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# Parametric optimization of process parameters for Electric discharge Machining of Tungsten carbide (93% WC and 7%Co)

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### Abstract

Nowadays there is a huge demand of High Strength Temperature Resistance (HSTR) alloys such as titanium, carbide, nimonics and ceramics in aerospace, defence and electronics. Among these alloys machining of tungsten carbide alloy is of interest, because of its numerous applications. Complex shapes of tungsten carbide are not generally made by traditional manufacturing process. To machine tungsten carbide with high accuracy, non-traditional machining process like Laser beam machining, Electron beam machining and Electrical discharge machining are a proper choice. In the present paper, the authors have machined Tungsten carbide (93% WC and 7%Co) with copper electrode. The machining is performed on EDM MODEL 500 X 300 ENC with VELVEX EDMVEL-2 as dielectric oil. The 17 experiments are carried out based on RSM (Box-Behnken) method. Further, in order to find the optimum combination grey relational approach is used. The results showed that pulse-on-time of 40 $\mu$ s, pulse-off-time of 2 $\mu$ s and current of 8A are optimum combination for machining of Tungsten carbide (93% WC and 7%Co). Lastly, the confirmation experiment has been conducted.

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## 1. Introduction

With the increase in demand for complex and intricate shapes made from alloys of high strength and hardness have a wide variety of applications in industry, aerospace, marine, surgeries equipment etc. (Kumar et al., 2010; Sharma and Singh 2016, 2018). These hybrid materials include stainless steel, tungsten carbide alloys, ceramics, glass etc. Stainless steel alloys find its applications in various fields such as power generation, medical applications, automotive industry, architecture and building construction. Similarly, other hybrid materials are also used in various fields. Machining of such alloys which are difficult to machine is a very important problem in industries nowadays. The demand for these newly developed materials has increased for the last 40 years in different engineering applications because of its outstanding material properties such as high strength, toughness, hardness, temperature strength, oxidation resistance etc. Machining of these materials are faced with severe difficulties because of high coefficient of expansion, work hardening rate, low thermal conductivity and high ductility etc. Low thermal conductivity property of material causes high temperature at the tool

surface which is in contact with the surface of work-piece which often leads to reduction in tool life, surface finish and tolerances. Making complex and intricate shapes is very difficult to achieve with traditional machining methods. Chip formation is yet another phenomenon which is mostly affected because of its low thermal conductivity and high work hardening capability. High ductility property of some material has caused formation of built-up edges on the cutting tool and finally leads to chattering of tool.

It is hard to find a suitable tool material for machining these new materials using conventional machining methods. Therefore, a need for new machining methods known as non-traditional machining method raised for those, who would machine hybrid materials like ceramics, tungsten and its alloys, high strength polymers, stainless steel and other alloys. These non-traditional machining methods are capable of machining wide range of difficult machine materials disregard of their hardness. There are dozens of non-conventional machining process; most of them are having same applications. Therefore, non-traditional machining processes are often classified according to the energy used during machining (Groover, 2002).

Table 1 presents the classification of non-traditional machining processes (Pandey and Shan, 2001). Abrasive jet machining (AJM), Water Jet machining (WJM), Ultrasonic machining (USM), Abrasive water jet machining (AWJM) are the processes under mechanical processes. Electrochemical machining (ECM), Electrochemical grinding (ECG), Electrochemical drilling (ECD) are the processes under electro chemical. Under chemical machining two processes i.e. Chemical machining and photochemical machining (PCM). Electron beam machining (EBM), Electric discharge machining (EDM), Laser Beam machining (LBM), Ion Beam Machining (IBM) are thermo-chemical processes.

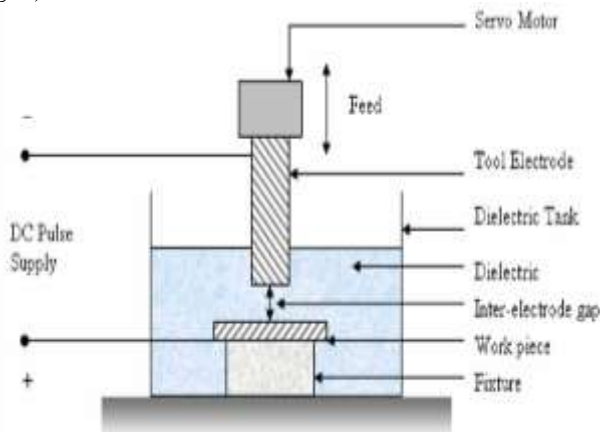
**Table 1.** Classification of non-traditional machining processes

Non-Traditional machining process			
Mechanical	Electro-chemical	Chemical	Thermo-chemical
AJM	ECM	CHM	EBM
WJM	ECG	PCM	EDM
USM	ECD	-	LBM
AWJM	-	-	IBM

In the present paper, the authors have performed electric discharge machining of Tungsten carbide with an aim to obtain optimal parametric combination. The results show that pulse-on-time of 40 $\mu$ s, pulse-off-time of 2 $\mu$ s and current of 8A are optimum combination for machining of Tungsten carbide (93% WC and 7%Co).

### 1.1. Electric discharge machining

Electric discharge machining (EDM) came into existence in 1766 and was discovered by Joseph Priestley, it is a non-traditional machining process (Rao, 2001, Singh and Sharma 2017). Electric discharge machining has other names such as die sinking, spark machining, wire erosion, spark eroding or wire burring. In this process work-piece and tool electrode are immersed in the dielectric fluid and DC power supply is supplied to them. Due to discharge current the dielectric fluid is ionized which causes spark formation between electrode and work-piece which leads to the removal of material from work-piece by fusion and vaporization mechanism (as shown in Fig. 1).



**Fig.1.** Electrical discharge machining (EDM) process

The process has become more popular nowadays because of its capability to machine hard electrically conductive materials which is difficult with the conventional process (Jahan et al., 2011), but it has certain limitations (Kumar et al., 2010).

- Alteration in the properties of outer machined surface.
- Requires post processing after machining.
- Formation of heat affected zone (HAZ) and micro cracks.
- Low material removal rate.

To deal with these problems, researchers have used abrasives such as silica, aluminium oxide, graphite, silicon carbide, etc. to achieve improved performance.

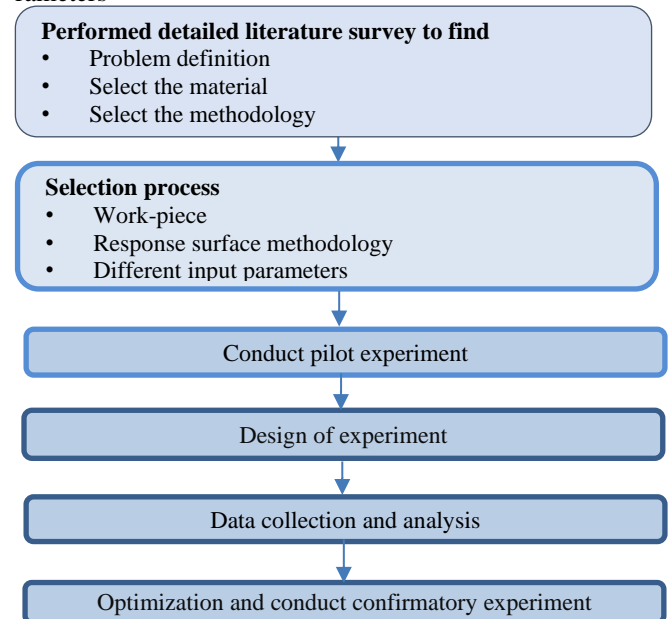
## 2. Literature review

Table 2(a) presents the review of literature for electrical parameters and Table 2(b) presents the review of literature for non-electrical parameters. Non electrical parameters consist of electrode material, flushing pressure, working time, electrode size and tool rotation which has been discussed below in Table 2(b).

## 3. Research Methodology

The authors developed a basic research framework as shown in Fig. 2 below which presents a step by step procedure adopted in this study. The steps involved are as follows.

1. Firstly, selection of material and methodology is performed.
2. After conducting literature survey varying and fixed input parameters are selected.
3. Numbers of pilot experiments were done to find the scale of varying input parameters.
4. RSM Box-Behnken approach with 5 centre point is being used. A total of 17 experiments were performed.
5. Best combination is being found out among the 17 experiment by using GRA method.
6. Graphs are being plotted for various input and output parameters



**Fig. 2.** Research framework

#### 4. Basic concept of Grey Relation Analysis

GRA (Grey Relational Analysis) is based upon grey theory given by Deng, 1989 it is an effective method to handle the

uncertainty in the multi- input data. In this literature the GRA is used in various fields such as engineering, as well as in industrial and forecasting areas.

**Table 2 (a).** Literature related to the effect of EDM electrical parameters

S. No.	Author/year	Material used	Methodology	Work done	Remarks
1.	Lee and Li (2001)	Work piece:- Tungsten carbide Electrode:- coper, graphite, copper tungsten		The current paper manages the broad investigation of the impacts of EDM machining parameters on the machining parameters of tungsten carbide.	The author found that <ul style="list-style-type: none"> <li>• Work-piece as anode and electrode as cathode better machining performance is achieved.</li> <li>• MRR diminishes with increase in open circuit voltage. MRR rises with rise in peak current and becomes stable at high peak current.</li> </ul>
2.	Kansal et al., (2006)	Work-piece:-H-11 Die steel Electrode:-Copper Powder:- Silicon	Taguchi	The current article manages the machining of H-11 Die Steel and to find the optimal parameter.	The author found that peak current and silicon powder concentration are the significant parameters for machining H-11 Die steel.
3.	Guu and Hou (2007)	Workpiece:- Fe- Mn-Al Electrode:- Coper powders	-	In the present paper author used AFM technique to find the impact of pulse-on-time and current on surface composition, micro hardness and surface roughness.	The author obtained that high energy causes formation of deeper crakes. The effect of pulse-on-time is dominant then current. Chemical composition of the surface changed after machining.
4.	Kansal et al., (2007)	Work-piece:- AISI D2 Die steel Electrode:- Copper Powder:- Silicon	Taguchi	In this paper author used copper electrode to machine D2 Die steel and obtained the foremost combination such as Peak current = 10 A Powder concentration = 4 g/l, Pulse-on time = 100 $\mu$ s, Pulse-off time = 15 $\mu$ s, Gain = 1 mm/s	The author said that peak current and powder concentration is the dominant among the rest.
5.	Soni et al., (2015)	Electrode- brass Workpiece- Ti50Ni39Cu11 Graphite, Aluminium oxide powders	RSM	The authors used brass wire to cut Ti50Ni39Cu11 alloy and optimization is done by using RSM method. The foremost combinations are Pulse on Time (Ton) = 120 $\mu$ s, Pulse of time (Toff) = 48 $\mu$ s, Spark Gap voltage (SV) = 60v, Servo Feed (SF) = 2180 $\mu$ m and Wire speed (WS) = 5mm/m.	RSM, GRA and entropy analysis was been successfully used to find the best parametric combination.
6.	Gurjar and Kumar (2015)	Workpiece- Die steel H13	Taguchi	In the present article, the author conducted experiment to find out optimal combination for machining Die steel H13 using Taguchi L9 method.	Current is the significant parameter to obtain high MRR and low TWR for machining Die steel H13.
7.	Singh and sharma (2016)	Workpiece- Tungsten carbide (WC-Co)	GRG	This article showed a detailed comparison of different input parameters.	The author found that pulse-on-time is the most important input parameter among the rest input parameters for machining tungsten carbide alloy.
8.	Joshi et al., (2017)	Work piece:- Ti-6Al- 4V Electrode:- Copper	Taguchi	In the present article the author used Taguchi L9 method is utilized to compare the impact of pulse on time, pulse off time and current on the output parameters such as EWR and MRR.	The author found that pulse on time has noticeable impact on MRR. Pulse off time and current has impact on TWR. In general current is the most significant factor.

**Table 2(b).** Literature survey related to the impact of non-electrical parameters on EDM

S. No.	Author/year	Material used	Methodology	Work done	Remarks
1.	Lonardo and Bruzzone (1999)	Work-piece:- Alloy steel (Cr,V,Mo) Electrode:- Graphite and Copper	-	The present paper deals with the effect of flushing and electrode material on MRR, electrode wear, Surface roughness.	The author found that with the use of copper electrode lower surface roughness can be obtained. Flushing increases both MRR and electrode wear.
2.	Mohan et al., (2002)	Work-piece:- Al-SiC MMCs Electrode:- Copper and Brass Powder:- SiC	-	The present article deals with the machining of Al-SiC composite by EDM.	The author found with positive polarity of work-piece. MRR rises with rise in peak current. Surface roughness decreases with decrease in peak current. Rise in quantity of SiC powder in tank leads to lowering of MRR.
3.	Amorim and Weingaertner (2007)	Electrode- copper, graphite Work piece –AISI P20 tool steel Graphite powder	-	This paper deals with the impact of positive and negative polarity of copper and graphite electrode on volumetric relative wear, MRR, surface finish of AISI P20 tool steel	From literature survey it is observed that graphite electrode having –ve polarity gives best result for MRR, both graphite and copper electrode give lowest value of volumetric wear ratio and copper with –ve polarity give best result for surface roughness.
4.	Kung et al., (2007)	Electrode- copper Work piece- WC(6%Co) Aluminium powder	RSM	This paper deals with the effect of aluminium powder concentration on WC alloy. According to the author the MRR increases upto a certain limit with increase in Al powder concentration and after that decreases and vice-versa with EWR.	From literature survey it is found that Al abrasive powders are very useful to enhance the MRR and decrease EWR.
5.	Li Zigong et al., (2018)	Workpiece- Ti-6Al- 4V Electrode- Brass	RSM	In the present article author has lead down a comparison between copper electrode and La2O3 coated copper electrode with different amount of concentration of La2O3 .And found out best concentration of La2O3.	The comprehensive study showed that La2O3 concentration of 1.2g/l showed improved micro-hardness and reduction of 2.61% in electrode wear rate.

The steps in GRA are as follows:

1. Normalization of experimental results
2. Calculating the deviational sequence
3. Calculate GRC (Grey relational coefficient) which represent the relationship between normalized and ideal results.
4. Calculate GRG (Grey relational grade) which is arithmetic mean of GRC (grey relational coefficients).
5. Providing ranks to grey relational grade which will give the optimal result

The normalized value obtained as mentioned in step 1 are obtained using equation (1) “higher is better” for material removal rate and micro-hardness and equation (2) “lower is better” for surface roughness.

$$x_i^*(k) = \frac{x_i^o(k) - \min x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad (1)$$

$$x_i^*(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad (2)$$

Where  $x_i^*(k)$  is normalised value of original sequence,  $x_i^o(k)$  is the  $i^{\text{th}}$  sample of original sequence,  $\max x_i^o(k)$  is maximum value of the original sequence and  $\min x_i^o(k)$  is the minimum value of the original sequence.

#### 4.1. GRC (grey relational coefficient):

The grey relational coefficient  $\gamma_{0,i}(k)$  represents the relationship between normalized and ideal results. The GRC coefficient is expressed in equation (3)

$$\gamma_{0,i}(k) = \frac{\Delta_{\min} + \varepsilon \Delta_{\max}}{\Delta_{0i}(k) + \varepsilon \Delta_{\max}} \quad (3)$$

Where  $\Delta_{\min}$  is minimum deviational sequence,  $\Delta_{\max}$  is maximum deviational sequence,  $\Delta_{0i}(k)$  is deviation sequence and  $\varepsilon$  is distinguishing coefficient which range from 0 to 1 and  $\varepsilon$  is set as 0.5

## 4.2. GRG (Grey relational grade)

The grey relational grade is the arithmetic mean of grey relational coefficient (GRC) as described in the equation (4).

$$\beta_i = \frac{1}{n} \sum_{k=1}^n \gamma_{0,i}(k) \quad (4)$$

Where  $\beta_i$  is the grey relational grade for  $i_{th}$  experiments and  $n$  stands for number of responses.

## 5. Experiment details

The experiments are carried out on EDM MODEL 500 X 300 ENC as shown in Fig 3. Tungsten carbide alloy with 7% cobalt constituent is taken as work-piece and electrolytic copper is taken as electrode material, (as shown in figure 4(a) and (b) specifications in detail are mentioned in the table below, while EDM oil VELVEX EDMVEL-2 is used for experimentation. Properties and specifications of tool and work piece are presented in Table 3. The varying input parameters and levels are shown in Table 4 and the fixed input parameters are shown in Table 5 respectively.

**Table 3.** Properties and specification of Tool and work-piece

S.No.	Tool		Work-piece	
	Properties	Details	Properties	Details
1.	Material	Electrolytic copper	Material	Tungsten carbide (WC)
2.	Composition	99.9% copper	Composition	WC = 93%, Co = 7%
3.	Melting point	1083°C	Melting point	2870°C
4.	Electric resistivity	9 $\mu\Omega\text{cm}$	Thermal conductivity	100W/mK
5.	Density	8.924g/cm <sup>3</sup>	Hardness	85HRC
6.	Dimensions	Diameter = 17mm Height = 20mm	Dimensions	Diameter = 25mm Height = 9mm
7.	-----	-----	Density	14.8 g/cm <sup>3</sup>

**Table 4.** Varying Input parameters and level

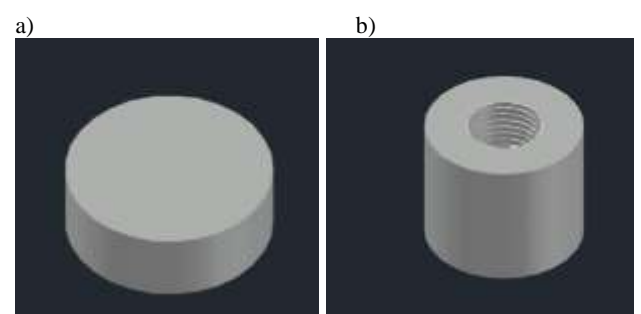
S.No	Factors	Level (-1)	Level (0)	Level(1)
1.	Pulse-on-time ( $\mu\text{s}$ )	10	25	40
2.	Pulse-off-time ( $\mu\text{s}$ )	2	5	8
3.	Current (A)	6	12	18

**Table 5.** Specification of fixed input parameters

S.No	Fixed input parameters	Specification
1.	Work-piece	Tungsten carbide alloy
2.	Tool	Copper
3.	Dielectric	VELVEX EDMVEL-2
4.	Voltage	200V



**Fig. 3.** Experimental set up



**Fig. 4.** Tungsten carbide work piece (a), Copper Electrode (b)

### 5.1. Material Removal rate

To calculate material removal rate initial and final weight of the samples are calculated after each experiment at same conditions as shown in equation (5):

$$\text{MRR} = \frac{W_i - W_f}{t \times d} \quad (5)$$

Where  $w_i$  is initial weight (in g),  $w_f$  is final weight (in g),  $t$  is machining time (in min) and  $d$  is density (in  $\text{g}/\text{mm}^3$ ). MRR is calculated on weighing machine having a least count 0.0001g.

## 5.2. Micro-hardness

Micro-hardness depends upon the load applied ( $P$ ) and the average of the diagonals of imprint ( $d$ ). The indenter is square pyramidal in shape with apex angle of  $136^\circ$  is used. The hardness number is

$$\text{HV} = 1.854 \frac{P}{d^2} \quad (6)$$

Where  $P$  the load is applied and in Newton and  $d$  the average value of two diagonals in millimetre. Micro-hardness (MH) is measured using micro-hardness tester (Model MVH –S AUTO) of ominitech industries Pune, India. Imprint diagonal size is measured using Quintent software. The load of 1kg was applied for a dwell time of 15 second on each sample once.

## 5.3. Surface roughness

Surface roughness is measured on Perthometer (Model SJ-301 of Mitutoyo, Japan). Arithmetic mean method ( $R_a$ ) is used to obtain surface roughness as shown in equation 7.

$$R_a = \frac{1}{L} \int_0^L h(x) dx \quad (7)$$

The equipment has a range of  $0.01 \mu\text{m}$  to  $100 \mu\text{m}$ . Each surface is measured thrice at three places and their average is taken as surface roughness value. The tracing length of 2.5mm is taken every time.

## 6. Parametric optimization of process parameters

In this part grey relational approach is utilized to optimize the EDM parameters.

### GRA (grey relational analysis)

The RSM (Box-Behnken with 5 centre point) gives 17 experiments. Values of material removal rate, micro-hardness, surface roughness are normalized in 0 to 1 range using eq. (1) and eq. (2) as shown in table 6. Grey relational grade values which depict the relationship between ideal and normalized values are calculated using eq. (3) and along with that grey relation grade values which are the average of grey relational coefficients are calculated using eq. (4). The ranks are allotted to all the grey relational grade values in the decreasing order from maximum to minimum as shown in table 7. The average value of grey response for all the input parameters is shown in table 8.

## 7. Results and Discussions

The confirmatory experiment is carried out to find out predicted GRG using equation 8

$$\alpha = \alpha_m + \sum_{k=1}^n (\alpha_k - \alpha_m) \quad (8)$$

Where  $\alpha_m$  = Mean of all GRG values

$\alpha_k$  = Average of GRG value at minimum rank optimize machining parameters for tungsten carbide alloy

The confirmatory experiment values are presented in Table 9, Combinations  $A_1B_1C_2$  and  $A_3B_1C_2$  are the optimal settings, it is observed that from initial setting of  $A_1B_1C_2$  there is increase in material removal rate from 1.0477 to 2.3046, increase in micro-hardness of 1239 to 1361 and decrease in surface roughness from 1.86 to 1.26 and GRG value has also improved from 0.4529 to 0.8632. Hence from the above result it can be said that grey relation is successfully implemented to optimization.

## 8. Conclusions and future scope

The main objective in this work is exploring spark machining process for hard to machine material like tungsten carbide. (93% WC and 7% Co). Firstly experiments were performed in order to determine whether electrodes are acceptable for machining. Then input parameters and their working ranges by referring the literature survey were select-ed to investigate their influence on output characteristics i.e. material removal rate, surface roughness and micro-hardness. For this purpose, seventeen experiments were conducted. Further, to optimize the results, grey relation analysis method is used to handle the multi objective dataset. The best combination for machining Tungsten carbide over the given range is successfully obtained. The results show that experiment 14 has maximum GRG value with the optimal combination i.e. pulse-on-time  $40 \mu\text{s}$ , pulse-off-time  $2 \mu\text{s}$  and current 12A. In the future work other composition of tungsten carbide could be used to increase machining capability of the tungsten carbide. The possibility of using suitable solvent to lower the emission of hazardous fumes can also be explored. The results can be further optimized by using evolutionary optimization techniques like, genetic algorithms, particle swarm optimization or ant bee colony.

**Table 6.** Experimental values of output parameters (MRR, Micro-hardness, surface roughness)

Stand-ard	Run	T <sub>ON</sub> μs	T <sub>OFF</sub> μs	Cur- rent, A	MRR, mm <sup>3</sup> / min	Micro- hardness (HVN)	SR μm
11	1	25	2	18	1.7972	1276	1.06
3	2	10	8	12	1.3067	1228	3.74
7	3	10	5	18	1.0443	1238	2.79
1	4	10	2	12	1.0447	1239	1.86
6	5	40	5	6	1.9348	1315	3.06
4	6	40	8	12	1.9406	1311	2.68
10	7	25	8	6	1.1873	1245	2.87
16	8	25	5	12	1.2737	1273	2.19
12	9	25	8	18	1.5993	1256	2.59
5	10	10	5	6	0.8607	1235	3.98
8	11	40	5	18	2.6959	1341	2.99
9	12	25	2	6	1.2991	1249	1.63
15	13	25	5	12	1.4512	1268	2.26
2	14	40	2	12	2.4126	1346	1.19
14	15	25	5	12	1.2991	1242	1.83
17	16	25	5	12	1.3486	1255	1.97
13	17	25	5	12	1.4443	1248	1.94

**Table 7.** GRA values of MRR, Micro-hardness and surface roughness

Normalized Value			Grey Relational Coefficients			Grey Relational Grade	RANK
MRR	MH	SR	MRR	MH	SR		
0.5103	0.4068	1.0000	0.5052	0.4574	1.0000	0.6542	3
0.2430	0.0000	0.0822	0.3978	0.3333	0.3527	0.3613	16
0.1000	0.0847	0.4075	0.3572	0.3533	0.4577	0.3894	15
0.1003	0.0932	0.7260	0.3572	0.3554	0.6460	0.4529	12
0.5853	0.7373	0.3151	0.5466	0.6556	0.4220	0.5414	5
0.5884	0.7034	0.4452	0.5485	0.6277	0.4740	0.5501	4
0.1780	0.1441	0.3801	0.3782	0.3688	0.4465	0.3978	14
0.2250	0.3814	0.6130	0.3922	0.4470	0.5637	0.4676	11
0.4025	0.2373	0.4760	0.4556	0.3960	0.4883	0.4466	13
0.0000	0.0593	0.0000	0.3333	0.3471	0.3333	0.3379	17
1.0000	0.9576	0.3390	1.0000	0.9219	0.4307	0.7842	2
0.2389	0.1780	0.8048	0.3965	0.3782	0.7192	0.4980	6
0.3218	0.3390	0.5890	0.4244	0.4307	0.5489	0.4680	10
0.8456	1.0000	0.9555	0.7641	1.0000	0.9182	0.8941	1
0.2389	0.1186	0.7363	0.3965	0.3620	0.6547	0.4710	9
0.2659	0.2288	0.6884	0.4051	0.3933	0.6160	0.4715	8
0.3180	0.1695	0.6986	0.4230	0.3758	0.6239	0.4742	7

**Table 8.** Average GRG values for all the Levels

Grey relational grade Parameters	Level (-1)	Level (0)	Level (+1)	Max-Min	Rank	Symbol
T <sub>ON</sub> (μs)	0.3853	0.4832	0.6924	0.3071	1	A
T <sub>OFF</sub> (μs)	0.6248	0.4896	0.4389	0.1859	3	B
Current (A)	0.4437	0.6312	0.5686	0.1875	2	C
Total mean of grey response grade is 0.4831						

**Table 9.** Confirmatory experiment

Process parameters	Initial values A <sub>1</sub> B <sub>1</sub> C <sub>2</sub>	Optimal parameters		Error (Percentage)
		Predicted	Experimental A <sub>3</sub> B <sub>1</sub> C <sub>2</sub>	
MRR	1.0447	-	2.4026	-
SR	1.86	-	1.29	-
GRG	0.5016	0.8822	0.84295	-4.65

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## 碳化钨（93%WC 和 7%Co）的电火花加工的工艺参数的参数优化

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### 關鍵詞

高强度耐热合金，  
碳化钨，  
放电加工，  
非传统加工，  
灰色关联分析

### 摘要

如今，航空航天，国防和电子领域对高强度耐高温（HSTR）合金（如钛，碳化物，镍和陶瓷）的需求巨大。在这些合金中，碳化钨合金由于其众多的应用而受到关注。碳化钨的复杂形状通常不是通过传统的制造工艺制成的。为了高精度地加工碳化钨，非传统的加工工艺（例如激光束加工，电子束加工和放电加工）是一个不错的选择。在本文中，作者用铜电极加工了碳化钨（93%WC 和 7%Co）。在 EDM MODEL 500 X 300 ENC 上以 VELVEX EDMVEL-2 作为介电油进行加工。基于 RSM (Box-Behnken) 方法进行了 17 个实验。此外，为了找到最佳组合，使用了灰色关联方法。结果表明，40 s 的脉冲接通时间，2 s 的脉冲断开时间和 8 A 的电流是加工碳化钨（93%WC 和 7%Co）的最佳组合。最后，进行了确认实验。

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