EXPERIMENTAL STUDY INTO GROOVE MACHINING USING ROTARY DISK ELECTRICAL DISCHARGE MACHINING WITH SILICON POWDER-MIXED DIELECTRIC

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Abstract
In the present study, an effort has been made to generate grooves on Nimonic75® super alloy with rotary copper disk of varied aspect ratio through powder-mixed EDM. Taguchi’s orthogonal array L18 (2¹×3⁷) has been adopted to investigate the effects of one noise factor viz. aspect ratio with two levels and seven control factors namely peak current, pulse on time, pulse off time, gap voltage, rotational speed, powder particle size and powder particle concentration with three levels each, on responses namely material removal rate and surface roughness. In addition, micro-structural studies via SEM and XRD has been performed of the machined surface. On the basis of results obtained, it was found that aspect ratio; peak current, rotational speed and powder particle concentration plays a significant role in improvement of the machining characteristics. The results revealed significant performance improvement with the powder-mixed dielectric.

Keywords: Superalloys, RD-EDM, powder-mixed fluid, optimization

1. Introduction

Super alloys are advanced engineering materials, having high potential for aerospace and defense industries. Nimonic 75®, a nickel-chromium heat resistant super alloy, finds its application in the manufacturing of aerospace fasteners, gas turbine engineering and heat treatment equipments. Machining of groove on difficult-to-machine materials such as super alloys and composites, through conventional machining is challenging, involving high surface finish, low tool wear, minimization of burr formation, better dimensional accuracy and reduced machining cost (Kozak and Rajurkar, 2001).

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Electrical Discharge Machining (EDM), a non-conventional machining process, is used to shape electrically conductive high strength materials, through repetitive spark discharges between tool electrode and work material, separated by a small distance with dielectric fluid (McGeough, 1998). The process has wide advantages to machine advanced materials such as super alloys, composites etc., since there is no cutting force which subsequently reduces the mechanical stress, chatter and vibration problems, as are prominent in conventional machining (Singh et al., 2004).

Nevertheless the EDM technologies have major limitations when dealing with fine surface finish over the process area. This is in view of the fact that the EDMed surface is characterized by a series of randomly laid tiny craters produced by spark discharges, and resolidification and deposition of material ejected from the craters, referred as recast or white layer. It requires some form of supplementary finishing processes such as hand polishing, etching, burnishing etc. (Kozak and Rajurkar, 2001; Singh and Yeh, 2012). Indeed this is one reason that explains the need of final polishing of machined surface performed after EDM.

Recently, EDM with powder-mixed in dielectric fluid (PM-EDM) has been a focus of an intense research work in order to overcome these technological performance barriers. The development of this hybrid process is an outcome of such machining requirements involving the mechanical interaction of powder and thermal interaction of spark discharges (Singh and Yeh, 2012; Chow et al., 2000; Chow et al., 2008; Wong et al., 1998). In powder-mixed EDM process, the fine powders are suspended
in dielectric fluid for enhancing the machining capability. The mechanical interaction assists in removal of recast layer due to abrasion, thus improving the surface finish (Kozak and Rajurkar, 2001; Singh and Yeh, 2012). Powder-mixed EDM is also known as Abrasive Electrical Discharge Machining (AEDM).

EDM and its variant processes have been employed for groove and slit machining of difficult-to-machine materials. The fabrication of groove and slit are possible with rotating pin electrode (RPE) and Wire EDM (WEDM). However, both processes can obtain precision controlled geometry, but RPE is a slow process whereas in WEDM, the susceptibility of wire breakage is a practical problem (Chow et al., 1999; Yeo and Murali, 2003). Moreover, WEDM process is not suitable for machining blind grooves. Other developments in the groove machining by spark erosion technique have been the usage of rotary disk electrode and the usage of foil as tool electrode (Koshyet et al., 1993; Chow et al., 1999; Murali and Yeo, 2004).

Rotary Disk Electrical Discharge Machining (RD-EDM), one of the variant processes of EDM, has been gaining popularity as an alternative method to fabricate geometrical features like grooves & slits. It utilizes rotational effect of disk electrode in a direction parallel to the axis of the work piece material to produce grooves and slits (Koshyet et al., 1993; Chow et al., 1999). Past literature identifies that the Al and SiC powders mixed during the RD-EDM process have resulted in high MRR and better surface finish (Chow et al., 2000; Chow et al., 2008). The powder additives such as silicon, graphite, SiC and aluminium mixed into the dielectric fluid have been found to increase the spark gap facilitating high frequency discharge initiation generating high MRR and better surface finish (Wong et al., 1998).

From the preceding literature review, it can be seen that mixing powders into the dielectric fluid has brought significant enhancement in the field of fine finishing and machining rates during EDM. In this paper, various factors affecting the powder-mixed rotary disk EDM are investigated. Review of the past work also revealed that thus far, the research findings in the area of powder-mixed rotary disk EDM for groove machining of Ni-based super alloy are scanty.

2. Experimentation

2.1 Experimental design

Based on the past work, eight suitable process parameters viz. one noise factor having two levels and seven control factors three levels each, to be varied during experimentation were chosen, and assigned specific levels, on the basis of preliminary experiments. The Taguchi’s orthogonal array L18 (2^3 x 3^7) was selected to accommodate the considered eight factors, and perform experimental runs, with each run to be replicated thrice, for better accuracy of results.

The control factors considered were peak current (A), pulse on time (µs), pulse off time (µs), gap voltage (V), rotational speed (rpm), powder particle size (mesh), powder particle concentration (g/l) each having three levels. Aspect ratio of disk electrode was considered as a noise factor having two levels. Table 1 shows the factors and respective levels. The plan of adding powders is to remove recast layers from the work surface and to improve its quality during the EDM process. Different grain sizes and different concentrations of aluminum powder particles were suspended in the dielectric fluid.

The performances measures considered were material removal rate, MRR (g/min) and surface roughness SR (µm). MRR was calculated on the basis of weight difference of the work material, before and after machining, using electronic digital weighing machine (Make Dolphin, range 0-600 g, sensitivity 0.001 mg). SR of the machined groove specimens were measured by a Mitutoyo surface roughness tester, with an accuracy of 0.01 µm.

Table 1: Factors and levels

<table>
<thead>
<tr>
<th>Factors</th>
<th>Unit</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>-</td>
<td>0.005, 0.036, -</td>
</tr>
<tr>
<td>Ip</td>
<td>A</td>
<td>8, 12, 16</td>
</tr>
<tr>
<td>Ton</td>
<td>µs</td>
<td>100, 200, 400</td>
</tr>
<tr>
<td>Toff</td>
<td>µs</td>
<td>10, 20, 100</td>
</tr>
<tr>
<td>Vg</td>
<td>V</td>
<td>40, 45, 50</td>
</tr>
<tr>
<td>N</td>
<td>rpm</td>
<td>100, 125, 150</td>
</tr>
<tr>
<td>PPS</td>
<td>mesh</td>
<td>200, 250, 300</td>
</tr>
<tr>
<td>PPC</td>
<td>g/l</td>
<td>2, 4, 6</td>
</tr>
</tbody>
</table>

2.2 Material

In the present study, Nimonic75 plate of size 60 x 40 x 4 mm has been used as a work material. The hardness of the work material being 42.5 HRc. Electrolytic copper disk electrodes, of variable aspect ratio were used for groove machining, as shown in Fig.1.

Fig.1 Disk electrodes of varied aspect ratio
2.3 Experimental setup and procedure

In order to investigate the effect of powder-mixed in the dielectric fluid on the machining characteristics during rotary disk EDM of Nimonic 75, the modified experimental setup was fabricated, as shown in Fig. 2. The rotary head was attached to the servo head of conventional EDM (Model S-25, Make: Sparkonix, India) equipped with ISOPULSE P25 generator. The polarity of the disk electrode was set as positive.

![Fig.2. Schematic diagram of powder-mixed RD-EDM setup](image)

The rotational speed of the disk electrode was controlled by a variable regulated power supply. The shaft of the driven disk supported with two bearings on both sides imparted smooth motion to the driven shaft. A proximity inductive sensor (M18 NPN No 8mm) was attached at the top of the rotary disk electrode setup for measuring the rotational speed of disk electrode, within the dielectric fluid.

Superior grade kerosene oil, Kero (supplied by Indian Oil), has been used as dielectric fluid. To determine the effects of suspended silicon powder on the machining performances, an extra machining container was fabricated having size 480x340x2.5 mm and having a capacity to store 18 litres of the dielectric fluid (Fig.2).

A fixture assembly was placed at the bottom of the powder-mixed tank to hold the work material. To avoid the settling of the metal powder, a stirrer assembly was incorporated in the machining tank. A dielectric circulation pump was installed for proper circulation of the powder-mixed dielectric fluid in the discharge working gap (power rating: 0.3 hp) and flow rate of dielectric was maintained at 2 litres/min with an ejector nozzle of 4 mm.

The depth of cut was set as 4 mm, for groove machining. The limit switch turns off the machine after the desired depth has been achieved. After each experimental runs, the burn dielectric fluid containing debris and contaminated particle was re-circulated through filter with the help of the pump, for new fresh dielectric fluid.

### 4. Results and Discussion

#### 4.1 Analysis of MRR

The experimental results of respective runs were considered for calculating the S/N ratio for MRR for larger-the-better (LB) using equation 1.

\[
(S/N)_j = -10 \log \left[ \frac{1}{n} \sum_{j=1}^{n} 1/y_j \right] \tag{1}
\]

where \(y_j\) = value of the characteristic in an observation \(j\); \(n\) = number of repetitions in a trial.

Table 2 shows the response table for S/N ratio for the MRR (larger-the-better). The optimal machining performance for the MRR has been obtained at as been obtained at aspect ratio: 0.036 (level 2), peak current: 16 A (level 3), pulse on time: 200 µs (level 2), pulse off time: 20 µs (level 2), gap voltage: 50 V (level 3), rotational speed: 125 rpm (level 2), powder particle size: 300 mesh (level 3) and powder particle concentration: 6 g/l (level 3) settings due to their high S/N ratio.

The main effect plots of eight factors based on the S/N ratio (larger-the-better) for MRR, is shown in Fig.3. Accordingly, the optimal parametric settings are A2, B3, C2, D2, E3, F2, G3 and H3.

As shown in Fig.3, with an increase of aspect ratio of the copper disk electrode, the MRR increased during powder-mixed RD-EDM.

![Fig.3 Main effect plots for S/N ratio of MRR](image)
Thus, when the disk comes into contact with the suspended silicon powder particles, promotes a series of discharges (bridging effect) by forming a chain-like structure, resulting in high erosion of the work material. The findings are in concurrence with the results of earlier researchers (Singh et al., 2012). The disk electrode having lower AR(0.005), have smaller frontal surface.

It is observed that MRR obtained during investigation increased with peak current settings (8-16 A). The silicon powder particles mixed in dielectric fluid gets energized and acts as a conducting element which collides with the electrons and ion during each pulse on time, and gathers higher energy to release more number of carriers. This leads to increase in the frequency of sparks, causing faster erosion of the work material.

MRR was found to increase with rotational speed of disk electrode (from 100-125) rpm. This is due to the fact that rotation of the disk electrode imparts a whirl to the flowing dielectric fluid, which facilitates the mechanical interaction of suspended silicon powder particles and also assists in scooping of the debris during powder-mixed RDE-EDM.

It was found, that the obtained MRR at powder particle size 200 mesh (level-1) was higher in comparison to 250 mesh (level-2) powder particle size. This may be due to the reason that larger powder particle size results in enlarged inter-electrode gap, thus occupying more area for machining. Further, increased size of powder particle has lower electrical resistivity making the dielectric fluid more conductive (Tzeng and Lee, 2003). The maximum MRR was observed with finer particle size 300 mesh (50 µm, level-3) of silicon which increased the machining efficiency. This might be due to the effective removal of debris and finer size powder particles, thus preventing the short circuiting and subsequent arcing (Tzeng and Lee, 2003; Singh et al., 2010). The maximum MRR has been obtained with 6 g/l powder particle concentration.

### 4.2 Analysis of surfaceroughness (SR)

The S/N ratio for SR for smaller-the-better(SB) was calculated using equation 2.

\[
(S / N)_{SB} = -10 \log \left( \frac{1}{n} \sum_{j=1}^{n} y_j^2 \right) \quad (2)
\]

Table 3 shows the response table for S/N ratio for the SR (smaller-the-better). The optimal parameters settings obtained as shown in Table 3 are aspect ratio: 0.005 (level 1), peak current: 8 A (level 1), pulse on time: 100 µs (level 1), pulse off time: 10 µs (level 1), gap voltage: 50 V (level 3), rotational speed: 100 rpm (level 1), powder particle size: 300 mesh (level 3), powder particle concentration: 4 g/l (level 2).

The influence of the process parameters on surface roughness with silicon powder-mixed RD-EDM is presented main effect plot, as shown in Fig.4.

### Table 3  Response table for SR

<table>
<thead>
<tr>
<th>Level</th>
<th>AR</th>
<th>Ip</th>
<th>T&lt;sub&gt;on&lt;/sub&gt;</th>
<th>T&lt;sub&gt;off&lt;/sub&gt;</th>
<th>Vg</th>
<th>N</th>
<th>PPS</th>
<th>PPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-6.23*</td>
<td>-7.2*</td>
<td>-7.6*</td>
<td>-7.6*</td>
<td>-8.2</td>
<td>-7.3*</td>
<td>-8.0</td>
<td>-7.9</td>
</tr>
<tr>
<td>2</td>
<td>-9.41</td>
<td>-7.6</td>
<td>-7.6</td>
<td>-7.7</td>
<td>-7.8</td>
<td>-8.0</td>
<td>-8.0</td>
<td>-7.4*</td>
</tr>
<tr>
<td>3</td>
<td>-8.5</td>
<td>-8.1</td>
<td>-8.0</td>
<td>-7.3*</td>
<td>-7.3*</td>
<td>-8.0</td>
<td>-7.3*</td>
<td>-8.0</td>
</tr>
<tr>
<td>∆</td>
<td>3.17</td>
<td>1.28</td>
<td>0.59</td>
<td>0.45</td>
<td>0.90</td>
<td>0.77</td>
<td>0.69</td>
<td>0.58</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

![Fig.4 Main effect plots for S/N ratio of SR](image_url)
The rotation of the disk electrode flushes the debris effectively, and further addition of silicon powder within the kerosene enlarges the inter-electrode gap. This enlarges the discharge heat area and reduces the current density which allows the dispersion of controlled discharge energy over the work material. The melting and/or vaporising of localised metal surface generates small amount of molten pool and creates shallow craters.

The surface roughness has been found to increase with an increase in the rotational speed of the disk electrode. The disk electrode rotation assists in the removal of debris from the inter-electrode gap. Further addition of silicon powder makes the removal of silicon powder and debris from the inter-electrode gap ineffective and hence increases the surface roughness, due to gap contamination and subsequent arcing.

It is seen by the increase of the powder particle size from 200-250 mesh, the surface roughness slightly increases, due to the inter-electrode gap contamination. This disturbs the discharging process and indeeds the rapid shorting between the disk electrode and work material (Tzeng and Lee, 2003; Singh et al., 2010). It is also seen that the surface roughness decreases with an addition of silicon powder concentration up to 4 g/l as shown in Fig.5. It may be due to the easy flow of the powder particles in the inter-electrode gap, which leads to uniform machining and improved surface finish.

4.3. SEM and XRD analysis

The micro-structural analysis of the machined work specimens was carried out on Scanning Electron Microscope (SEM) (JEOL - JSM-6610LV) having magnification up to 300000 and an accelerating voltage: 0.3 - 30kV. Fig.6-8 shows the SEM images of external appearance of the groove, with two aspect ratio.

Fig.6 (a) and Fig 6 (b) represents the micrographs with better outlook of grooves, using powder-mixed RDE-EDM.

Fig.6 (a) and Fig 6 (b) represents the micrographs with better outlook of grooves, using powder-mixed RDE-EDM. The picture shows no re-solidified layer on the boundary layer and machined surface of grooves.

Fig.7(a) and Fig.7 (b), shows SEM image of the bottom of the grooves. The image shows craters formed on work surface with better surface finish. This is due to the increase in gap between the disk electrode and the work material, and uniform dispersion of discharge energy, which generates shallow craters and thus improved surface finish.

Fig.7  SEM (bottom of grooves) with (a) AR: 0.005 and (b) AR: 0.036

Fig.8(a) and Fig.8(b), shows microstructure of the surface of the grooves, showing less micro cracks and more uniform dispersion of powder generating better surface finish after powder-mixed RD-EDM.

Fig.8 SEM (microstructure of grooves) with (a) AR: 0.005 and (b) AR: 0.036

Fig.9 (a) and (b), shows the XRD patterns obtained after powder-mixed RDE-EDM indicating, that there is no carbide formation, except for traces of silicon. This is due to the fact that silicon powder additives disturb the carbon nuclides and impart a polished surface after powder-mixed RD-EDM.

5. Confirmation Test

The confirmation tests were carried out to validate the experimental results, using specific combination of predicted parametric settings. It was observed that MRR increased from 0.028 to 0.041 g/min, whereas
the SR improved from 3.20 to 2.12 µm. Furthermore, the S/N ratios of MRR and SR for the optimal level are increased to 3.31, and 3.58 dB, from their initial maximum values, respectively.

6. Conclusion

The MRR was found to increase with an increase of aspect ratio of disk electrode, at all parametric settings. This is attributed to the fact that larger aspect ratio of disk electrode have larger frontal thickness, and thus an increase in the electric field density. Silicon powder additives of finer particle size resulted in increased MRR. With the addition of powder additives into dielectric fluid, spark gap increases, resulting in wide discharge channel. Thus, finer silicon powder particles get energized and traverse in a zig-zag fashion, forms clusters and bridges the spark gap between tool and work. This facilitates the increase in discharging frequency, and hence enhances the MRR. The higher the particle size, lower will be the frequency. The maximum average S/N ratio for material removal rate was -28.85 dB for finer particle size 300 mesh, as compared to 200 and 250 mesh particle sizes as 29.11 dB and 29.66 dB, respectively. The disk electrode having lower aspect ratio erodes less amount of the work material during grooving due to the smaller frontal area. The surface roughness was further decreased after addition of silicon powder. The best surface finish has been achieved at powder particle concentration 4 g/l. The addition of silicon powder improved the surface finish. It was observed that RDE-EDM with addition of silicon powder led to shallow craters as impact force acting on the work material was smaller.

References


Tzeng, Y.F. and Lee, C.Y. (2001), Effect of powder characteristics on electro discharge machining
