ANALYSIS AND SYNTHESIS OF INFLUENCE OF TOOL-ELECTRODE MATERIALS IN ELECTRIC DISCHARGE MACHINING OF M2 HIGH-SPEED TOOL STEEL

CHANDRA MOULI A¹, PARAMESWARA RAO CHVS² & DEVA KUMAR MLS³

¹Research Scholar, Department of Mechanical Engineering, JNTU Anantapuramu, India

²Professor and Principal, Narayana Engineering College, Gudur, India

³Professor, Department of Mechanical Engineering, JNTU Anantapuramu, India

ABSTRACT

Molybdenum high-speed steel particularly termed as M2 High-Speed Tool Steel specifically in the manufacture of Milling Cutters, Thread roll Dies, and other emerging areas like automobile, defense, aerospace, bio-medical segments has an extensive applications. Machinability studies for this type of the material are having extreme significance. M2 steel has the higher toughness and inhomogeneity, resulting in decreased machinability. These features of the M2 steel demands an advanced machining process. Electric Discharge Machining (EDM), a versatile process in machining the advanced materials, in which the thermal conductivity and the electrical resistivity of the work piece and the tool electrode plays a key role in determining the performance of the process. In the present work, relative studies has been conducted on the EDM of M2-Steel utilizing two different electrodes namely graphite and copper. Taguchi's L_{27} orthogonal array was utilized to design the experiments. Peak current (I_p), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), and voltage (V) were selected as the input process parameters. The performance of the machining process is evaluated by measuring the three different responses namely material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR). The experimental results indicated that the Graphite tool electrode ensued 12.84 % higher MRR, and 11.59% lower SR than the copper tool electrode. Copper tool electrode resulted in a 3.61 % lesser electrode wear rate (EWR).

KEYWORDS: Electric discharge machining, M2 steel, Material removal rate (MRR), Electrode wear rate (EWR), Surface roughness (SR).

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1. INTRODUCTION

Machining of Tool steel materials is extremely hard to be machined through traditional machining methods due to their intense hardness and toughness. M2 steel is classified as "medium" machinability tool steel in the annealed condition and its machinability features are less than 50% in contrast to that of the other hardened tool steel materials which considerably ease in machining. The electric discharge machining (EDM) process has emerged as a useful technique for generating cavities with smaller and close tolerances [1]. Besides, EDM was a proven effective economic method for generating shapes faster with the best accuracy for all electrically conductive materials irrespective of their hardness [2]. EDM is a versatile machining process that has the ability for processing the complex and hard materials without any shape constraints [3]. In this process, the erosion for the work material is occasioned through a sequence of spark discharges in between the tool electrode and work piece as both are submerged in a dielectric medium. In the EDM process, the tool-electrode profile is imitated on the work material. The tool-electrode dimensions are represented in the manner that sparking gap in between work material surface to

be developed and tool-electrode is needed to be retained. The proper inter-electrode gap needs to be selected for better material removal rate (MRR) and the fine surface features. The process performance is greatly reliant on the tool-electrode material and the electrode tool-design. The simple tool-electrodes are generally made by the traditional processes, whereas the intricately shaped tool-electrodes are developed by the casting, machining and sometimes thermal spraying procedures. The EDM machined is generally controlled through CNC for the tool-electrode progress in machining [4]. The selection of the appropriate electrode crucially influences the machining time, manufacturing costs, surface features and dimensional accuracy. The choice of the tool-electrode material is a vital resolution in the EDM experimentation for die-sinker EDM. The key process responses for the selection of tool-electrode material are MRR, EWR, SR, dimensional accuracy, machinability, and cost of tooling. The features of the various tool-electrode materials and their effect on EDM process performances including the manufacture of tool-electrodes has been summarized in past researches for the EDM process [5-6]. Conversely, owing to the random behavior of the EDM process, the base for the selected materials is majorly grounded on the data from the experiments. On the other hand, the EDM process is constrained by its relatively lower material removal rates. In the interest of enhancing the process effectiveness, researchers have performed enormous work. The influence of the process parameters under the various types of tool electrode materials such as copper, brass on the qualitative and quantitative responses [7] were analyzed by earlier researchers. The surface features Titanium material processing through EDM using special grade graphite tool electrodes for die-sinker EDM application reported better-enhanced machining responses with graphite [8]. In the later years, the influence of different tool-electrode materials (brass, tungsten-copper and graphite) have been compared for the EDM on the Aluminum LM6 [9]. The authors have reported that higher material erosion and better surfaces are noticed during the application of the graphite electrode [9]. The influence of brass, graphite and copper electrodes on EDM for machining 316 stainless steel for the MRR and SR responses were studied and noticed that the brass electrode performed the copper electrode with finer surfaces [10]. The brass tool performed best followed by the copper tool when different aspects of surface integrity were analyzed [11]. The influence of the different tool electrodes on the EDM of Titanium material was reported to the high MRR achieved by zinc and brass- zinc tool-electrodes in contrast to the copper tool-electrode. Copper exhibited the least tool wear as well as the least recast layer, succeeded by the brass and zinc tool-electrodes [12]. The EDM performance with the tool- electrodes developed by the laser sintering process during EDM of titanium [13] were reported by authors. A review of the literature revealed that numerous work has experimented on the EDM process utilizing the various tool-electrode materials. However, very limited work has reported in the EDM process because of M2 Steel material as work material and copper and graphite as the tool-electrode materials. In the present work, experimentation has done to examine the material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR) of EDM process for M2 steel considering peak current (I_p), pulse-on time (T_{ON}), pulse-off time (T_{OFF}) and voltage (V) as process parameters. Two different electrodes namely copper and graphite were reviewed for this experimentation. Statistical analysis has been performed after the EDM process to identify the key process parameters influencing the machining process.

2. EXPERIMENTAL PROCEDURE

2.1. Materials and Methods

The experimentation was performed on SPARKONIX-S-35 ZNC (die-sinker) EDM machine. The EDM was performed with cylindrical graphite and copper tool-electrodes of 10 mm diameter. The chemical composition of M2 steel is listed in Table 1 and the key properties of the M2 steel and tool-electrodes are listed in Table 2.

Table 1: Chemical Composition of M2 High-Speed Tool Steel

Elements	C	Cr	W	Mo	V	Si	S	P	Mn	Fe
Weight in %	0.9	4.1	6.1	4.92	1.78	0.38	0.001	0.025	0.25	Balance

Table 2: Properties of Work piece and Tool-Electrodes

Material	Properties		
	Density (g/cm3)	Melting Point (oC)	Thermal Conductivity (W/m.k)
M2 High Speed Tool Steel	8.138	4680	41.5
Copper	8.960	1084	401
Graphite	2.26	3600	98

2.2 Process Parameters and Experimental Planning

The EDM process parameters nominated in the present work are peak current, pulse-on time, pulse-off time and voltage. The performance measures nominated are material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR). The selected process parameter and their levels were listed in Table 3. The experimentation has been performed on the Sparkonix S-35 EDM Machine represented in Figure 1. The experimentation is performed with three levels and four factors utilizing the design of experiments (DOE) methodology by selecting a three-level orthogonal array (OA) L_{27} . Taguchi designs confer to the experimental design as ‘off-line quality control’. A total of 27 experiments (L_{27}) have been performed with graphite and copper electrodes. The selected graphite and copper tool materials were shown in Figure 2 and Figure 3 respectively for the machining process. The MRR and EWR were calculated by using Eqn. (1) and Eqn. (2) respectively.

Table 3: Process Parameters and their Levels for Machining

Process Parameters					
Parameter	Symbol	Units	Levels		
			Low	Medium	High
Peak Current	I_P	A	10	20	30
Pulse-on Time	T_{ON}	μs	100	200	300
Pulse-off Time	T_{OFF}	μs	20	30	40
Voltage	V	V	15	25	35

$$MRR = \frac{\text{Volume of the work material eroded}}{\text{Time}} \text{mm}^3/\text{min} \quad (1)$$

$$EWR = \frac{W_b - W_a}{\text{Time} * \text{Density}} \text{mm}^3/\text{min} \quad (2)$$

Where W_b = Weight of the electrode before machining

W_a = Weight of the electrode after machining

Figure 1: Die-Sinker EDM Machine (Make: Sparkonix S-35)

Figure 2: Graphite Electrode

Figure 3: Copper Electrode

Figure 4: M2 High-Speed Tool Steel Specimen after Machining

3. RESULTS AND DISCUSSIONS

The Machined samples of M2 high-speed tool steel is shown in Figure 4. The results are discussed in this section.

3.1 Influence of Process Parameters on Material Removal Rate

The influence of different process parameters such as peak current (I_p), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), and voltage (V) on MRR are represented in Figure 5.

Figure 5: Influence of Process Parameters on Material Removal Rate (MRR)

Results from Fig.5(a) shows that the peak current (I_p) is directly related to MRR. This phenomenon is associated with the reason that an increasing peak current (I_p) generates intensified sparks that produce the high temperatures, in turn occasioning more melting and erosion from the work piece. Similar trends have been noticed with both copper and graphite electrodes. The copper electrode cannot sustain a high current density. So material removal rate (MRR) is limited. Further, the remaining factors could not affect MRR considerably as compared to the peak current. Results from Figure 5(b) shows that MRR has increased with T_{ON} up to a threshold limit of 100 μs to 200 μs, and thereafter MRR decreased considerably. It is noticed from Fig.5(c) that MRR tends to decrease continuously with the increase of pulse-off time for copper electrode, whereas pulse-off time shown the least significant influence in the case of the graphite electrode. This could be occasioned for the reason that an increase in the T_{OFF} , the temperature of the electrode tends to decrease noticeably. Results from Figure 5(d) indicate that with the increase in voltage (V), MRR tends to decrease initially and increase consecutively, for copper tool, whereas for the graphite tool MRR tends to increase consequently for the increase in voltage (V). This in turn occasions in the decrease of MRR. Results from Figure 5(d) shows that MRR has no significant effect on the copper electrode, whereas

the gradually decreased in the application of the graphite electrode. The Taguchi based mathematical relation for correlating the MRR and the process parameters for the copper and graphite electrodes is shown the Eqn. (3) and Eqn. (4) respectively.

$$MRR_{Copper} = 78.5 - 2.745 (I_p) + 0.0383 (T_{ON}) - 0.407 (T_{OFF}) - 3.68 (V) - 0.1083 (I_p^2) + 0.00828 (V^2) + 0.00382 (I_p) (T_{ON}) \quad (3)$$

$$MRR_{Graphite} = -30.8 + 4.77 (I_p) - 0.030 (T_{OFF}) - 0.0729 (I_p^2) + 0.0447 (I_p) * (T_{OFF}) \quad (4)$$

3.2. Influence of Process Parameters on Electrode Wear Rate

It is very important to analyze the tool wear in the EDM process, which ultimately determines the tooling costs associated with the machining process.

Figure 6: Influence of Process Parameters on Electrode Wear Rate (EWR)

Figure 6(a) reflects the influence of peak current on EWR for copper and graphite electrodes. The EWR is noticeably high for the instance of the copper electrode as compared to that of the graphite electrode. It has been noticed EWR of very

negligible as less than 1% with the graphite electrode, for all the instances of peak current. For instance, at $T_{ON}= 100 \mu s$, it has been noticed higher electrode wear, increased EWR noticed 9.89% ($I_P= 10 A$), 19.29% ($I_P= 20 A$), and 29.09 % lesser ($I_P= 30 A$) for copper electrode as compared to that of graphite. The experimentation has been performed with straight polarity (i.e. tool-electrode is cathode and work piece is anode), where the flow of electrons from the tool-electrode liberates intense energy on the surface of tool and work piece, which may cause tool-electrode erosion. It is also noticed that the magnitude of EWR depends on the choice of tool-electrode materials as well as discharge energy. The greater the melting point of tool-electrode material will result in low erosion from the electrode. As the copper tool melting point ($1084^{\circ}C$) which is far less as compared to that of graphite-tool ($3600^{\circ}C$), this occurrence is more for copper- electrode at low I_P (10 A and 20 A). Figure 6(b) represents the influence of pulse-on time on EWR. It can be noticed that EWR tends to decrease with the increase in T_{ON} for both copper and graphite electrodes. It has been observed that EWR for graphite electrode is higher up to $T_{ON}=200\mu s$ and at higher T_{ON} (300 μs) the copper electrode noticed higher EWR. Results from Figure 6(c) represents the copper electrode has high EWR ($T_{ON}= 20 \mu s$) and the graphite electrode witnessed higher EWR ($200 \mu s \leq T_{ON} \leq 300 \mu s$). Results from Figure 6(d) shows the influence of voltage on the EWR. It has been witnessed that the voltage factor is having the least influence on the EWR. It is also noticed that EWR is least sensitive to T_{ON} . The likely reason is that copper-tool is the best heat conductor as compared to that of graphite (Thermal conductivity of copper is 401 W/m K, whereas for graphite is 98 W/m K), extended pulse-on time occasioned in the decrease of temperature at the tool-electrode surface, which in turn resulted in lesser EWR. The Taguchi based mathematical equation for correlating the EWR and the process parameters for the copper and graphite electrodes are listed in the Eqn. (5) and Eqn. (6) respectively.

$$EWR_{Copper} = 0.186 + 0.0298 (I_P^2) + 0.000568 (T_{ON}) - 0.00924 T_{OFF} + 0.00891 (V) - 0.000005 (T_{ON}^2) + 0.00032 (I_P)(T_{ON}) - 0.00481(I_P)(V) + 0.000034 (T_{ON})(T_{OFF}) \quad (5)$$

$$EWR_{Graphite} = 0.753 - 0.0426 (I_P) - 0.001917 (T_{ON}) + 0.00748 (T_{OFF}) + 0.001816 (I_P^2) \quad (6)$$

3.3 Influence of Process Parameters on Surface Roughness

Surface roughness (SR) is directly related with the roughness average of the machined surfaces in the EDM process. Always the low SR values are preferred from the precision and accuracy point of view. R_a is the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. Simply put, R_a is the average of a set of individual measurements of surface peaks and valleys. Reveal the R_a formula for more insight. The mean average of SR of the EDM'ed surface is measured by roughness tester (Make: Talysurf S-3+). Results depicted in Figure 7 represents the influence of process parameters on surface roughness. Figure 7(a) represents the trends of responses for SR values under the effect of peak-current for copper and graphite electrodes. Peak current is responsible for the high intense spark striking on the work piece with at high peak-current occasioning the higher material erosion owing to the developed impact forces. This in turn results in the increased energy penetration in the work material surface that ultimately consequences in wider and deeper crater formation, resulting in a rougher surface [16]. Figure 7(b) represents the responses for the effect of T_{ON} on the SR. The higher sparking times prolong the material melting and vaporization phenomenon, which in turn occasioned on the increase of SR owing to the deep crater formation. The graphite electrode is less vulnerable under thermal shocks. Figure 7(c) shows the influence of T_{OFF} on the performance of SR. It can be witnessed that T_{OFF} influence on the SR is for only a limited. Graphite electrode can allow high current density and thus MRR can be enhanced easily. Figure 7(d) represents the

developments for SR in the effect of voltage parameters. On the other hand, the low SR for the graphite electrode is occasioned to less energy density owing to the stable sparking cycles as compared to that of the copper electrode. On an average at all levels the graphite electrode outperformed the copper tool in the view of surface roughness for EDM. The Taguchi based mathematical correlation for the SR and the process parameters for the copper and graphite electrodes are shown the Eqn. (7) and Eqn. (8) respectively.

Figure 7: Influence of Process Parameters on Electrode Wear Rate (EWR)

$$SR_{Copper} = 8.24 - 0.1105 (I_p) + 0.0064 (T_{ON}) - 0.0196 (T_{OFF}) - 0.13333 (V) + 0.00639 (I_p^2) + 0.000228 (T_{ON}) * (V) + 0.00302 (T_{OFF}) * (V) \quad (7)$$

$$SR_{Graphite} = 3.13 + 0.1848 (I_p) + 0.01429 (T_{ON}) - 0.0535 (T_{OFF}) - 0.1397 (V) + 0.00474 (T_{OFF}) * (V) \quad (8)$$

4. CONCLUSIONS

The present work has confined to the experimentation on the performance comparison of two different electrodes namely copper and graphite during electric discharge machining (EDM) of M2 High-Speed Tool Steel by Taguchi design of experiments. It has been examined the key EDM process parameters like peak current (I_p), pulse-on time (T_{ON}), pulse-off time (T_{OFF}), and voltage (V). Results from present work have arrived at the following conclusions:

- Graphite electrode exhibited a 12.84% higher material removal rate (MRR) more than that of the copper electrode. The highest MRR (104.958 mm³/min) is attained at achieved at $I_p=30$ A, $T_{ON}=200$ μ s, $T_{OFF}=40$ μ s, and $V=35$ V.
- Copper electrode outperformed graphite electrode by 3.61 % less EWR. Copper electrode Peak-current and pulse-on time are identified as the key process parameters influencing the MRR and SR, whereas pulse-off time and voltage factors have the limited influence on MRR and SR. But in some instances like low values of peak-current (10 A) higher pulse-on time (300 μ s), the graphite electrode performed better than copper.
- Graphite electrode outperformed the copper tool electrode by 11.59 % in the view of SR by generating fine surfaces. The Melting point of graphite is more than three times higher than that of copper. Thus it tends to retain its form even at high EDM temperature.
- The present work could assist in categorizing the substantial factors that are competently controlled to time-consumption, minimize the errors, and other qualitative features. This work could deliver the prospective researchers and EDM industries some actual guidelines to opt specific process parameter for attaining the anticipated MRR, EWR and SR in the EDM of M2 High-Speed Tool Steel.

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