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Diamond Face Grinding of WC-Co Composite with Spark Assistance: Experimental Study and Parameter Optimization

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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 composite (WC-Co) with electrical spark discharge incorporated within face of wheel and flat surface of cylindrical workpiece. A face grinding setup for electro- discharge diamond grinding (EDDG) process 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 increase in current and wheel speed while it decreases with increase in pulse on-time for higher pulse on-time (above 100 µs). The most significant factor has been found as wheel speed affecting the robustness of electro- discharge diamond face grinding (EDDFG) process.

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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.[1] 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. Cemented carbides are enjoying over-increasing popularity in industry. Cutting tools are the most common application of cemented carbides based on the tungsten carbide. Other applications of WC-Co composites include wire drawing dies, rock drilling bits and other mining tools, dies for powder metallurgy, indenters for hardness testers, cutting tools for sheet metal operations and other applications where hardness and wear resistance are critical factors.

Electro-discharge machining has been used for machining of WC-Co composites but presence of full surface microcracks are the major problem. Koshy et al.[2] have found a new way machining of cemented carbide without surface micro-cracks and reduced cutting forces by using electrical discharge diamond grinding (EDDG).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 can be operated in three different configurations (1) Electro-Discharge Diamond Surface Grinding (EDDSG) (2) Electro-Discharge Diamond Cut-off Grinding (EDDCG) (3) Electro-Discharge Diamond Face Grinding (EDDFG). Fig. 1 shows the different configurations of EDDG.

EDDSG is used to machine flat surfaces by using periphery of the metal bonded diamond grinding wheel. A metal bonded grinding wheel acts as an electrode required for EDM action. The grinding wheel is mounted on the ram of the machine such that its axis is parallel to the machine table. Since the work is normally held in a horizontal orientation, peripheral grinding is performed by rotating the grinding wheel about a horizontal axis. The relative motion of the workpart is achieved by reciprocating the workpiece. Physical contact between metallic bond and workpiece is avoided by a gap-sensing mechanism of the servo system. In this mode, the thickness of the metal bonded diamond grinding wheel is usually less than that of the workpiece.

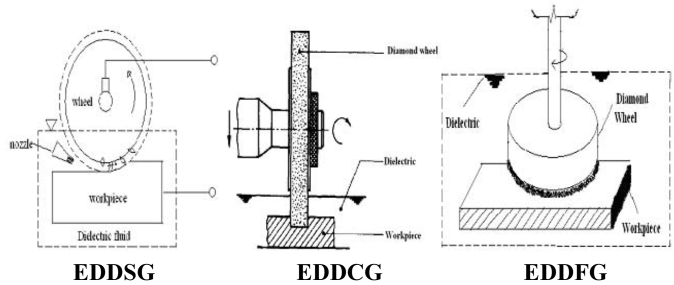

Fig. 1 Configurations of Electro-Discharge Diamond Grinding (EDDG)

EDDCG 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. 2).

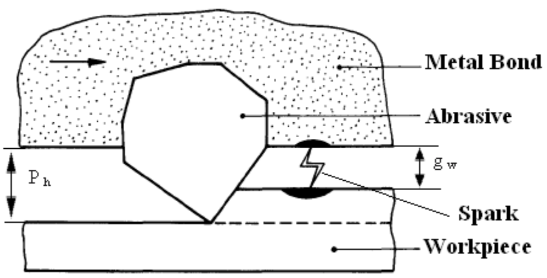

Fig. 2 Schematic representation of a section of the wheel-work interface in EDDFG[10]

EDDFG 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 this mode, the diameter of the metal bonded diamond grinding wheel is usually kept larger than that of the cylindrical workpiece diameter.

In recent past, several attempts[2-10] have been carried out for employing the viability of EDDG. Grodzinskii and other researchers[3-6] have done extensive experimental work on EDDG. But they all are more of an exploratory in nature. The role of electrical discharge on grinding forces, grinding wheel wear, and geometrical accuracy while grooving and cutting-off of cemented carbide and few other advanced ceramics have been experimentally studied by Aoyama and Inasaki.[7] They used electrically conducting diamond grinding wheel which is made by making grooves around the periphery of the wheel to insert resinoid bonded diamond grains of 100 μm grit size. They found that the normal and tangential grinding forces decrease with an increase in the applied voltage at the expense of an increase in wheel wear. Rajurkar et al.[8] have been reported the characteristics of EDM-grinding hybrid process, which they call Abrasive electro-discharge grinding (AEDG). Experiments have been conducted to machine Al-SiC composite, and titanium alloy with copper bonded diamond wheel. The electrical parameters, such as peak current and pulse on-time, and wheel speed as mechanical parameter have been identified to be the main parameters influencing the process responses for a particular wheel and servo reference voltage.

Koshy et al.[9] have been found a way for removing problem of rapid wear of diamond wheel due to graphitization during grinding of ferrous materials (HSS) by using electrical discharge diamond grinding (EDDG). The role of current and wheel speed on the material removal rate, the grinding forces and power consumption have been studied to elucidate the mechanism of material removal. The role of current during EDDG of cemented carbide has also been studied.[2] Such studies are advantageous for exploring the possibility of use of less expensive abrasive in place of costly diamond wheel. Choudhury et al.[10] have studied the effect of current on MRR and grinding forces for different voltage, pulse on-time and duty factor during EDDG of HSS. It has been observed that tangential grinding force decreases with increase in voltage and duty factor for a particular value of current. They have also reported the effect of process parameters on the MRR. They have shown that the feasibility of EDDG has been experimentally tested in cut-off grinding configurations. However, no research work has been observed by the authors so for related to EDDG in face grinding configurations.

In EDDFG, 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 EDDFG are MRR, WWR, ASR and grinding forces. The process parameters affecting the performance measures are wheel speed, current, pulse on-time and duty factor.[9,10] The mechanism of MRR, WWR and ASR during EDDFG is very complicated and process dependent. To select the machining parameters properly, several mathematical models[11-14] 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 EDDFG process.

In this study, an alternative approach based on the Grey relational analysis[11-14] has been used to determine the optimum machining parameters more efficiently. In the present paper effect of EDDFG 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. Section 2 presents Taguchi methodology based experimentation. Section 3 presents an experimental study done on a newly developed experimental setup on EDM machine to find the parameter settings during EDDFG. Section 4 presents the optimization using GRA. The next section describes results and discussion. Finally, the paper concludes with a summary of this study.

2. EDDFG Setup

A face grinding setup (Fig. 3) for EDDG process has been designed and fabricated. A photograph of the setup is shown in Fig. 4. 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. 2). The setup consists of electrically conductive metal bonded diamond grinding wheel, motor, shaft, V-belt and bearing. A brief description of design consideration for some of the components is given below.

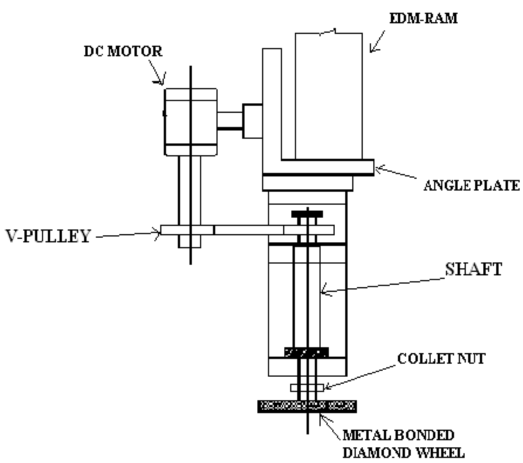

Fig. 3 EDDFG attachment

Fig. 4 EDDFG set up assembled on EDM machine

The primary function of shaft is to rotate the metal bonded diamond grinding wheel. Shaft is a rotating element of the attachment and is held between the two bearings. At one end of shaft metal bonded diamond grinding wheel is mounted and another end V-pulley is mounted for rotation. Design of the shaft requires the selection of some input parameters like material, motor power and motor RPM. Here, steel (C25Mn75) material is used for the shaft.[15,16] A motor of 0.5 kW and 3,000 RPM is used. By calculating the wheel velocity, motor torque, moment of bearing, equivalent twisting moment and yield stress in shear for steel (C25Mn75) the diameter of shaft is calculated as 15 mm. The V-belt is used to transmit power from driver to driven pulley. The belt is provided with a certain amount of initial tension to avoid slip. The V-belt has a trapezoidal cross section so that it contacted the side of pulley also. Belt of width 8 mm and thickness of 4 mm is selected. First tension of belt is calculated and it is compared with the allowable stress and found that belt tension is less than the allowable stress. Therefore the size of the belt which is selected is safe. Bearing is used to support movement of the shaft. It permits a relative motion between the contact surfaces of the members while carrying the load. Selection of the bearing needs the weight of the shaft, grinding wheel and pulley. Based on the values of equivalent load and dynamic capacity the selected bearing is ISI No.6204.[15,16]

Motor is another important part of the attachment and is located on 170 mm × 60 mm vertical flat plate. Motor is used to drive shaft of attachment with the help of belt. In our EDDFG attachment smooth power transmission are required because fluctuation in the speed affects the spark and maximum time of operation continuously is up to 10 hrs. According to these parameters, a single-phase motor of 0.5 kW is selected which capable to provide the speed to the shaft in the range of 500-3,000 RPM. Metal bonded diamond grinding wheel is mounted on the shaft with the help of collar. In EDDFG process wheel rotation is required and gap between both electrodes should be constant during machining. According to the requirements, the specification of selected metal bonded diamond grinding wheel as shown in Table 1.

Table 1 Specification of grinding wheel

Abrasive	Diamond
Grain size	80/100
Grade	M (Medium)
Concentration	75%
Bonding material	Bronze
Depth of abrasive	5 mm
Wheel diameter	30 mm

The EDDFG is a controlled electro-discharge process assisted by diamond grinding. This system uses the ELEKTRA PULS EDM ram servo control system to regulate the wheel feed rates. 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 EDDFG 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 EDDFG performance.

3. Taguchi Methodology-based Experimentation

Experiments were conducted on an ELEKTRA PULS EDM machine attached with self designed grinding attachment in face grinding mode. The machining parameters (or control factors) taken are the wheel speed (700-1100 RPM), current (4-8A), pulse on-time (50-150μs), and duty factor (0.57-0.70). The numerical values of factors at different levels are shown in Table 2. The Selection of the parameter range was based on pilot experimentation. The initial setting of parameters was: wheel speed - 700 RPM, current - 4 A, pulse on-time - 50 μs, and duty factor - 0.57.

Table 2 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)	700	900	1100
C	Current (A)	4	6	8
T	Pulse on-time (μs)	50	100	150
DF	Duty factor	0.57	0.63	0.70

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) × 4 + 1 = 9.

Hence, a standard L_9 OA was taken for experimentation. The experiments are performed as per standard L_9 OA (Table 3). The quantitative values of responses MRR (mm^3/min), WWR (g/min), and ASR (μm) for all experimental runs have been tabulated in Table 3.

Table 3 Experimental observations for WC-Co Composite using L9 OA

Exp.No.	Factor level				MRR	WWR	ASR
	S	C	T	DF	(mm^3/min)	(g/min)	(μm)
1.	1	1	1	1	0.05193	0.008994	3.07
2.	1	2	2	2	0.17430	0.017020	3.13
3.	1	3	3	3	0.26980	0.040890	3.23
4.	2	1	2	3	0.13180	0.005195	3.02
5.	2	2	3	1	0.37740	0.017580	3.73
6.	2	3	1	2	0.24620	0.013940	2.79
7.	3	1	3	2	0.25000	0.006110	3.70
8.	3	2	1	3	0.32740	0.010980	3.24
9.	3	3	2	1	0.35980	0.011890	4.09

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 90 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 90 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:

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

were W_i 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; ρ is density of workpiece (14.6 g/cm^3). The WWR is calculated by using the following formula:

$$WWR(g/\min) = \frac{W_{wi} - W_{wf}}{t} \tag{2}$$

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.

4. Experimental study of EDDFG

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

4.1 Effect of current

The effect of current on MRR, WWR and ASR is shown in Figs. 5-7, respectively, under the condition of different pulse on-time, 0.63 duty factor and 900 RPM wheel speed. A metal bonded diamond grinding wheel is used for a machining time of 90 minutes.

The effect of current on the MRR is shown in Fig. 5 for pulse on-times of 50,100 and 150 µs. 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 100 µs. 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 de-ionisation 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. It also causes a cooling effect on the wheel and workpiece surface. More energy is required to establish the plasma channel.

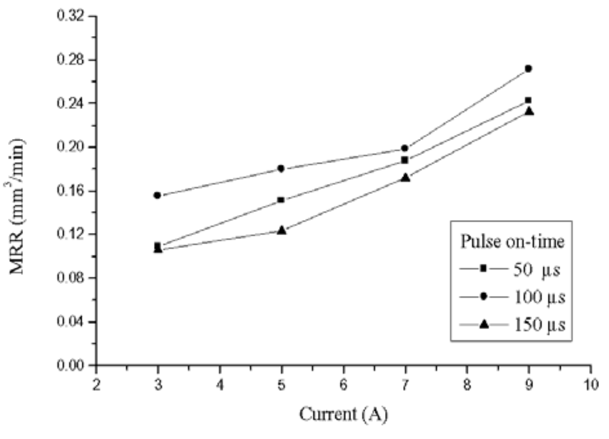

Fig. 5 Effect of current on MRR for different pulse on-time (duty factor = 0.63, wheel speed = 900 RPM)

The effect of current on WWR is shown in Fig. 6. In the experimental range of 3-9 A with a pulse on-time setting of 50 µs, 100 µs and 150 µs. 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 3A for pulse on-time of 50 µs and 100 µs. Observation is also made that WWR is least for pulse on-time of 100 µs.

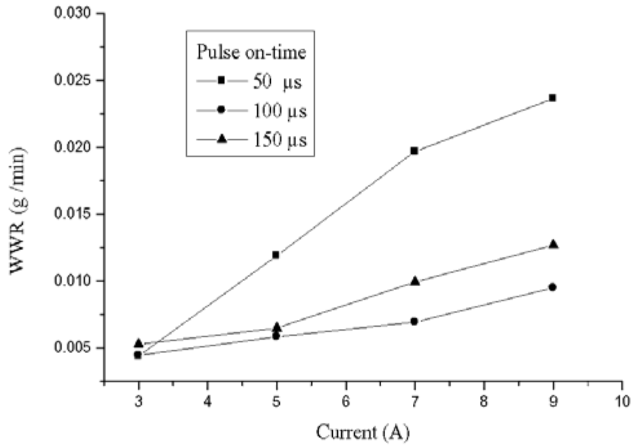

Fig. 6 Effect of current on WWR for different pulse on- time (duty factor = 0.63, wheel speed = 900 RPM)

The effect of current on ASR is shown in Fig. 7. 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. 6 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.

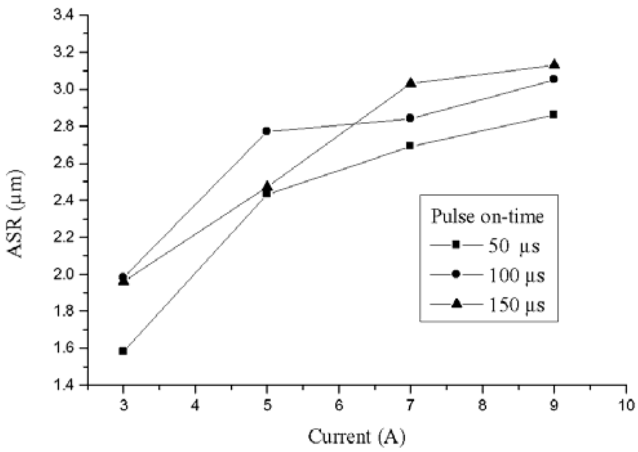

Fig. 7 Effect of current on ASR for different pulse on-time (duty factor = 0.63, wheel speed = 900 RPM)

4.2 Effect of wheel speed

The effect of wheel speed on MRR, WWR and ASR is shown in Figs. 8-10, respectively, for different value of current. Here, pulse on-time 100 μs and duty factor of 0.63 was taken. A metal bonded diamond grinding wheel is used for a machining time of 90 minutes.

The effect of wheel speed on MRR is shown in Fig. 8 for current of 3A, 5A and 7A. 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 5A and 7A 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 3A, the initial increase in MRR with wheel speed diminishes at the higher end of the wheel speed is due to wheel glazing.

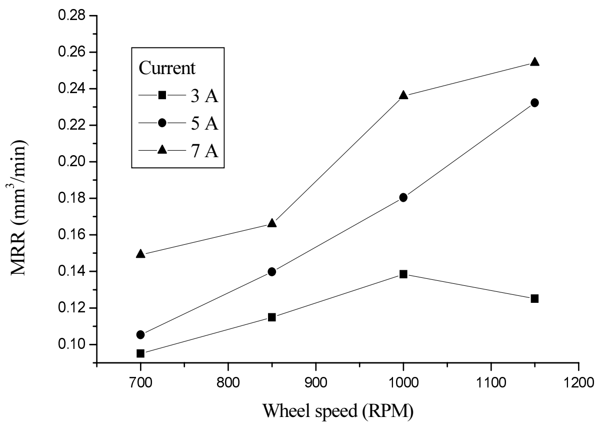

Fig. 8 Effect of Wheel speed on MRR at different current (pulse on-time = 100 μs, duty factor = 0.63)

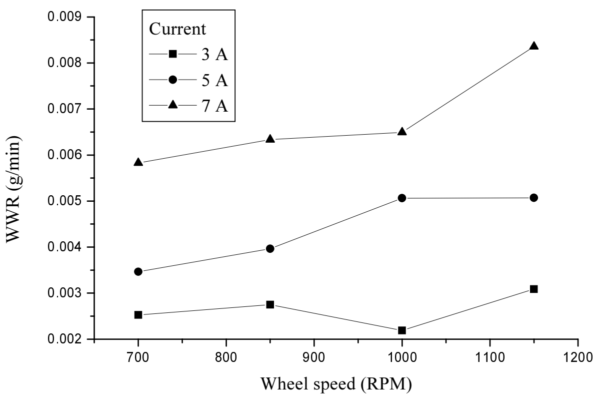

Fig. 9 Effect of Wheel speed on WWR at different current (pulse on- time = 100 μs, duty factor = 0.63)

The effect of wheel speed on WWR is shown in Fig. 9 for current of 3A, 5A and 7A. 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. 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 1000 RPM the WWR is minimum for 3A.

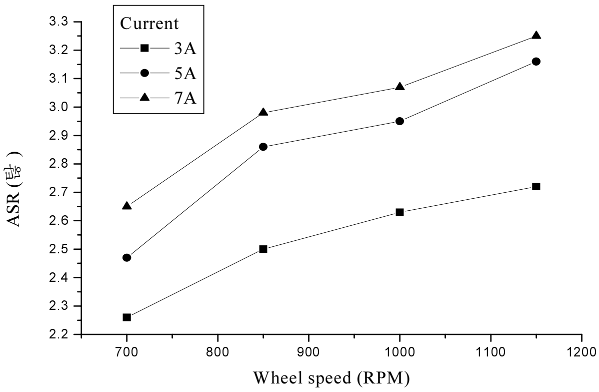

Fig. 10 Effect of Wheel speed on ASR at different current (pulse on-time = 100 μs, duty factor = 0.63)

The effect of wheel speed on ASR is shown in Fig. 10 for current of 3A, 5A and 7A. 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.

5. Optimization using GRA

Electro-discharge diamond face grinding (EDDFG) is a hybrid machining process in which a metal bonded diamond grinding wheel removes material by mechanical erosion, and it also acts as an electrode for electro-discharge action, which results in thermal erosion. Adjusting wheel speed and electro-discharge pulse parameters can control the mechanical grinding and electro-discharge erosion. For the evaluation of machining performance of EDDFG MRR, WWR and ASR are considered as output parameters. Higher MRR, better ASR, and lower WWR can be obtained by proper selection of EDDFG parameters.

In GRA, when the range of sequences is large or the standard value is large, the function of factors is neglected. However, if the factors measured unit, goals and directions are different, the grey relational analysis might produce incorrect results. Therefore, original experimental data must be pre-processed to avoid such effects. Data pre-processing is the process of transforming the original sequence to a comparable sequence. For this purpose, the experimental results are normalized in the range of zero and one, the process is called grey relational generating. Three different types of data normalization according to whether we require the Smaller the better (SB), the Larger the better (LB), and Nominal the better (NB).[17] The normalization is taken by the following equations.

Smaller the better (SB)

$$X_i^*(k) = \frac{\min X_i(k)}{X_i(k)} \tag{3}$$

Larger the better (LB)

$$X_i^*(k) = \frac{X_i(k)}{\max X_i(k)} \tag{4}$$

Nominal the better (NB)

$$X_i^*(k) = \frac{\min\{X_i(k), X_{ob}(k)\}}{\max\{X_i(k), X_{ob}(k)\}} \tag{5}$$

Where i =1,2,…,m; k =1,2,…,n; $X_i^*(k)$: the normalized value of the k^{th} element in the i^{th} sequence, $X_{ob}(k)$: the desired value of the k^{th} quality characteristics, max $X_i(k)$ is the largest value of $X_i(k)$, and min $X_i(k)$ is the smallest value of $X_i(k)$, m is the number of experiments and n is the number of quality characteristics.

A grey relational coefficient is calculated to display the relationship between the optimal and actual normalized experimental results. The grey relational coefficient can be expressed as

$$r_{0,i}(k) = \frac{\Delta\min + \zeta\Delta\max}{\Delta_{0,i}(k) + \zeta\Delta\max}, \quad i = 1,...,m\ ;\ k = 1,...,n \tag{6}$$

Where $r_{0,i}(k)$ is the relative difference of k^{th} element between comparative sequence X_i and the reference sequence X_0 (also called as grey relational coefficient), $\Delta_{0,i}(k)$ is the absolute value of difference between $X_0(k)$ and $X_i(k)$,

$$\Delta_{0i}(k) = \left|X_0^*(k) - X_i^*(k)\right|$$
$$\Delta\max = \max_i \max_k \left|X_0^*(k) - X_i^*(k)\right|$$
$$\Delta\min = \min_i \min_k \left|X_0^*(k) - X_i^*(k)\right|$$

ζ is a distinguishing or identification coefficient, and its value lie between zero and one. In general, it is set to 0.5.[18]

The average grey relational coefficient is the grey relational grade. But, the importance of each quality characteristic may be different. To overcome this problem, the grey relational grade is computed by using entropy measurement[19] (to determine the corresponding weights of the quality characteristics).

$$\Gamma_{0,i} = \sum_{k=1}^{n} w_k r_{0,i}(k), \quad i = 1,2,...,m \tag{7}$$

The weight (w_k, Σw_k = 1) for each performance characteristic can be computed by using the entropy method. In information theory, entropy is a measure of how disorganized a system is. As applying the concept of entropy to weight measurement, an attribute with a large entropy means it has a great diversity of responses so the attribute has a more significant influence on the response.[20] Recently, entropy measurement method was used to decide the weights in grey relational analysis. According to the definition proposed by,[19] the mapping function f_i: [0,1]→[0,1] used in entropy should satisfy three conditions: (1) $f_i(0) = 0$, (2) $f_i(x) = f_i(1-x)$, (3) $f_i(x)$ is monotonic increasing in the range of $x \in (0, 0.5)$.Thus, the following function $w_e(x)$ can be used as the mapping function in entropy measure.

$$w_e(x) = xe^{(1-x)} + (1-x)e^x - 1 \tag{8}$$

The maximum value of this function occurs at x = 0.5, and the value $e^{0.5}-1 = 0.6487$.In order to let the mapping result in the range (0, 1),[19] defined new entropy as

$$W \equiv \frac{1}{(e^{0.5}-1)} \sum_{i=1}^{m} w_e(x_i) \tag{9}$$

The proposed a step by step procedure to calculate the weights of each quality characteristics, those are as follows.[19]

Sum of the grey relational coefficient in all sequences for each quality characteristic

$$D_j = \sum_{i=1}^{m} r_i(j), \quad j = 1,...,n \tag{10}$$

Normalized coefficient

$$k = \frac{1}{(e^{0.5}-1)\times m} = \frac{1}{0.6487\times m} \tag{11}$$

Entropy of each quality characteristic

$$e_j = k\sum_{i=1}^{m} w_e\left(\frac{r_i(j)}{D_j}\right), \quad j = 1,...,n \tag{12}$$

Sum of entropy

$$E = \sum_{j=1}^{n} e_j \tag{13}$$

Weight of each quality characteristic

$$w_j = \frac{\frac{1}{n-E}\left[1-e_j\right]}{\sum_{j=1}^{n}\frac{1}{n-E}\left[1-e_j\right]}, \quad j = 1,...,n \tag{14}$$

Grey relational grade can be calculated by multiplying grey relational coefficients with their corresponding weight of quality characteristics.

6. 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 using Eqs. (3) and (4) which is summarized in Table 4. The grey relational coefficient for three quality characteristics, against different experimental runs have also been calculated using Eq. (6) which is shown in tabular form in Table 5.The grey relational coefficients for three quality characteristics of each deviation sequence were calculated using Eq. (6) keeping distinguishing coefficient ζ= 0.5. The calculated weight for MRR, WWR and ASR has been found to be 0.33295, 0.33428, and 0.33273, respectively. The grey relational grade values were also computed using Eq. (7). Table 5 lists the grey relational coefficient and grade at each experiment based on L_9 orthogonal array. The sequence with largest grey relational grade indicates the closest value to the desired value of the quality characteristics. It is clearly observed from Table 5 and Fig. 11 that the EDDFG parameter setting of experiment number 4 has the highest grey relational grade. Thus, the fourth experiment gives the best multi-performance characteristics among the 9 experiments.

Table 4 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

Table 5 The calculated grey relational co-efficient, grey relational grade and rank

Exp. No.	Grey relational co-efficient			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 6 The response table for grey relational grade

Symbol	Machining parameters	grey relational grade			Effect	Rank
		Level 1	Level 2	Level3		
S	Wheel speed	0.4670	0.6574	0.5666	0.1904	1
C	Current	0.5960	0.5515	0.5434	0.0526	3
T	Pulse on-time	0.5743	0.5915	0.5251	0.0664	2
DF	Duty factor	0.5437	0.5671	0.5800	0.0363	4

The main effects of each control factor on grey relational grade are given in Table 6 and response plot is shown in Fig. 12. The optimum input parameter level corresponds to maximum average grey relational grade is $S_2 C_1 T_2 DF_3$ i.e., wheel speed at 900 RPM, current at 4 A, pulse on-time 100 μs and duty factor 0.70. The results of ANOVA (Table 7) show the quantitative contribution of each control factor on performance. The quantitative contributions of input factor in increasing order are wheel speed, pulse on-time, current and duty factor. The value of MRR (mm^3/min), WWR (g/min) and ASR (μm) at this optimum level has been found as 0.3845, 0.007042 and 3.606, respectively, after conformation run (Table 8). 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 7) 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. The percentage contribution of each control factor to the total variance is 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 $S_2 C_1 T_2 DF_3$. 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.

Table 7 Result of ANOVA

Factor	SS	df	V	F	PC (%)
S	0.05441	2	0.02720	15.90#	79.58
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
Error (Pooled)	0.00684	2	0.00171		
Total	0.06838	8			100

* pooled factors, Tabulated F-ratio at 95% confidence level: $F_{0.05; 2; 4} = 6.94$

Significant at 95% confidence level

Table 8 Results of confirmation experiment

	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

Improvement of the grey relational grade = 0.189

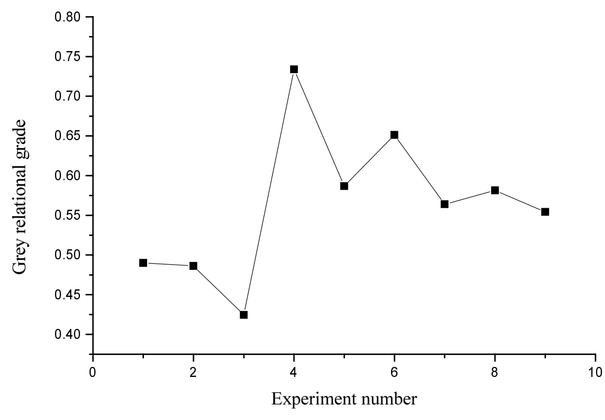

Fig. 11 Variation of grey relational grade with experiment number

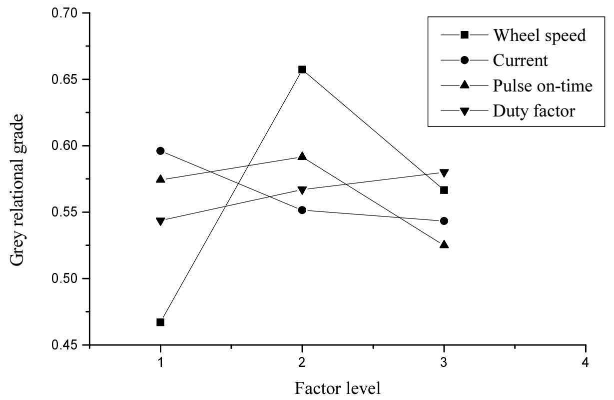

Fig. 12 Grey relational grade graph

7. Conclusions

Based on experiments, results the conclusions are summarized as follows:

1. The combination of electrical discharge machining and diamond face grinding improves the machining performance while machining WC- Co Composite.
2. Electro-discharge diamond face grinding experiments on WC-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 100 μs).The WWR and ASR increase with increase of wheel speed and current.
3. The factors setting found as best combination of process variables is: wheel speed- level 2 (900 RPM), current- level 1 (4A), pulse on-time-level 2(100 μs) and duty factor- level 3 (0.70).
4. The percentage contribution of different factors in increasing order is 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 EDDFG robustness has been identified as wheel speed.
5. Improvement in MRR by 86.49%, reduction in WWR by 21.70% but deterioration in ASR by 14.86% have been found during EDDFG at the optimum parameter setting against initial parameter setting while performing simultaneous optimization of multiple quality characteristics.
6. Experimental as well as predicted optimum levels are nearly equal to each other and therefore confirm the success of the experiment.

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