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Research paper

Application of a Hybrid Approach Using PCA based TOPSIS Method for Multi Objective Optimization of EDM Process Parameters During Machining of H11 Die Steel Using P/M Processed Metal Matrix Composite

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Abstract

Metal matrix composites (MMC) are found to have many applications in the space and aviation industries. This paper presents the details of a comparative study made on the machinability of H11 die steel by electric discharge machining (EDM) process using copper and powder metallurgy (P/M) processed Cu-Cr MMC as the tool. Taguchi method was used for the experimental design and experiments were conducted using L_9 orthogonal array for each tool. The present work investigates the influence of machining parameters such as peak current (I_p), pulse on time (T_{on}), duty cycle (DC) and gap voltage (V_g) on material removal rate (MRR), tool wear rate (TWR), diametral overcut (DOC) and surface roughness (SR). Cu-Cr composite tool demonstrates better performance than copper tool. Multi-objective optimization was performed using a combination of principal component analysis (PCA) with technique for order of preference by similarity to ideal solution (TOPSIS) to achieve the optimum parameter setting for copper and Cu-Cr tool. The optimal results obtained for copper tool was at I_p=3A, T_{on}=150µs, DC=80%, V_g=40V and for Cu-Cr tool was at I_p=3A, T_{on}=200µs, DC=90%, V_g=50V.

***Keywords**: Electric Discharge Machining, Metal matrix composite, PCA, Powder Metallurgy, Taguchi, TOPSIS*

1. Introduction

Over the last few decades, the developments in metal matrix composites are being much focused by several researchers and industrialists for their application in aerospace, defense and automotive industries [1]. The applications require a superior performance under high cycle fatigue loading conditions. The traditional machining techniques are incompetent for machining MMCs because of higher manufacturing cost and surface roughness. The reinforcing components in MMCs often make it difficult and uneconomical to be machined by traditional methods. Hence, non-conventional machining process such as EDM is a significant method for processing of MMCs due to its capability to machine intricate geometries with higher accuracy [2]. EDM removes material with a sequence of continuous discharge between the electrodes. The temperature rises to 8000-12000℃ that results in melting and evaporation the workpiece. Usually copper and graphite materials are used as tool electrodes in EDM. But for prolonged machining, high tool wear is the foremost shortcoming of these tools. Hence, study is going on to develop a high electrical, thermal and wear resistant tool for EDM which is easily fabricable and available.

2. Literature Survey

Various researchers are aiming to fabricate composite tool electrode for EDM by powder metallurgy. Some MMCs such as tungsten-copper, copper-tungsten carbide, copper-chromium, copper-zirconium bromide, etc. have been used as tool electrode for EDM which give better performance than the conventional copper or graphite tools [3-7]. Studies show that machining using W–Cu MMC tool was lesser than Cu tool [8]. EDM process under reverse polarity condition using WC–Cu composite tool demonstrated enhanced wear resistance of machined surface. The Cr–Cu composite gives not only higher MRR, thinner recast layer, better corrosion resistance of workpiece and less cracks were observed using Cu-Cr composite tool as compared to Cu electrodes [9]. Fabrication of ZrB2–Cu composite by infiltration method gives high MRR and low TWR than Cu and graphite tool [10]. During the machining of En31 steel by EDM process using P/M processed Cu-Cr-Ni MMC as the tool, hard alloyed layer was formed and the surface roughness measured was 3.19µm [11]. EDM of H11 steel was conducted by means of various tool materials and results showed that copper electrode exhibited higher MRR than the CuW composite electrode. Also it has been noticed that each machining parameter has an effect on the surface roughness during the process [12]. Multi-criteria optimization of the process parameters has been performed using a hybrid technique of PCA and TOPSIS while machining H11 die steel by P/M processed Cu-Cr-Ni MMC [13] and a combination of PCA and fuzzy inferences scheme with Taguchi technique for $AlSiC_p$ composite has also been conducted [14].

The past study shows that much work has been done using MMC as workpiece material, but extensive research has not been carried out by using metal matrix composite as tool material. In addition, no work has yet been reported using Cu-Cr MMC and H11 die steel as tool and work piece respectively. Therefore a comparision between the machining performance of copper and Cu-Cr composite tool on H11 die steel is necessary. The present study aims at machining of H11 die steel by electric discharge machine using copper and Cu-Cr composite tools and evaluate the effect of input parameters that is I_p, V_g, DC and T_{on} on the response characteristics MRR, TWR, DOC and SR. Multi-criteria optimization has been used to achieve the optimum parameter set by combining PCA with TOPSIS to achieve highest MRR and lowest TWR, DOC and SR.

3. Methodology

3.1 Setup of the Experiment

The present study involves the use of die sinking type EDM machine of model Electronica Smart ZNC, as shown in Figure.1 The dielectric employed in the device was commercial grade EDM oil. The work material chosen for the experiment was H11 die steel with a dimension of 118.8 x 84.2 x 19.0mm. It is a chromium hot work steel with high wear resistant, compressive strength properties having composition 5% chromium, 0.35% carbon, 1% silicon, 0.4% manganese, 0.03% phosphorous, 0.02% sulphur, 1.5% molybdenum, 0.01% cobalt, 0.01% copper, 0.45% vanadium. Conventional copper and Cu-Cr MMC having 10mm diameter and 20mm length were chosen as the tool material. The Cu-Cr composite is composed of 80% copper by weight comprising the matrix and 20% chromium by weight which is the reinforcement. The MMC tool has been fabricated by powder metallurgy process with the sintering temperature of 650° C and compacting pressure of 4tons. The machining time taken for each experimental run was of 15 minutes. The roughness of the machined surface was determined by means of a profilometer having a portable stylus.

Figure 1: Electric Discharge Machine

3.2 Experimental Design

The experiments were carried out by using the Taguchi method. As shown in Table 2, four parameters were considered in this study each varied at three levels. Taking the number of aspects and the levels into account, Taguchi's L_9 orthogonal array was chosen to design the experiments.

Table 1: Input parameters and the levels

Parameters(Units)	Levels		
	1	2	3
I_p (A)	3	6	9
T_{on} (µs)	100	150	200
DC	7	8	9
V_g (V)	30	40	50

3.3 Principal Component Analysis (PCA):

For achieving the optimum set of processing parameters involving highest MRR and lowest TWR, SR and DOC simultaneously, PCA technique has been implemented. The values of the output variables attained during the welding were normalized. The normalized data obtained lies within the range 0 to 1; 1 regarded as the most suitable value and 0 as the least suitable value. The steps of PCA method are given below:

(i) The normalized value for 'higher-the-better' and 'lower-the-better' measure is performed by means of eq. (1) and (2):

$$X_a^*(b) = \frac{x_a - [\min(x_a(b))]}{[\max(x_a(b))] - [\min(x_a(b))]} \quad . \tag{1}$$

$$X_a^*(b) = \frac{[\max(x_a(b))] - x_a}{[\max(x_a(b))] - [\min(x_a(b))]} \tag{2}$$

where, a = 1,2,....,i experimental runs
b = 1,2,.....,j output parameters
$X_a^*(b)$= the value of output parameter b after normalization

(ii) The relation between every pair of quality aspects (j and k) has been scrutinized by means of eq. (3).

$$\rho_{bc} = \frac{\mathrm{cov}(Q_b - Q_c)}{\sigma_{Q_b} * \sigma_{Q_c}} \tag{3}$$

where, b= 1,2,.....,m c= 1,2,....,m b≠c
where, ρ_{bc} is correlation coefficient, σ_{Qb} and σ_{Qc} indicates standard deviation of b and c respectively.

(iii) Evaluation of the principal component score (PCS):
a. The calculation of Eigen value λ_c and the comparative Eigen vector β_{cb}c = (1, 2,...m) was done from the correlated matrix generated from all the quality aspects.
b. The PCS of the relative and standardized reference series are computed from eq. (4) as given below:

$$Y_a(c) = \sum_{b=1}^{m} X_a^* \beta_{cb} \tag{4}$$

where, a=0,1,2,....m c= 1,2,.....m
$Y_a(c)$ is the PCS of the c^{th} factor in the a^{th} sequence. $X_a^*(b)$ is the standardized value of the b^{th} factor in the a^{th} series, and β_c is the b^{th} factor of Eigen vector β_c

(iv) Estimation of quality loss $\Delta_{0,1}(c)$ is described as the total value of subtraction of a^{th} experimental value for c^{th} output and the ideal value. It is determined by $[Y_0(c) Y_a(c)]$.

3.6 TOPSIS

TOPSIS states that the preferred option should have a negligible distance from the positive ideal solution and extreme distance from the negative ideal solution (N. P Senapati, S. Tripathy, S. Samantaray, 2016). The optimal set of data attained by PCA procedure is merged with TOPSIS technique to obtain the optimal parameter set. The procedure is illustrated as follows:

(i) The principal components obtained in step-(iv) of PCA method are arranged in the decision matrix form and the input data are set in the manner shown below:

$$D_m = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

(ii) Normalized values of decision matrix are obtained using eq. (5):

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \quad (5)$$

where, r_{ij} signifies the normalized value of A_i regarding characteristic X_j.

(iii) Expanded values of weighted normalized decision matrix, $V=[V_{ij}]$ are determined from eq. (6):

$$V = W_j r_{ij} \quad (6)$$

where, $\sum W_j = 1$

(iv) The positive and negative ideal solutions are calculated using eq. (7) and eq. (8) respectively.

$$A^+ = \{(\max v_{ij}, iCj), (\min v_{ij}, iCj)\} \quad (7)$$

$$= \{v_1^+, v_2^+, \ldots \ldots v_j^+ \ldots \ldots v_n^+\}$$

$$A^+ = \{(\min v_{ij}, iCj), (\max v_{ij}, iCj)\} \quad (8)$$

$= \{v_1^-, v_1^-, \ldots.. v_1^- \ldots. v_1^-\}$
Here, j= {1, 2, 3…….n}

(v) Every option of the ideal solution is accomplished from n-dimensional Euclidean distance that can be calculated using eq. (9) and eq.(10):

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \quad i= 1,2,\ldots.n \quad (9)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad i= 1,2,\ldots.n \quad (10)$$

(vi) The comparative closeness to ideal solution is illustrated by eq. (11):

$$C_i^+ = \frac{S_i^+}{S_i^+ + S_i^-} \quad (11)$$

The excellent alternative can be acquired with highest relative coefficient value.

4. Results and Discussion

4.1 Influence of machining parameters on MRR:

Figure 4.1 exhibits the behaviour of MRR with input parameters. The increasing peak current generates a spark and leads to quick melting and evaporation of material thereby increasing the MRR. With the increase in T_{on}, the plasma channel becomes wider and positive ions attack the workpiece more actively, further causing melting and vaporization of the work material which further increases the MRR. This variation occurs with increasing V_g the spark energy intensifies and the temperature of the job surface rises causing material melting and hence increasing the MRR.

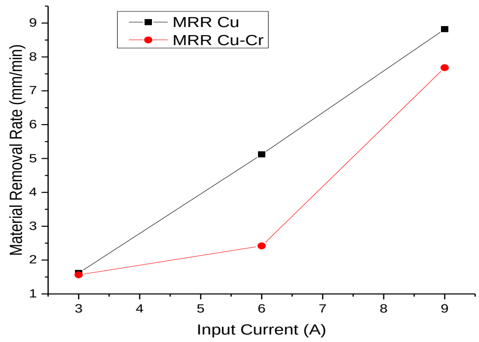

Figure 4.1.1: I_p vs MRR

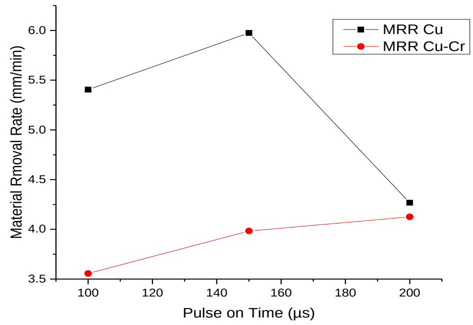

Figure 4.1.2: T_{on} vs MRR

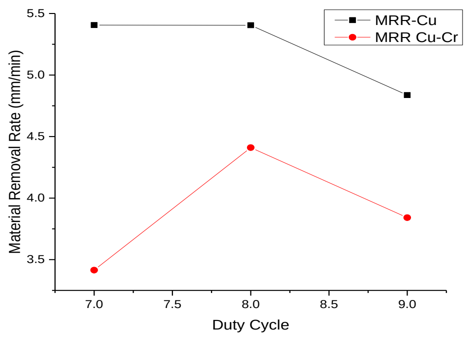

Figure 4.1.3: DC vs MRR

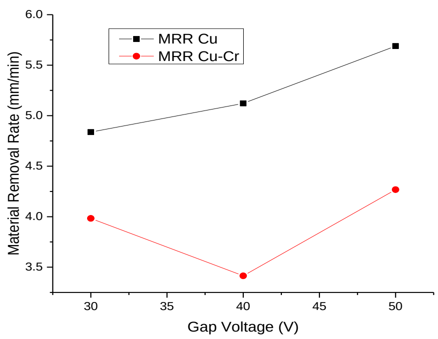

Figure 4.1.4: V_g vs MRR

4.2 Effect of machining parameters on TWR:

Figure 4.2 exhibits the behaviour of input parameters with TWR. With increasing I_p, there is increase in spark energy which results in high temperature that melts and vaporizes the tool and the work material. At the starting of electric discharge, the size of plasma channel is smaller and lighter electrons shift along the direction of the tool and causes erosion of the tool. But with time the plasma channel's size is increased and more positive ions shift in the direction of the job and more removal of the material from the workpiece occurs. With increasing V_g, the pulse energy increases. As one end of the pulse is on the tool and other end is on workpiece, this amplifies the amount of tool wear.

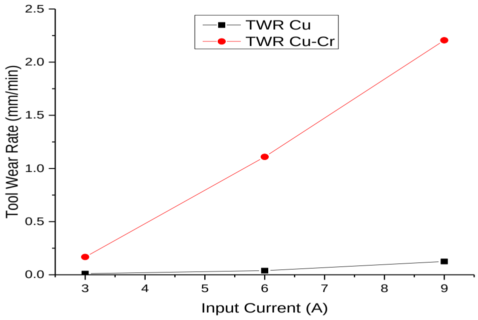

Figure 4.2.1: I_p vs TWR

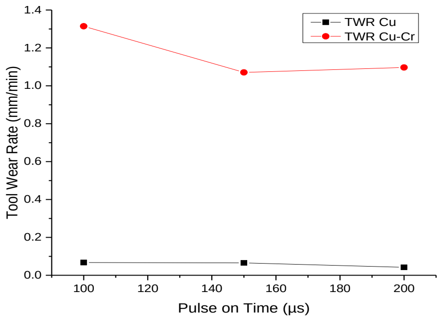

Figure 4.2.2: T_{on} vs TWR

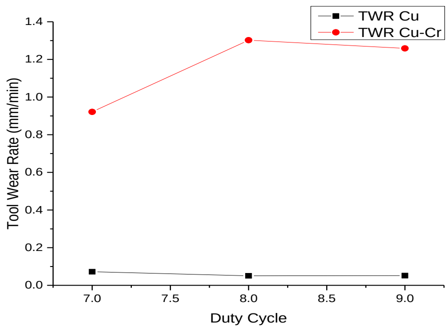

Figure 4.2.3: DC vs TWR

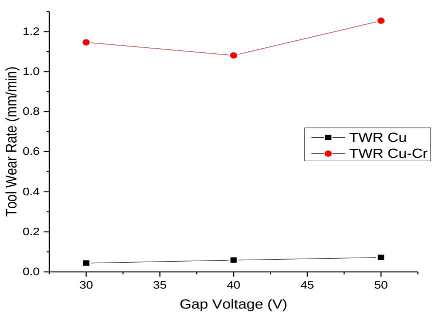

Figure 4.2.4: V_g vs TWR

4.3 Effect of machining parameters on Diametral overcut:

Figure 4.3 exhibits the behaviour of input parameters with DOC. With the increase in I_p there is increase in spark energy and the wearing away of material occurs the job surface creating a cavity larger than the tool. The plasma channel diameter increases with increase in T_{on}, because of which the electrons attack the surface more rapidly causing greater sparks and eroding the material with greater overcut. Increase in V_g creates greater spark energy due to which the workpiece surface gets heated and melts the material.

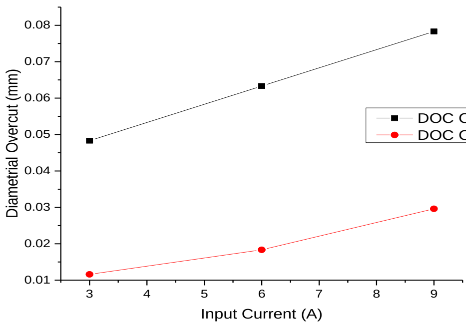

Figure 4.3.1: I_p vs DOC

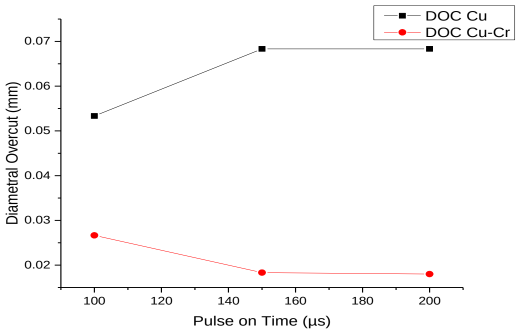

Figure 4.3.2: T_{on} vs DOC

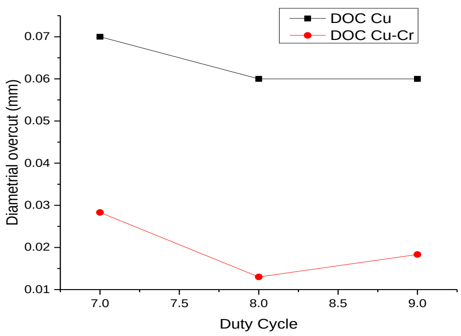

Figure 4.3.3: DC vs DOC

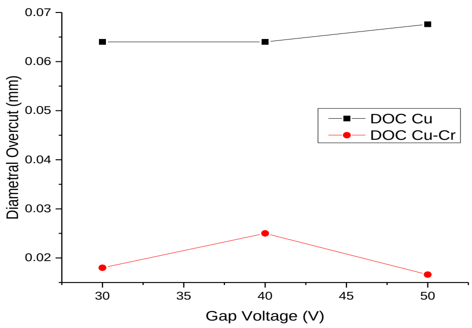

Figure 4.3.4: V_g vs DOC

4.4 Influence of input parameters on SR:

Figure 4.4 shows the behaviour of process parameters with SR. The increase in SR is caused by increasing spark energy that results in surface crater on the workpiece. The increased discharge energy of plasma channel and the duration of energy transfer to the tool leads to the development of a larger depression on the molten workpiece material resulting in greater SR. The gap voltage does not have much effect on SR.

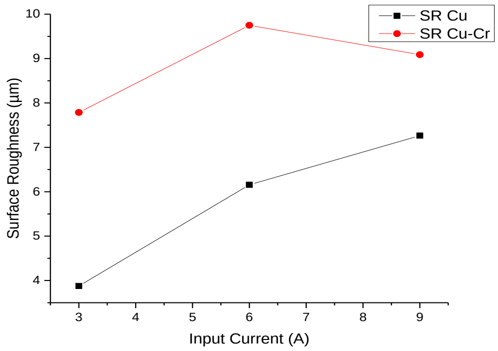

Figure 4.4.1: I_p vs SR

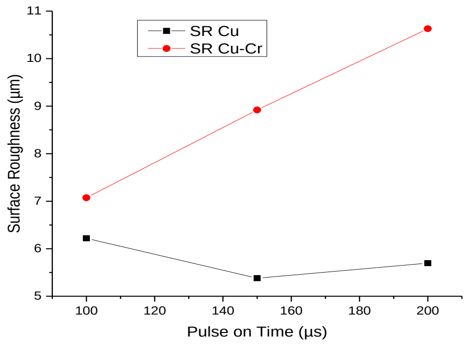

Figure 4.4.2: T_{on} vs SR

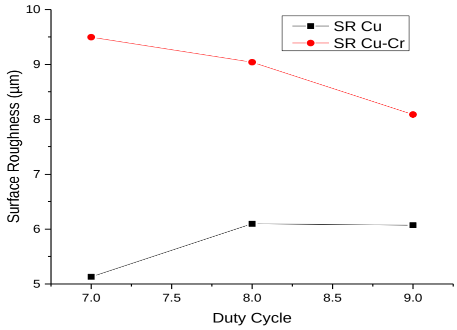

Figure 4.2.3: DC vs SR

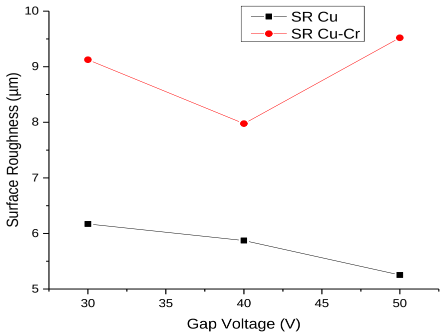

Figure 4.2.4: V_g vs SR

5. Confirmatory Experiment

After estimation and prediction of optimal parameter setting using the combination of PCA and TOPSIS technique, confirmation tests were carried out at Ip=3A, Ton= 150µs, DC=80% and Vg= 40 V for copper tool and at I_p=3A, T_{on}=200µs, DC=90%, V_g=50V for Cu-Cr tool with machining time= 15 minutes and it was observed that the responses of predicted optimal solutions were equivalent to the responses obtained after confirmation tests.

6. Conclusion

The conclusions made from this experimental study are:
(a) The optimum set of process parameters obtained during machining using copper electrode are I_p=3A, T_{on}=150µs, DC=80%, V_g= 40V. Using Cu-Cr tool, optimal set of process parameters is I_p =3A, T_{on} =200µs, DC =90%, V_g = 50V.
(b) The machined surface shows traces of chromium deposit that possibly transferred from the composite electrode during the process, thus increasing the machinability of the workpiece.
(c) Optimal parameter solution has been obtained so that machining can be done using those parametric values for economic use of resources in the engineering and industrial field.

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