INFLUENCE OF ELECTRICAL PARAMETERS IN POWDER MIXED ELECTRIC DISCHARGE MACHINING (PMEDM) OF HASTELLOY

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ABSTRACT

PMEDM is a complex machining process which is controlled by a number of machining parameters. Each machining parameter has its own influence on performance of the process. The objective of this paper is to analyze the effect of electrical parameters on the performance of this process. Peak current, gap voltage, pulse on time and duty cycle are taken as machining parameters. Material removal rate, tool wear rate, % wear ratio and surface roughness are taken as response parameters to measure process performance. The experimental investigations are carried out using copper electrode. Nineteen experiments are performed on hastelloy using electronica make smart ZNC electric discharge machine tool. Variations of response parameters are plotted against input machining parameters. The study indicates that all the input machining parameters strongly affect the machining performance of hastelloy.

KEYWORDS: PMEDM, hastelloy, electrical parameters, material removal rate (MRR), tool wear rate (TWR), percentage wear ratio (%WR), surface roughness.

1. INTRODUCTION

Different non-traditional machining techniques are progressively used in manufacturing of complex machining components in modern metal industry. However electrical discharge machining (EDM) specially has achieved incredible success and draw researcher’s consideration because of its wide industrial applications. This technique uses thermal energy to machine all electrical conductive, high strength and temperature-resistant materials in a contactless manner. The development of 8000-12000 °C in EDM process is able to melt material of any hardness value. The capability of EDM to machine materials irrespective of their hardness and toughness makes its use in manufacturing of mold, die, automotive, nuclear reactor, spacecraft and surgical components. But on the other hand low machining efficiency and poor surface quality are the major drawbacks of this process that restricts its use in mechanical manufacturing. Researchers did a lot of work to overcome these drawbacks and to enhance process capabilities. Rotating of electrode, orbiting of electrode, application of ultrasonic vibrations and addition of powders in dielectric fluid of EDM are some of the techniques suggested by researchers to enhance process capabilities. PMEDM has more complex mechanism than conventional EDM. Powder particles play an important role during machining. Under the application of suitable voltage (80-120V), an electric potential in the range of $10^5 – 10^7$ V/m is developed between two electrodes of the process facing each other with a spark gap of 25 50 µm. The powder fills...
up the spark gap. Under the influence of high electric potential, these powder particles energized, get accelerated, act as conductors and form chains in sparking gap. Due to bridging of spark gap, the insulating strength of dielectric fluid reduces. This leads to increase in gap size between tool electrode and workpiece. Due to easy short circuiting and hence more discharging frequency, the MRR increases. The added powder also changes the shape of channel carrying the discharge energy. The widening and enlarging of channel carries more uniform discharge energy among powder particles. This produces shallow craters and hence improvement of surface finish. The performance of PMEDM depends upon wise selection of process input parameters. Four different types of input parameters i.e electrical parameters, non electrical parameters, electrode parameters and powder parameters influence the performance of PMEDM process. The aim of present research work is to analyze the effect of electrical parameters on PMEDM of hastelloy material. Hastelloy is a high-strength, nickel based, corrosion resistant alloy. In addition to outstanding resistance to all manner of pitting and cracking, parts made of this alloy find good use across a wide range of chemical applications that might otherwise oxidize the metal. Hastelloy exhibits advantages such as high-temperature strength in vacuums and atmospheres that are chemically inert. The major applications of this material are in making of pressure vessels of nuclear and chemical reactors, pipes and valves in chemical industry, aerospace engine parts and gas turbine engine combustion zone components such as transition ducts, combustor cans, spray bars and flame holders as well as in afterburners, tailpipes and cabin heaters. It is recommended for use in industrial furnace applications because it has unusual resistant to oxidizing, reducing and neutral atmospheres.

2. LITERATURE REVIEW
Researchers have done work to analyze/improve surface finish and other machining output parameters for various hard and tough materials by adding powders of different materials in the dielectric of during EDM of various materials. In addition, some work has been done to optimize the machining input parameters for yielding maximum process output for different work materials. Narumiya H., et al. [1] reported that under properly controlled machining conditions, aluminium & graphite powders yields better surface finish as compare to the surface finish obtained by suspending silicon powder in dielectric. Mohri N., et al. [2] studied machining characteristics of H-13 die steel by adding silicon powder in dielectric fluid. Under properly controlled machining conditions, the fine & corrosion resistant surfaces having surface roughness of 2µm were produced. Ming Q.Y., et al. [3] reported the reduction in surface roughness, reduction in tool wear rate and improvement in machining rate by the addition of additives (conductive & inorganic oxide particles). They further noticed that these changes are quite appreciable in mid finish machining and finish machining phases. Wong Y.S., et al. [4] investigated that graphite powder particles enhances machining rate of SKH-54 tool steel. Tzeng F.Y., et al. [5] applied the optimization strategy to reduce the functional variability of EDM process. Kansal H.K., et al. [6] tried to optimize the process parameters of
PMEDM by using response surface methodology technique. Kansal H.K., et al. [7] establishes optimum process conditions for PMEDM of Al-10%SiC\textsubscript{p} metal matrix composites by an experimental investigation using response surface methodology. Aluminium powder was suspended into the dielectric fluid of EDM. Tzeng Y.F., et al. [8] described the application of the fuzzy logic analysis coupled with Taguchi methods to optimise the precision and accuracy of the high-speed electrical discharge machining process. Study was done to optimize process input parameters. A fuzzy logic system was used to investigate relationships between the machining precision and accuracy for determining the efficiency of each process parameter. Kansal H.K., et al. [9] investigate the effect of silicon powder mixed into the dielectric fluid of EDM on machining characteristics of AISI D2 steel and reported the appreciably enhancement of material removal rate of AISI D2 steel. Salman O., et al. [10] investigates different EDM parameters (current, pulse on-time, pulse off-time, arc voltage), the \( R_s \) (\( \mu m \)) roughness value as a result of application of a number of copper electrode-hardened powder metals (cold work tool steel) to a work piece. the literature. Singh S. et al. [11] compares machinability study carried out on stir-casted 6061Al/Al\textsubscript{2}O\textsubscript{3}p/20p work specimens with copper electrode tools by using plain dielectric fluid and silicon carbide (SiC) abrasive powder-suspended dielectric fluid. It was found experimentally that abrasive particle size, abrasive particle concentration and pulse current are the most significant parameters that affect the surface characteristics. Chiang K.T., [12] proposes mathematical models for the modeling and analysis of the effects of machining parameters (the discharge current, pulse on time, duty factor and open discharge voltage) on the performance characteristics in the EDM process of Al\textsubscript{2}O\textsubscript{3}+TiC mixed ceramic. It was concluded that the main two significant factors on the value of the material removal rate (MRR) are the discharge current and the duty factor. The discharge current and the pulse on time also have statistical significance on both the value of the electrode wear ratio and the surface roughness. Kansal H.K., et al. [13] develops an axisymmetric two-dimensional model for PMEDM using the finite element method to predict the thermal behavior and material removal mechanism in PMEDM process. Dvivedi A., et al. [14] investigated the effect of pulse-on \( (T_{on}) \), pulse-off \( (T_{off}) \), pulse current \( (I_p) \), gap control setting and flushing pressure on EDM of cast Al 6063-SiC\textsubscript{p} metal matrix composite by using taguchi’s technique to obtain an optimal setting of the EDM process parameters. It was found that MRR increases with increasing \( I_p \) and \( T_{on} \) up to an optimal point. The effect of \( I_p \) was predominant on MRR as compared to other parameters. Kumar A., et al. [15] tried to find out optimal process parameters of abrasive mixed electrical discharge machining (AEDM). Taguchi methodology was adopted for planning and analysing the experiments for optimising the multiple performance characteristics. The process input parameters, viz. concentration of silicon in dielectric fluid, current, pulse-on time, duty factor were chosen to study process performance in terms of MRR and surface roughness. The investigations results shown that with addition of silicon abrasive powder (2 g/lt) in kerosene dielectric fluid,
material removal rate improves by 23% and surface roughness is reduced by 35 %. Furutani K., et al. [16] described the influence of the discharge current and the pulse duration on the titanium carbide (TiC) deposition process by EDM with titanium (Ti) powder suspended in working oil. It was noticed that Ti powder reacted with the cracked carbon from the working oil, then depositing a TiC layer on a work piece surface. From the available literature, it was concluded that the few researchers investigated the effect of powder particles mixed in dielectric fluid by taking electrical parameters as process input parameters. But no work is reported on the influence of electrical parameters during PMEDM of hastelloy. In the present research work it was decided to investigate the influence of peak current, gap voltage, pulse on time and duty cycle during EDM of hastelloy by suspending fine aluminium powder in dielectric fluid.

3. EXPERIMENTAL DETAIL AND PROCEDURE

Experiments were performed on Electronica make standard EDM machine; model smart ZNC with straight polarity. The existing huge work tank (internal dimensions: 800 x 500 x 350 mm and dielectric capacity of 400 liters) of machine was replaced with 6.5 liters capacity machining tank. This machining tank (made up of sheet metal) was developed in workshop. It was done to avoid wastage of dielectric fluid. 30 gram of fine aluminium powder (mesh size 300-400 µm) was thoroughly mixed in 5 liters of standard EDM oil to obtain desired concentration of powder. This solution was used as dielectric fluid for conducting the experiments. A small stirring system and a dielectric circulation pump was used in machining tank to ensure uniform distribution of powder particles in dielectric circulation system. A special fixture was made in machine shop and used to hold the workpiece in machining tank. A rectangular piece of magnet was placed in machining tank to collect the debris produced during experimentation. Various experimental conditions used during experimentation are listed in table 1.

<table>
<thead>
<tr>
<th>Working parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric fluid</td>
<td>EDM oil + al. powder</td>
</tr>
<tr>
<td>Polarity, P</td>
<td>Positive (+)</td>
</tr>
<tr>
<td>Peak current, I_p (A)</td>
<td>0.5, 3, 5, 7, 9</td>
</tr>
<tr>
<td>Pulse on time, T_on (µs)</td>
<td>50, 100, 150, 500, 750</td>
</tr>
<tr>
<td>Gap Voltage, G_p (V)</td>
<td>40, 50, 60, 70, 80</td>
</tr>
<tr>
<td>Duty factor</td>
<td>7, 8, 9, 10</td>
</tr>
<tr>
<td>Powder concentration (g/l)</td>
<td>6</td>
</tr>
<tr>
<td>Working time (min)</td>
<td>20</td>
</tr>
<tr>
<td>Dielectric pressure (kg/cm²)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Table 2 Chemical composition of hastelloy

<table>
<thead>
<tr>
<th>Ele.</th>
<th>Ni</th>
<th>Co</th>
<th>Cr</th>
<th>Mo</th>
<th>Fe</th>
<th>Si</th>
<th>Mn</th>
<th>C</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>65</td>
<td>2</td>
<td>16</td>
<td>16</td>
<td>3</td>
<td>0.08</td>
<td>1</td>
<td>0.01</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 3 Properties of aluminium powder

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Thermal conductivity (300 K) W·m⁻¹·K⁻¹</th>
<th>Electrical resistivity (20 °C) nΩ·m</th>
<th>Melt. point K</th>
<th>Specific heat capacity (25 °C) J·mol⁻¹·K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.70</td>
<td>237</td>
<td>28.2</td>
<td>933.47</td>
<td>24.200</td>
</tr>
</tbody>
</table>

Hastelloy (specimen 60 x 40 mm) was used as workpiece material and 8.14 mm diameter copper rod was used as tool electrode. Table 2 and table 3 enlist chemical composition of hastelloy and various properties of aluminium powder respectively. Nineteen experiments were performed on hastelloy specimen to produce circular holes. Each experiment has different values of input machining parameters. In the first five experiments the current values are changed at different intervals for each experiment. During these five experiments, the process other parameters namely the voltage, pulse on time and duty cycle etc. are kept constant. For the next five experiments, the values of voltage changes for each experiment and other input parameters including current remains unchanged. In the next five experiments the pulse on time values are changed all other parameters i.e current, voltage and duty cycle etc. are kept constant. For the next four experiments, the values of duty cycle changes for each experiment and other input parameters remain unchanged. The necessary readings are taken after each experiment to calculate process response parameters as discussed below.

**Material removal rate (MRR):** It is defined as the weight of material eroded from workpiece surface per unit time. It is measured as:

\[ \text{MRR} = \frac{\text{Work piece weight loss (g)}}{\text{Machining Time (min)}} \]

**Tool wear rate (TWR):** It is defined as the weight of material eroded from tool electrode surface per unit time. It is measured as:

\[ \text{TWR} = \frac{\text{Work piece weight loss (g)}}{\text{Machining Time (min)}} \]

**Percentage wear ratio (%age WR):** It is defined as the ratio of tool wear rate to material removal rate. It is generally expressed in percentage. It is measured as:

\[ \%\text{WR} = \frac{\text{TWR}}{\text{MRR}} \times 100 \]

**Surface roughness:** The arithmetic surface roughness value (Rₐ) is used to access the surface condition. Rₐ is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement. It can be represented as:

\[ Rₐ = \frac{1}{L} \int_{0}^{L} |h(x)| \, dx \]

Where, h(x) is the value of roughness profile & L is evaluation length.
Measurements were carried out of 6 mm measurement length at the bottom of the holes using Mitutoyo SJ-201P surface roughness tester. Three values of $R_a$ were taken at different angles for each machined surface. The average value is taken as $R_a$ value. A cut off length of 0.8 mm was used for the surface roughness measurement.

The values of input machining parameters and corresponding output response parameter obtained for each experiment are shown in table 4.

### Table 4 Input machining parameters and output response parameters

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Pulse on time (μs)</th>
<th>Duty cycle (μs)</th>
<th>MRR (g/min)</th>
<th>TWR (g/min)</th>
<th>% WR</th>
<th>Ra (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>60</td>
<td>150</td>
<td>9</td>
<td>0.00250</td>
<td>0.000050</td>
<td>2.000000</td>
<td>1.1125</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>60</td>
<td>150</td>
<td>9</td>
<td>0.03320</td>
<td>0.000153</td>
<td>0.460829</td>
<td>2.888</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>60</td>
<td>150</td>
<td>9</td>
<td>0.06681</td>
<td>0.000622</td>
<td>0.930233</td>
<td>3.12</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>60</td>
<td>150</td>
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<td>0.12864</td>
<td>0.002199</td>
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<td>5</td>
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<td>60</td>
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<td>0.18329</td>
<td>0.001348</td>
<td>0.735294</td>
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</tr>
<tr>
<td>6</td>
<td>5</td>
<td>40</td>
<td>150</td>
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<td>0.074670</td>
<td>0.000381</td>
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<tr>
<td>8</td>
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<td>3.12</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>70</td>
<td>150</td>
<td>9</td>
<td>0.05850</td>
<td>0.000719</td>
<td>1.229508</td>
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<td>10</td>
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<td>2.42915</td>
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<td>5</td>
<td>60</td>
<td>150</td>
<td>10</td>
<td>0.07281</td>
<td>0.001016</td>
<td>1.395349</td>
<td>4.3342</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSION

The next phase after experimental work is the analysis and discussion of results. In this section the effect of controlling parameters such as current, voltage, pulse on time and duty cycle on material removal rate, tool wear rate and percentage wear rate and surface roughness are presented. The plots showing the effect of parameters on responses have drawn accounting the effect of all factors.
4.1 Effects of peak current

![Graph of Material removal rate vs Peak current](image1)

**Fig. 1 Effect of peak current on Material removal rate**

Fig. 1 depicts that rate of material removal is very small at low values of peak current. It is due to the reason that at low current, a small amount of heat is produced out of which some heat is absorbed by machine components and surroundings etc and left heat is utilized to melt and vaporize work material.

![Graph of Tool wear rate vs Peak current](image2)

**Fig. 2 Effect of peak current on tool wear rate**

As the current is increased, more powerful spark with higher energy is produced. Due to this a lot of heat is generated and a substantial amount of heat is used to melt and vaporize the work material. This leads to increase in MRR.

![Graph of Tool wear rate vs Peak current](image3)

**Fig. 3 Effect of peak current on % wear ratio**

The variation of TWR with peak current is shown in Fig. 2. TWR increase initially with peak current due to the reason more powerful sparking with higher energy occurs which produces more heat at higher currents. It is further observed that at very high current values,
tool erosion rate diminishes slightly. Fig. 3 shows the variation of % wear ratio with peak current. The variation of curve signifies that % wear ratio decrease initially with increasing peak current because MRR increase at higher slope than TWR. But with further increase in peak current, % wear ratio increase as slope of tool erosion rate is more than work erosion rate. But at higher values of peak current more heat is generated at work surface in positive polarity EDM. This leads to faster workpiece erosion rate as compare to tool erosion rate.

Fig. 4 depicts the variation of surface roughness with peak current. The variation of curve shows that surface roughness increase with increase in peak current. This is because of the reason that more powerful sparking at higher currents have more pressure energy to strike on work surface to produce more deeper and wider craters.

4.2 Effects of gap voltage

Fig. 5 represents the rate of material removal with the increase in gap voltage. Keeping all other factors constant, increase in gap voltage increases the energy per spark. This results in increase in MRR. But at higher values of gap voltage, inadequate cooling of work material is due to unfavorable concentrated discharging. It results in lowering of MRR.

Fig. 6 illustrates the variation of TWR with gap voltage. The variation of curve shows that TWR increases initially due to reason of availability of more energy per spark during discharging. Concentrated discharging in spark gap then slightly lowers down TWR and then it again increases up.

Fig. 7 explains the variation of % wear ratio with gap voltage. % wear ratio initially increases because the TWR increase at higher slope than MRR initially. But the ratio then slightly lowers down due to lowering of tool erosion rate. However at high gap voltage values, %WR is
higher because of low MRR and high TWR at higher gap voltage.

4.3 Effects of pulse on time

Increase in pulse on time or pulse duration leads to increase in duration of sparking and expansion of plasma channel. The variation of curve in Fig. 9 shows that MRR increases produces more wider and deeper craters on work surface.

Fig. 7 Effect of gap voltage on % wear ratio

Fig. 8 Effect of gap voltage on surface roughness

Fig. 9 Effect of pulse on time on material removal rate

Fig. 10 Effect of pulse on time on tool wear rate

Fig. 8 depicts the variation of surface roughness with gap voltage. Surface roughness initially decreases with gap voltage. At higher gap voltage values, more rough surfaces produced because discharges with higher pressure energy

slightly with an increase in pulse on time up to 100 µs.

**Fig. 11 Effect of pulse on time on % wear ratio**

![Graph showing the effect of pulse on time on % wear ratio.](image)

Electrode: Cu  Workpiece: hastelloy  Dielectric: EDM oil + Al powder  Polarity: +ve

It is due to increase in sparking time which causes more melting and vaporizing the work material. However with further increase in pulse on time, the effect of expansion of plasma channel is more than the effect of increase in sparking time. Due to expansion of plasma channel, the energy density of discharging spots decreases which is not enough to melt the work material and hence rate of material removal lowers down.

It is observed from Fig. 10 that TWR lowers down with the increase in pulse on time. The phenomena may be attributed to expansion of plasma channel at higher pulse on time as explained above. Fig. 11 depicts that % wear ratio decreases initially with an increase in pulse on time due to the reason that TWR decreases at faster rate as compare to MRR. It is further observed that at higher pulse on time, the % wear ratio is very high. It is because of the reason that MRR decreases at faster rate due to expansion of plasma channel as compare to TWR at higher pulse on time. Fig. 12 represents the variation of surface roughness with pulse on time. The trend of variation of curve shows that surface roughness decreases with increase in pulse on time. This behavior of surface roughness is due to expansion of plasma channel with increase in pulse on time. The discharging spots of expanded plasma channel have low energy density which produces less widened less deepened craters on work surface.

**4.4 Effects of duty cycle**

Increase in duty cycle means increase in pulse on time and decrease in pulse off time. Fig. 13 represents that keeping all other factors constant, increase in duty cycle leads to increase in MRR. It is due to the reason that with an increase in pulse on time, total machining time and hence total current utilization time increases.
It is observed from Fig. 14 that TWR initially lowers down to minimum with an increase in duty cycle upto 8. This event may be attributed to the lowering of discharge energy due to expansion of plasma channel at higher pulse on time. But at higher duty cycle, the spark retains itself in spark gap for more time in the total cycle duration. Moreover reduced pulse off time provides insufficient cooling time to electrode and hence the electrode wears fastly.

It is observed from Fig. 15 that in the selected range of values of duty cycle, % wear ratio lowers down to minimum with an increase in duty cycle upto 8. This is due to lowest TWR at this value of duty cycle. However at higher values of duty cycle, % wear ratio increases due to fast erosion rate of tool electrode at higher duty cycle. Fig. 16 shows that surface roughness decreases initially with an increase in duty cycle because of the reason of expansion of plasma.
channel with increase in pulse on time. Keeping all factors constant and increasing pulse duration results in expansion of plasma channel. The discharge spots in expanded plasma channel have lesser striking energy which produces small and shallow craters on work surface. But at higher duty cycle, sparking occurs for more duration in the complete cycle. Moreover decreased pulse off time results in insufficient cooling of work piece. Due to this short circuiting occurs and process becomes unstable. This leads to deeper and widened craters on work surface.

5. CONCLUSIONS
This study has investigated the influence of electrical parameters during PMEDM process. The following conclusions can be derived based on the results and discussion for the hastelloy with copper electrode in the investigated range:
1. All the selected electrical input parameters have strong influence on MRR, TWR, WR and surface roughness.
2. Higher peak current is desirable factor to yield more material erosion rate but it has adverse effect on surface finish of newly machined surfaces.
3. Wear ratio decreases at higher peak currents. This is favorable in terms of machining efficiency of the process.
4. Wear ratio decreases at smaller gap voltage. This increases machining efficiency of the process.
5. Higher pulse on time is undesirable factor for material erosion rate but it has favorable effect on surface finish of newly machined surfaces.
6. Higher duty cycle is enviable for faster workpiece erosion but surface finish of work material vanish due to insufficient cooling of work material at higher duty cycle.

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7. REFERENCES


