Araştırma Makalesi **BAUN Fen Bil. Enst. Dergisi, 21(1), 139-151, (2019)**

DOI: 10.25092/baunfbed.532597 **J. BAUN Inst. Sci. Technol., 21(1), 139-151, (2019)**

Optimization of machining performance parameters in wire EDM of metals with different thermophysical properties

Hacı Bekir ÖZERKAN[1,*]

[1]*Gazi Üniversitesi Teknik Bilimler MYO. Makina ve Metal Teknolojileri. Böl., Ostim OSB, Ankara.*

Geliş Tarihi (Recived Date): 03.04.2018
Kabul Tarihi (Accepted Date): 15.11.2018

Abstract

CNC Wire electric discharge machining (WEDM) is different mode of electro discharge machining (EDM) in which conductive, stretched small diameter thin wire is used as tool. It has been widely used to shape machine elements by electrical sparks. In cutting with WEDM, suitable input parameters for the work piece material should be selected due to the its specifications. However the desired machining performace outputs like material removal rate (MRR) and surface roughness (Ra) parameters can be controlled in this way. In this study the role of thermophysical properties of work piece materials are researched in WEDM. And also, in this presented study an attempt has been made to Grey relational analysis to obtain desirable performance characteristics through the selection of appropriate process parameters. For this purpose, aluminum, copper and high speed steel (HSS) are machined with various parameters. As a result, the greatest MRR was obtained in the cutting of copper and in HSS and aluminum processes, respectively. And also if the detected surface roughness values are evaluated from lowest to highest copper, HSS and aluminum metals, respectively.

Keywords: *Grey relational analysis, wire EDM, optimum machining parameters.*

[*] Hacı Bekir ÖZERKAN, ozerkan@gazi.edu.tr, https://orcid.org/0000-0002-7214-9985

Farklı termofiziksel özelliklere sahip metallerin tel elektro erozyon ile işlenmesinde performans parametrelerinin optimizasyonu

Özet

CNC tel elektro erozyon (WEDM), iletken, gerilmiş küçük çaplı ince telin takım olarak kullanıldığı bir erozyon işlemidir (EDM). Makine elemanlarını, elektriksel kıvılcımlarla şekillendirmek için yaygın olarak kullanılmaktadır. WEDM ile kesmede, iş parçası malzemesi için uygun giriş parametrelerinin seçimi, malzemenin özellikleri dikkate alınarak yapılmalıdır. Ancak bu şekilde arzu edilen işparçası işleme hızı (İİH) ve yüzey pürüzlülüğü (Ra) parametreleri bu şekilde kontrol edilebilir. Bu çalışmada, WEDM'de elektriksel iletkenlik ve iş parçası malzemesinin diğer termofiziksel özelliklerinin rolü araştırılmıştır ve Grey analizi ile optimum işleme parametreleri tespit edilmiştir. Bu amaçla, alüminyum, bakır ve yüksek hız çeliği (HSS) çeşitli parametreler ile işlenmiştir. Sonuç olarak, en büyük MRR, bakırın kesilmesinde ve sırasıyla HSS ve alüminyum işlemlerinde elde edilmiştir. Ayrıca tespit edilen yüzey pürüzlülük değerleri ise en düşükten en yükseğe doğru sırasıyla bakır, HSS ve alüminyum metallerinin işlenmesi sonrasında ölçülmüştür.

Anahtar kelimeler: *Gri ilişkisel analiz, tel EEİ, ideal kesme değerleri.*

1. Introduction

The diffuculties of WEDM can be defined as high surface roughness, low MRR, wire breakage and bending, lateral cut gap size and dimensional differences. All these problems are depending on choosing suitable input parameters such as pulse on time (T_{on}), pulse off time (T_{off}), average servo voltage (V_a), wire feed (f_w), discharge current (I) and wire tension (t_w) [1,2]. The remarked input parameters are also specify the desired machining performance values like MRR and Ra. This evaluation process is best determined by a comparative experimental study. Generally, MRR, Ra and f_w increase with the increment of Va, discharge current, and T_{on} during WEDM process [3-6]. Until now, many studies have been conducted on the effect of electrical processing parameters on the machining performance. Goswami and Kumar (2014), studied MRR, surface integrity and wire wear rate in WEDM of Nimonic 80 A alloy. Higher currents have expanded the melting zone and wider and deeper craters on the surface are observed [7]. Torres et al.(2015) analyzed the effect of I, Ton, duty cycle and servo voltage making statiscal regression in machining of Inconel 718 and expressed that, current for electrode wear and T_{on} have significant influence on surface roughness [8]. Bobbili et al. (2015), presented a comparative study of armour materials such as Al7017 and rolled homogeneous armour (RHA) steel applying “buckingham pi theorem” to model the input variables and thermo-physical characteristics of WEDM on MRR and Ra of Al 7017 and RHA steel. It has been interpreted that; MRR is higher in machining metal with low melting temperature and specific heat and also formation of deep and large craters increases with a higher current and larger pulse-on time [9]. In a study in which the squeeze cast A413 alloy was cut with WEDM, the agreement of ANOVA analysis and experimental results showed that the most influential parameters of MRR and Ra are T_{on}, T_{off}, peak current (IP) values [10]. In a study of Ti6Al4V alloy cut with WEDM; when the values of Ton, Toff, I, Va, fw and tw increase, the cutting width is increased and also the increment of Ton, Va, water pressure and fw increase the MRR is declared [11]. In a study in which statistical analysis and experimental studies were evaluated together, it was emphasized that the most effective parameters on MRR and Ra are discharge current and T_{on} [12-16]. The thermophysical properties of the workpiece, plays a important role in affecting the EDM process. Therefore, the electrical and thermal conductivity, specific heat capacity, are of great importance. These thermophysical properties are very relevant to the melting and scaling temperatures of the material. In general, metals with lower melting temperatures can machine easily. The thermophysical properties of the materials are expressed by an important variable called thermal diffusivity (α) shown in heat equations (1) and (2) [17].

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha} + \frac{\partial T}{\partial t} \tag{1}$$

$$\alpha = \frac{k}{\rho c_p} \tag{2}$$

$$S = \frac{\frac{\varepsilon . U . I}{\pi r_c^2} t_d}{\rho\left(H_m + c_p * (T_s + T_0)\right)} \tag{3}$$

Where; "α" symbolizes the ratio of the thermal conductivity "k" to the product of mass density "U" and specific heat "c_p" called the heat capacity and measures the conductive thermal energy according to the storing ability of thermal energy of a material. By Eq. 3, erosion amount can be calculated since the melting temperature is durable (T_s) [18]; here the input values of EDM are symbolized like as, specific heat capacity c_p (J/(kgK), thermal conductivity of material k (W/(mK), arc duration t_d (μs), derosion front temperature T_s(K), initial temperature T_o (K) density ρ (kg/m³), latent heat of melting H_m (kJ/kg) and voltage U (V). So in general erosion models, these thermo properties are not dependent on temperature, and researchers have assumed these values to be constant. Though, these properties are depending on the temperature changes and machining performance accuracy influences of that. For example, the thermal conductivity and specific heat properties of pure copper changes for temperatures up to 3500 K [19]. When the copper liquid is converted, the thermal conductivity is significantly changed since the specific heat increases to the melting point and remains relatively constant thereafter. Different materials exhibit different behaviors in response to changes in temperature during processing in the direction of their thermophysical properties, and these properties can vary widely [20]. In addition, another formula developed by Palatnik on the machinability (erosion wear resistance) of conductive metals with EDM (Eq. 4) clearly demonstrates the effect of these properties on the erosion ability.

$$R_{er} = c_p . \rho . k_c T_m^2 \tag{4}$$

Although EDM machining is an excellent manufacturing technique for electrically conductive metals, the work done on this field is rapidly increasing day by day. However in EDM, workpiece conductivity is very important because the spark means the discharge of electrons. Electrons move faster in good conductors. In this regard, it is very important that rapid dissipation of heat over a large area due to the thermal resistance value of the workpiece during the discharge where the spark falls. Because this affects the MRR and the crater sizes that will form on the surface. Therefore, in this study three metals with different conductivities and melting temperatures were processed to compare the effect on MRR and Ra values.

2. Experimental study and Grey relational analysis

Since EDM is a manufacturing technique in which shaping is realized by thermal energy, so it is a definite opinion that the values of MRR and Ra will be different because of generated sparks at the same current level. These sparks remove different amounts of material where it falls. Because all metals and alloys have different thermal resistance, electrical and thermal conductivity. However, which previously known to be effective of physical and mechanical properties of the workpiece material in selecting the processing parameters, make reliable data bank for the pre-processing estimation of the performance output values. The presentation of experimental data in the catalogs of the manufacturer's firms, as the value of the customer processing, provides the user with great convenience. Thus, parameter selection will become easier in shaping thousand kinds of metal alloys with EDM.

Table 1. Some physical and mechanical properties of Cu, Al, HSS (M7) [21].

	Electrical Conductivity (S/m) at 20°C	Modulus of Elasticity (GPa)	Specific Heat Capacity (J/g-°C)	Thermal Conductivity (W/m-K)	Melting Point (°C)	Density (g/cc)	Vickers Hardness
Aluminum	3.69xE7	68	0.900	210	660.37	2.69	15
Copper	5.85xE7	110	0.385	385	1083.6	8.96	100
S400(M7) High Speed Steel	0.154xE7	217	0.460	19.0	1426.67	8.30	640

Therefore, in this study; Cu, Al and HSS metals with different melting temperatures, modulus of elasticity, electrical conductivities and thermal conductivities were selected especially for the purpose of comparing the processing performances. These specific features of these metals are listed in Table 1. During the experiments, the process parameters selected are pulse duration (T_{on}), pulse-interval (T_{off}), servo voltage (SV), wire tension (t_w) and wire feed (f_w) to achieve desired performance characteristics material removal rate (MRR) and surface roughness (Ra). These parameters were selected in the range of values for these three different metals which recommended by the machine manufacturer and shown in Table 2. In choosing the processing parameters of these three different materials, the values suggested by the machine manufacturer are taken into consideration. However, since the processing performance of three metals with different melting temperatures, electrical conductivities and elasticity modulus are compared in the study, so that highest values which recommended for HSS metal by the company software are used in three materials processing. Table 2 gives the levels of various parameters for each materials proposed by the WEDM manufacturer. Values marked with an asterisk in the Table 2 are selected for the three metals.

Table 2. The processing parameters levels proposed by the machine tool manufacturer.

Materials	**Levels**	**Ton (μs)**	**Toff (μs)**	**Servo Voltage (V)**	**Wire feed (m/min)**	**Wire tension (N)**
Al	Low (1)	11	13	18	80	150
	Medium (2)	13	14	20	90	160
	High (3)	15	15	22	105	170
Cu	Low (1)	12	14	21	80	150
	Medium (2)	14	16	25	90	160
	High (3)	16	18	28	105	170
M7-HSS	Low (1)	**13***	**14***	**32***	**80***	**150***
	Medium (2)	**15***	**30***	**35***	**90***	**160***
	High (3)	**17***	**45***	**40***	**105***	**170***

Machinings were performed on the Sodick SLC600G brand WEDM machine (Figure 1). As the samples, 20x200mm square bars were used, obtained from the market. 0.25mm diameter brass wire was used in cutting operations. In all processes, the water pressure is fixed at 55 bar.

Figure 1. WEDM machine used in experiments.

In order to get the appropriate and accurate results, the design of experiments technique is used to get data. Taguchi L27 orthogonal array experimental designs of three levels were selected for the materials and the experiments were conducted. Hence an Grey relational analysis and regression were used for selecting appropriate process parameters to achieve desired MRR and Ra through multi-objective optimization. Grey analysis is the estimation of the conditions under which the desired output parameters will give the best result in experimental studies. It is generally desirable that the MRR is high and the Ra is low when evaluating manufacturing process performance outputs. Therefore, in statistical studies if the number of outputs is more than one, it is best to use these values in the ascending or descending order calculations. Since this is possible with grey relational analysis, the optimal machining performance outputs of the three different metals in this study were evaluated simultanously as maximum MRR and minimum Ra.

The interaction between processing parameters and processing performance can be found using Grey analysis. In such experimental processes of manufacturing, interpretation and evaluation can be carried out freely, with some experiments being ignored, rather than complete experiments. In this case, some input variable factors can be neglected. Also, if the output of the input factors is different, ie a part of the outputs can change to a decreasing fraction, the Grey analysis is an ideal approach to evaluate the results multiple times. As a result, Grey relational grade coefficient (Γ) can use multiple performance datas together with three different calculation styles.

(1) Higher is the better (HB):

$$x_i^*(k) = \frac{x_i^{(0)}(k) - min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - min x_i^{(0)}(k)} \quad (5)$$

(2) Lower is the better (LB):

$$x_i^*(k) = \frac{max\, x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - min x_i^{(0)}(k)} \quad (6)$$

(3) Desired value $x^{(0)}$:

$$x_i^*(k) = 1 - \frac{\left|x_i^{(0)}(k) - x_i^{(0)}\right|}{\max x_i^{(0)}(k) - min x_i^{(0)}(k)} \quad (7)$$

where $x_i^*(k)$ is the normalized data matrice components of Grey analysis, min $x_i^{(0)}(k)$ is the minimum value of performance outputs (MRR or Ra) data series, max $x_i^{(0)}(k)$ is the maximum value of performance outputs (MRR or Ra; $x_i^{(0)}(k)$) data series and $x_i^{(0)}$ is the desired or pre-specified value. In this analysis, the relationship between the output values produced and the input values is expressed by "Grey relational grade coefficient Γ". Here $x_0(k)$ the and $x_i(k)$ are shown like below:

$x_0(k) = x_0(1), x_0(2), \ldots x_0(n)$ (reference series) (8)

$x_i(k) = x_i(1), x_i(2), \ldots x_i(n) \in X$, (comparative series) (9)

here i=1, . . . ,m:

Then, the Grey grade coefficients can be found out by Eq.(10) and the overall grey relational grade values by Eq.(11) [16,22,23]. Absolute value of difference between x_0 and x_i is defined as "$\Delta_{oi}(k)$".

$$\Gamma_{oi} = \frac{\Delta_{min} + \varphi \Delta_{max}}{\Delta' + \varphi \Delta_{max}} \quad (10)$$

Where 1) i=1,….,m, k=1,….,n, j∈i

2) $\Delta_{0i}(k) = |x_o\ (k) - x_i\ (k)|$

3) $\Delta_{min} = \min_{\forall j \in i} \min_{\forall k} \left|x_0\ (k) - x_j\ (k)\right|$ (min. value of Δ_{oi})

4) $\Delta_{max} = \max_{\forall j \in i} \max_{\forall k} \left|x_0\ (k) - x_j\ (k)\right|$ (max. value of Δ_{oi})

Here "φ" is the distinguishing coefficient with φ∈[0, 1], and generally φ= 0.5 is used [16, 22, 23].

$$\Delta' = \sqrt{\sum_{k=1}^{n}\left(\frac{\Delta_{0i}^{2}(k)}{n}\right)} \quad (11)$$

The brass wire with 0,25 mm diameter was used as the tool in the processes. For processes performed with the L27 test design (Table 3). MRR (mm^3/min) and Ra (μm) values were used for performance evaluation after the operations.

3. Results and discussion

MRR is an important perfomance scale which always desired most higher. MRR depends on mainly thermophysical properties of the workpiece rather than its hardness. Excess temperature increase in the plasma channel leads to discharge of material. Removal of the material is due to instantaneous evaporation caused by melting. The molten metal is partly removed and mixed with the dielectric fluid. So the temperature and its convection is so important in EDM. Table 3 shows MRR and Ra values determined from the processing of copper, aluminum, and HSS metals with WEDM. When the results are examined in general; the highest processing speed and the lowest surface roughness have been achieved in the processing of copper. In the processing of HSS metal, MRR is larger than aluminum processes but Ra is lower. If these three metals are to be compared, the smallest processing speed and the roughest surfaces are obtained in the processing of aluminum, followed by HSS and Cu, respectively. According to Eqs. 3 and 4, as the specific heat, the coefficient of thermal conductivity, the density and the melting temperature increase, the resistance of the metals to EDM increases. As can be seen in Table 3, the best machinability is followed by HSS and Al respectively. Given the thermal conductivity, density, melting temperature and specific heat capacity values of aluminum, it was expected that the MRR values would be higher than the HSS steel. But overall it was lower than HSS. In this case, it can be said that the cutting process is caused by oxidation in the water. Oxidation forms an instant, weak and insulating oxide layer on the surface of the machined surface. It is inevitable that this layer will reduce the melting effect of the surface sparks and thus the thermal conductivity. Therefore, by the water's contact over the workpiece, the uncontrolled insulation on the surface has come to fruition. This insulating layer is the experimental result that the continuity of the machinability is reduced by the effect of the plasma channel temperature and the increasing servo voltage.

Table 3. L27 Orthogonal array and experimental results.

Exp. No	Control factors					Al		Cu		HSS (M7)	
	Ton	Toff	SV	Wf	Wt	MRR (mm^3/min)	Ra (μm)	MRR (mm^3/min)	Ra (μm)	MRR (mm^3/min)	Ra (μm)
1	13	14	32	80	150	1,94	3,9	6,52	2,02	6,41	2,37
2	13	14	32	80	160	1,702	3,86	6,492	2,05	5,952	2,16
3	13	14	32	80	170	1,504	3,94	6,254	2,06	6,754	2,44
4	13	30	35	90	150	1,666	3,95	6,646	1,9	7,626	2,81
5	13	30	35	90	160	1,968	3,84	6,678	1,99	6,748	2,61
6	13	30	35	90	170	3,18	3,86	6,69	2	6,54	2,53
7	13	45	40	105	150	3,162	3,92	6,102	1,92	6,822	2,49
8	13	45	40	105	160	2,884	3,77	6,124	2,01	7,084	2,63
9	13	45	40	105	170	2,676	3,67	6,106	1,94	6,796	2,53
10	15	14	35	105	150	6,218	3,82	8,238	2,22	6,968	2,43
11	15	14	35	105	160	6,23	4,9	8,28	2,15	7,47	2,64
12	15	14	35	105	170	3,652	4,99	8,292	2,22	5,592	2,13
13	15	30	40	80	150	2,584	5,04	7,884	2,08	6,984	3,13
14	15	30	40	80	160	2,626	4,99	7,596	2,1	6,526	2,46
15	15	30	40	80	170	5,568	4,98	7,578	2,11	5,408	2,41
16	15	45	32	90	150	5,88	5,17	7,78	2,24	7,08	3,01
17	15	45	32	90	160	5,852	5,05	7,592	2,36	7,492	3,19
18	15	45	32	90	170	5,814	5,08	7,664	2,27	5,384	2,18
19	17	14	40	90	150	3,276	5,7	9,096	2,33	6,106	2,48
20	17	14	40	90	160	3,148	5,6	9,278	2,45	6,778	3,05
21	17	14	40	90	170	7,5	5,97	9,23	2,4	5,12	2,13
22	17	30	32	105	150	8,742	5,54	9,632	2,52	8,202	3,03
23	17	30	32	105	160	8,714	5,32	9,574	2,48	6,484	2,45
24	17	30	32	105	170	8,736	5,23	9,646	2,5	6,786	3,05
25	17	45	35	80	150	7,278	6,05	8,468	2,4	6,698	3,18
26	17	45	35	80	160	6,78	6,18	8,42	2,47	7,12	3,13
27	17	45	35	80	170	7,132	6	8,102	2,5	6,862	3,25

The continuity of the process is ensured by the breakdown of the barrier layer formed by the oxidation of Al by the plasma arc and the spark generated by the increased voltage. It is believed that with the impact force of spark and the deeper melting of the accumulating high energy, surface roughness increases over Al surface. At the beginning of the process and at any moment because of the conductivity of the water, the formation of the servo voltage and the plasma channel is continuous despite the oxidation. However, since the oxidation does not completely break down the conductivity, it is thought that the higher the energy density, the higher the processing voltage. Thus, when plasma is formed, the spark discharged on to the surface with higher force and energy and forms deep craters. In copper with the best electrical conductivity, the MRR is the largest and Ra is the smallest. Shortly, the oxidation is important.

The calculated and measured machining performance values are MRR and Ra shown in Table 3. Firstly, 27 data of MRR are used as the reference sequence showed as $x_0(k)$. The L27-array values of machining parameters (Ton, Toff, SV, Ws, Wt) were set as three comparative sequence Xi(k), i=1,2,3,4,5; k=1..27. In order to calculate the three characters of Grey relational analysis: normalization matrice, absolute value matrice, grey relational coeffiecent and Grey grade calculation of the original MRR and Ra data of each sequence were calculated by Eq.5 for higher MRR and Eq.6 for lower Ra. And then the Grey relational grades for both machining parameters on MRR and Ra can be obtained by Eq.11. Those calculated Grey grade coefficient datas are shown in Table 4.

Table 4. The results of grey relational grade analysis.

Exp. No	**Control factors**					**Al**		**Cu**		**HSS**	
	Ton	**Toff**	**SV**	**Wf**	**Wt**	**Grey grades for Max. MRR and Min. Ra**					
1	1	1	1	1	1	0,596198688	11	0,541355276	14	0,581173117	9
2	1	1	1	1	2	0,604018697	10	0,516818479	20	0,677820798	3
3	1	1	1	1	3	0,578142077	12	0,501359659	21	0,579617602	10
4	1	2	2	2	1	0,577985999	13	**0,685666387**	**1**	0,589764883	8
5	1	2	2	2	2	0,61445845	8	0,574419831	10	0,526492873	17
6	1	2	2	2	3	0,631347875	7	0,565443028	12	0,532222396	16
7	1	3	3	3	1	0,613649685	9	0,636363636	5	0,568127354	11
8	1	3	3	3	2	0,654035581	6	0,536406894	15	0,553921534	14
9	1	3	3	3	3	0,686835312	5	0,609649312	6	0,553118991	15
10	2	1	2	3	1	**0,741182134**	**1**	0,524648098	19	0,603239053	6
11	2	1	2	3	2	0,547654546	15	0,559131157	13	0,600661565	7
12	2	1	2	3	3	0,451462888	23	0,529461049	17	0,685617923	2
13	2	2	3	1	1	0,424124841	25	0,567033944	11	0,45875503	23
14	2	2	3	1	2	0,429565027	24	0,535737372	16	0,554115601	13
15	2	2	3	1	3	0,511016529	20	0,52880609	18	0,511072664	20
16	2	3	1	2	1	0,506968436	21	0,482001945	23	0,483779781	21
17	2	3	1	2	2	0,51614011	18	0,432872146	27	0,515131821	19
18	2	3	1	2	3	0,511845793	19	0,463956094	25	0,635777118	5
19	3	1	3	2	1	0,39019425	27	0,591027074	9	0,519542734	18
20	3	1	3	2	2	0,393424519	26	0,59425125	8	0,449054282	25
21	3	1	3	2	3	0,548760464	14	0,596294039	7	0,666666667	4
22	3	2	1	3	1	0,7008	4	0,662747294	3	**0,691780822**	**1**
23	3	2	1	3	2	0,712168113	3	0,654634527	4	0,554604034	12
24	3	2	1	3	3	0,72208538	2	0,67032967	2	0,449757333	24
25	3	3	2	1	1	0,528617792	16	0,491697008	22	0,42695081	27
26	3	3	2	1	2	0,490891716	22	0,471666717	24	0,473234797	22
27	3	3	2	1	3	0,521085738	17	0,437519055	26	0,434108527	26

Table 5. Average grey relational grade by factor levels (Al. , Max. MRR and min Ra).

Factor		*Level 1*	*Level 2*	*Level3*
A	ton	**0,617408***	0,515551	0,556448
B	toff	0,539004	**0,591506***	0,558897
C	v	**0,605374***	0,567187	0,516845
D	wf	0,520407	0,521236	**0,647764***
E	wt	0,564414	0,551373	**0,57362***
Best machining factor combination- A1B2C1D3E3*				

Table 6. Average grey relational grade by factor levels (Cu, Max. MRR and min Ra).

Factor		*Level 1*	*Level 2*	*Level3*
A	ton	0,574165	0,513739	**0,574463***
B	toff	0,550483	**0,60498***	0,506904
C	v	0,547342	0,537739	**0,577286***
D	wf	0,510222	0,553992	**0,598152***
E	wt	**0,575838***	0,541771	0,544758
Best machining factor combination - A3B2C3D3E1*				

Table 7. Average grey relational grade by factor levels (HSS, Max. MRR and min Ra).

Factor		*Level 1*	*Level 2*	*Level3*
A	ton	**0,573584***	0,560906	0,518411
B	toff	**0,595933***	0,540952	0,516017
C	v	**0,574382***	0,541366	0,537153
D	wf	0,521872	0,546493	**0,584537***
E	wt	0,547013	0,545004	**0,560884***
Best machining factor combination- A1B1C1D3E3*				

Tables 5, 6 and 7 show the best combination of treatments, calculated according to the average grey grades. Table 5 shows that A1B2C1D3E3 is the most ideal combination of processing for aluminum with the highest MRR and lowest Ra. These values are respectively Ton=13μs, Toff=30μs, SV=32V, Wf=105m/min and Wt=170N. The highest MRR and the lowest Ra for copper ideal grey combination is shown in Table 6 as A3B2C3D3E1. These values are respectively Ton=17μs, Toff =30μs, SV=32V, Wf=105m/min and Wt=150N. And in Table 7 it is seen that A1B1C1D3E3 is the best combination of the highest MRR and the lowest for Ra for HSS. These values are respectively Ton=13μs, Toff =14μs, SV=32V, Wf=105m/min and Wt=150N. It is clearly seen from Fig.2 that the machining parameters' setting of experimental run "10" for Al, run number "4" for Cu and "22" for HSS has the highest Grey relational grade. Therefore, experiment no 10 for Al, 4 for Cu and 22 for HSS is the optimal machining variables for achieving maximum MRR and minimum Ra simultaneously among all the 27 machinings.

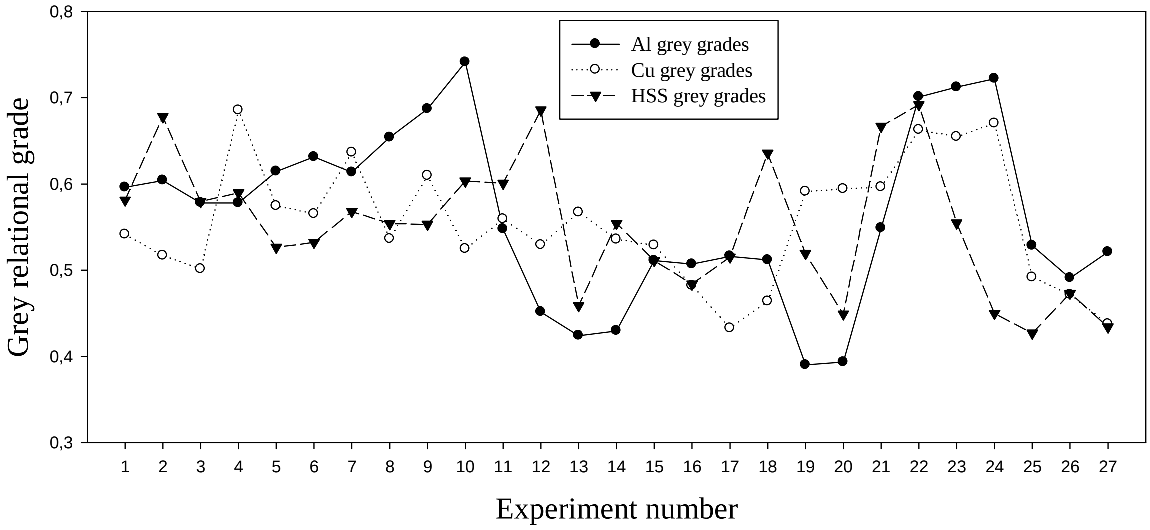

Figure 2. Grey relational grades versus experiment run.

4. Conclusion

In this WEDM study, taking into account the Taguchi L27 mixed orthogonal table, 27 experiments were sufficient for the selection of ideal processing parameters for Al, Cu and HSS metals which have different thermo-physical properties. And this study also presents the effect of different thermo physical properties such as electrical and thermal conductivity, elatisite modulus, specific heat capacity, melting temperature value, density and hardness of Al, Cu and HSS metals on processing performance. The results presented below were excluded from this study.

- The highest MRR values were obtained in the processing of Cu with the highest electrical and thermal conductivity. Subsequently, HSS and Al-metal processes are introduced. Normally, when the second highest MRR values were expected in the processing of Al, this was an unexpected result. This is thought to be due to the fact that the processes are carried out in an aqueous medium and, depending on it, the formation of a weak, passive and shallow oxide layer on the surface of Al which reduces conductivity.
- All metals are processed in the same processing parameters. Therefore, Palatnik equation is an ideal approach of changing of MRR and Ra values according to the thermophysical properties. However, in this work the erosion ability of metals with sparks is different due to oxidation in Al. Ra values are also highest in Al. This has been determined in decreasing order of HSS and Cu metals. The specific heat capacity of an object, known as the heat required to change the temperature of the unit mass in a unit degree, is the highest metal Al in this work. This is followed by HSS and Cu, respectively, in decreasing order. Therefore, this thermophysical property caused a different volumetric removal effect on the surface with each spark falling on the surface among these three metals at the same current density. It is thought that, during the crater formation, the major part of the spark energy moves rapidly inwardly from the bottom of

the molten metal causing the thermal energy loss in metals with high thermal conductivity. Because of the high thermal capacity in Al, it is believed that the spark discharge energy has undergone too much loss, so that it melts too much at the same volumetric energy density.

- A metal with high heat conduction, it is thought that most of the energy for crater formation on the work surface of the spark accelerates inward from under the melted part of the metal to generate thermal energy loss.

As a result, material removal is largely influenced by the thermophysical properties of the workpiece, rather than material properties such as hardness and strength. And also the grey relational model can be extensively carried out to different manufacturing situations where performance is specified by many machining variables by various grade requirements.

References

[1] Rao, R.V., Pawar, P.J., Modeling and optimization of process parameters of wire electrical discharge machining, **Journal of Engineering Manufacturing**, 223, 11,1431–1440, (2009).

[2] Gauri, S.K, Chakraborty, S., A study on the performance of some multi-response optimization methods for WEDM processes, **International Journal of Advanced Manufacturing Technology**, 49, (1–4),155–166, (2010).

[3] Mohan, B., Rajadurai, A. and Satyanarayana, K., Effect of SiC and rotation of electrode on electric discharge machining of Al–SiC composite, **Journal of Materials Processing Technology**, 124, 3, 297-304, (2002).

[4] El-Hofy, H.A.G., **Advanced machining processes: nontraditional and hybrid machining processes**, McGraw Hill Professional, (2005).

[5] Rozenek, M., Kozak, J., Dabrowski, L. and Łubkowski, K., Electrical discharge machining characteristics of metal matrix composites, **Journal of Materials Processing Technology**, 109, 3, 367-370, (2001).

[6] Padhi, P., Mahapatra, S., Yadav, S. and Tripathy, D. Multi-objective optimization of wire electrical discharge machining (WEDM) process parameters using weighted sum genetic algorithm approach, **Journal of Advanced Manufacturing Systems**,15, 85-100, (2016).

[7] Goswami, A. and Kumar, J., Investigation of surface integrity, material removal rate and wire wear ratio for WEDM of Nimonic 80A alloy using GRA and Taguchi method, **Engineering Science and Technology, an International Journal**, 17, 4, 173-184, (2014).

[8] Torres, A., Puertas, I. and Luis, C., Modelling of surface finish, electrode wear and material removal rate in electrical discharge machining of hard-to-machine alloys, **Precision Engineering**, 40, 33-45, (2015).

[9] Bobbili, R., Madhu, V. and Gogia, A. Modelling and analysis of material removal rate and surface roughness in wire-cut EDM of armour materials, **Engineering Science and Technology, an International Journal**, 18, 4, 664-668 (2015).

[10] Soundararajan, R., Ramesh, A., Mohanraj, N. and Parthasarathi, N., An investigation of material removal rate and surface roughness of squeeze casted A413 alloy on WEDM by multi response optimization using RSM, **Journal of Alloys and Compounds**, 685, 533-545 (2016).

[11] Arikatla, S.P., Mannan, K.T. and Krishnaiah, A., Experimental Investigations on Kerf width and Material Removal Rate in Wire Electric Discharge Machining of Titanium Alloy, **International Journal of Emerging Research in Management &Technology**, 4, 11, 105-109, (2015).
[12] Lodhi, B.K. and Agarwal, S., Optimization of machining parameters in WEDM of AISI D3 steel using Taguchi technique, **Procedia CIRP**, 14, 194-199, (2014).
[13] Mathew, B. and Babu, J., Multiple process parameter optimization of WEDM on AISI304 using Taguchi grey relational analysis, **Procedia Materials Science**, 5, 1613-1622, (2014).
[14] Mandal, A., Dixit, A.R., Das, A.K. and Mandal, N., Modeling and optimization of machining nimonic C-263 superalloy using multicut strategy in WEDM, **Materials and Manufacturing Processes**, 31, 7, 860-868, (2016).
[15] Devarasiddappa, D., George, J., Chandrasekaran, M. and Teyi, N., Application of Artificial Intelligence Approach in Modeling Surface Quality of Aerospace Alloys in WEDM Process, **Procedia Technology**, 25, 1199-1208, (2016).
[16] Hsia, K. H. and Wu, J. H., A study on the data preprocessing in Grey relation analysis, **Journal of the Chinese Grey System Association**, 1, 47–53, (1998).
[17] Weingärtner, E., Kuster, F. and Wegener, K., Modeling and simulation of electrical discharge machining, **Procedia CIRP**, 2, 74-78, (2012).
[18] Klocke, F., Schneider, S., Harst, S., Welling, D. & Klink, A. Energy-based approaches for multi-scale modelling of material loadings during Electric Discharge Machining (EDM), **Procedia CIRP**, 31, 191-196, (2015).
[19] Gathers, G., Thermophysical properties of liquid copper and aluminum. **International journal of Thermophysics**, 4, 209-226, (1983).
[20] Grimvall, G., **Thermophysical properties of materials**, 255, Elsevier Science B.V., (1999).
[21] https://www.matdat.com
[22] Acır, A., Canlı, M.E., Ata, İ., Çakıroğlu, R., Parametric optimization of energy and exergy analyses of a novel solar air heater with grey relational analysis, **Applied Thermal Engineering**, 122, 330-338, (2017).
[23] Huang, J. and Liao, Y., Optimization of machining parameters of wire-EDM based on grey relational and statistical analyses, **International Journal of Production Research**, 41, 1707-1720, (2003).