangra, A. Jain, S. Grover, J Sci Ind Res, 69 (**2010**), 606–612
[17] J. T. Huang, Y. S. Liao, Int J Prod Res, 41 (**2003**) 8, 1707–1720
[18] K. Krishnaiah, P. Shahabudeen, Applied Design of Experiments and Taguchi methods, PHI Learning Private Limited, New Delhi, 2012
[19] Y. Kuo, T. Yang, G. W. Huang, Engineering Optimization, 40 (**2009**) 6, 517–528
[20] H. Aybin, A. Bayram, U. Esme, Y. Kazancoglu, O. Guven, Mater. Tehnol., 44 (**2010**) 4, 205–211