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STUDY OF MATERIAL REMOVAL RATE AND ELECTRODE WEAR RATIO FOR MICRO ELECTRICAL DISCHARGE MILLING OF AISI 420 AND STAVAX ESR

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ABSTRACT

This paper investigates micro electrical discharge (ED) milling for AISI 420 and Stavax ESR stainless steel using tungsten carbide electrode. For each of the materials, experiments have been conducted using the full factorial combination of gap voltage, capacitance and feed rate. Two responses material removal rate (*MRR*) and electrode wear ratio (*EWR*) are analyzed. Both *MRR* and *EWR* are found to be higher for AISI 420 compared to that of Stavax for the same machining parameters and environment. Empirical models are developed for the estimation of *MRR* and *EWR*. The empirical relationship shows that the feed rate and capacitance are the most important factors for *MRR*. However, gap voltage and capacitance are the main influential factors for *EWR*. Although the trend of relationship of *MRR* and *EWR* is found to be similar for both materials, the level of influence is found to be significantly different. For multiple optimization of *MRR* and *EWR*, the machining parameters are determined analytically and verified experimentally. The optimized values of gap voltage and feed rate are 100 V and 6 μm.s^{-1} for both materials. However, the optimized capacitance is 8.55 nF and 1 nF for AISI 420 and Stavax ESR respectively. The verification experiment shows that the measured values of *MRR* and *EWR* are within 5-10% of the predicted values. For the Stavax ESR the *MRR* and *EWR* are found lower than that for AISI 420. The possible reasons of these lower *MRR* and *EWR* are discussed.

Keywords: AISI 420, Stavax ESR, Micro ED milling, *MRR*, *EWR*

Nomenclature:

ANOVA	Analysis of variance
C	Capacitance (nF)
df	Degree of freedom
ED	Electrical discharge
EDM	Electrical discharge machining
EWR	Electrode wear ratio
f	Feed rate (μm.s^{-1})
MRR	Material removal rate (μg s^{-1})
MS	Mean square
SS	Sum of square
V	Gap voltage (V)

1. INTRODUCTION

Micro manufacturing is constantly pushing toward smaller scales and becomes the most exciting frontiers of today. The micromachining technologies are being applied in the manufacture of various components of micro electro mechanical systems (MEMS) such as micro-fluidic circuits, micro valves, micro filter, micro mold cavities, etc. (Ali, M.Y., 2009; Kim et al, 2005). Fabrication of three dimensional (3D) micro products is a bottleneck in micro fabrication technologies. Although LIGA (Lithography, Electroforming, and Molding) is a guideline for producing high quality 3D micro components, however, it is complex, expensive and based on lithographic process which is environmentally unfriendly (Hung et al., 2000). Focused ion beam (FIB) micromachining is an alternative for few tens of micrometers to sub-millimetre sized micro components. The FIB is a LIGA competitive process for high surface finish (2-5 nm R_a) and accuracy (submicrometer) with aspect ratio up to 10 (Ali and Loo, 2007). Micro meso mechanical manufacturing (M^4) is another alternative for machining miniaturized products from hard materials. The M^4 technique includes tool based micro milling, ultra-precision milling and turning, electro discharge machining (EDM), etc. Micro EDM, a miniaturized version of EDM, is a cheaper, simpler but powerful alternative for micromachining of sub-millimetre sized components. The process is flexible and the products require no subsequent de-burring process (Chen et al, 2006, Morgan et al, 2006, Wang and Zhu, 2008). Delivering low energy discharge at high frequency is the key to make micro products with high accuracy and surface finish (Liao and Yu, 2004). There are several types of micro EDM such as micro electrical discharge (ED) milling, grinding, and wire electrical discharge machining. As these processes are material dependent, selection of electrode, optimization of surface finish, material removal rate (*MRR*), and electrode wear ratio (*EWR*) are remained the main concern for researchers (Mehfuz and Ali, 2008). Tungsten carbide is widely used as an electrode material because of its super hardness, wear resistance, high thermal conductivity, etc. Its high strength and rigidity enable it to be machined into high aspect ratio electrodes and other microstructures [Yan et al, 2006]. Pure nickel is used in LIGA process for making micro mold cavities because of its well-known electroforming capability. Other materials such as beryllium copper (protherm moldmax), beryllium nickel, etc. are also widely used as mold materials. AISI 420 and Stavax ESR are the choices for conventional mold materials (Yuan et al, 2003; Ong et al, 2006; Ruprech et al, 2002). Stavax ESR is a modified AISI 420 produced by electro-slag-refining (ESR) technique. It is widely used as a tool material due to the characteristics of high corrosion resistance, wear resistance, polishability, machinability, and stability in hardening. The chemical composition and selected properties of AISI 420, Stavax ESR, and tungsten carbide are listed in Table 1 (Parmaco, 2006; Uddeholm, 2007; Conforma, 2006). Molds that made of Stavax ESR require less maintenance; ensure consistent cycle time and low production cost. Considering these characteristics, Stavax ESR is also a choice as a tool material for micro replication such as micro injection molding, micro hot embossing, etc. Although processing of Stavax ESR using ultra-precision turning, milling, grinding, etc. is reported (Ding et al, 2002; Neo et al, 2003), literature related to processing of Stavax using micro EDM are very limited. The machinability of Stavax ESR can be assumed similar to that of AISI 420 at macro scale. However, slightest variation in process conditions and material compositions causes direct and significant impact on micromachining. Thus, the objectives of this research are to:

i. study the influence of micro ED milling process parameters on *MRR* and *EWR* for AISI 420 and Stavax ESR,
ii. formulate empirical models for *MRR* and *EWR*, and
iii. compare *MRR* and *EWR* for AISI 420 and Stavax ESR.

In this research the definition of response variables are as follows.

MRR = weight of work material per unit time

$$EWR = \frac{volume\ of\ electrode\ wear\ per\ unit\ time}{volume\ of\ work\ material\ removed\ per\ unit\ time}$$

2. EXPERIMENTAL PROCEDURE

Experiments were conducted by using a computer numerical control (CNC) resistance-capacitance (R-C) type micro ED milling machine integrated with Miniature Machine Tool (DT-110, Mikrotools Inc., Singapore). The maximum travel ranges of this machine are x = 210 mm, y = 110 mm, and z = 110 mm. Each axis has an optical linear scale with resolution of 0.1 µm, and fully closed feedback control and compensation to ensure high accuracy. The schematic diagram of micro ED milling is illustrated in Figure 1. The tool electrode was a cylindrical tungsten carbide rod of 50 mm long and 300 µm diameter. The electrode was end faced using micro wire electrical discharge grinding to maintain a flat end.

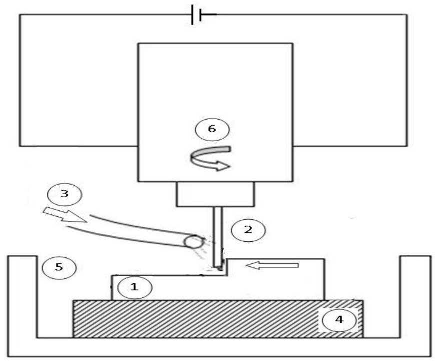


Figure 1: Schematic diagram of micro ED milling (1: workpiece, 2: electrode, 3: dielectric channel, 4: workpiece base, 5: dielectric tank and 6: spindle)

Table 1: Properties of AISI 420 and Stavax ESR work material and tungsten carbide electrode material (Parmaco, 2006; Uddeholm, 2007; Conforma, 2006)

Property	AISI 420	Stavax ESR	WC
Composition (wt%)	C:0.5, Si:1.0 Mn:1.0, Cr:13.0, Fe:balance	C:0.38, Si:0.3, Mn:0.7, Cr:13.6, Ni:0.8, V:0.3, Fe:balance	WC = 94 and Co = 6
Density (gm cm^{-3})	7.75	7.8	15.8
Melting point (^{0}C)	1450	1450	2870
Thermal conductivity ($W.m^{-1}.K^{-1}$)	22	24	84.2
Specific heat capacity ($J.g^{-1}.K^{-1}$)	0.46	0.46	0.044
Electrical resistivity ($Ohm.mm^2.m^{-1}$)	0.6	0.6	0.2
Modulus of elasticity (GPa)	215	190	700
Hardness (HRC)	50	60	70

The workpiece was 50 mm x 20 mm x 5 mm sized small bar of AISI 420 and Stavax ESR. The dimension of the micro channel made on this workpiece was 300 µm wide, 500 µm deep and 5 mm long. The dielectric fluid used in these experiments was EDM-3 synthetic oil and the polarity of the workpiece was positive. The sketch of the workpiece and micro channels are shown in Figure 2a. The ED milling parameters are listed in Table 2. For each of the factorial combination of parameters, as listed in Table 3, experiments were conducted on both workpiece materials. The machining time for each of the channels was 60-80 minutes depending on the parameters. For each of the experiments, the initial and final weight of workpiece and electrode were taken using a digital weighing machine of 10 µg resolution (B 204-S Mettler Toledo, Switzerland). Then, *MRR* and *EWR* were calculated and listed in Table 3. After completing all 8 runs, both samples were cleaned in ultrasonic bath, and then dried and gold coated for inspection using scanning electron microscope (SEM) (JSM-5600, JEOL, Japan). One of the SEM images of the machined micro channel is shown in Figure 2b (Run #4: 95 V gap voltage, 10 nF capacitance, and 4 μms^{-1} feed rate) as an example.

Table 2: Levels of micro ED milling parameters and other fixed machining conditions

Control Factor	**Code**	**Level**	
		-	+
Gap Voltage (V)	A	95	100
Capacitance (nF)	B	1	10
Feed rate (μms^{-1})	C	4	6
<u>Fixed parameters</u>			
Tool electrode	Tungsten carbide		
Workpiece	AISI 420 and Stavax ESR		
Tool electrode dia. (μm), length (mm)	300, 50		
Spindle speed (rpm)	2000		
Polarity	Workpiece positive		
Dielectric fluid	EDM-3 (Synthetic oil)		
Machined channel size (μm)	Width: 300, depth: 500 Length: 5000		

Table 3: Factorial combination of micro ED milling parameters and the responses

	Machining parameters			AISI 420		Stavax ESR	
Run	Gap voltage (V)	Capacitance (nF)	Feed rate (μms^{-1})	*MRR* (μg.s^{-1})	*EWR*	*MRR* (μg.s^{-1})	*EWR*
1	100	1	4	0.4818	0.0493	0.3218	0.0680
2	95	1	4	0.4143	0.1073	0.3774	0.1130
3	100	10	4	0.5806	0.0905	0.4653	0.1219
4	95	10	4	0.4981	0.1440	0.4755	0.1044
5	100	1	6	0.4783	0.0586	0.4134	0.0834
6	95	1	6	0.3933	0.0927	0.4065	0.1202
7	100	10	6	0.6562	0.1129	0.4657	0.1289
8	95	10	6	0.6190	0.1113	0.4453	0.1126

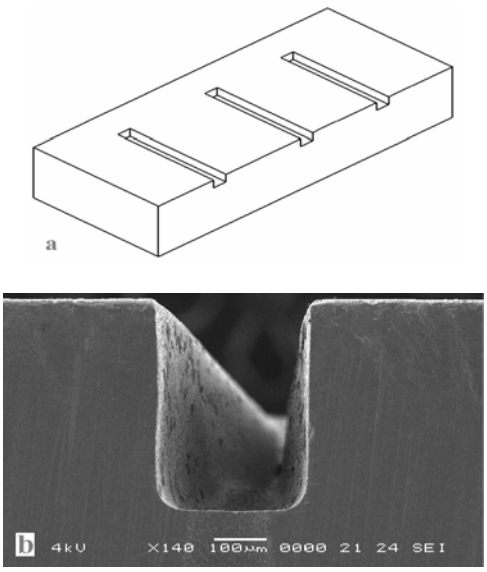


Figure 2: (a) Sketch of workpiece and micro channels, (b) SEM image of micro channel (width: 300 μm, depth: 500 μm, length: 5 mm) on Stavax ESR machined by micro ED milling (Run #4: 95 V gap voltage, 10 nF capacitance, and 4 μms^{-1} feed rate)

3. RESULTS AND ANALYSIS

The three process parameters (gap voltage, capacitance, and feed rate) and two responses (*MRR* and *EWR*), as listed in Table 3, were analyzed using Design Expert (Version 7, State-Ease Inc., MN, USA) software. The objectives were to identify the individual and interactive influence of process parameters on *MRR* and *EWR* by the analysis of variance (ANOVA). In addition, empirical modelling and multiple optimization of the responses are discussed in the following subsections.

3.1 MRR for AISI 420 and Stavax ESR

The ANOVA for the main and interaction effect of parameters on *MRR* for AISI 420 and Stavax ESR is listed in Table 4. It can be observed that capacitance and feed rate and their interaction are significantly contributing to *MRR*. Gap voltage and other interactions are found to be insignificant. The empirical models for the estimation of *MRR* for AISI 420 and Stavax ESR are expressed by Eqn. (1) and (2) respectively. The Models F-value of 7.04 and 12.94 for Eqn. (1) and (2) respectively indicate that the models are significant.

There are only 4.5% and 1.59% chances that these large F-values of 7.04 and 12.94 respectively can occur due to noise. From the interaction graph between capacitance and feed rate, as shown in Figure 3, it can be noticed that *MRR* increases with the increase of capacitance and feed rate for both materials. However, comparison of p-value (Table 4) of capacitance and feed rate indicates that capacitance has stronger contribution to *MRR* than feed rate for both AISI 420 and Stavax ESR. Similarly, it can be seen that the interaction of capacitance and feed rate is more significant than the feed rate alone.

$$MRR_{AISI420} = 0.487 - 0.0144C - 0.0123f + 0.0061Cf \quad (1)$$

$$MRR_{Stavax} = 0.20 + 0.03C + 0.034f - 0.0042Cf \quad (2)$$

3.2 EWR for AISI 420 and Stavax ESR

The ANOVA for the main and interaction effect of parameters on *EWR* for AISI 420 and Stavax ESR is listed in Table 5. It can be observed that gap voltage and capacitance individually and interactively contribute to *EWR*. The empirical models for the estimation of *EWR* for AISI 420 and Stavax ESR are expressed by Eqn. (3) and (4) respectively. The Model F-values (Table 5) indicate that the models are significant. There are only 3.65% and 0.80% chances that the models can be insignificant due to noise. From the interaction between gap voltage and capacitance, as shown in Figure 4, it can be noticed that *EWR* decreases with the increase of gap voltage for AISI 420. However, for Stavax ESR, the *EWR* increases with the increase of gap voltage for higher level of capacitance and gap voltage only (Fig. 4b, top right corner). Otherwise, *EWR* decreases with the increase of gap voltage (Fig. 4b, bottom right corner). The p-values of gap voltage, capacitance and their interaction (Table 5) indicate that all of them are significantly contributing to *EWR* for both the materials. However, gap voltage is less significant among them.

$$EWR_{AISI\,420} = 1.014 - 0.00966V - 0.039C + 0.000447VC \quad (3)$$

$$EWR_{Stavax} = 1.017 - 0.0095V - 0.123C + 0.00128VC \quad (4)$$

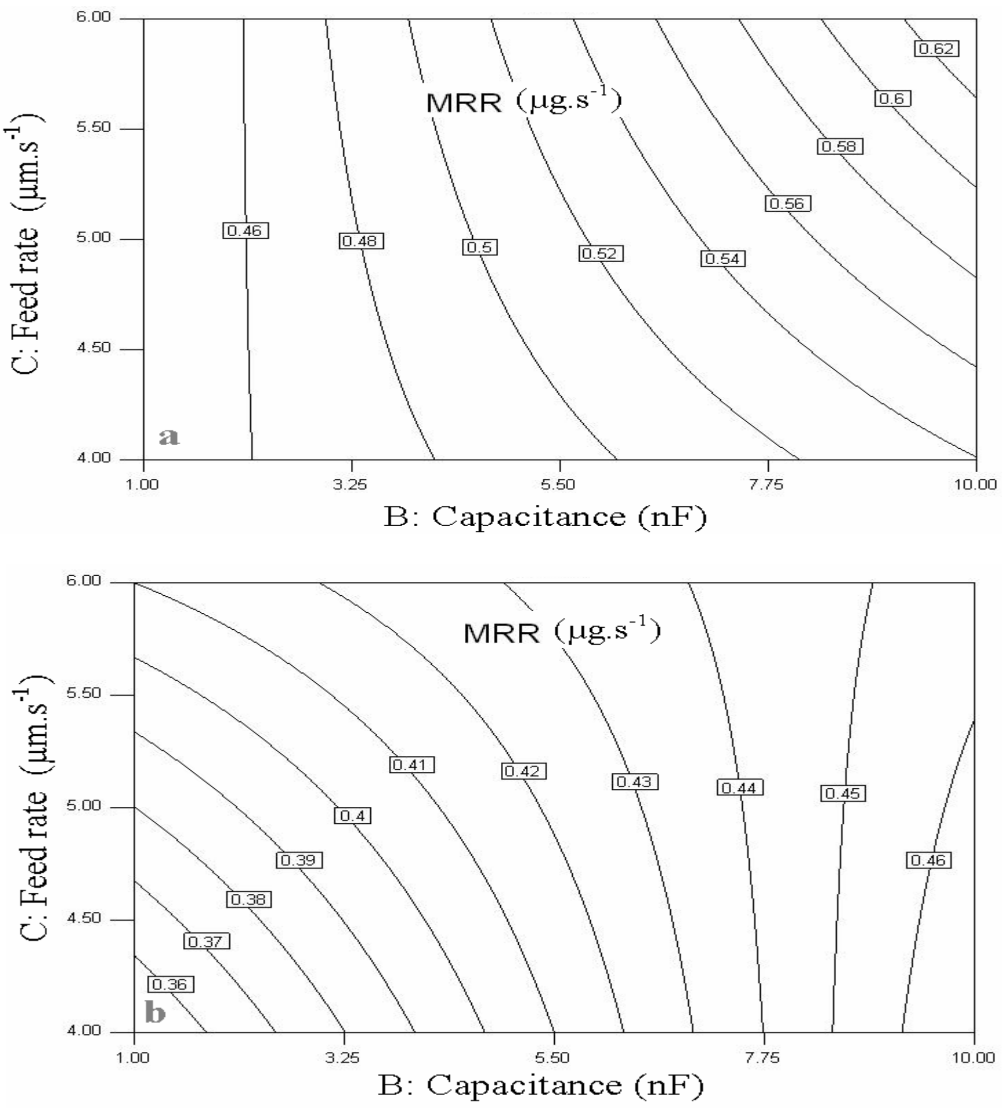


Figure 3: Interaction of micro ED milling parameters of capacitance and feed rate on *MRR* of (a) AISI 420 and (b) Stavax ESR (Electrode: Tungsten carbide, Gap voltage: 97.5 V)

Table 4: ANOVA for main and interaction effect of parameters on *MRR*

	SS	df	MS	F value	p-value (Prob > F)
AISI 420					
Model	0.053	3	0.018	7.04	0.045
B-Capacitance	0.043	1	0.043	17.21	0.014
C-Feed rate	0.0037	1	0.0037	1.48	0.29
BC	0.0061	1	0.0061	2.45	0.193
Residual	0.01	4	0.0025		
Cor total	0.063	7			
Stavax ESR					
Model	0.018	3	0.0059	12.94	0.0159
B-Capacitance	0.014	1	0.014	30.25	0.0053
C-Feed rate	0.001	1	0.001	2.26	0.2073
BC	0.0028	1	0.0028	6.19	0.0676
Residual	0.0018	4	0.00046		
Cor total	0.02	7			

Table 5: ANOVA for main and interaction effect of parameters on *EWR*

Source	SS	df	MS	F value	p-value (Prob > F)
AISI 420					
Model	0.00564	3	0.00188	8.03	0.0361
A-Gap voltage	0.0026	1	0.0026	11.08	0.05291
B-Capacitance	0.0028	1	0.0028	12.16	0.0252
AB	0.0002	1	0.0002	0.86	0.0357
Residual	0.0009	4	0.00023		
Cor total	0.0066	7			
Stavax ESR					
Model	0.0282	3	0.00094	18.58	0.0082
A-Gap voltage	0.000288	1	0.000288	5.69	0.0756
B-Capacitance	0.000865	1	0.000865	17.08	0.0145
AB	0.00167	1	0.000167	32.98	0.0046
Residual	0.000202	4	0.000051		
Cor total	0.00302	7			

3.3. OPTIMIZATION AND VERIFICATION EXPERIMENT

The micro ED milling parameters were further optimized for multiple optimization of responses i.e., maximum *MRR* and minimum *EWR*. The optimum process parameters are listed in Table 6. The optimized values of *MRR* and *EWR* are listed in Table 7. Using the optimized machining parameter, three verification experiments were conducted for each of the materials by fabricating straight microchannels. Then, the average values of *MRR* and *EWR* were calculated and listed in Table 7 for comparison with the predicted values. The standard deviation of the measured responses was 0.06 and 0.25 for *MRR* and *EWR* respectively.

Table 6: Optimized micro ED milling parameters

Parameter	AISI 420	Stavax ESR
Gap voltage (V)	100	100
Capacitance (nF)	8.5	1
Feed rate (μms^{-1})	6	6

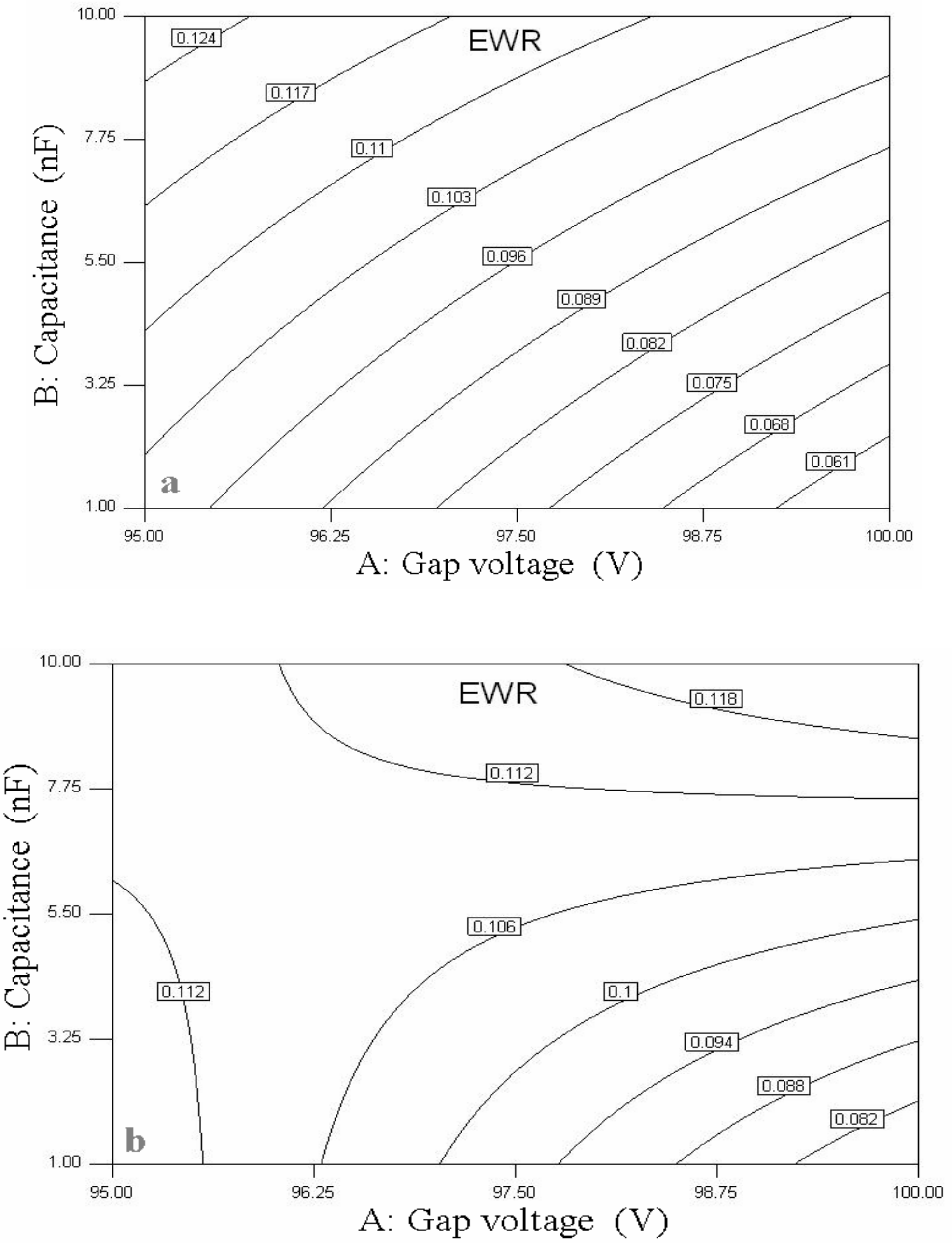
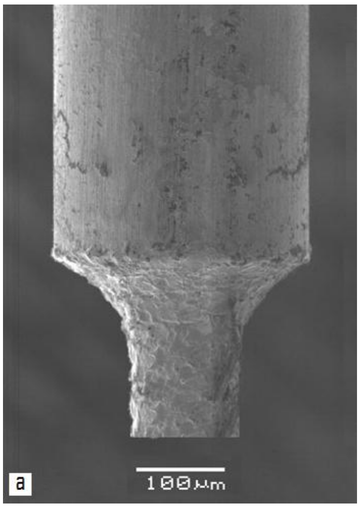


Figure 4: Interaction of micro ED milling parameters of gap voltage and capacitance on *EWR* of (a) AISI 420 and (b) Stavax ESR (Electrode: Tungsten carbide, Feed rate: 5 μms^{-1})

Table 7: Predicted and measured values of *MRR* and *EWR* for optimized process parameters

Material and channel	Predicted optimum value		Measured value		* Error (%)	
	MRR (μgs^{-1})	EWR	MRR (μgs^{-1})	EWR	MRR	EWR
AISI 420						
Straight Channel	0.605	0.094	0.550	0.101	9.1	- 7.4
Star shaped microcavity			0.562	0.098	7.1	- 4.2
Stavax ESR						
Straight Channel	0.410	0.076	0.37	0.08	9.7	- 5.26
Star shaped microcavity			0.384	0.081	6.3	-6.6

$$* \quad Error\,(\%) = \frac{Predicted\ value - Measured\ \ value}{Predicted\ value} \times 100$$



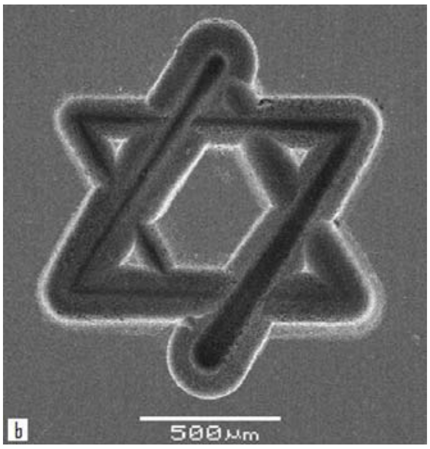


Figure 5: Microcavity on Stavax ESR produced by micro ED milling with optimum parameters (100 V gap voltage, 8.55 nF capacitance, and 6 μms^{-1} feed rate). (a) Dressed electrode and (b) "Star" shaped microcavity

In the second verification experiment, star shaped microcavities were machined on both AISI 420 and Stavax ESR materials using optimized values of micro ED milling parameters. The electrode and the star shape on Stavax are shown in Figure 5 as an example. The milling times for this machining were recorded and the material removal from the workpiece and electrode was calculated by weighing them before and after machining. Then, the *MRR* and *EWR* were calculated and listed in Table 7.

4. DISCUSSIONS

This section discusses the justification of this study, reasons and limitations for the selection of process parameters and their controlling mechanism. It also compares the responses for two variant of steels AISI 420 and Stavax ESR.

1. The literature discussed *MRR* and *EWR* of micro ED milling for a single material in various cases. The results were also compared with other materials (Kim et al., 2005; Yuan et al. 2004). Numerous studies were performed for EDM with steel substrates. Stavax ESR was processed with ultraprecision machining (Ding et al., 2002; Lauwers, 2004), but the micro EDM of Stavax is rarely reported. However, in this paper, the micro EDM is studied for two variants of steel AISI 420 and Stavax ESR. It is assumed that the trend of responses will be similar in nature but vary in magnitude because of variations in chemical composition and material properties such as thermal conductivity.

2. In this experimental study, the machining parameters (Table 2) are selected based on literature review and preliminary experiments. The range of voltage of this machine (DT 110) is 80-120 V and the selected voltage values are in the middle of the range for stable functioning of the machine. However, it is better to select the values with larger spread (e.g., 90 and 100 V). The available capacitances are 0.1, 1 and 10 nF where 0.1 nF is usually used for nano surface finish to ensure very low energy discharge. As the responses are *MRR* and *EWR*, the next higher level of capacitance is chosen. Previous studies of ED milling of beryllium copper alloy [Mehfuz and Ali, 2008] and preliminary experiments of this study showed that the optimized feed rate is about 5 μms^{-1}. As a result, the higher and lower levels of feed rate are selected as 4 and 6 μms^{-1}. Hence, the empirical models expressed by Eqn. 1-4 are valid for 95-100 V gap voltage, 1-10 nF capacitance, and 4-6 μms^{-1} feed rate. However, these equations may also be used for the estimation of responses for other parameter values that are very close to the range specified above.

3. Micro ED milling has several process parameters, such as voltage, current, capacitance, pulse duration, feed rate, polarity, dielectric flow type, etc. Based on the circuit type of the machine, these parameters are also varied. The machine used in this research has the R-C circuit, which ensures low energy discharge with high pulse frequency and thus, suitable for micro-scale EDM. It is assumed that the pulse on-time and pulse off-time is equal and less than 1 μs [Wong et al., 2003; Khan et al., 2009]. For this given design and machine architecture, the controllable parameters are capacitance, voltage, and feed rate.

4. The machine used in the experiments (DT 110, Mikrotools) has no servo mechanism for auto feeding. Hence, CNC is used to provide feed with an accuracy of 0.01%. For any abnormal occurrences, such as sudden high discharges, etc. machine stops the process automatically and gives an alarming sound. For the experiment, sample with negligible abnormal occurrences has been considered to get the best possible results. If any run (experiment) encounters any abnormal occurrences (i.e., machine stops), then that particular experiment need to be

repeated. However, no such occurrence was observed in this experimental study.

5. This paper compares the *MRR* and *EWR* of two closely related steels (Table 7). The predicted values of *MRR* (Eqn. 1 and 2) are found to be 9-10% larger than the measured values of *MRR*. Whereas, the predicted values of *EWR* (Eqn. 3 and 4) are found to be 5-8% smaller than the measured values of that response. The optimized results show that the values of *MRR* and *EWR* both are lower (68% and 81% respectively) for Stavax ESR compared to that of AISI 420. This can be explained from the basic mechanism of material removal such as melting, oxidation, spalling, etc. [Lauwers et al, 2004; Wong et al, 2003].
   - For the low energy discharge, melting and vaporization is most significant for material removal [Wong et al., 2003]. Although the melting point is same for both materials (Table 1), the thermal conductivity of Stavax ESR (24 $Wm^{-1}k^{-1}$) is slightly higher (at room temperature. However, at high temperature environment the thermal conductivity of Stavax ESR goes as high as 27 $Wm^{-1}k^{-1}$ [Uddeholm, 2007]. As a result, during micro ED milling, Stavax ESR allows more amount of heat to transfer without melting and evaporation and finally reduces the *MRR*.
   - As the Stavax ESR contains nickel and vanadium; it has more resistance to corrosion and wear. This property may reduce the oxidation during micro ED milling which occurs at high temperature beneath a liquid dielectric medium. The high polishability of Stavax ESR also reduces the chance of spalling.

5. CONCLUSIONS

In this experimental research, the comparison of *MRR* and *EWR* is studied for micro ED milling of AISI 420 and Stavax ESR. The effect of gap voltage, capacitance and feed rate are analyzed and statistical models (Eqn. 1-4) are developed. The micro ED milling parameters for the multiple optimization of *MRR* (max.) and *EWR* (min.) are identified (Table 6) with the desirability of 65-70%. The desirability values of the optimization are not so high which might be the cause of measurement uncertainties at microscale. However, this level of desirability can be acceptable for the estimation of responses *MRR* and *EWR*. The verification results showed that the models predict 9% higher *MRR* and 5-7% lower *EWR* for both materials. From this study, the following conclusions can be drawn.

1. *MRR* is found to be strongly influenced by the capacitance compared to that of feed rate. However, the gap voltage is found to have almost no influence on *MRR* and hence it is not included in the models (Eqn. 1 and 2). There is a significant interaction between capacitance and feed rate. Higher feed rate causes electrical discharge at faster rate which finally influences the MRR. However, too high level of feed rate may cause short circuit.
2. As *EWR* is found to be affected by gap voltage, capacitance and their interaction, feed rate is not included in the models (Eqn. 3 and 4). *EWR* always decreases with the increase of gap voltage for AISI 420. However, for Stavax ESR, *EWR* increases with the increase of gap voltage for higher level of capacitance only. For lower level of capacitance, the *EWR* decreases with the increase of gap voltage. Low capacitance generated very small amount of heat and most part of that passed through the tungsten electrode of high thermal conductivity. As a result, it removes less volume of material from electrode.
3. Machining time of Stavax ESR is longer than that of AISI 420 because of higher hardness and thermal conductivity. It finally results into lower *MRR* and consequently higher *EWR* for Stavax ESR.
4. This comparative study shows that the micro ED milling parameters for AISI 420 are not directly applicable for Stavax ESR for fabricating miniaturized components. Stavax ESR is more difficult to cut and its *MRR* is lower than that of AISI 420. However, the trend of *MRR* and *EWR* is similar for both work materials in most of the cases.
5. This research can be continued and furthered with a wider range of machining parameters values by applying higher level of measurement accuracy. In addition, the basic science of lower *MRR* for Stavax ESR compared to AISI 420 can be sought.

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