AN EXPERIMENTAL STUDY OF DIE SINKING ELECTRICAL DISCHARGE MACHINING OF AISI D2 TOOL STEEL USING DIFFERENT ELECTRODE MATERIALS

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Abstract. *The Electrical Discharge Machining (EDM), a thermal process, is one of the effective non-conventional machining processes, being widely used in the production of tools, dies, molds and complex-shaped components made of materials that are extremely difficult-to-machine. EDM process exhibits a great potential for tool, die and mold making industries, since it offers a lower cost alternative with improved dimensional accuracy and surface finish, as compared to its counterpart of conventional machining techniques.*

*This paper presents details and results of an experimental study of EDM carried out on hardened work material AISI D2(62HRc), a non-shrinking die steel, mainly used in tooling industry for high quality press tools, cold extrusion tools and dies, punches, casting moulds etc. with two different tool electrode materials namely copper and graphite. An attempt has been made to study the influence of the most important control factors in EDM viz. pulse current (**Ip**), pulse ON-time (T_{ON}), duty cycle (τ) and sparking gap voltage (**Vg**) having two levels each, on performance measures, such as material removal rate, tool electrode wear and dimensional overcut. Analyzed results indicate that Ip, T_{ON} and Vg are the most important influencing parameters affecting the response parameters, with graphite electrode giving better results.*

Keywords: *Electric discharge machining, Tool steel, DoE, MRR, TEW.*

1. Introduction

The growing competitiveness and complexity in manufacturing dies, molds and punches for tooling industry with higher efficiency, greater flexibility, better part quality and low machining costs have changed the face of manufacturing processes, attracting a significant amount of research interests. Electric Discharge Machining (EDM) is a promising non-conventional manufacturing technique to machine hard materials that are exact and difficult-to-machine, producing high dimensional accuracy, complex shapes and improved surface finish (Ho and Newman, 2003).

The EDM, a thermal process, shapes electrically conductive materials, removing metal with the help of controlled series of rapidly reoccurring electrical discharges (sparks) at short intervals with in a small gap between the pre-shaped tool and the work material electrodes immersed in the dielectric media, with converted thermal energy eroding the material by melting and/or vaporization (Benedict, 1987). The spark erosion mechanism removes metal from the work material in a complex combination of electrical, thermal and mechanical effect (Yahya and Manning, 2003). During the pulse ON time (T_{ON}), the electrical energy from the spark discharges is converted into thermal energy, which in turn generates a plasma between the two electrodes (Shobert, 1983) at extremely high temperature ranging from 8000-12000ºC, sometimes rising up to 20,000 ºC (Pandey and Shan, 1980; McGeough, 1988), with considerable heating of the localized area of the work material surface, leading to melting and/or vaporization of each pole forming a single crater. When the pulsating direct current supply (~20000-30000 Hz) is switched off, the sheath of vapor around the spark (plasma) collapses, creating a void drawing in the circulating dielectric fluid which flushes the molten material or macroscopic swarf, often referred to as debris, and cooling the spot where spark has just occurred. During the pulse off-time (τ) the flushing away of the debris takes place, meanwhile allowing the reionisation process of the dielectric fluid thus providing favourable conditions for the next discharge. The basic parameters of the EDM process are controlled by ON and OFF time during EDM, where the switching on and off takes place thousands of times per second making it an instantaneous act. The improper flushing results in DC arcing. Due to the improved flushing conditions, the off-time is less, increasing the efficiency of the process (Guitrau, 1997). EDM as a reproductive shaping process uses a pre-shaped tool electrode which defines the localized area in which the spark erosion occurs, and the shape of the electrode is mirrored in the work material (Kőnig et al., 1988). Melting and vaporization of the work material plays an importantrole in material removal process, leaving tiny craters over the EDMed surface. The tool electrode and work piece being separated by a small gap (no contact) and with no cutting force being applied by the tool electrode over the work material during EDM, the chances of residual mechanical stresses, chatter and vibration are eliminated as is prominent in conventional machining processes (Singh et al., 2004).

Due to the thermal energy during EDM, a heat affected zone (HAZ) consisting of several layers is created at the work material surface, with the upper layer as recast layer commonly known as white layer, followed by HAZ beneath it. (Ramaswamy and Rao, 1998). The white layer resulting due to solidification of a melted zone is known to exhibit high hardness, good resistance to corrosion and good adherence to the EDMed surface (Cusanelli et al., 2004). This recast layer contains micro-cracks, which may create some problems of the machined part for certain applications. Singh and Pandey (2001) overviewed that the pulse current and pulse ON time can be utilized suitably to improve the thickness of the white layer; however, the presence of white layer may be desirous at times due to its properties as surface modification technique. The redeposit recast or white layer is comparatively hard than the bulk work material providing the benefits for certain applications of surface alloying requiring abrasive, wear and chemical resistance (Lee et al., 2004). The EDM surface alloying of the work material surface can also be achieved by using composite electrodes (solid tubular) or by mixing powder additive in the dielectric.

The recent development in the field of EDM is focused on the increased material removal rate (MRR), reduced tool electrode wear and improved surface finish. EDM is a versatile technique, being widely used in tool; die and mold making industries, for machining hardened tool and die steels, advanced materials (super alloys, engineering ceramics and metal matrix composites). EDM has opened new fields and applications, and is also being applied increasingly in manufacture engineering such as sports, medical and surgical instruments, optical, dental and jewellery industries including automotive, aerospace & aircrafts (Stovicek, 1993). Conventional machining methods such as turning, milling and grinding of heat treated tool steels is often difficult, if the hardness of the work material is not greater than 30 HRc. The main limiting factors of conventional machining of hardened tool steels is the rapid tool wear, poor surface finish, low machining rates, and incompatibility to produce complex shapes. The advantage of EDM is well established, however too slow, but allows the tool steel to be heat treated, before machining, avoiding the problems of dimensional variability and other characteristic of post treatment (Arthur, 1996).

The development of more stable EDM process as well as improved effectiveness is of great interest to industry and academics. At the present time, there is a distinct lack of experimental studies that look into any great depth in the application of the EDM process in machining tool and die steel with different electrode materials. The aim of the presented research work is to determine the best optimal settings of the process parameters namely Pulse current (Ip), Pulse ON-time (T_{ON}), Duty cycle (τ) and Sparking gap voltage (Vg), on EDM of AISI D2 using two different cylindrical electrode materials viz. copper and graphite. The experiments were conducted on the basis of design of experiment (DOE) with four control factors having two levels each and the performance measures(response) studied are Material Removal rate, MRR (mm^3/min.), Tool Electrode Wear ,TEW(%) and Diameteral overcut, DOC (mm). Further, the experimental results analyzed using the statistical methods of ANOVA (Analysis of Variance) are presented and discussed.

2. Past work

Literature review identities that much work has been done on various aspects of electrical discharge machining on low carbon steels, carbides and few die steels with only one or two tool electrode material, taking one factor a time approach. Some researchers, Pantel et al. (1998) and Gangadhar and Philip (1991), have sought to improve the wear and corrosion resistance by surface alloying techniques using tool electrodes fabricated using powder metallurgy or using composites electrodes. Liu et al. (1997) performed the electric discharge machining of polycrystalline diamond (PCD) and studied the effect of pulse on-time, peak current and polarity on the performance measures such as MRR and surface roughness. The investigation revealed that performance measures increased with the peak current and pulse-on time, and best results were obtained with negative polarity of steel toothed electrode.

The small localized area in which the electrical discharge occurs raising the temperature of small portion of the work material above its melting points, which is removed by vaporization or flushing of the dielectric (Shobert, 1983). Lahiri et al. (1978) have studied the effects of magnetic fields on MRR and relative electrode wear (REW) per pulse during EDM of H. S. S. work material with copper electrode immersed in kerosene oil. The results concluded that the magnetic field affects the spark erosion process, and the metal removal and crater shapes was high at higher pulse widths. Amorim and Weingaertner (2004) suggested appropriate parameters setting for die sinking EDM of high strength copper alloy (ASTM C-17200) with copper and copper tungsten tool electrode. It was observed that the best results of material removal rate and surface texture were obtained by copper-tungsten electrode for duty factor 0.5, where as EDM with copper electrodes, the increase in pulse current promoted higher level of relative electrode wear. The depth of the recast (white) layer, the phase transformation zone and the conversion zone increases with the rise of pulse current and pulse on time. The surface roughness increases with both discharge current and pulse duration. George and Philip (1978) reviewed the analysis of EDM performance and tool wear in Cu-die steel system, and stated that the pulse current and pulse width are the two machining parameters that show a high degree of correlation with metal erosion. They further found anode wear decreases with pulse duration, and dielectric flushing at high pressure also helps to improve the metal erosion rate, also increasing relative electrode wear. Work carried out by Barash (1962) was specifically concerned with the surface roughness and residual stresses arising from the electro-discharge machining and found that the depth of spherical craters formed on the EDMed surface to be proportional to the surface roughness, with increased roughness values resulting due to high pulse current. Krishnan et al. (1978) employed an electronic controller developed for use with EDM sinking machine to improve its productivity and reduce operator's involvement. The work material En-24 steel was EDmachined with cylindrical copper electrode by varying pulse ON and pulse current and it was concluded that the inclusion of the controller improved the machining rate with out affecting tool wear and surface finish. EDM of 5Cr die steel (George and Venkatesh, 1980), cemented carbide (Pandey and Jillani, 1987) and Gt-20 grade of cemented carbide (Raman et al., 1997) have also been reported. EDM of AISI D3, high carbon and high chromium (Soni and Chakraverti, 1995) have also been investigated for the physico-mechanical effect of machined surface, MRR, wear ratio and the effect of electrode material properties on surface roughness and dimensional accuracy of the eroded hole.

Coldwell et al. (2003) assessed the drilling and tapping of AISI D2 and H13 with carbide cutting tools and with hybrid HSM/EDM. Some researchers (Kuneida et al., 1997 and 2003) have employed Dry EDM where gas (oxygen and others) were used as the working media. The molten metal debris ejected from the work material surface by electrical sparks are removed and flushed away by high velocity gas jet, resulting in significant material removal rate, with remarkably less tool electrode wear and thinner white layer. Crookall (1978) performed an analysis of EDM utilization in Industrial tooling Manufacture by conducting machining trails. The analysis covered forging dies, plastic mould, casting dies, extrusion dies and press tool dies mainly used in tooling industry. It was admitted by them that material removal rate on some die materials in the unhardened state by conventional machining methods is greater, then by EDM, but due recognition must be given to the technological advantages of EDM, which can machine hard materials in the hardened state, thus avoiding distortion, change in physical and mechanical properties resulting after heat treatment. Conventional machining of hardened material often results in rapid tool wear, poor surface finish and low MRR. Amorim and Weingaertner (2002) studied the influence of duty factor on the die-sinking electrical discharge machining of high strength aluminium alloy used as for injection moulding tools under rough machining. The alloy AMP 8000 was ED machined by cylindrical copper electrodes and it was observed that the elevation of duty factor from 0.5 to 0.8 promoted better results for MRR and volumetric relative wear. The EDM technique is being utilized extensively in nuclear power plants modification, since this process are performed in a dielectric fluid, they are best suited for under water applications, which is necessary due to radiation effects (Mc Gough, 1989). Guu and Hocheng (2001), analyzed EDM of AISI D2 tool steel for high-cycle fatigue and the processed surface layer and the cross-section were examined by scanning electron microscopy (SEM). The experimental results showed that the fatigue life of the EDMed specimens was shorter than the mechanically polished samples which can be attributed to the micro damage in the resolidified surface layer produced by EDM. It was also noticed that the effect of the magnitude of the pulse current on the fatigue life of the specimen is more significant than the pulse on-time. Lee and Yur (2000) analysed the experimental results of EDMed surfaces using Taguchi approach while machining AISI 1045 and AISI D2 with copper electrode. It was reported that pulse current, pulse on time and work material are the most influencing factors for surface roughness.

It has been found that an extensive literature do exists on EDM of hardened steels, AISI H13, carbon steels and carbides, but in contrast there is only scarce published work available on the electric discharge machining of AISI D2, despite its wide application in tooling industry.

3. Experimentation:

3.1 Machine:

The machining trials were carried out on the basis of Design of Experiment (DOE), on an Electronica Electric Discharge Machine, Model Elektra 5535 PS, Z-axis numerically controlled. The dielectric fluid Spark Erosion oil (SEO 250, flash point 94 ^{o}C, Make IPOL) was used. The polarity of the tool electrode was positive and that of work material (AISI D2) as negative.

3.2. Material:

The work material used for the experimental investigation is High Carbon High Chromium die steel alloyed with molybdenum and vanadium. IS Designation: T160 Cr Mo 12, hardened and tempered to 62 HRc, a deep hardening steel (non-shrinking) tool steel with excellent toughness, outstanding wear resistance and good machining properties, which is also referred as AISI D2 steel. The percentage composition is 1.5–1.7% C, 11.0–13.0% Cr, 0.1–0.35% Si, 0.25 – 0.50 % Mn, 0.8 % Mo, 0.8% V and balance Fe. It was quenched in oil medium at 840ºC and tempered at 200º.C, was used as work material, its hardness being 62HRc. The tested specimen size was 100 mm ×100 mm ×10 mm. The AISI D2 is used for high-efficiency cutting tools (dies and punches), blanking tools, wood working tools, shear blades for cutting thin materials, thread rolling dies, drawing, deep drawing and extrusion tools, pressing tools, cold rolls for multiple roller stands, gauges, and plastic mold.

The tool electrode materials used were copper and graphite each cylindrical in shape and 20 mm in diameter. Melting point of copper is 1084ºC and that of graphite is 3727ºC.

3.3 DoE and experimental conditions

For experimentation, a factorial experiment was performed. The general scenario in a factorial experiment is as follows: there is an output (or response) variable that depends on a number of input variables (called factors). Each factor is tested at a number of settings (called levels). All possible combinations of the levels of all the factors form the treatments in the experiment. The factorial approach is a scientific one that allows one to study the interactions among different factors, along with the effects of individual factors. Even when one is interested only in the effects of individual factors, the factorial approach results in higher precision as compared to the single factor (or one factor at a time) approach.

Based on the literature survey, four control factors were selected and were assigned specific levels determined on the basis of prelim experiments as in Table 1. The process parameters identified to be chosen for the experimentation are Pulse current (Ip), Pulse ON-time (T_{ON}), Duty Cycle (τ) and Gap voltage (Vg) as control factors, each having two levels, with the objective to study the interactions. Material Removal Rate (MRR- mm^3/min), Tool Electrode Wear (TEW-%) and Diametral overcut (DOC-mm) were selected as response functions so as to access the EDM performance measures.

Nevertheless, with the aim of simplification and also reducing the number of experimental runs only two levels were considered. A half replicate of the full 2^4 factorial design was selected so that number of runs were reduced to $2^{4-1} = 2^3 = 8$ runs (Lieb, 1975). The experimental runs were performed on die-sinking EDM machine (E-ZNC) based on the design matrix (orthogonal array -L8) Table 2. The depth of cut for all the experimental runs was set at 4 mm. The response variable MRR (mm^3/min) and TEW (%) for each run was calculated on the basis of volume/weight difference. Optical microscope was used to measure the diameter of the eroded hole. The same runs were repeated with different electrode material.

Table 1: Machining parameters and their levels

Control Factors	Symbol	Unit	Level	
			Low (-)	High (+)
A-Pulse Current	Ip	A	10	20
B-Pulse On Time	Ton	μsec	100	200
C-Duty Cycle	τ	%	50	80
D-Gap Voltage	Vg	V	40	45

Table 2: Experimental runs (L8 orthogonal array)

Experiment Number	A (I_P) (Amps)	B (T_{ON}) (μsec)	C (τ) (%)	D (V_g) (Volts)	Parameter Level (treatment)
Y1	10	100	50	40	1
Y2	20	100	50	45	ad
Y3	10	200	50	45	bd
Y4	20	200	50	40	ab
Y5	10	100	80	45	cd
Y6	20	100	80	40	ac
Y7	10	200	80	40	bc
Y8	20	200	80	45	abcd

4. Results and discussions

The experimental results are analyzed on the basis of the Analysis of Variance (ANOVA) technique that divides the variability of the response parameters into different parts for each considered effect, to find that which parameter are statistically significant for MRR, TEW and DOC for both the tested tool electrode materials. For EDM operations, Material removal rate is a 'higher-the better' case, whereas Tool electrode wear and Diameteral Overcut are 'lower-the-better' performance characteristics.

4.1 Analysis of the response factors using copper electrode

Figure 1(A) shows the graphs between the main affects of process parameters namely Ip (A), T_{ON} (B), τ (C) and Vg (D) respectively, presenting the estimated value of the response factors in relation to each of design factors for copper electrode. It may be noted that in each graph the factors of interest varies from its low levels to high level in such a way that the rest of the factors remains constant in their mean values (central). It is seen that the Ip is the main control factor that affects the MRR, where MRR increases with the increase in the Ip. Thus for improved values of MRR i.e. 'higher-the better', factor A (Ip) and factor C (τ) must be high, whereas factors B (T_{ON}) and D (Vg) must be low. From figure 1A (b) it is seen that to achieve 'lower-the better' for response variables TEW, the factors Ip (A), T_{ON}(B), τ(C) must be high where as Vg (D) to be low. Also from figure it is seen that for 'lower –the-better' DOC factors Ip (A), T_{ON} (B), τ(C) are to be low whereas and Vg (D) is to be high.

Table 3 shows the summarized results of analysis of variance (ANOVA) for MRR, TEW and DOC using copper electrode. This table gives the statistical significance of each effect by the usual ANOVA F-test (Fisher, 1925) which is used to determine which control factors have most influencing effect on the performance measures of EDM, usually significant when the F value is large. The main effects of Ip (pulse current) on the response parameter MRR is quite significant as compared to T_{ON}, τ and Vg. This may be attributed to the fact that the spark energy increases with the increase in pulse current, resulting in increased MRR. The percentage contribution of each control factors on the response factors calculated as per standard method ANOVA is also listed in Table 3. It also indicates the same results as shown in figure 1(A). Pulses On time and gap voltage are the significant factors that affect the TEW and DOC respectively.

4.2 Analysis of the response factors using graphite electrode

Figure 1(B) shows the graphs between the main effects of process parameters namely Ip (A), T_{ON} (B), τ (C) and Vg (D) respectively using graphite electrode. In each graph the factors of interest varies from its low levels to high level in such a way that the rest of the factors remains constant in their mean values (central). It is seen that the Ip is the main control factor that affects the MRR, where MRR increases with the increase in the Ip. Thus for improved values of MRR i.e. 'higher-the better', factor A (Ip) and factor C (τ) must be high, whereas factors B (T_{ON}) and D (Vg) must be low. From figure 1B (b) it is seen that to achieve 'lower-the better' for response variables TEW, the factors Ip (A), T_{ON} (B), τ(C) and Vg (D) must be high. Also from figure it is seen that for 'lower - the-better' DOC factors Ip (A), T_{ON} (B), Vg (D) are to be low whereas and τ(C) is to be high.

Table 4 shows the summarized results of analysis of variance (ANOVA) for MRR, TEW and DOC using graphite electrode. This table gives the statistical significance of each effect by the usual ANOVA F-test. The main effects of Ip (pulse current) on the investigated response parameters are quite significant as compared to T_{ON}, τ and Vg. This may be attributed to the fact that the spark energy increases with the increase in pulse current, resulting in increased MRR, TEW and also the overcut, resulting due to side sparks. The percentage contribution of each control factors on the response factors calculated as per standard method ANOVA is also listed in Table 4. These results are in good agreement with those shown in figure 1(b).

5. Conclusions:

In this investigation, the ANOVA F-test is employed to determine the main (significant) influencing control factors (process parameter) affecting the response variables. The following conclusions were made:

1. Based on the results of ANOVA analysis, the main influencing control factor for MRR is pulse current (Ip), for TEW is pulse ON time (T_{ON}) and for DOC is gap voltage (Vg), using copper electrode. These factors can be used to significantly to improve the response factors.
2. Using graphite electrode, the main influencing factors for MRR is Pulse current (Ip), for TEW is pulse current (Ip) and pulse ON time (T_{ON}) and for DOC is Pulse current (Ip), pulse ON time (T_{ON}) and duty cycle (τ). These factors can be used to significantly to improve the response factors.
3. MRR was observed to be higher for larger pulse current and pulse ON time settings.
4. Of the both tested tool electrodes, graphite electrode gave better results.
5. Factors pulse current and pulse ON time has the largest influence of the considered factors, which will result in great improvement in the MRR, and reduction in TEW and DOC.
6. In the case of TEW parameter, the control factor pulse ON time was the most influential using copper electrode and was the second significant after pulse current when graphite electrode was used.

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Table 3: Analysis of Variance (ANOVA) for copper electrode

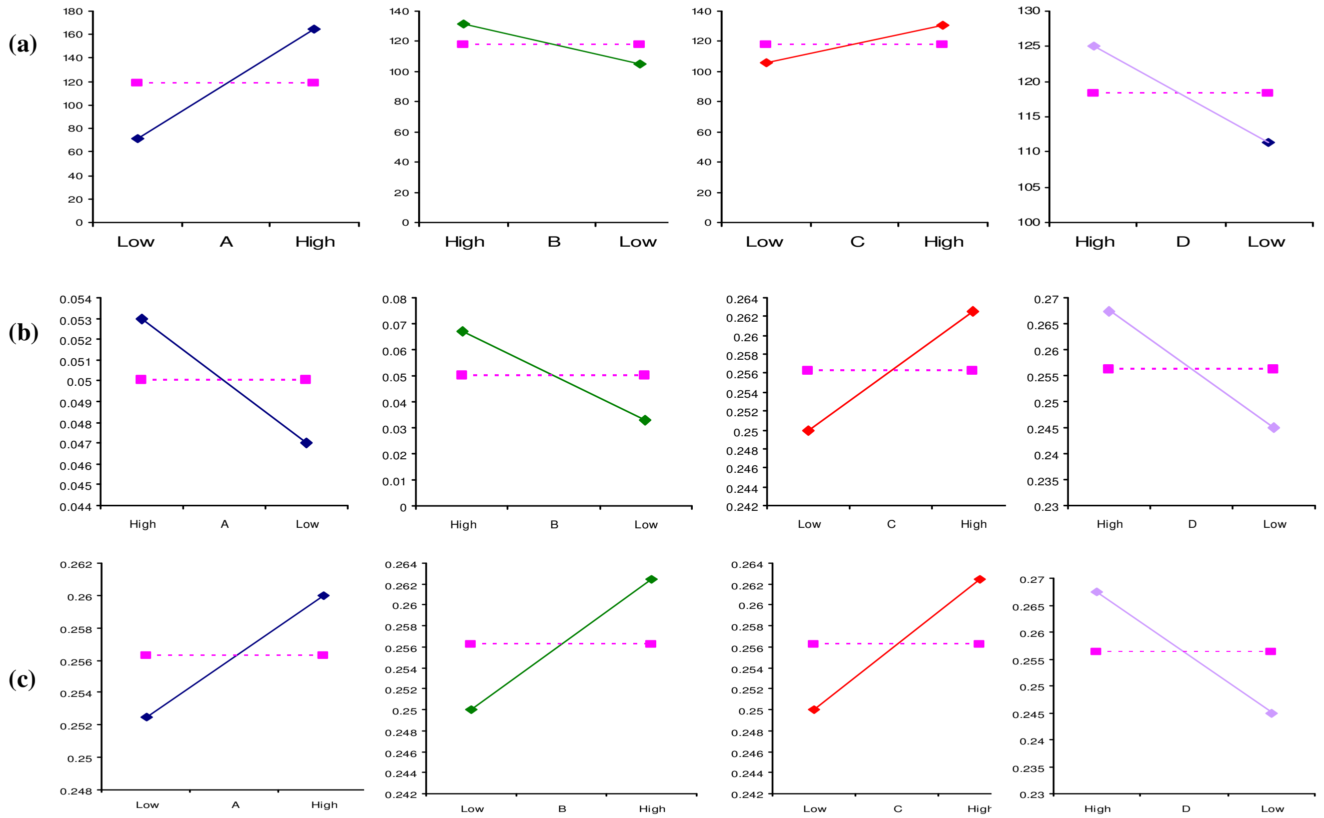
Response Factors	Control Factors	Degrees of Freedom	Sum of Squares	Mean Square	F-value	% Degree of Contribution
MRR	A: Ip	1	18225.5	18225.5	55.86**	**80.95**
	B: T_{ON}	1	1537.5	1537.5	4.71	6.82
	C: τ	1	1282.22	1282.22	3.92	5.7
	D: Vg	1	489.78	489.78	1.50	2.17
	Error	3	978.80	326.26		4.36
	Total	7	22513.80			100%
TEW	A: Ip	1	0.00006	0.00006	1.28	1.59
	B: T_{ON}	1	0.00231	0.00231	49.14**	**60.79**
	C: τ	1	0.00115	0.00115	24.46*	**30.26**
	D: Vg	1	0.00014	0.00014	2.98	3.68
	Error	3	0.00014	0.000047		3.68
	Total	7	0.0038			100%
DOC	A: Ip	1	0.0003856	0.0003856	3.47	8.2
	B: T_{ON}	1	0.0002984	0.0002984	2.69	6.35
	C: τ	1	0.0015876	0.0015876	14.30*	**33.76**
	D: Vg	1	0.0020975	0.0020975	18.89*	**44.61**
	Error	3	0.0003327	0.0001111		7.08
	Total	7	0.0047022			100%

Table 4: Analysis of Variance (ANOVA) for graphite electrode

Response Factors	Control Factors	Degrees of Freedom	Sum of Squares	Mean Square	F-value	% Degree of Contribution
MRR	A: Ip	1	20248.14	20248.14	44.49**	**81.08**
	B: T_{ON}	1	3147.22	3147.22	6.91	12.6
	C: τ	1	208.44	208.44	0.45	0.83
	D: Vg	1	1.25	1.25	0.0027	0.005
	Error	3	1366.3	455.04		5.48
	Total	7	24971.35			100%
TEW	A: Ip	1	0.0876	0.0876	34.62**	**44.33**
	B: T_{ON}	1	0.0756	0.0756	29.88*	**38.26**
	C: τ	1	0.0019	0.0019	0.75	0.96
	D: Vg	1	0.0249	0.0249	9.84	12.60
	Error	3	0.0076	0.00253		3.85
	Total	7	0.1976			100%
DOC	A: Ip	1	0.0009	0.0009	47.4**	37.4
	B: T_{ON}	1	0.0008	0.0008	42.10**	**33.23**
	C: τ	1	0.0006	0.0006	31.57*	**24.93**
	D: Vg	1	0.00005	0.00005	2.63	2.077
	Error	3	0.000057	0.000019		2.363
	Total	7	0.002407			100%

* Significant at 5% level of Significance
** Significant at 1% level of Significance

A. Copper Electrode



B. Graphite Electrode

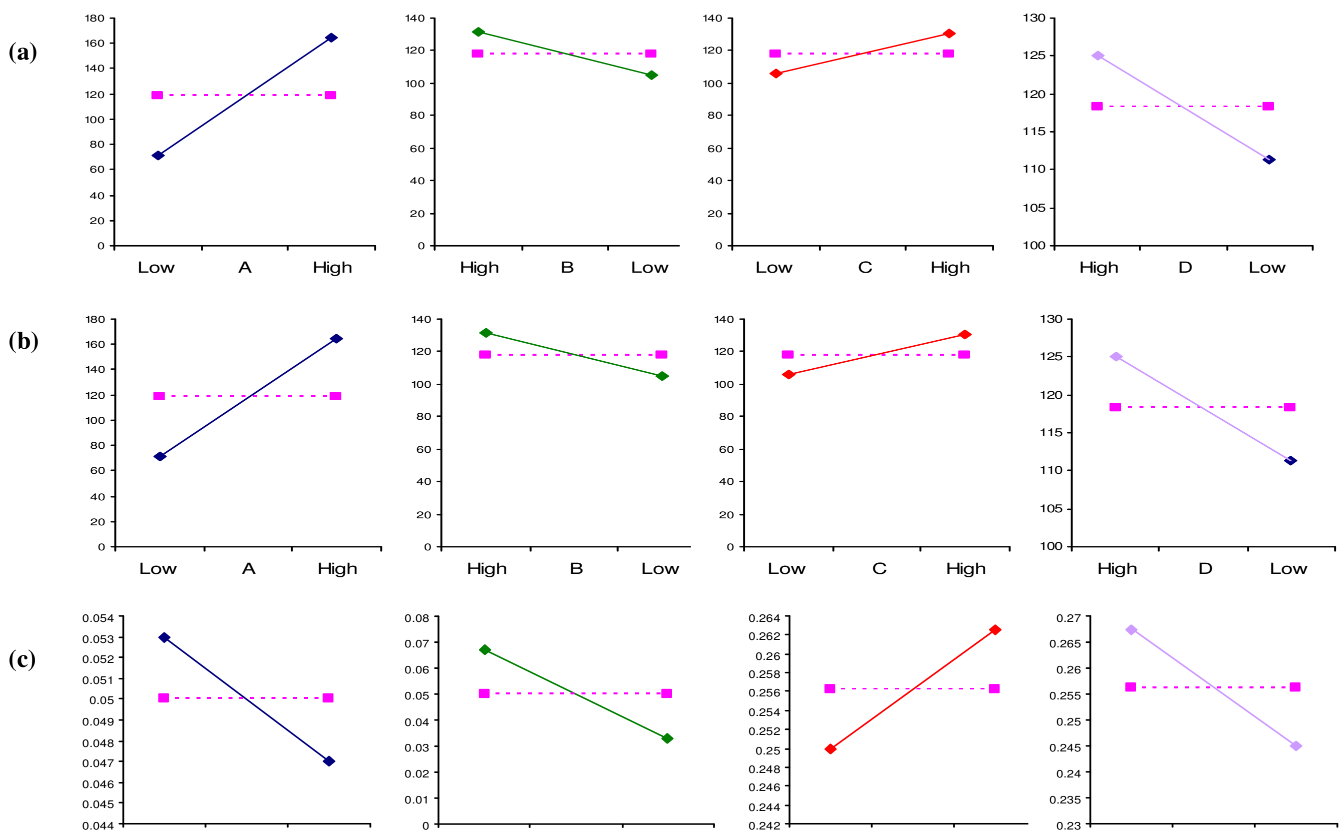


Figure 1: Multiple graphs showing main effects of process parameters on (a) MRR (b) TEW (c) Diameteral Overcut using (A) copper electrode and (B) graphite electrode