EXPERIMENTAL STUDY OF THE PROCESS OF ELECTRICAL DISCHARGE DIAMOND GRINDING WITH CHANGING POLARITY OF ELECTRODES

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Abstract: Electro-discharge machining (EDM) characteristics of tungsten carbide-cobalt composite are accompanied by a number of problems such as the presence of resolidified layer, large tool wear rate and thermal cracks. Use of combination of conventional grinding and EDM (a new hybrid feature) has potential to overcome these problems. This article presents the face grinding of tungsten carbide-cobalt (WC-Co) composite with electrical spark discharge incorporated within face of wheel and flat surface of workpiece. A grinding setup for electro-discharge diamond grinding (EDDG) process with changing polarity of electrodes is developed. The effect of input parameters such as wheel speed, current, pulse on-time and duty factor on output parameters such as material removal rate (*MRR*), wheel wear rate (*WWR*) and average surface roughness (*ASR*), are investigated. The present study shows that *MRR* increases with increasing current and wheel speed, while it decreases with increasing pulse polarity reversal time to increase pulse on time (1-5 s). The most significant factor has been found as wheel speed affecting the robustness of EDDG process.

Keywords: diamond abrasive machining, electro-discharge machining, hybrid machining, optimization, tungsten carbide-cobalt composites.

1. Introduction

Advanced engineering materials are having greatly improved thermal, chemical and mechanical properties such as improved strength, heat resistance, wear resistance, and erosion resistance. Applications of these materials are in those areas where high specific characteristics are needed. Composite materials are widely used advanced engineering materials but they use is escalating due to lack of appropriate machining techniques.

Methods with the activation of processes in the cutting zone by initiating electric discharges in it are widely used in the final abrasive processing of such difficult-to-machine conductive materials. The method of diamond spark grinding, developed at NTU "KhPI" at the turn of the last quarter of the last century, continues to be in demand in industrial practice and is an analogue base for new developments in this direction [1, 2].

Electro-discharge machining has been used for machining of WC-Co composites but presence of full surface microcracks are the major problem. Authors of the research have found a new way machining of cemented carbide without surface micro-cracks and reduced cutting forces by using of EDDG process with changing polarity of electrodes [3, 4]. This hybrid machining process has been developed by combining EDM with metal bonded diamond grinding.

In this process, synergetic interaction effect of electro-discharge action and abrasion action are employed to increase the machining performance of constituent processes. The electrical discharges of EDDG cause considerable decrease in grinding forces, and grinding wheel wear; and also effectively resharp the grinding wheel. The abrasive action in this process helps to increase material removal rate (*MRR*) and surface quality.

EDDG is used to cut workpiece into pieces. It is performed using periphery of the thin metal bonded diamond grinding wheel. The grinding wheel is mounted on the ram of the machine such that its axis is parallel to the machine table. While machining, the rotating wheel is fed downward using servo control, for material removal in cut-off configuration. The metallic wheel bond and the work surface are physically separated by the dielectric for a particular voltage setting. The workpiece is thus simultaneously subjected to heating due to electrical sparks, occurring between the wheel bond and the work surface, and abrasion by diamond grains having protrusion height P_h more than the inter-electrode gap-width g_w (Fig. 1).

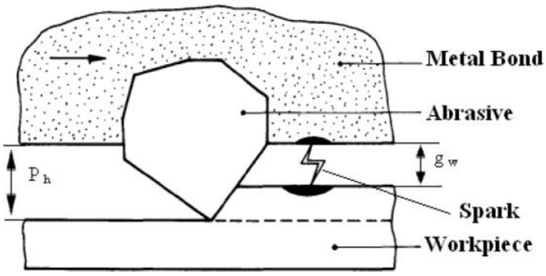

Fig. 1. Schematic representation of a section of the wheel-work interface in EDDG.

EDDG is performed using flat face of the metal bonded diamond grinding wheel. In this mode, the metal bonded diamond grinding wheel rotates about vertical spindle axis and fed in a direction perpendicular to the machine table. While machining, the rotating wheel is fed downwards under the control of servo system. The metal bonded grinding wheel and the work surface are physically separated by a gap, the magnitude of which depends on the local breakdown strength of the dielectric for a particular gap voltage setting. The workpiece is thus simultaneously subject to heating due to electrical sparks occurring between the metal bonded grinding wheel and the workpiece, and abrasion by diamond grains having protrusion height more than the inter-electrode gap.

In EDDG, the most important task is to select appropriate machining parameters for achieving high machining performance. Usually the machining parameters are determined based on pilot experimentation. The most important performance measuring parameters in EDDG are *MRR*, *WWR*, *ASR* and grinding forces. The process parameters affecting the performance measures are wheel speed, current, pulse on-time and duty factor [5].The mechanism of *MRR*, *WWR* and *ASR* during EDDG is very complicated and process dependent. To select the machining parameters properly, several mathematical models [6] based on experimental and analytical approaches are required. Each of these approaches has its own limitations in giving a comprehensive and precise relationship between the machining variables and the machining behavior in a specific situation. In these approaches an objective function with constraints is required to be formulated and further optimal machining parameters can be obtained using optimization techniques. Therefore, considerable knowledge and experience are required to model and optimize the EDDG process.

In this study, an alternative approach based on the Grey relational analysis [7, 8] has been used to determine the optimum machining parameters more efficiently. In the present paper effect of EDDG input parameters such as wheel speed, current, pulse on- time and duty factor on output parameters (*MRR*, *WWR* and *ASR*) has been studied. The paper is organized in the following manner. Presents Taguchi methodology based experimentation. Presents an experimental study done on a newly developed experimental setup on EDM machine to find the parameter settings during EDDG. The next section describes results and discussion. Finally, the paper concludes with a summary of this study.

2. Research Methodology

A face grinding setup for EDDG process has been designed and fabricated. A photograph of the setup is shown in Fig. 2. This setup has been designed keeping in view the fundamental mechanism of the process and basic functional requirements of different parts. The metal bonded diamond grinding wheel and the workpiece are physically separated by a gap the magnitude of which depends on the local breakdown strength of the dielectric for a particular gap voltage setting. The workpiece was thus simultaneously subjected to heating due to electrical sparks, occurring between the metal bonded diamond grinding wheel and the workpiece, and abrasion by diamond grains having protrusion height (P_h) more than the inter-electrode gap width (g_w) (Fig. 1). The setup consists of electrically conductive metal bonded diamond grinding wheel, motor, shaft, V-belt and bearing.

Fig. 2. EDDFG set up assembled on EDM machine

The EDDG is a controlled electro-discharge process assisted by diamond grinding. This system uses a device to change the polarity of the electrodes. The diamond grinding and electro-discharge erosion can be controlled by adjusting wheel feed rate and electro-discharge pulse parameters. The abrasion process helps to speed up the removal of metals (when machining alloys) and both the metal bonds and the non-conductive ingredients (when machining conductive ceramics and composites). In particular, the abrasion can also smooth off the protrusions of non-conductive ingredients so that the electro-erosion can be accelerated. The electro-discharge process in EDDG also helps to dress the metal-bonded grinding wheel on-line as a result of the polarity effect of EDM. Consequently, the grinding wheel can maintain its grinding ability or delay the process of becoming dull. Even the wheel loading (or choking) during grinding material with adhesive chips, can be prevented because of the dressing effect. When properly controlled, the mutual assistance of abrasion and electrical erosion can greatly improve EDDG performance. Experimental studies have been carried out on 3D642E machine, modernized for the process of electrical discharge grinding with changing polarity of electrodes. Additional energy was introduced into the cutting zone from NO 6506 pulse generator, which converts 380V alternating current into a monopolar pulse current. The pulse frequency and relative pulse duration were controlled from the generator. The polarity change was carried out using a device that was connected from the pulse generator to the machine spindle. The machining parameters (or control factors) taken are the wheel speed (1250-2500 RPM), current (4-8A), polarity reversal time pulse on-time (1-5 s), and duty factor (0.50-0.80). The numerical values of factors at different levels are shown in Table 1. The Selection of the parameter range was based on pilot experimentation. The initial setting of parameters was: wheel speed – 1250 RPM, current – 4 A, pulse on-time – 1 s, and duty factor – 0.50.

Table 1. Machining parameters and their levels used in the experiment for WC-Co Composite

Symbol	Machining parameters	Level1	Level 2	Level 3
S	Wheel speed (RPM)	1250	1875	2500
C	Current (A)	4	6	8
T	Pulse on-time (s)	1	3	5
DF	Duty factor	0.50	0.65	0.80

In the present case of four parameters at three different levels assuming no interaction between factors, the total degree of freedom (*dof*) has been calculated by using the following formula: *dof* = (number of levels -1) for each factor + (number of levels -1) (number of levels -1) for each interaction +1: $dof = (3-1) \times 4 + 1 = 9$.

Hence, a standard *L*9 OA was taken for experimentation. The experiments are performed as per standard *L*9 OA (Table 2). The quantitative values of responses *MRR* (mm^3/min), *WWR* (g/min), and *ASR* (µm) for all experimental runs have been tabulated in Table 2.

Table 2. Experimental observations for WC-Co composite using *L*9 OA

Exp.No. -	Factor level				*MRR* (mm^3/min)	*WWR* (g/min)	*ASR* (µm)
	S	*C*	*T*	*DF*			
1	1	1	1	1	0.088	0.012	3.84
2	1	2	2	2	0.296	0.023	3.91
3	1	3	3	3	0.459	0.056	4.04
4	2	1	2	3	0.224	0.007	3.78
5	2	2	3	1	0.642	0.024	4.66
6	2	3	1	2	0.419	0.019	3.49
7	3	1	3	2	0.425	0.008	4.63
8	3	2	1	3	0.557	0.015	4.05
9	3	3	2	1	0.612	0.016	5.11

Experiments were performed on 20 mm diameter of cylindrical workpiece made of WC-10wt%Co composite. The spark erosion oil was used as dielectric liquid. Each workpiece was machined for 10 minutes before measuring output parameters. Performing an experiment more than once, i.e., replicating the experiment can often reduce the effects of variability on experimental results. Single set of experiment will not give any indication of variability. Variability on experimental results can be precisely captured by increasing the number of repetions of each set of experiments by simultaneously experimental cost will increase. Minimum two repetitions are required to avoid variability on experimental results. Three repetitions are the appropriate from both points of view i.e. capturing the variability and avoiding the unnecessary increase in experimental cost. Hence, it was decided to select the trials in random order and to complete three repetitions in each set of experiments. Amount of material removal after 10 minutes was obtained by finding weight difference before and after machining using precision electronic digital weight balance with 0.1mg resolution. The

MRR is calculated by using the following formula:

$$MRR\left(mm^3/\min\right)=\frac{\left(W_i-W_f\right)\times 1000}{t\times \rho},\quad (1)$$

were W is initial weight of workpiece in gram (before machining); W_f is final weight of workpiece in gram (after machining); t is machining time in minutes; p is density of workpiece (14.6 g/cm^3). The *WWR* is calculated by using the following formula:

$$WWR\left(g/\min\right)=\frac{W_{wi}-W_{wf}}{t},\quad (2)$$

were W_{wi} is initial weight of wheel in gram (before machining); W_{wf} is final weight of wheel in gram (after machining); t is machining time in minutes. A Talysurf surtronic 25 at 0.8 mm cutoff value was applied to measure the average surface roughness (*ASR*) of each machined specimen.

3. Experimental study

The experimentation was successfully completed on EDDG using the fabricated attachment on EDM machine. The effect of various input parameters on output parameters was studied during EDDG of WC- Co composite.

3.1 Effect of current

The effect of current on *MRR*, *WWR* and *ASR* is shown in Figs. 3-5, respectively, under the condition of different pulse on-time, 0.65 duty factor and 1875 RPM wheel speed. A metal bonded diamond grinding wheel is used for a machining time of 10 minutes.

The effect of current on the *MRR* is shown in Fig. 3 for pulse on-times of 1 s, 3 s and 5 s. It is seen that within the range of current investigated, *MRR* increase with an increase in current for a particular pulse on-time. This is due to the fact that, as current increase, more energy is discharge per pulse causing more thermal softening from workpiece, so the removal of material is made easier by diamonds grains. The other region for increasing the *MRR* is due to declogging of the wheel by electrical discharge. It is also seen that *MRR* decrease with increasing pulse on-time for above 3 s. This is due to increase pulse on-time on constant duty factor the increase in pulse off-time. The pulse off-time is the time required for re-establishment of insulation in the working gap or deionisation of the dielectric of the end of each discharge duration, thus stabilizing the machining process. A longer pulse off-time increase the overall machining time and hence reduce the *MRR*.

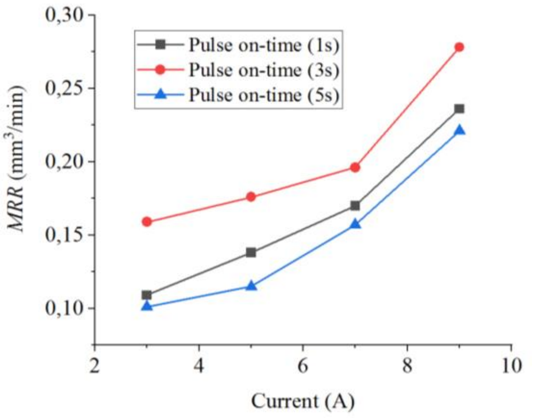

Fig. 3. Effect of current on *MRR* for different pulse on-time (duty factor 0.65, wheel speed 1875 RPM)

It also causes a cooling effect on the wheel and workpiece surface. More energy is required to establish the plasma channel. The effect of current on *WWR* is shown in Fig. 4.

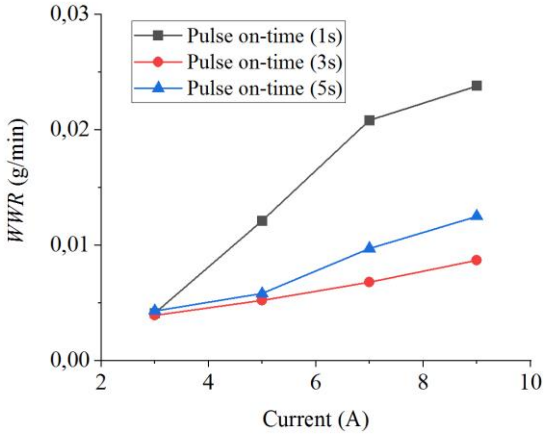

Fig. 4. Effect of current on *WWR* for different pulse on- time (duty factor 0.65,

wheel speed 1875 RPM)

In the experimental range of 3-9 A with a pulse on-time setting of 1 s, 3 s and 5 s. The *WWR* increase with increase current for all pulse on-time, because at high current, the abrasive grains held mechanically in the bond are dislodged rather easily on the application of a tangential grinding load, due to thermal softening of the bond material. It is also observed that there is no variation in *WWR* at current of 4A for pulse on-time of 1 s and 3 s. Observation is also made that *WWR* is least for pulse on-time of 3 s.

The effect of current on *ASR* is shown in Fig. 5. An increase in current results in increased energy per spark. Consequently, the MRR will increase as the energy input increases, resulting in bigger craters on the workpiece and poor surface finish. At higher current, increase in maximum protrusion height of grains also leads to deterioration of surface finish. From Fig. 4 it is also obvious that *ASR* increases with pulse on-time with constant duty factor, wheel speed. For a constant duty factor higher the pulse on-time lower will be the pulse off-time and vice versa. The pulse off-time is the time required for re-establishment of insulation in the working gap or de-ionization of the dielectric at the end of each discharge duration, thus stabilizing the machining process. With too short a pulse off-time, there is not enough time to clear the debris from the inter electrode gap between grinding wheel and the workpiece as well as for de-ionization of the dielectric, so arcing takes place and surface finish deteoriates.

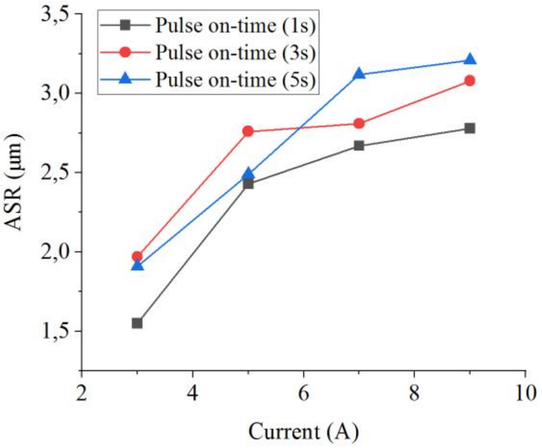

Fig. 5. Effect of current on *ASR* for different pulse on-time (duty factor 0.65, wheel speed 1875 RPM)

3.2 Effect of wheel speed

The effect of wheel speed on *MRR*, *WWR* and *ASR* is shown in Figs. 6-8, respectively, for different value of current. Here, pulse on-time 3 s and duty factor of 0.65 was taken. A metal bonded diamond grinding wheel is used for a machining time of 10 minutes.

The effect of wheel speed on MRR is shown in Fig. 6 for current of 4A, 6A and 8A. It is shown that for a given value of wheel speed the *MRR* is higher for higher current. At high current more discharge energy is supplied between the grinding wheel and workpiece causing more thermal softening from the workpiece, so it is easily removed by diamonds grains. Further, it is also observed that 6A and 8A input current *MRR* increase with increasing wheel speed.

This is because when wheel speed increase, the flow of gap current through the grinding zone by way of spark discharge increase then *MRR* also increase. At current of 4A, the initial increase in *MRR* with wheel speed diminishes at the higher end of the wheel speed is due to wheel glazing.

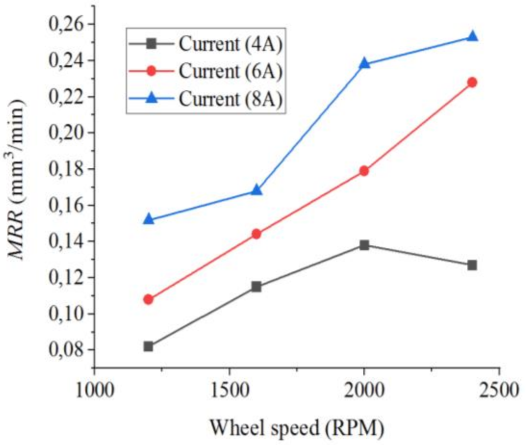

Fig. 6. Effect of wheel speed on MRR at different current (pulse on- time 3 s, duty factor 0.65)

The effect of wheel speed on *WWR* is shown in Fig. 7 for current of 4A, 6A and 8A. It is shown that for a given value of wheel speed the *WWR* is higher for higher current. At high current more energy is supplied between the grinding wheel and workpiece causing more thermal softening from the grinding wheel, so it is easily removed by diamond grains and thermally originated fracture of the abrasive.

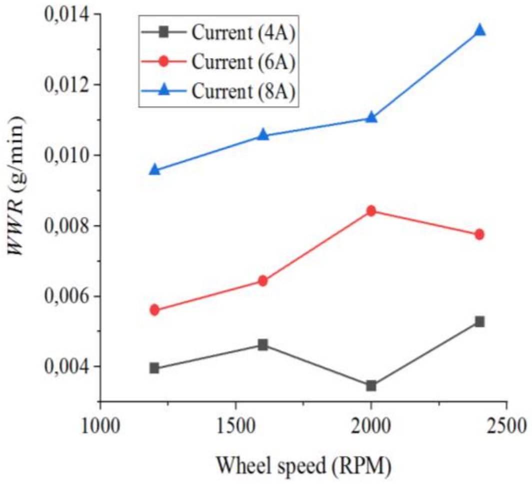

Fig. 7. Effect of wheel speed on *WWR* at different current (pulse on- time 3 s, duty factor 0.65)

Further, it is also observed that at a particular current *WWR* increases with increase in wheel speed. This is due to improved flushing of dielectric and debris is thrown away from working gap. A condition conductive to effective spark discharges is thus created and encourages process stability. The enhance in number of spark discharges per unit time due to effective flushing increases removal rate from workpiece as well as grinding wheel. The experimental results indicate that 1250 RPM the WWR is minimum for 4A.

Effect of wheel speed on *ASR* is shown in Fig. 8 for current of 4A, 6A and 8A.

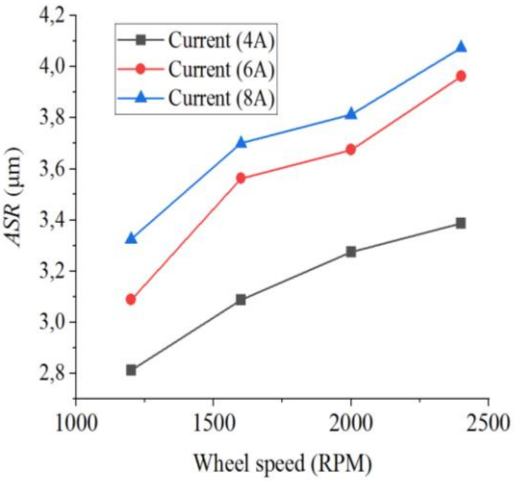

Fig. 8. Effect of wheel speed on *ASR* at different current (pulse on-time 3 s, duty factor 0.65)

The *ASR* increases with increase in wheel speed for all current values, because with an increase in wheel speed, as the number of abrasive-workpiece interaction per unit time increase, the number of spark discharges per unit grain increases.

Larger craters are formed, leading to rough surface finish. It is also seen that with increase in current the *ASR* increase for a particular wheel speed. This may be probably due to formation of more craters over the entire surface of the workpiece, which results is higher *ASR*.

4. Results and discussion

In the present study, *MRR* is larger the better (LB) type and *WWR* as well as *ASR* are smaller the better (SB) type. After data preprocessing, the normalized values for each quality characteristic *MRR*, *WWR* and *ASR*, against different experimental runs have been calculated which is summarized in Table 3.

Table 3. The result of normalization of three response variables

Exp.No.	*MRR*	*WWR*	*ASR*
1	0.1375	0.5776	0.9100
2	0.4618	0.3052	0.8926
3	0.7148	0.1270	0.8639
4	0.3492	1.0000	0.9259
5	1.0000	0.2955	0.7492
6	0.6523	0.3726	1.0000
7	0.6624	0.8502	0.7547
8	0.8675	0.4731	0.8628
9	0.9533	0.4369	0.6831

The grey relational coefficient (GRC) have also been calculated which is shown in tabular form in Table 4. GRC for three quality characteristics of each deviation sequence were calculated keeping distinguishing coefficient ζ at level 0.5.

The calculated weight for *MRR*, *WWR* and *ASR* has been found to be 0.33295, 0.33428, and 0.33273, respectively. GRC values were also computed. Table 5 lists the GRC and grade at each experiment based on L9 orthogonal array.

Table 4. The calculated grey coefficient, grey relational grade and rank

Exp. No.	Grey relational coefficient			Grey relational grade	Rank
	MRR	WWR	ASR		
1	0.3334	0.4994	0.6377	0.4901	7
2	0.4859	0.3775	0.5960	0.4862	8
3	0.4110	0.3256	0.5379	0.4246	9
4	0.5197	1.0000	0.6813	0.7340	1
5	1.0000	0.3743	0.3871	0.5868	3
6	0.5536	0.4018	1.0000	0.6513	2
7	0.5609	0.7377	0.3924	0.5639	5
8	0.7649	0.4444	0.5359	0.5815	4
9	0.9022	0.4280	0.3334	0.5543	6

Table 5. The response table for grey relational grade

Symbol	Machining parameter	Grey relational grade for levels			Effect
		1	2	3	
S	Wheel	0.4670	0.6574	0.5666	0.1904
C	Current	0.5960	0.5515	0.5434	0.0526
T	Pulse on-time	0.5743	0.5915	0.5251	0.0664
DF	Duty factor	0.5437	0.5671	0.5800	0.0363

The sequence with largest grey relational grade (GRD) indicates the closest value to the desired value of the quality characteristics. It is clearly observed from Table 5 and Fig. 9 that the EDDG parameter setting of experiment number 4 has the highest GRD and gives the best multi-performance characteristics.

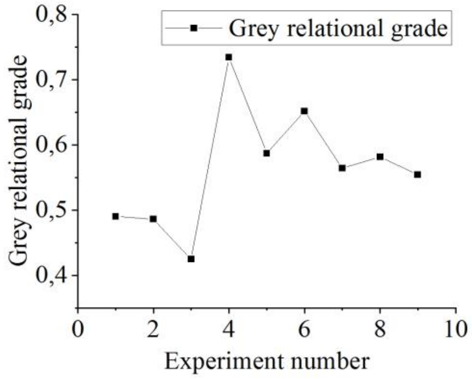

Fig. 9. Variation of grey relational grade with experiment number

The main effects of each control factor on GRD are given in Table 6 and response plot is shown in Fig. 10. The optimum input parameter level corresponds to maximum average GRD is $S_2C_1T_2DF_3$ i.e., wheel speed at 1875 RPM, current at 4 A, pulse on-time 3 s and duty factor 0.80.

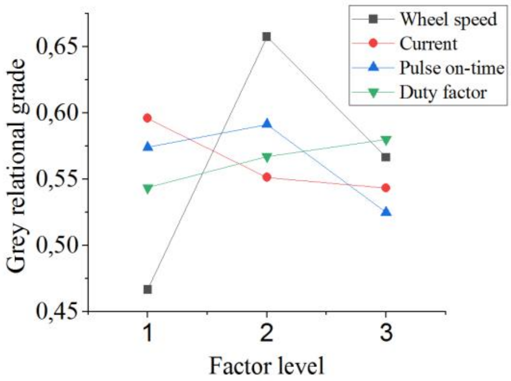

Fig. 10. Grey relational grade graph

The results of ANOVA (Table 6) show the quantitative contribution of current and duty factor.

Table 6. Result of ANOVA (Error (pooled): SS = 0.00684, df = 2, V = 0.0017)

Factor	SS	df	V	F	PC (%)
S	0.05441	2	0.0272	$15.0^{\#}$	79.5
C	0.00481	2	0.00240	Pooled	7.03
T	0.00712	2	0.00356	2.08	10.42
DF	0.00203	2	0.00101	Pooled	2.97
Total	0.06838	8	-	-	100

After conformation run (Table 7), the optimum values of *MRR* (mm^3/min), *WWR* (g/min) and *ASR* (μm) were found.

Table 7. Results of confirmation experiment

Data	Initial Setting	Optimum values	
		Prediction	Experiment
Level	$S_1C_1T_1DF_1$	$S_2C_1T_2DF_3$	$S_2C_1T_2DF_3$
MRR (mm^3/min)	0.05193	-	0.3845
WWR (g/min)	0.0089	-	0.007042
ASR (μm)	3.07	-	3.606
MSNR (dB)	0.4901	0.7341	0.6791

The result of confirmation test shows that quality characteristics *MRR* and *WWR* have been improved considerably, while *ASR* deteriorates slightly. The results of the ANOVA (Table 6) indicate that the control factor S (wheel speed) has the most significant impact on the multiple quality characteristics.

The parameter of control factor S should be carefully set to avoid process variance. We have obtained data on the following contribution of factors to the overall result: duty factor 2.97%, current 7.03%, pulse on-time 10.41%, and wheel speed 79.57%. Three confirmation experiments were conducted at the optimum setting of the machining parameters. The optimum parameter levels were set at the $S_2C_1T_2DF_3$. The average value of *MRR*, *WWR*, and *ASR* were found to be 0.3845 mm^3/min, 0.007042 g/min, and 3.606 μm.

5. Conclusion

The combination of electrical discharge machining and diamond grinding with changing polarity of electrodes improves the machining performance while machining WC-Co composite.

Experiments on WC-10wt%Co composite indicate *MRR* increases with increase in current and wheel speed while it decreases with increase in pulse on-time for higher pulse on-time (above 3 s).The *WWR* and *ASR* increase with increase of wheel speed and current. The factors setting found as best combination of process variables is: wheel speed – 1875 RPM, current – 4A, pulse on-time – 3 s and duty factor – 0.80.

The percentage contributions of different factors in increasing order are: duty factor 2.97%, current 7.03%, pulse on-time 10.41% and wheel speed 79.57% for simultaneous optimization of MRR, WWR and ASR. Hence, the most significant factor affecting the EDDG robustness has been identified as wheel speed.

Improvement in MRR by 86.49%, reduction in WWR by 21.70% but deterioration in ASR by 14.86% have been found during EDDG at the optimum parameter setting against initial parameter setting while performing simultaneous optimization of multiple quality characteristics.

Experimental as well as predicted optimum levels are nearly equal to each other and therefore confirm the success of the experiment.

Bibliography

[1] **Gutsalenko Yu., C. Iancu, T. Tavrina, M. Rucki, and A. Rudnev** (2019) Environmental actuality, technological competitive environment and prediction of the prospects of anhydrous diamond-spark grinding using solid lubricants. *Ann. „Constantin Brancusi” Univ. Targu Jiu, Eng.*

Ser., 2: 13-17.

[2] **Pogrebnoy, N. A., Yu. A. Sizyi, Yu. G. Gutsalenko, and O. A. Volkov** (2007) Steel strengthened surface layer forming as result of thermofriction preprocessing and diamond-spark grinding. *Proc. of the 7th Int. Conf. "Research and Development in Mechanical Industry" (RADMI 2007)*: 241-245.

[3] **Strelchuk, R., and A. Shelkovoy** (2021) Optimization of the interelectrode gap in electrical discharge grinding with changing electrode polarity. *Lect. Notes Mech. Eng. Proc. of the DSMIE-2021*: 143-152.

[4] **Strelchuk, R.** (2020) Investigation of the removal of the diamond layer of a wheel during ED grinding with changing polarity of electrodes. *Ann. „Constantin Brancusi" Univ. Targu Jiu, Eng. Ser.*, 2: 45-49.

[5] **Koshy, P., V. Jain, and G. Lal** (1996) Mechanism of material removal in electrical discharge diamond grinding. *Int. J. Mach. Tools Manuf.*, 36: 1173-1185.

[6] **Choudhury, S., V. Jain, and M. Gupta** (1999) Electrical discharge diamond grinding of high speed steel. *Mach. Sci. Technol.*, 3: 91-105.

[7] **Singh, P., K. Raghukandan, and B. Pai** (2004) Optimization by Grey relational analysis of EDM parameters on machining Al-10%SiCP composites. *J. Mater. Process. Technol.*, 155-156: 1658-1661.

[8] **Thangaraj, M., M. Ahmadein, N. Alsaleh, and A. Elsheikh** (2021) Optimization of abrasive water jet machining of SiC reinforced aluminum alloy based metal matrix composites using Taguchi–DEAR technique. *Materials*, 14: 6250.