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An Experimental Study on the Effect of Operating Parameters during the Micro-Electro-Discharge Machining of Ni Based Alloy

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Abstract**—**Ni alloys have managed to cover wide range of applications such as automotive industries, oil gas industries, and aerospace industries. However, these alloys impose challenges while using conventional machining technologies. On the other hand, Micro-Electro-Discharge machining (micro-EDM) is a non-conventional machining method that uses controlled sparks energy to remove material irrespective of the materials hardness. There has been always a huge interest from the industries for developing optimum methodology and parameters in order to enhance the productivity of micro-EDM in terms of reducing machining time and tool wear for different alloys. Therefore, the aims of this study are to investigate the effects of the micro-EDM process parameters, in order to find their optimal values. The input process parameters include voltage, capacitance, and electrode rotational speed, whereas the output parameters considered are machining time, entrance diameter of hole, overcut, tool wear, and crater size. The surface morphology and element characterization are also investigated with the use of SEM and EDX analysis. The experimental result indicates the reduction of machining time with the increment of discharge energy. Discharge energy also contributes to the enlargement of entrance diameter as well as overcut. In addition, tool wears show reduction with the increase of discharge energy. Moreover, crater size is found to be increased in size along with the increment of discharge energy.

Keywords**—**Micro EDM, Ni alloy, discharge energy, micro-holes.

I. Introduction

Ni alloy is well known for their high temperature strength and high corrosion resistance properties. Because of these important properties, they are heavily employed for military aircraft and space engines, oil and gas industries, and biomedical industries. Due to the complex nature of Ni alloy, machining of Ni based alloy always imposes challenges to the machining community [1]. One of these complex properties includes low thermal conductivity which may lead to temperatures rise at the tool rake face. Others properties include work-hardening tendency while machining, high thermal affinity to tool materials which may result in welding/ adhesion of workpiece material to the cutting edge, and also existence of hard abrasive particles (e.g. carbides, oxides) resulting in intense tool wear [2]. During cutting, heat generation happens mainly because of the accumulation of plastic deformation during chip removal and also by the between tool-chip interface and workpiece-tool interface [3]. Since these superalloys experience metallurgical reformation during their fabrications stage, this change makes them tougher, stronger, and more oxidation and also corrosion resistant. As a result, they become more challenging to be machined. Particularly, for Ni based alloy, associated high temperature properties impose machining complexity. High cutting force and temperature combine, together during the Ni based alloy machining process, and direct towards the tool edge breakdown in terms of chipping and deformation. Moreover, work hardening is experienced by most of the metal as well, which in turn may also compromise the fatigue strength and geometric accuracy of the part [4]. In order to prevent these methodological complications involved in traditional machining processes, non-traditional technologies like and micro-EDM have been implemented tremendously for the machining of hard-to-cut material like Ni based alloy. The applications having restrictions on dimensional accuracy with complex geometries are primarily benefitted from this new methodology. Micro-EDM is one of the important branches of EDM, which is also considered as noncontact material removal process. Material is removed by the generated succeeding electrical sparks or discharges. These discharges convert electrical energy into thermal energy and raise the temperature between workpiece and tool by creating plasma Chanel. Therefore, the material removal from tool and workpiece takes place mainly by melting and vaporization [5]. However, the difference between normal EDM and micro-EDM processes comes from it smaller tool size, lower discharge energy, and axes motion which is at micron level in case of micro-EDM [6]. The major advantage of EDM or micro-EDM over the traditional machining processes is due by the fact that, it is an electro-thermal process of eliminating materials regardless of material's hardness. Cutting force during the EDM process is also insignificant due to the non-contact method [7]. Therefore, the error associated with the tool deformation due to cutting force is approximately null. Concerns related to machining chatters, mechanical stress, and vibration problems during the machining can also be eradicated, due to the non-contact nature of the process [8].

There have been studies on both macro and micro scale EDM of Ni based alloy in the recent past. Several studies investigated on the effect of different operating parameters under macro scale electro-discharge machining and assessed the machinability of Ni based alloy. Demands from MEMS

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application inspires the study of fabrication of micro-holes on nickel alloy with the help of micro EDM process [9]. Deep micro-holes of 50 mm diameter size with an aspect ratio of 10:1 were machined with the help of micro-EDM process [10]. During EDM machining of Ni based alloy, the surface integrity is found to be inversely proportional to material removal rate (MRR) and thus suggested low MRR for better surface [11]. Material removal rate using electrodes made of brass is comparatively higher during drilling of micro-holes in Ni–Ti alloy [12]. Theisen and Schuemann investigated the electro discharge machining of nickel-titanium alloys using tungsten and copper electrode. They described that crack depth and surface roughness both are affected by the current and voltage changes [13]. Chen et al. studied the impacts of machining on Ni Al Fe alloys. They suggested that melting temperature and thermal conductivity of alloy are reversely proportional with MRR [14]. By exploring the heat transfer coefficient of Ti49Ni49 - Ti50Ni50 - Cu10Ni40Ti50 alloys, Lin et al. also concluded that melting point and heat transfer coefficient of the material influences MRR in opposite manner [15]. Daneshmand et al. did an investigation on Ni-Ti alloy using cupper electrode and de-ionized water as dielectric [16]. Their study recommended that MRR increases, with the increase of pulse on time, pulse current and voltage, irrespective of tool rotation. On the other hand, MRR reduces with increment of pulse off time. Al Ahmari et al. also investigated a new hybrid process on Ni-Ti alloy which is a combination of micro EDM and laser beam machining [17]. As a result, 50–65% reduction in machining time was achieved without affecting the quality of micro-holes as compared to the standard micro-EDM process. However, there are not many studies done on micro EDM of haste alloy using RC generator. Therefore, in the present investigation, an effort has been taken to study material removal rate, tool wear, and over cut using micro-EDM process while fabricating blind micro-holes on Ni alloy. For this purpose, variation of discharge energy as well as tool rotation has been done to investigate their effect.

II. Materials & Methodology

A desktop micro-EDM machine tool from SmalTech is used in this paper for conducting micro-electro-discharge machining on Ni alloy workpieces. Overall view of the micro-EDM experimental setup is shown in Fig. 1. The key elements of the micro-EDM setup include the machine tool itself, the pulse generator, micro scope coupled with the CCD camera along with the monitor for the purpose of witnessing the sparking phenomenon and locating the machining region precisely.

Table I shows overall experimental parameters used in this study. Firstly, a series of blind micro-holes are machined using micro-EDM setup on Ni workpiece using the tungsten carbide milling electrode (Fig. 2). Micro holes are machined by using different discharge energy by varying the electrical parameters. The specific sets of parameters are listed in Table II. In this study, a resistor–capacitor (RC)-type pulse generator is used for providing the required discharge energy for micro-EDM machining. This discharge energy is basically half of the product of capacitor and voltage only. Therefore, voltage and capacitor are the main two electrical parameters for RC micro-EDM. After machining, Ni samples are washed with ethanol, normal tap water, and deionized water, respectively. Ni sample is placed in a small glass-biker containing ethanol, and then ultrasonic cleaner is used to remove remaining loose materials from the machined surface for 5 minutes. Then, the sample is rinsed with deionized water following that ultrasonic cleaning process. Finally, the experimental data are collected by using different characterization techniques to assess the precision of the micro-holes, MRR and surface crater size. The quality of the micro-holes and tool condition is evaluated using the scanning electron microscope (SEM) images and optical images respectively. Both unmachined and machined surfaces have been investigated by using EDX spectrum analysis to find out the potential alterations in the elemental composition of the surface after micro-EDM process.

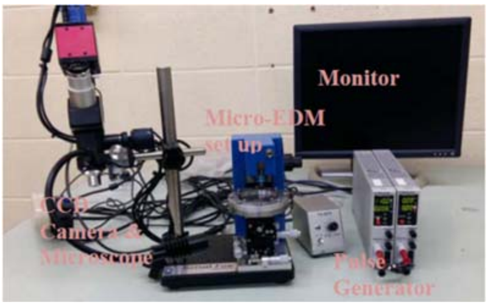


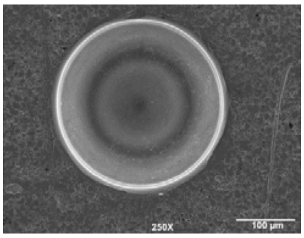
Fig. 1 Experimental setup

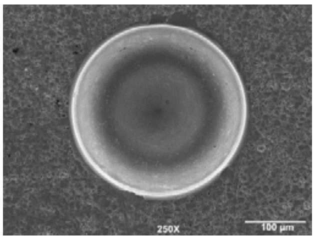
TABLE I
EXPERIMENTAL PARAMETERS

Parameters	value
Work piece	Ni alloy
Electrode	Tungsten carbide (287μm)
Polarity	Electrode negative, workpiece positive
Dielectric	EDM oil
Discharge voltage	60V, 85 V, 110V
RPM	1000, 2000, 3000
Capacitor	60pF, 1000 pF, 4500pF

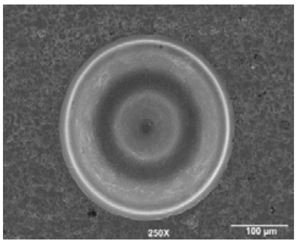
TABLE II
PROCESS PARAMETERS

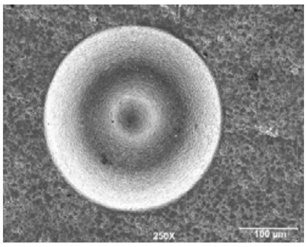
Rpm	Voltage (V)	Capacitance (pF)	Discharge Energy = $1/2CV^2$(μJ)
1000	60	60	0.054
	85	60	0.108375
	110	60	0.1815
2000	60	1000	1.8
	85	1000	3.6125
	110	1000	6.05
3000	60	4500	8.46
	85	4500	16.97875
	110	4500	28.435



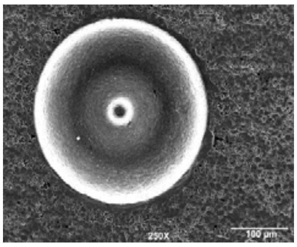


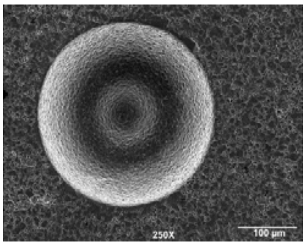
(a) DE=0.054 μJ (b) DE= 0.108375 μJ



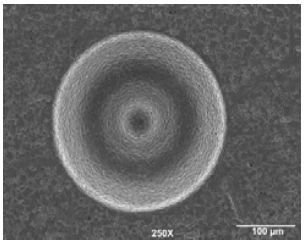


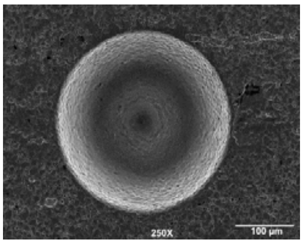
(c) DE= 0.1815μJ (d) DE= 1.8 μJ



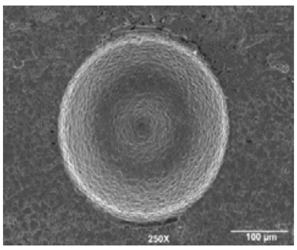


(e) DE= 3.6125 μJ (f) DE= 6.05 μJ





(g) DE=8.46 μJ (h) DE=16.97875 μJ



(i) DE=28.435 μJ

Fig. 2 Micro-holes on Ni alloy using different discharge energy (1000 rpm)

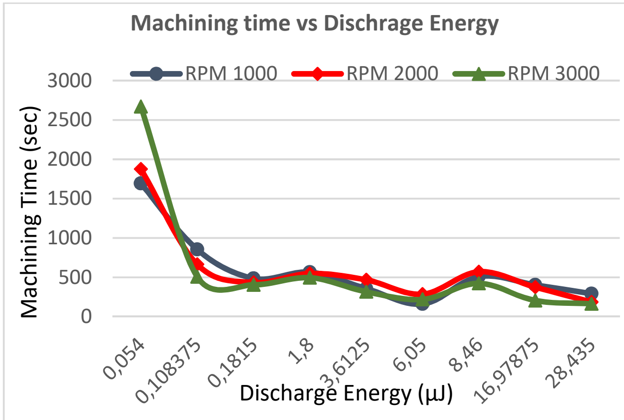


Fig. 3 Effect of discharge energy on machining time

III. Results & Discussion

A. Effect of Discharge Energy on MRR

In this study, 30 μm deep blind micro holes are machined on Ni alloy surface by using 287 μm tungsten carbide milling tool which is available commercially. Now, there are three sets of voltage, capacitance and RPM used in this process. Therefore, 27 sets of experiments have been carried on as shown in Table II. Nine sets of discharge energy were utilized for three different tool rotation as can be seen from Fig. 3. During the process, negative polarity electrode was used in order to maximize material removal rate and minimize tool wear. Fig. 3 shows the variation of machining time with the discharge energy for three different rpm. As can be seen from the figure, reduction of machining time with the increase of discharge energy is common for all rpm. In this case, an increase in discharge energy actually yields an increase in MRR which contributes to the reduction of machining time. However, there are some anomalies in the graph and the reason behind those anomalies point is due to the low voltage gap since the low voltage gap often causes short circuit, resulting in no material removal. Therefore, even with the increases in discharge energy, the machining time decreases at those points. On the other hand, the effect of rpm seems not that significant. Although, higher rpm causes the highest machining time for the lowest discharge energy level, eventually it lessens the machining time compared to other lower rpm setting. It could be due to the lowest voltage setting as well as the expansion of spark due to high rotation.

B. Effect of Discharge Energy on Tool Wear

The effect of tool rotation on tool wear for different energy level has been plotted on Fig. 4. The general trend of tool wear is the decreasing tendency with the increasing discharge energy, which is due by the fact that higher discharge energy reduces the machining time; as a result, tool wear reduces because of less machining time or operational hour. This trend is similar for three different tool rotations. However, there are some anomalies found on 1.8 μJ, and 8.46 μJ. At these two energy settings, the voltage used is 60 V which is the stray voltage for the machine. Due to the low voltage gap, and manual control of tool feed, short circuiting often happens, which in turn may increase the machining time as well as tool wear.

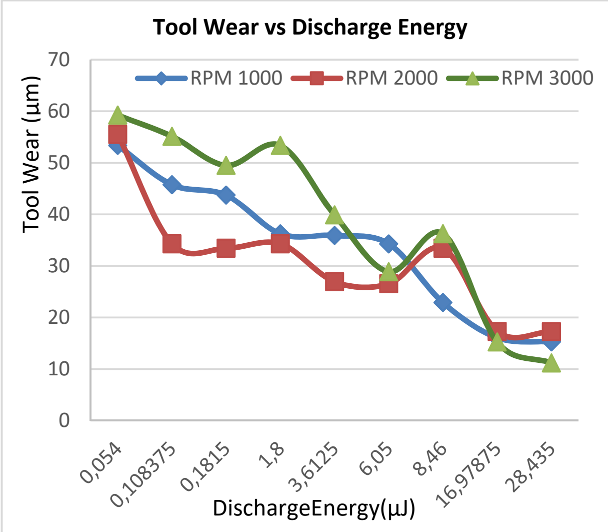


Fig. 4 Effect of discharge energy on tool wear

For the higher tool rotation, the tool wear appears more than those in lower tool rotation. This is due by the fact that higher tool rotation helps to remove molten material from the melted area more frequently, which in turn exposes fresh area of the workpiece to tool electrode. Consequently, spark can initiate efficiently due to the exposed fresh area from both the tool and workpiece which are also free from molten debris. Therefore, melting and flushing of debris from workpiece in the vicinity of the spark can be enhanced while using higher tool rotation and thus accelerates the tool wear as well [18].

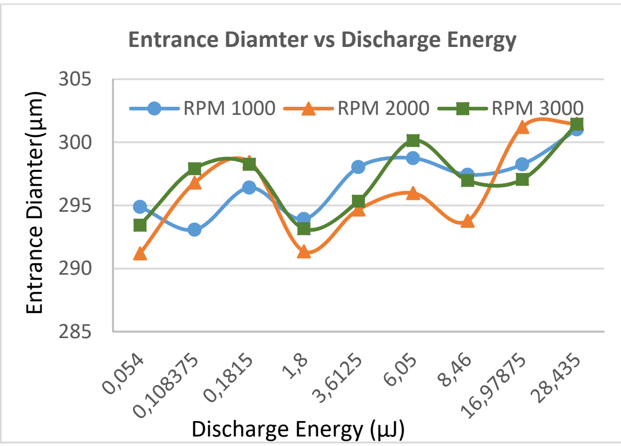


Fig. 5 Effect of discharge energy on Entrance diameter variation

C. Effect of Discharge energy on Overcut

As can be seen from Fig. 5, entrance diameter range varies from 301.49 µm.-291.2 µm and increases overall with the increase of discharge energy. For the higher discharge energy, the entrance diameter has more enlargement than the low energy. This is due by the fact that lower discharge energy causes smaller scale of material removal which produces smaller craters. Consequently, these smaller craters result in small diameter enlargement. Another reason for the increased diameter variation may be because of the fact of long persisting discharge energy column occurs at high discharge energy. When the discharge duration becomes longer, it assists in electron coming from negative terminal bumping with the neutral particles in the dielectric fluid, thus resulting in greater ionization effect. The greater the number of electrons and ions bumping with the workpiece, the bigger the micro-hole expansion becomes [19]. This trend is true for the three different rpm. However, there are some points in the curve (1.8 µJ, and 8.46 µJ) that show opposite trend which might be due to the lowest or stray voltage value at those particular points. High voltage helps to remove debris faster from the machined area, thus removes materials efficiently and lowers the chance of short circuit as well as secondary sparking phenomenon which in turns results in less machining time as well more diameter variation. Again, for the higher tool rotation diameter enlargement is evidently more due to the reason that higher tool rotation can clear the debris faster than lower tool rotation, which in turn can contribute more in the material removal. Moreover, the higher tool rotation comes along with tool deflection than the lower tool rotation.

The overcut generally affects good dimensional accuracy and finishes of the machined workpiece. The lower and consistent is the size of the overcut, the more predictable will be the resulting dimension. Fig. 6 shows the variation of overcut with discharge energy. It has been found that with the increase of discharge energy, the overcut increases due to the enlargement of entrance diameter.

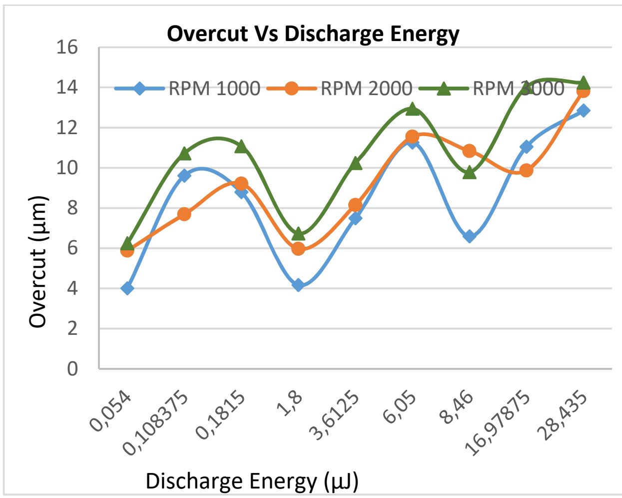


Fig. 6 Effect of discharge energy on overcut

D. Effect of Discharge Energy on Crater Size

As can be seen from Fig. 7, the size of crater shows increasing tendency with the increment of discharge energy. The reason behind the bigger crater size for the higher discharge energy is due by the fact that bigger amount of material removal takes place by the higher discharge energy which in turn creates larger craters than those from smaller discharge energy. This trend is more or less identical for all the electrode rotational speeds used during the experiment.

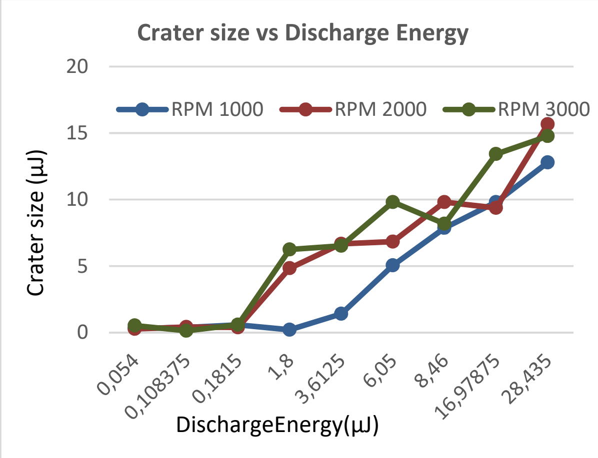
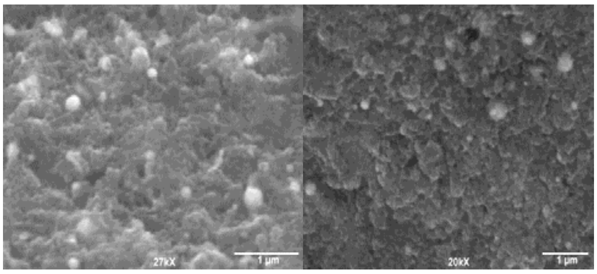
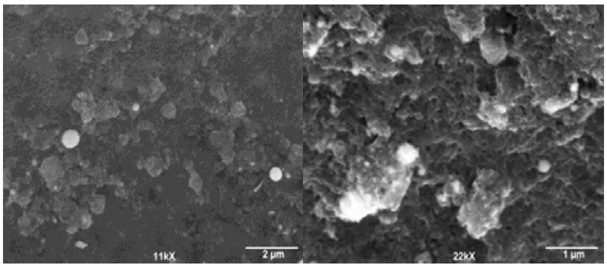


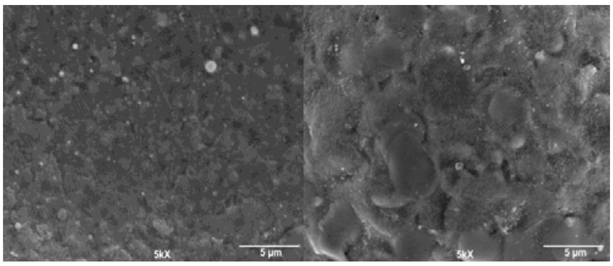
Fig. 7 Effect of discharge energy on crater size



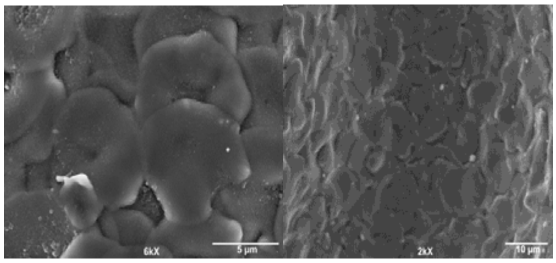
(a) DE=0.054 μJ (b) DE= 0.108375 μJ



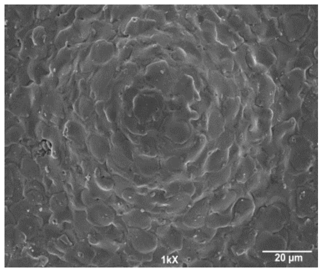
(c) DE= 0.1815 μJ (d) DE= 1.8 μJ



(e) DE= 3.6125 μJ (f) DE= 6.05 μJ



(e) DE= 3.6125 μJ (f) DE= 6.05 μJ

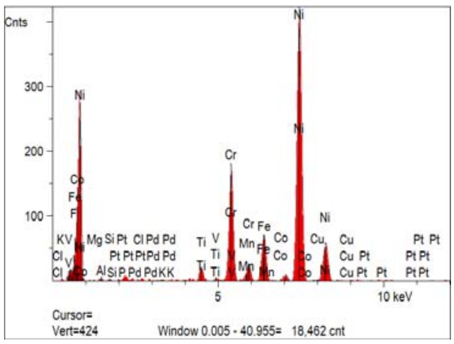


(i) DE=28.435 μJ

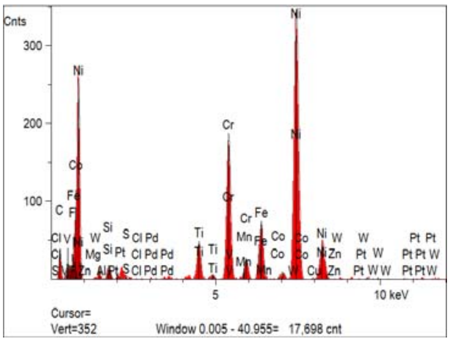
Fig. 8 Crater formed for different discharge energy (1000 rpm)

Fig. 8 represents zoomed SEM image of the blind holes. As can be seen from the images, crater size gradually increases with the discharge energy. Due to the different magnification used during SEM, the size might not be showing gradual enlargement with the gradual increase of discharge energy.

To analyze the composition change of Ni alloy, EDX is done on the sample before and after machining. Figs. 8 (a) and (b) show the EDX spectrum for Ni alloy. Detail elements analysis can be seen from Tables III and IV. As can be seen from the element tables, W is not present before machining, as it comes from tool material. Other than that, there is an evident of increment in the oxygen amount after machining which may be because of the oxidation of molten material due to the high temperature during EDM process. Also there is small reduction in Ni amount due to the increased oxygen amount.



(a) Before machining



(b) After machining

Fig. 9 EDX spectrum analysis of Ni Haste Alloy before and after machining

TABLE III
ELEMENT ANALYSIS REPORT OF NI ALLOY BEFORE MACHINING

Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	Error 2-sig	MDL 3-sig	
C	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
N	Ka	0.18	0.874	0.219	wt.%	0.823	1.227	
O	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
F	Ka	2.08	2.038	0.693	wt.%	0.359	0.480	
Mg	Ka	0.26	0.160	0.070	wt.%	0.286	0.431	
Al	Ka	2.00	0.816	0.394	wt.%	0.275	0.391	
Si	Ka	1.30	0.390	0.196	wt.%	0.219	0.322	
P	Ka	0.39	0.095	0.053	wt.%	0.200	0.303	
Cl	Ka	0.71	0.128	0.081	wt.%	0.182	0.274	
K	Ka	1.03	0.162	0.113	wt.%	0.178	0.265	
Ti	Ka	10.54	1.547	1.325	wt.%	0.236	0.281	
V	Ka	0.37	0.057	0.052	wt.%	0.208	0.314	
Cr	Ka	86.80	14.132	13.146	wt.%	0.551	0.297	
Mn	Ka	2.27	0.389	0.383	wt.%	0.227	0.317	
Fe	Ka	37.73	7.189	7.182	wt.%	0.484	0.350	
Co	Ka	0.73	0.184	0.194	wt.%	0.347	0.516	
Ni	Ka	236.18	71.048	74.605	wt.%	1.819	0.628	
Cu	Ka	1.69	0.586	0.667	wt.%	0.496	0.704	
Pd	La	0.31	0.053	0.101	wt.%	0.507	0.770	
Pt	La	0.18	0.151	0.528	wt.%	2.734	4.128	
			100.000	100.000	wt.%			Total

TABLE IV
ELEMENT ANALYSIS REPORT OF NI ALLOY AFTER MACHINING

Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	Error 2-sig	MDL 3-sig	
C	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
N	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
O	Ka	2.09	3.392	0.978	wt.%	0.497	0.660	
F	Ka	2.10	2.462	0.843	wt.%	0.464	0.630	
Mg	Ka	0.14	0.082	0.036	wt.%	0.297	0.451	
Al	Ka	4.63	1.885	0.917	wt.%	0.313	0.415	
Si	Ka	1.56	0.475	0.240	wt.%	0.234	0.342	
P	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
S	Ka	2.13	0.471	0.272	wt.%	0.208	0.300	
Cl	Ka	0.41	0.078	0.050	wt.%	0.197	0.298	
Ti	Ka	22.58	3.599	3.105	wt.%	0.304	0.288	
V	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
Cr	Ka	91.36	16.382	15.355	wt.%	0.633	0.363	
Mn	Ka	1.48	0.282	0.280	wt.%	0.260	0.377	
Fe	Ka	37.95	8.100	8.154	wt.%	0.543	0.380	
Co	Ka	0.00	0.000	0.000	wt.%	0.000	0.000	
Ni	Ka	190.01	60.800	64.327	wt.%	1.759	0.668	
Cu	Ka	1.20	0.445	0.510	wt.%	0.520	0.753	
Zn	Ka	0.19	0.090	0.106	wt.%	0.548	0.828	
Pd	La	0.31	0.058	0.111	wt.%	0.557	0.845	
W	La	1.45	0.996	3.299	wt.%	2.662	3.777	
Pt	La	0.47	0.403	1.417	wt.%	2.952	4.367	
			100.000	100.000	wt.%			Total

IV. CONCLUSIONS

In this study, RC-type micro-EDM machine is utilized to conduct an experimental study in micro-EDM of blind micro-holes on Ni haste alloy. Based on the exerimental results presented in this study, following conslusions can be considered.

- Effect of dischrage energy on machining time for three different tool rotations is investigated and, it is perceived that machining time reduces with the increasing value of discharge energy, and also for high tool rotation, this machining time seems more efficient than those with lower tool rotation.
- Effect of discharge energy on tool wear suggests that tool wear reduces with the increasing discharge energy due to the reduced contact machining time of tool.
- The effect of discharge energy on the micro hole overcut advocates that, overcut increases with the increasing discharge energy and overcut become more significant in higher tool rotation due to more tool deflection.
- Crater forms during micro-EDM also increases in size with the increment of discharge energy and the reason behind this is possibly the larger material removal by the bigger energy sparks.
- Finally, EDX analysis of Ni alloy surface before and after machining validates that the machined surface experiences some modifications like addition of oxygen due to the oxidation process during micro-EDM due to high temperature and also some reduction in Ni amount.

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