CHAPTER-3

Results and Discussion

3.1. Introduction

This chapter discusses the effect of variation in EDM process parameters; pulse current, voltage and pulse on time on machinability indices namely; Material Removal Rate (MRR), Tool Wear Rate (TWR) and Relative Wear Ratio (RWR) as well as on surface integrity characteristics such as surface roughness, microhardness and residual stress under both polarities using three different tool materials. At the last part of this chapter, it also describes the micro-magnetic analysis of the machined sample.

Various theoretical, as well as experimental works, have been developed to recognize the fundamental processes involved in electrical discharge machining. From the application point of view, it is one of the most popular manufacturing process used in die production. It is a preferred machining method because of its unique quality like contactless between the workpiece and tool electrode without developing any mechanical stress on the workpiece. As it is an electro-thermal process, therefore particular emphasis must be given to surface integrity. The surface, as well as subsurface damage, may be considered which are based on thermal fatigue or generation of white layer on the EDMed surface after the material erosion. The surface morphology is associated with various surface characteristics such as micro-hardness profile, surface roughness, residual stress geometric, crack density, white layer, etc. The surface morphology of an EDMed surface is progressively more important to fulfil the rising anxiety of complicated structure performance, durability, and reliability. It plays a vital role in the industry and manufacturing sector because of the inspection of product geometry, roughness, and dimensional accuracy. The surface integrity element measurement is more time taking process with the use of precious apparatus such as microhardness tester, XRD, SEM and surface roughness tester, etc. The surface roughness is the significant factor which is used to assess EDMed surface quality. To seek the influence of process parameters of EDM on account of the surface roughness in a specimen, the surface profile on the machined samples were calculated using the various equipment namely surface roughness tester, atomic force microscopy etc. EDM parameters are namely pulsed current, pulse on time and voltage affect the surface integrity and machinability indices like MRR, TW, HV etc.

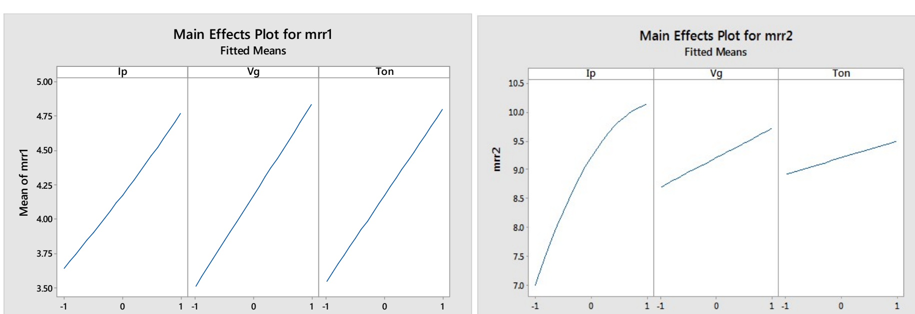
Therefore, the exploratory EDM experiments (as discussed in Section 2.1) were conducted by ZNC-EDM by drilling a rectangular hole in high carbon high chromium die steel using three rectangular tools such as copper, copper-tungsten, and graphite. Results obtained from the experiments are discussed in the subsequent sections. For the analysis of the relation between the input process parameters (Ip, Vg, Ton, τ) with responses (MRR, TW, SR, HV, RS, rms, peak) mean of main effect plot has been considered. Currently, the various graphs were attained by the Minitab 16 software showing the result of every the input parameters separately on the machining response. The curvature is indicating more amount of inclination which was the significant majority curvature, whereas the curvature being parallel to the mean line has the least considerable influence over the machining response like MRR, TW, SR, etc. All the ANOVA Tables (Table A.1 to Table A.42) are given in Appendix A.

3.2. Material Removal Rate (MRR)

Typically, MRR in the EDM process is more time consuming than that of the conventional manufacturing process (i.e., grinding, lathe, grinding etc.) because the chips are removed by thermally process using various tools. To justify these mechanical process, the MRR is solely reliant upon the various factors like pulse current in every discharge, discharge rate, types of tool and workpiece, dielectric fluids. Furthermore, MRR also depends on the hardness and conductivity of workpiece which requires optimized input process parameter. Moreover, dimensional accuracy is essential factors as close tolerance products are needed to be manufactured in tools and mold Industries. Since there is no contact between the electrodes. Therefore, no mechanical stresses and chatter are produced in the EDM process.

The second order polynomial equation for MRR under both polarities of the copper tool is shown in Eq. 3.1 and Eq. 3.2. Figure 3.1. (a) depicts the main effect plot for MRR while the copper tool is connected with positive polarity. The improvement of current results an increase in MRR. It occurs because of more amount of metal melted and vaporized due to increased pulse energy in the machining process. It also observes that MRR improved consistently with the pulse on time up to specific optimized value, and then it starts to decrease due to the formation of the large plasma channel. This full plasma channel reduces the material erosion from the workpiece. Similar types of result was observed by Senthilkumar & Omprakash (2011) during the machining of the aluminium metal matrix composite. Increase in voltage increases the pulse energy supplied from the pulse generator which causes increased material removal rate.

On the other hand, Figure. 3.1 (b) shows the main effect plot for MRR using negative polarity of the copper tool. It also shows the linear relationship between pulse current and MRR. It observes because more amount of the metal melts and vaporized due to increased pulse energy in the machining process. Furthermore, it notices that MRR increases with the pulse on time up to particular value due to more flow of pulse energy to the workpiece surface which results in more melting and vaporization of material. Initially, the metal erosion takes place due to an increase of pulse on time. In EDM, the increase in pulse duration (in range of 200-1000µs) causes plasma channel expansion which reduces the energy density. The same trend in between MRR and pulse on time was also observed by the previous researcher (Daryl *et al*. (1989); Patel *et al*. (1989); Wang *et al*. (1999)). This weak energy density leads to reduce the MRR. The higher setting of voltage increases the pulse energy supplied from the pulse generator which causes the increment in MRR.



(a) (b)

Figure 3.1: Main effect plot for mean of material removal rate (mrr) for (a) positive polarity copper tool & (b) negative polarity copper tool

$mrr_1 = 4.1740 + 0.5613\ I_p + 0.6587\ V_g + 0.6238\ T_{on} + 0.0322\ I_p^2 + 0.0088\ I_p.V_g$

$$+ 0.0138\ I_p . T_{on} + 0.0312\ V_g . T_{on} \quad (3.1)$$

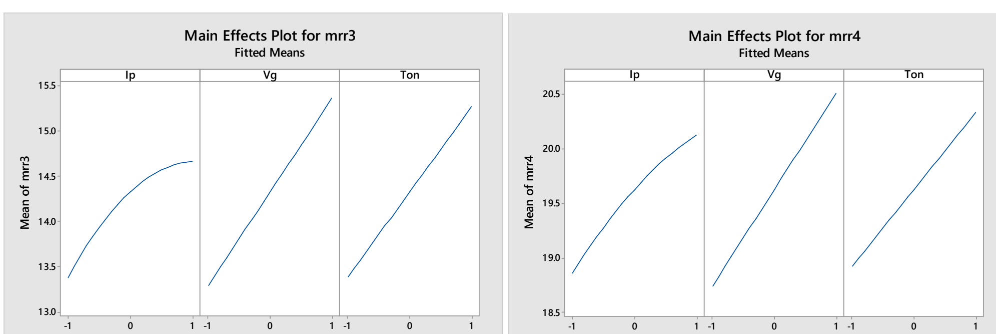
$$mrr_2 = 9.210 + 1.566\ I_p + 0.504\ V_g + 0.286\ T_{on} - 0.649\ I_p^2 + 0.729\ I_p . V_g + 0.656\ I_p . T_{on} - 0.846\ V_g . T_{on} \quad (3.2)$$

Table A.1 (refer appendix A) demonstrates the result of process parameters namely pulse current, pulse on time and voltage on MRR for positive polarity of the copper electrode during the EDM process. Table A.1 also provides the correlation coefficient and empirical model correlating the response (MRR in this particular case) with the independent variables along with their second-order interaction terms. The regression model indicates that the MRR of the machined sample increases with an optimized value of process parameters like pulse current, pulse on time and voltage during the EDM process. The correlation coefficient for this model is around 99.37%. The ANOVA analysis represents that the effect of EDM process parameters which are significant for direct interaction due to the low value of the p-value. From the two way interaction of process parameters, it was observed that the effect of process parameters on MRR is quite insignificant because of the higher p-value of process parameters. However, the value lack of fit is insignificant because of lower value which shows the adequacy of the developed model.

On the contrary, the linear relation which is described in Table A.2 (refer appendix A) reveals the statistically significant influences of the pulse current, pulse on time on MRR for negative polarity of the copper electrode during the machining process. The pulse current and pulse on time are significant, and voltage is insignificant for linear interaction. The effect of three process parameters resulted from two-way communication on MRR showed that these parameters are quite insignificant because of lower p-value.

Type of polarity also influenced the MRR. The negative polarity of the tool is more advantageous than positive polarity as it is associated with more energy transfer to the workpiece. The tool material properties such as thermal conductivity and electrical conductivity significantly affects the MRR as high thermal conductivity indicated better heat transfer rate and high electrical conductivity represented more availability of free electron for bombardment on the workpiece surface. In this experimental study, the negative polarity of the copper electrode shows more MRR than the positive polarity of the copper electrode.

A proposed second-order model of the MRR for both positive and negative polarities of copper tungsten tool is shown in Eq.3.3 and Eq.3.4. Figure 3.2 (a) and Figure 3.2(b) represents the main effect plot of the MRR regarding the pulse current, pulse on time and voltage using the copper-tungsten tool with positive polarity and negative polarity respectively. In both Figure 3.2 (a) and (b), It depicts that the MRR progressively increase with pulse current as high thermal loading on workpiece lead to more material melting and vaporization. Similarly, the trend is observed in between MRR and optimised value of pulse on time in both polarities. Therefore, the MRR improvement shows a linear relation with the initial stage of pulse on-time owing to the formation of a narrow plasma channel which results in the higher intensity of pulse energy striking on the workpiece surface. But this trend does not stratify for a longer pulse on time. This similar relation between MRR and pulse on time was also investigated by various researchers (Lee *et al*. (2004); Lin *et al*. (2000)). Moreover, the increase in voltage in the experiment for both the polarities, it is noticed that the width of spark gap increases, which allows the frequent breakdown of dielectric fluid leads more spark energy in machining zone. Hence MRR increases. The significant difference is observed in both Figures as all the process parameters for negative polarity of copper tungsten show drastically changes with MRR in comparison to positive polarity copper tungsten electrode.



(a) (b)

Figure 3.2: Main effect plot for mean of material removal rate (mrr) for

(a) positive polarity copper-tungsten tool & (b) negative polarity copper-tungsten tool

$mrr_3 = 14.3260 + 0.63875\, I_p + 1.03125\, V_g + 0.93875\, T_{on} - 0.30475\, I_p^2 - 0.12625\, I_p . V_g - 0.12375\, I_p . T_{on} - 0.15625\, V_g . T_{on}$ (3.3)

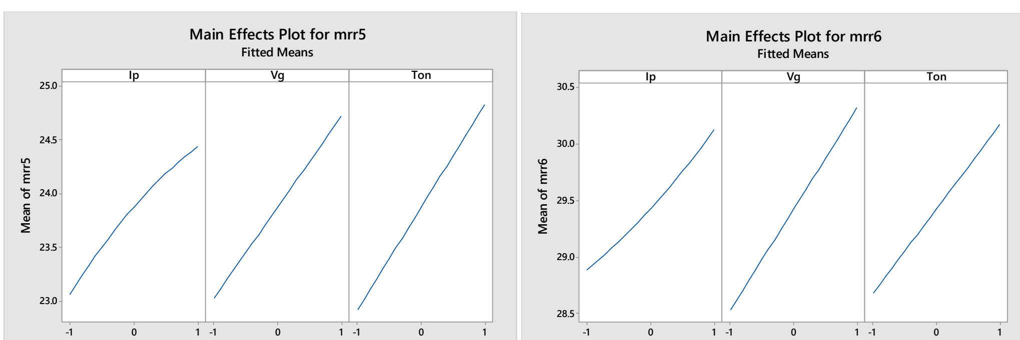
$mrr_4 = 19.6300 + 0.63375\, I_p + 0.88375\, V_g + 0.70625\, T_{on} - 0.13625\, I_p^2 - 0.00625\, I_p . V_g + 0.04125\, I_p . T_{on} + 0.00125\, V_g . T_{on}$ (3.4)

Table A.3 and Table A.4 (refer Appendix A) demonstrate the statistically significant effects of the pulse current, pulse on time and voltage on MRR for positive polarity of copper tungsten electrode during the machining process. In Table A.3, It observes that the higher value of the correlation coefficient of the model indicates the effect of process parameters which are statistically significant. Also, all the process parameters are also statistically significant as the p-value are quite small. The optimized setting of process parameters in the electro-discharge machining process results more MRR due to higher thermal loading on the machined surface. The lack of fit is 0.473 which indicates that the proposed model is reasonably good. On the other hand, in Table A.4, it notices that the correlation coefficient of this model is around 99.99%. The p- value is also small for linear interaction of process.

From the two way interaction, it observes that the interaction effect of pulse current and pulse on time are significant as p-value is small. On the other hand, it shows that the interaction effect between pulse current and voltage, voltage and pulse on time are insignificant as p-value is high. The lack of fit which is shown in Table A.4 is 0.152. This shows that the selected model is appropriate for the analysis of MRR.

In this experimental study, the negative polarity of the copper electrode shows more MRR than the positive polarity of the copper electrode. From the preliminary investigations, it was observed that all the EDM process parameters were essential to decide the MRR. Although the voltage and pulse current show a linear relation with the MRR. The MRR is solely reliant on the amount of pulse current which is applied in the EDM process, lower thermal conductivity and melting point of material leads to high MRR with melting and vaporization. The workpiece with low thermal conductivity indicates a small amount of heat loss because of its heat conduction, which results in more concentrated energy deliver dissolves the material. Moreover, the low melting point workpiece requires the more moderate amount of power for its melting. Further, the MRR dramatically improves with a significant value of process parameters like current and voltage. In this experimental study, negative polarity of copper tungsten tool provides more MRR than positive polarity. It occurs because the copper content in the copper tungsten electrode had a high melting point whereas the tungsten has a high breakdown voltage. These properties of copper and tungsten content in the tool results in the more amount of energy absorbed by the machined sample.

The MRR based on the regression model are described in the Eq. 3.5 and Eq.3.6. Figure 3.3 (a) and Figure 3.3 (b) represent the main effect plot of MRR when the graphite tool is used as the positive and negative polarity. In both the Figures, It reveals that the material removal mechanism depends upon the amount of pulse energy for the erosion of material. Therefore, the optimized value of different process parameters such as pulse current, voltage, and pulse on time used in EDM enhance the spark energy in the inter-electrode gap. This gradually raises in spark energy which eases the melting and vaporization results in higher material removal from the workpiece.



(a) (b)

Figure 3.3: Main effect plot for mean of material removal rate (mrr) for

(a) positive polarity graphite tool & (b) negative polarity graphite tool

$$mrr_5 = 23.8740 + 0.6875\, I_p + 0.8425\, V_g + 0.9525\, T_{on} - 0.1265\, I_p^2 - 0.0425\, I_p.\, V_g - 0.0975\, I_p.\, T_{on} - 0.0925\, V_g.\, T_{on} \quad (3.5)$$

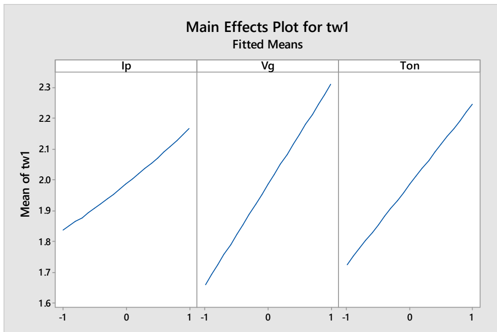
$$mrr_6 = 29.4240 + 0.6163\, I_p + 0.8912\, V_g + 0.7437\, T_{on} + 0.080\, I_p^2 + 0.1187\, I_p.\, V_g + 0.0962\, I_p.\, T_{on} + 0.0962\, V_g.\, T_{on} \quad (3.6)$$

Table A.5 and Table A.6 (refer appendix A) represent the correlation coefficient of these model. Table A.5 and A.6 reveal the correlation coefficient which is around 99.97% and 98.63%. These values are more remarkable. The MRR improves with process parameters like pulse current and voltage because of more melting and vaporization of the workpiece surface in EDM process. Table A.5 shows that all the p-value of EDM process parameters are lower than 0.05% for both linear and two-way interaction. Also, the lack of fit is also insignificant. But Table A.6 shows all EDM process parameters are insignificant due to higher p-value in two way interaction while linear interaction shows significant p-value.

As discussed previously that the MRR is dependent on all three process parameters, types of electrode and work material, and dielectric fluids and flushing condition. Furthermore, MRR also enhances with the optimized value of all three process parameters as a high density of spark energy results in more material erosion. Type of polarity also influences the MRR. In this present work, the negative polarity of the graphite electrode reveals large MRR than the positive polarity of the graphite electrode. When graphite acts as a cathode, it emanates electrons below its sublimation temperature. Therefore graphite promotes more bombardment of ions on the machined surface. This bombardment enhances more MRR in comparison of all three electrode.

3.3. Tool Wear (TW)

Equation 3.7 and Eq. 3.8 represent the process parameters and tool wear (response) which shows the result of the main effect plot of the regression analysis. Figure 3.4 (a) and Figure 3.4 (b) also shows the main effect plot for TW when the copper tool is used as the positive and negative polarity. In both the polarity case, it is noted that TW increases with pulse current. The more value of pulse current forms large crater formation on the tool surface lead to more TW. Also, it can be observed that TW increases with the pulse on time initially because the electrode surface gets more time to absorb spark energy in the machining process. As the voltage is proportional to spark energy. Therefore, more gap voltage provides more spark energy which is absorbed by the tool surface resulting in more electrode wear.



(a) (b)

Figure 3.4 : Main effect plot for mean of tool wear for

(a) positive polarity copper tool & (b) negative polarity copper tool

tw_1 =1.9860 +0.1650 I_p+0.3250 V_g+ 0.2600 T_{on}+ 0.0165 I_p^2 -0.0525 I_p. V_g - 0.0275 I_p. T_{on} -0.0075 V_g. T_{on} (3.7)

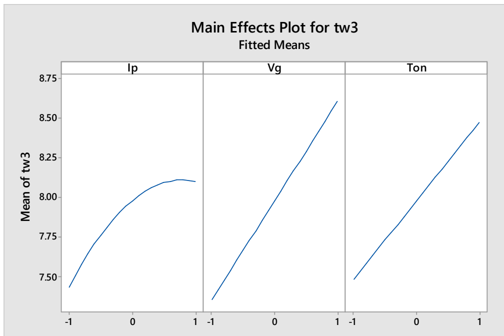
tw_2 = 3.95000 + 0.37000 I_p + 0.74500 V_g+0.54000T_{on} - 0.1025 I_p^2-0.07250 I_p. V_g - 0.04750 I_p. T_{on}- 0.11750 V_g. T_{on} (3.8)

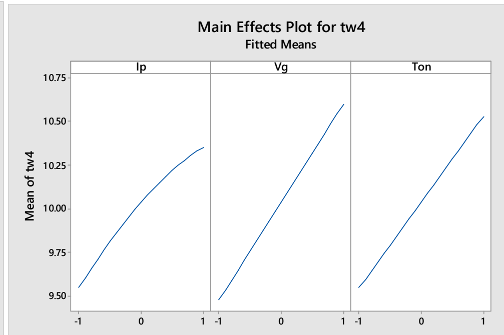
In tool wear study, both the ANOVA Table A.7 and Table A.8 (refer appendix A) represent the influence of all three EDM process parameters. The correlation coefficient is 98.96% in Table A.7. Therefore, the Table A.7 mention that all three EDM process parameters are quite significant due to the lower p-value in linear interaction whereas all the process parameters are insignificant for two way interaction because of more p-value.

The ANOVA Table A.8 represent the influence of all three EDM process parameters. The correlation coefficient is 99.97% in Table A.7. Therefore, Table A.7 mentions that all three EDM process parameters are quite significant due to the lower p-value of in linear interaction and two-way interaction. The lack of fit is 1.000. The developed regression model is statically significant to predict TW(refer appendix A).

During the EDM process, the tool material persists electrical and thermal conductivity, more melting point, low wear rate, and little deformation. However, due to the unpredictable nature of the EDM process, the basis of material selection is mainly empirical based on experimental data. EDM is an electro-thermal method. Therefore, the effect of the thermal properties of the tool on the material erosion is essential because of the high heat conductivity of the tool. It leads to a lower temperature on the tool surface. Therefore, tool material should have high heat conductivity which is used in the EDM process. On the contrary, a tool with a higher melting point and boiling point results in more material removal in the machining process. Tool wear rate increases considerably with a pulse time as the increase in pulse length over time increase the expansion of plasma. Type of polarity also influences the TW. In this current work, the negative polarity of the copper tool shows more TW than positive polarity copper tool. While comparing the real copper tool with the negative copper tool, it observes that the negative copper tool shows low vapour density soon after cracking of the dielectric fluid. It occurs as the discharge power distributed into anode is more significant than that into cathode because it is associated with more energy transfer to the workpiece. Tool material properties such as thermal conductivity and electrical conductivity significantly affect the TW. High thermal conductivity indicated better heat transfer rate and high electrical conductivity represents more availability of free electron for bombardment on the workpiece surface

A proposed second-order model of the TW for both polarities for copper tungsten tool is shown in Eq. 3.9 and Eq. 3.10. Figure 3.5 (a) and Figure 3. 5(b) show the main effect plot of TW while copper tungsten is connected both positive and negative polarity. These figures show that the TW is linearly improved with current due to higher melting temperature and cohesion energy of the sample generates more considerable TW. The positive tool depicted low TW as compared to the negative tool at a setting of high current. It may be more carbon black layer formed on a positive tool which results in low TW as compared negative tool. Also, both straight and reverse polarity condition reveals that the electrode wear improvement occurred with pulse duration due to good flushing in the inter-electrode gap. This flushing also avoids the arcing and short circuit. By changing the voltage supply in both polarities, the electrode wear fluctuates insignificantly between a certain ranges. So, there are almost linear variation found in between voltage of both electrodes on electrode wear. But the higher value of voltage generates high spark energy in the machining zone of the tool surface to erode more material.





(a) (b)

Figure 3.5: Main effect plot for mean of tool wear (tw) for

(a) positive polarity copper tungsten tool (b) negative polarity copper tungsten tool

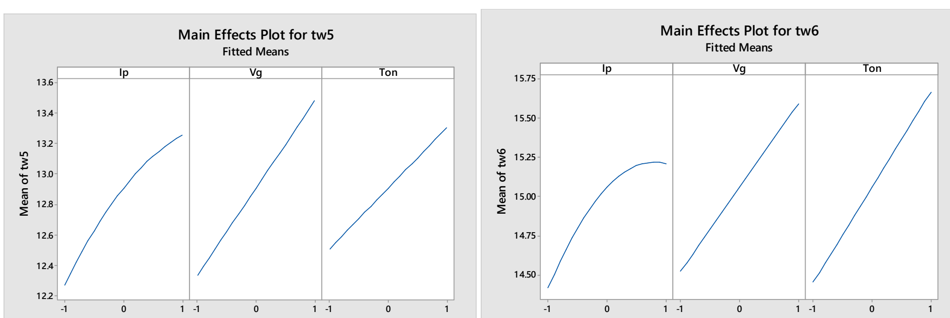
$$tw_3 = 7.9780 + 0.3325I_p + 0.6250V_g + 0.4950T_{on} - 0.2105\, I_p^2 - 0.0600\, I_p.\ V_g - 0.0450\, I_p.\ T_{on} - 0.0675\, V_g.\ T_{on} \quad (3.9)$$

$$tw_4 = 10.0380 + 0.4025\, I_p + 0.5575\, V_g + 0.4900T_{on} - 0.0880\, I_p^2 + 0.0050\, I_p.\ V_g - 0.0325\, I_p.\ T_{on} + 0.0025\, V_g.\ T_{on} \quad (3.10)$$

Table A.9 and Table A.10 (refer appendix) show the ANOVA for the effects of the pulse current, pulse on time and voltage on TW for both polarities of copper tungsten electrode. Table A.9 shows a significant effect of all EDM process parameters on TW along with reasonable correlation coefficient of 99.80%. All the p-value values for both linear and two interaction parameters are a small value. While the Table A.10 also reveals that all process parameters are significant but these all process parameters interaction are insignificant. The correlation coefficient is 99.39.

Typically, TW depends on the input process parameter like pulse current, pulse on time and voltage. The TW increases considerably with an optimized value of all EDM process parameters as an increase of plasma channel diameter results in more melting and vaporization of the tool. It is noticed that negative polarity of copper tungsten tool provides more TW than positive polarity copper tungsten tool. The copper tungsten shows excellent wear resistance because of its high melting point and good spark-resisting capacity.

The model of the TW for both polarities for copper tungsten tool is shown in Eq. 3.11 and Eq. 3.12. Figure 3. 6 (a) and Figure 3.6 (b) also illustrates the result of the main effect of TW for both polarities of the graphite tool. These figures describe the same mechanism of EDM process for both the positive and negative polarities which have been discussed earlier. The effect of the current is small for negative graphite tool as compared to positive graphite tool.



(a) (b)

Figure 3.6: Main effect plot for mean of tool wear (tw) using

(a) positive polarity graphite tool & (b) negative polarity graphite tool

$$tw_5 = 12.9080 + 0.49000\, I_p + 0.57000\, V_g + 0.39750\, T_{on} - 0.1455\, I_p^2 - 0.04750\, I_p.\, V_g - 0.08500\, I_p.\, T_{on} - 0.06500\, V_g.\, T_{on} \quad (3.11)$$

$$tw_6 = 15.0600 + 0.3950\, I_p + 0.5325\, V_g + 0.6050\, T_{on} - 0.2450\, I_p^2 - 0.0825\, I_p.\, V_g - 0.0550\, I_p.\, T_{on} - 0.0725\, V_g.\, T_{on} \quad (3.12)$$

Similarly, the corresponding ANOVA Table A.11 and Table A.12(refer appendix A) reveal the statistically significant effects of all linear and two-way interaction process parameters as the smaller p-value on TW for positive polarity of graphite electrode in the machining process. The TW increases with the increase of pulse current due to the formation of a thin carbon layer on the tool surface. The correlation coefficient for Table A.11 and Table A.12 are 99.96% and 99.90%. The lack of fit for Table A.11 is 0.076 which shows that the proposed regression model is quite right to predict the TW.

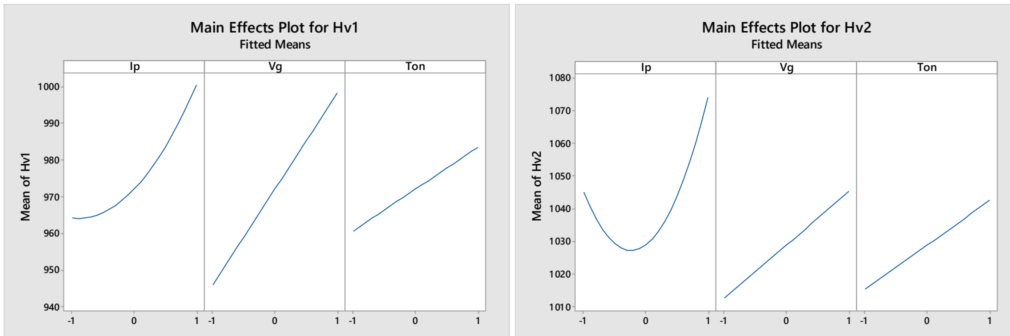
The TW with negative polarity graphite electrode shows linearly improvement the process parameters as depicted in Figure 3.6 (b). The TW increases with pulse current due to more thermal loading on the tool surface. The TW shows linear relation with the pulse on time because of more amount of heat flow to the tool surface. The TW increases with improvement in voltage supply due to that the increase of spark energy stored in the capacitor and the energy discharged to the electrode surface results in more electrode wear. Also, arcing occurs in the EDM process which lead to more TW in comparison to the MRR.

The graphite shows the large melting point. This temperature resistance capacity made graphite an idyllic tool material. The graphite also offers more electrical conductivity. It is easy available quickly and cheaply prepared. The graphite shows low relative wear at long discharge durations and more pulse currents as faster melting and vaporization of the workpiece. Small discharge energy of EDM the thermal conductivity of the workpiece lead to smaller removal rates. From this experimental analysis, it is noted that the negative polarity of the graphite tool exhibits more TW than positive polarity graphite tool. The negative polarity of the graphite tool transferred more energy to the tool in the machining process. Typically, high melting temperature, density, specific heat and latent heat of evaporation of the tool lead to high resistance to TW. The tool material properties such as thermal conductivity and electrical conductivity significantly affects the MRR.

3.4. Microhardness (HV)

The Eq. 3.13 and Eq.3.14 show the estimation of microhardness in the EDM process. Figure 3.7(a) and Figure 3.7(b) demonstrate the estimation of main effect plot for microhardness under polarities of the copper tool. The microhardness of the machined sample shows almost linear increment with pulse current using positive polarity copper tool. While this microhardness and pulse current shows non-uniform nature, it occurs because of the non-uniformity of microstructure and chemical composition of EDMed surface. This nonlinear trend between microhardness and pulse current was also obtained by Guu & Hou, (2007) during the EDM of ferrous alloy using the copper tool. Both Figure 3.7(a) and Figure 3.7(b) show that the microhardness increases with voltage and pulse on time. As enhance of the pulse current, the spark energy rises results more metal melting and vaporization. Simultaneously, the dielectric fluid flushes this action erode metal from the machining zone. But some metal is redeposited on the surface which leads to increase in microhardness with pulse current. On the other hand, this WLT enhances with a pulse on time for stable pulse current. The higher value of pulse on time permits the spark energy to enter more depth in the workpiece surface; it increases the WLT.

While higher pulse current is supplied, it results in a rise in temperature of the workpiece and achieves the melting point of the metal surface. As a result of the WLT gradually increases. In the EDM process, the temperature gradient with excellent rates of heating and chilling on EDMed sample results in the white layer formation, variation of micro-structural and microhardness. This Figure significantly represents an improvement of microhardness with process parameters. In the machining process both pulse current and pulse on time increase the considerable amount of discharge energy as a result quickly melt and evaporate of machined surface and break down the dielectric fluid. In the EDM process, simultaneously material removal takes place along with white layer forms on the workpiece surface. This white layer is also known as the recast layer it is hard as well as not etchable as material transform into martensite. Below the 'recast layer,' an intermediate layer is exhibited known as heat affected zone or dark band. Therefore, the combined observation of plastic deformation, white layer and dark band upon EDM of die steel led to changes in microhardness. While gap voltage is set at a higher value, the gap distance across the sparking region increases, and more removal of debris occurs. At the same time, more carbon content adheres on workpiece surface assist to the variation of phase along with high temperature, which promotes the microhardness. This improvement of microhardness in WL layer was also investigated by previous researchers (Mamalis *et al*. (1987); R. Bormann, (1991); Lee &Tsai (2003)).



(a) (b)

Figure.3.7: Main effect plot for mean of microhardness (HV) using

(a) positive polarity copper tool & (b) negative polarity copper tool

$$Hv_1 = 972.20 + 18.13\, I_p + 26.12\, V_g + 11.38\, T_{on} + 10.2\, I_p^2 - 6.12\, I_p.\, V_g + 3.12\, I_p.\, T_{on} - 2.37\, V_g.\, T_{on} \quad (3.13)$$

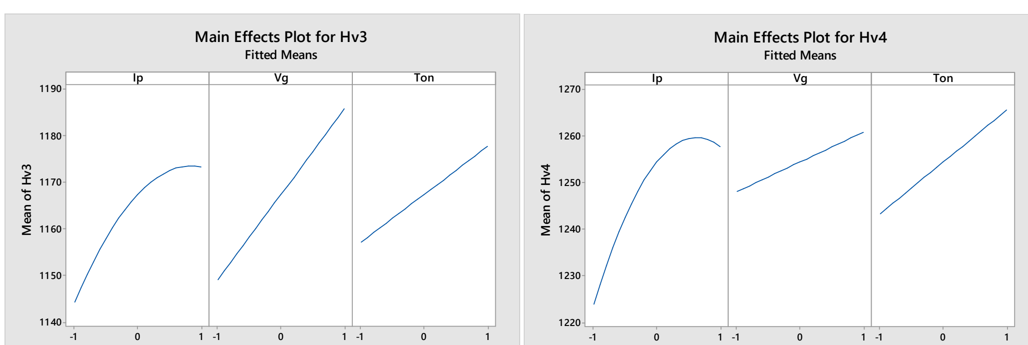
$$Hv_2 = 1029.00 + 14.50\, I_p + 16.25\, V_g + 13.50\, T_{on} + 30.50\, I_p^2 - 1.75\, I_p.\, V_g + 3.00\, I_p.\, T_{on} + 2.75\, V_g.\, T_{on} \quad (3.14)$$

The accompanying ANOVA Table A.13 indicates that the pulse current, pulse on time are statistically insignificant because of higher p-value and voltage is significant due to the small p-value for the linear interaction effect on hardness for positive polarity copper tool. But two-way interaction shows that all the p-value is more than 0.05%. This shows the insignificant nature. The lack of fit is 0.061 which specify that this model is quite helpful to predict the microhardness. The correlation coefficient of this regression model is around 82.91%.

ANOVA, as given in Table A.14, indicates the statistically significant effects of voltage and pulse on time and pulse current and pulse on time are insignificant in linear interaction case. However, two-way interaction shows that all the p-value are higher. The correlation coefficient of this regression model is 85.34% (refer appendix A).

Increase in EDM process parameters in both polarity conditions result in the improvement in microhardness. As the spark energy increases more amount of material is melted, but the amount of metal removed by the dielectric fluid is same, so more amount of metal is redeposited on the surface which leads to increase in microhardness with process parameters. Highest microhardness was obtained in case of machining with negative copper electrode than the positive polarity of the copper tool.

The microhardness measurement is taken at the altered area of the transverse section of the machined sample. It is found that microhardness changed as in-homogeneity of the layered structure. This continues change in hardness from base to deposited layer is observed with the increase of pulse current because the improved in pulse current lead to change the metallurgical structure which deposits more carbon particle on the machined surface. From the experimentation, it is observed that the carbon comes from the broken down of dielectric in EDM generates a carbide layer on the EDMed surface causes a significant improvement of surface hardness. This increase of hardness take place due to increases of a pulse on time. Therefore, the higher the energy discharged, it is simple to convert the material into martensite and disperse carbon into workpieces. Furthermore, the high voltage also helped to increase the spark energy in the machining process and lead to improve the hardness by cracking more die electric fluid which was described in Figure 3. 8 (a) and Figure 3.8 (b)). The Eq. 3.15 and Eq. 3.16 also represent the relation between process parameters with microhardness.



(a) (b)

Figure 3.8: Main effect plot for mean of microhardness (HV) using

(a) positive polarity copper tungsten tool (b) negative polarity copper tungsten tool

$$Hv_3=1167.40+14.50\,I_p+18.25\,V_g+10.25\,T_{on}-8.65\,I_p^2-4.50\,I_p.V_g+6.50\,I_p.T_{on}+2.25\,V_g.T_{on} \quad (3.15)$$

$$Hv_4=1254.40+16.88\,I_p+6.38\,V_g+11.13\,T_{on}-13.53\,I_p^2-12.12\,I_p.V_g-5.37\,I_p.T_{on}-1.38\,V_g.T_{on} \quad (3.16)$$

ANOVA, as given in Table A.15, indicates the statistically significant effects of the pulse current, pulse on time and voltage in linear interaction which are significant but in two way interaction, all process parameters are insignificant because of high p-value. The lack of fit is 0.09. Therefore this ANOVA reveals the adequacy of the developed model for the analysis of microhardness using positive polarity of copper tungsten. The correlation coefficient for this model is around 90.83% (refer Appendix A).

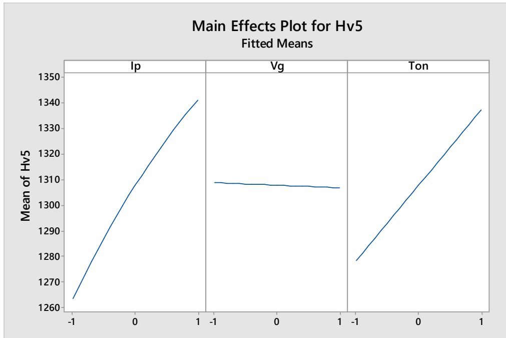
Table A.16 also reveals the statistical effects of the pulse current, is significant in direct interaction for negative polarity of copper tungsten electrode. On the other hand, two-way interaction shows that interaction of pulse current and voltage is significant. The correlation coefficient of this regression model is around 87.13%. The lack of fit is 0.05 which is quite good. Hence, this regression model helps to analyze the microhardness.

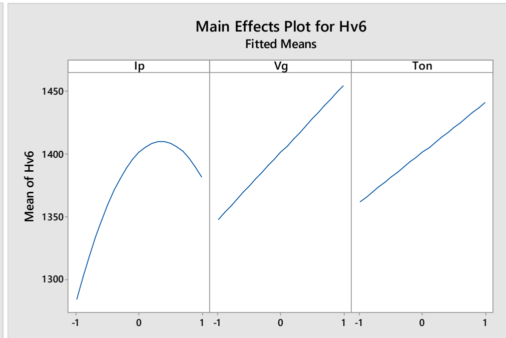
For the machined sample, the microhardness measurements are performed to attain more information about those layers which are dissimilar in structure. The increase in EDM process parameters in both polarity conditions results into increase in microhardness. The uppermost layer of machined surfaces is affected by high temperatures and quick cooling rates, results in the hard re-solidified layer. This high temperature rises in the EDM process due to a more significant value of process parameters. The highest microhardness is obtained in case of machining with a copper-tungsten positive electrode than the negative polarity of copper tungsten tool. The microhardness measurements increase as a longer pulse on time. It occurs as high discharge energy facilitates to change base material into martensite along with a deposit of carbon content on workpieces surface.

To seek the microhardness of machined sample using both polarities of graphite tool second-order models have been proposed which are shown in Eq.3.17 and

Eq.3.18. In Figure 3.9 (a), it shows that the microhardness improves with pulse current. Because of high pulse current enhance more spark energy which leads to melting more amount of material. But this more amount of melted metal is redeposited on the surface which leads to increase in microhardness. In the same Figure, microhardness shows a nonlinear trend with gap voltage. It may be the gap width between the inter-electrode gap in EDM process which improves with an increase of gap voltage. This gradually large gap width changes the spark energy which generates small change in the microstructure of EDMed surface. This minor change of microstructure results in non-uniform microhardness. Also, It can be noticed that the microhardness increases with the certain value of pulse on time because of more spark energy. This more sparks energy induced non-uniform metallurgy changes of machined surface.

From Figure 3.9 (b) the microhardness shows relation with pulse current inversely. It observes that the formation of the more uniform microstructure of EDMed sample due to good flushing of debris and avoidance of abnormal arcing. But both voltage and pulse on time show linearly improvement of the microhardness on the machined sample. It can be described as the increase in voltage and capacitance during the machining process; the metal erosion takes place by melting and evaporating. The melted metal flushed by the dielectric fluid. But, some portion of the melted metal resolidifies quickly on the machining area during pulse off time. This resolidified layer (white layer) is entirely dissimilar from the base metal. The resolidified layer is relatively hard as well as not etchable because the molten metal solidifies very quickly leads to martensite formation. An intermediate layer exists between the 'resolidified layer' and base metal named as heat-affected zone (dark band), where microstructural transformations occur.





(a) (b)

Figure.3.9. Main effect plot for mean of microhardness (HV) using (a) positive polarity graphite tool (b) negative polarity graphite tool

$$Hv_5=1307.80+ 38.75\ I_p-1.00\ V_g+ 29.50\ T_{on}-5.55\ I_p^2-17.00\ I_p.V_g-24.00\ I_p.T_{on} + 4.75\ V_g.T_{on} \quad (3.17)$$

$$Hv_6 =1401.6 + 48.9\ I_p + 53.4\ V_g+ 39.6\ T_{on}-68.7\ I_p^2 -23.1\ I_p.\ V_g+ 6.1\ I_p.\ T_{on} + 7.6\ V_g.\ T_{on} \quad (3.18)$$

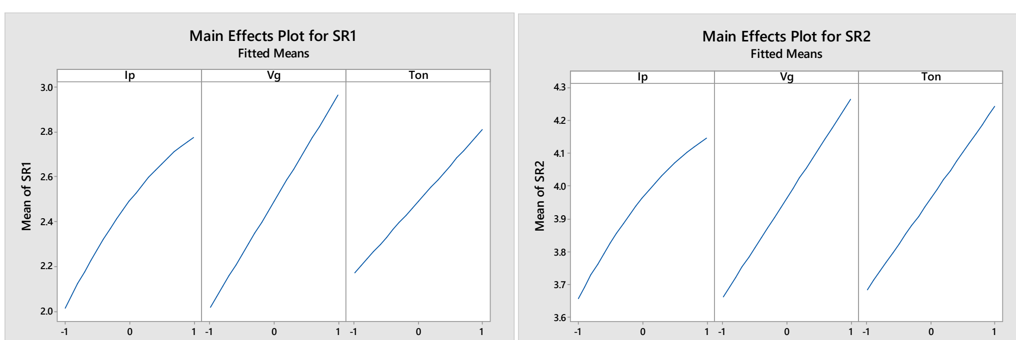
Corresponding ANOVA Table A.17 reveals the statistically significant effects of pulse current and pulse on time whereas voltage is not significant in the linear interaction of parameters. In the case of two-way interaction, the interaction of current and voltage and current and pulse on time shows significant because of low p-value. Both pulse current and voltage are statically significant. But pulse on time has an insignificant effect. It describes that the pulse current and voltage improve the MRR. On the other hand, the improvement pulse on time does not show the linear relation with the MRR. This increment of MRR leads to form microhardness in EDMed surface. The lack of fit is 0.098 which is a significant value to analyze the microhardness. The correlation coefficient of this regression model is 97.09%.

Table A.18 also reveals the statistical effects of the pulse current, pulse on time and voltage on hardness for negative polarity of graphite electrode during the machining process. Corresponding ANOVA Table indicates that the pulse current, pulse on time and voltage for both linear and two-way interaction are insignificant. Also, the correlation coefficient of this regression model is 79.90% (refer appendix A).

White layer observed in the EDMed sample shows more hardness as well as wear resistance as the rapid cooling of dielectric and the carbon deposition on the workpiece surface. Typically, the white layer structure, thickness, and hardness are mostly reliant on type of electrode material and electrical parameters. The microhardness increases as a pulse on time increases. It occurs because of metallurgical phase change and carbide formation on the machined surface during the EDM process. Also, the WLT variation is based on types of electrode and dielectric and flushing jet system. In EDM operation, the appearance of the surface finish is reduced due to more breakdown of dielectric an metal removal. The microcracks are observed on the resolidified due to differential thermal gradient on the machined surface. Increase in EDM process parameters in both polarity conditions results into increase in microhardness. As the spark energy increases more amount of material is melted, but the amount of metal removed by the dielectric fluid is more. Therefore, more amount of metal is redeposited on the surface which leads to increase in microhardness with process parameters. The unequal energy distribution in the EDM process in both tool polarities also helps to different energy transfer to both electrodes. This unequal energy leads to form non-uniform EDMed surface and deposit carbon content on the machined surface. The highest microhardness is obtained in case of machining with positive graphite electrode than the negative polarity of the graphite tool.

3.5. Surface Roughness (SR)

Both Eq. 3.19 and Eq. 3.20 represent the calculation of surface roughness in straight and reverse polarities of the copper tool. Figure3.10. (a) Illustrates the main effect plot for a surface with positive polarity of the copper tool whereas the main effect plot for surface roughness with process parameters is shown in Figure 3.9 (b) for the negative polarity of the copper electrode. In both Figures, it is observed that the surface roughness is reliant on the pulse current and pulse on time. A higher value of pulse current or pulse on time degrades the surface finish. The higher value of pulse current form deep and wide craters on the sample as huge amount material vaporizes from the sample. Hence, the surface topography of the machined sample with high currents is more irregular. In the machining process, progressively application of a pulse on time, more quantity of spark energy transfers to machine surface lead to decrease the surface finish. The surface roughness shows an increasing trend with an increase in voltage. This is due to more spark energy strike on the workpiece surface and produces a more prominent crater. As the increase of pulse current, the spark energy increases, resulting more amount of material melts and vaporize the amount of metal removed by the dielectric fluid in the machining process. Therefore, more amount of metal is re-deposited on the surface which lead to an increase in micro-hardness with pulse current. On the other hand, the average recast layer thickness improves with more value of pulse on time at a constant pulse current. A higher value of pulse on time permitted the electro-discharge energy to enter more depth of the material results in an increase of the WLT. While higher pulse current is supplied, it leads to a rise in temperature of the workpiece and attains the melting point of the metal surface as a results in the average white layer thickness increases. Formation of the white layer was accompanied with generation of cracks in the machined surface, thus the formation of white layer increase surface roughness. In this response study, it is reported that all the process parameters change with surface roughness are more for negative polarity of copper as compared to the positive polarity copper tool.



(a) (b)

Figure 3.10: Main effect plot for mean of surface roughness (SR) using (a) positive polarity copper tool & (b) negative polarity copper tool

$$SR_1=2.492+ 0.383\ I_p+ 0.475\ V_g+ 0.320\ T_{on} - 0.097\ I_p^2 -0.167\ I_p.\ V_g+0.023\ I_p.\ T_{on} - 0.055\ V_g.\ T_{on} \quad (3.19)$$

SR_2=3.964+ 0.2438 I_p+ 0.3013 V_g+ 0.2788 T_{on}- 0.063 I_p^2- 0.0513 I_p. V_g + 0.0362 I_p. T_{on} + 0.0188 V_g. T_{on} (3.20)

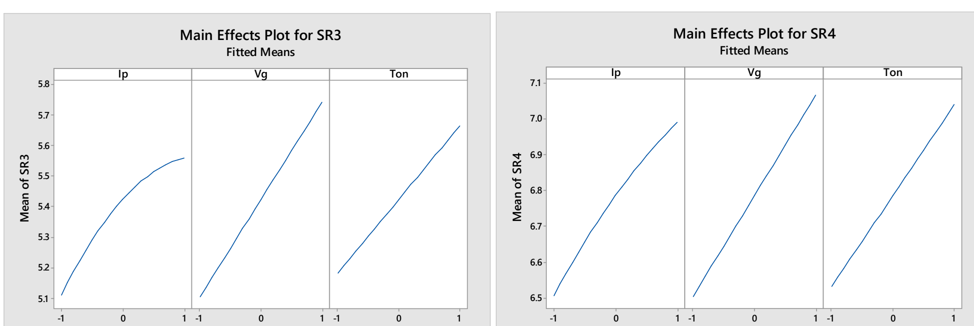
The accompanying ANOVA Table A.19 (refer appendix A) indicates the statistically significant effects of the pulse current, pulse on time and voltage on surface roughness in linear interaction of process parameters with positive polarity copper tool. But in a two-way interaction, all the process parameters shows are insignificant because of more p value. The correlation coefficient is also 90.33%. The values of lack of fit and correlation coefficient help to analyze the surface roughness of the EDMed specimen.

The accompanying ANOVA as noted in Table A.20(refer appendix A) indicates statistically significant effects pulse on time and voltage on surface roughness for negative polarity of the copper electrode. The two way interaction represent that all the process parameters are insignificant because of high, but the lack of fit is 0. 078% which is very good for the analysis surface roughness of EDMed sample. The correlation coefficient is 82.69%. Both the regression models present the robustness of the experimental procedure. The parametric effects of the pulse current, pulse on time and voltage on surface roughness were due to the high density of spark energy act on machined surface erode more material and generate deep and large craters. This model indicates that surface roughness of the machined sample rise with a higher value of process parameters like pulse current, pulse on time and voltage during the EDM process. This observation shows that the influence of process parameters are quite significant.

The surface morphology is associated with various surface characteristics such as microhardness profile, surface roughness, residual stress geometric, crack density, white layer, and crack density, etc. In this investigational effort, it observes that the surface roughness of the negative polarity copper tool is more than a positive polarity copper tool. The negative polarity of tool results in high crater density comparatively with positive electrode owing to better energy distribution at the workpiece; further surface roughness is higher with the copper electrode (under both polarity conditions) due to the availability of more free electrons causing more erosion of work material.

The pulse on time is the most influential parameters for surface roughness in comparison to current and voltage.

Eq. 3.21 and Eq.3.22 show the calculation of surface roughness for both polarities of copper tungsten electrode. In Figure 3.11(a) and Figure 3.12(b), the main effect plot for surface roughness of machined sample shows a similar trend with all the process parameters. In this experiment, it is observed that the surface roughness of the EDMed shows complicate structure surrounded by craters, spherical particles and melted drops as the increment in pulse on time. However, the higher value of current intensity results in noticeable surface roughness of specimens because of deep and large craters formed on the surface. Typically, surface roughness reliant on spark crater forms in a machining operation. Therefore, shallow crater and large diameter result in more surface roughness of EDMed sample. Also, surface roughness is profoundly affected by the gap voltage and capacitance in EDM operation. With the enhancement of the gap voltage, the surface roughness increases. This improvement of the surface roughness noticed because of considerable spark energy per pulse. If the spark energy are high, it would generate larger craters and ultimately fine surface roughness. For rougher finishing, a higher value of voltage and capacitance are needed.



(a) (b)

Figure 3.11: Main effect plot for mean of surface roughness (SR) using

(a) positive polarity copper tungsten tool & (b) negative polarity copper tungsten tool

$$SR_3 = 5.4240 + 0.2238\ I_p + 0.3187\ V_g + 0.2412\ T_{on} - 0.088\ I_p^2 - 0.0687\ I_p.\ V_g + 0.0288\ I_p.\ T_{on} + 0.0238\ V_g.\ T_{on} \quad (3.21)$$

SR_4=6.786+ 0.2412 I_p+ 0.2813 V_g+ 0.2538 T_{on}- 0.037 I_p^2- 0.0462 $I_p.V_g$ + 0.0262 $I_p.$ T_{on} + 0.0212 $V_g.$ T_{on} (3.22)

Table A.21 further reveals the statistically significant effects of the pulse current, pulse on time and voltage in linear interaction on surface roughness for the positive and negative polarity of copper tungsten tool. The two-way interaction which is described in this ANOVA Table shows that all three process parameters interaction effect are insignificant due to more p-value. The correlation coefficient is also 87.77%. In Table A.22, all three EDM process parameters are significant for linear interaction due to the low p-value. On the other hand, all these parameters are insignificant for two way interaction. The lack of fit is 0.052. This developed regression model is suitable to predict surface roughness (refer appendix A).

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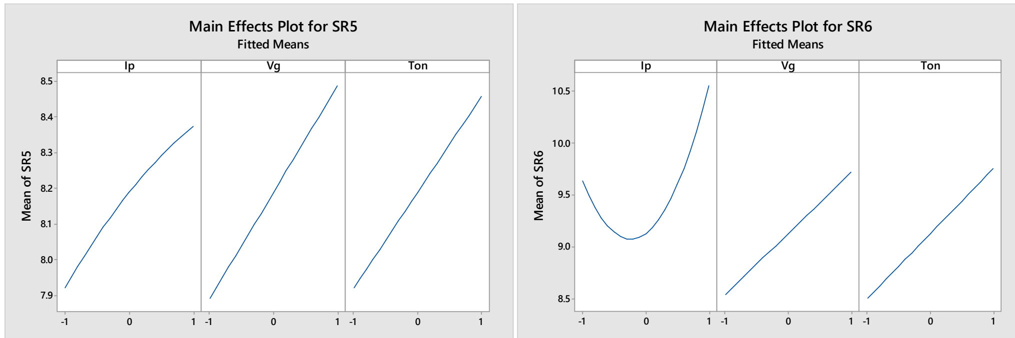
Experimental results indicate that the EDMed surface shows rougher with increases of the voltage, pulse current and pulse on time due to the formation of craters in a large amount with greater depth. The negative polarity of copper tungsten tool results in high crater density comparatively with positive copper tungsten electrode because of its wide energy distribution at the workpiece; further surface roughness is higher with copper tungsten electrode (under both polarity conditions) due to the availability of more free electrons causing more erosion of work material. Pulse on time is the most influential parameters for surface roughness in comparison to current and voltage. The removal rate is more significant for copper tungsten because of its lower melting point and thermal conductivity. The high amount of heat generated on the workpiece surface transmits more particles. Moreover, the enormous positive particles generate large heat as compared to the harmful particles with similar impact velocity. For smaller pulse on time, more negative particles are moving conditions requires the tool to have negative polarity. On the other hand, longer pulse on time, the EDM process is better capable with an electrode under positive polarity. Therefore, workpiece surface finish and an accurate geometry can be gained using copper-tungsten as a cathode material in the machining process. This arrangement of both tool and workpiece is known as negative polarity and, with copper tungsten tool. It is suitable for both roughing and finishing operations. In this study, the negative polarity of copper tungsten provides more surface roughness than positive polarity copper tungsten electrode.

The Eq. 3.23 and Eq.3.24 show the calculation of surface roughness for both polarities of graphite tool. Figure 3.12 (a) shows the main effect plot for surface roughness using a graphite tool as straight polarity. In this Figure, all the process parameters show a similar nature with surface roughness. Therefore, the surface roughness rises with a higher value of pulse current because more quantity of melted material erodes from the machined surface due to of high energy density. It generates deeper craters, which spread over the machined surface and leads to create an uneven surface. Moreover, longer pulse on time increases the surface roughness. It can be attributed that regular breakdown of dielectric fluid leads to form large as well as deeper crater and ridge rich surface on the machined sample. On the other hand, a higher value of the voltage increases spark energy lead to an increment of the crater size of the EDMed sample. The higher voltage in the EDM process increases the gap width between the inter-electrode gap results more erosion of melted material.

Figure 3.12 (b) shows the main effect plot for surface roughness using a graphite tool as straight polarity. It is noticed that the surface roughness rises with a higher value of pulse current because more quantity of melts material erodes from the machined surface due to of high energy density. It generates deeper craters, which spread over the machined surface and leads to create an uneven surface. It is found that a higher pulsed current caused an inferior surface finish of machined sample. The surface roughness and pulse current show nonlinear nature because of good flushing in the inter-electrode gap and avoid abnormal arcing promote the improvement of surface finish on EDMed sample. Moreover, longer pulse on time increases the surface roughness. It can be attributed that regular breakdown of dielectric fluid leads to form large as well as deeper crater and ridge rich surface on the machined sample. On the other hand, a higher value of the voltage increases spark energy which lead to an increment of the crater size of the EDMed sample. The higher voltage in the EDM process increases the gap width between the inter-electrode results more erosion of melted material.



(a) (b)

Figure 3.12: Main effect plot for mean of surface roughness (SR) using (a) positive polarity graphite tool & (b) negative polarity graphite tool

$$SR_5 = 8.190 + 0.2262\ I_p + 0.2987\ V_g + 0.2687\ T_{on} - 0.041\ I_p^2 - 0.0687\ I_p.\ V_g + 0.0362\ I_p.\ T_{on} + 0.0187\ V_g.\ T_{on} \quad (3.23)$$

$$SR_6 = 9.130 + 0.460\ I_p + 0.590\ V_g + 0.627\ T_{on} + 0.967\ I_p^2 - 0.043\ I_p.\ V_g + 0.140\ I_p.\ T_{on} + 0.200\ V_g.\ T_{on} \quad (3.24)$$

Table A.23 show the statistically significant effects of the pulse current, pulse on time and voltage in linear interaction due to the small p-value. On the other hand, these all parameters are insignificant. The lack of fit is 0.061 and correlation coefficient is 86.15%. Table A.24 also show the statistically insignificant effects of the pulse current, pulse on time and voltage in both linear and two-way interaction because of high p-value. But the lack of fit is 0.558. Therefore this developed model is proper to calculate the surface roughness(refer appendix A).

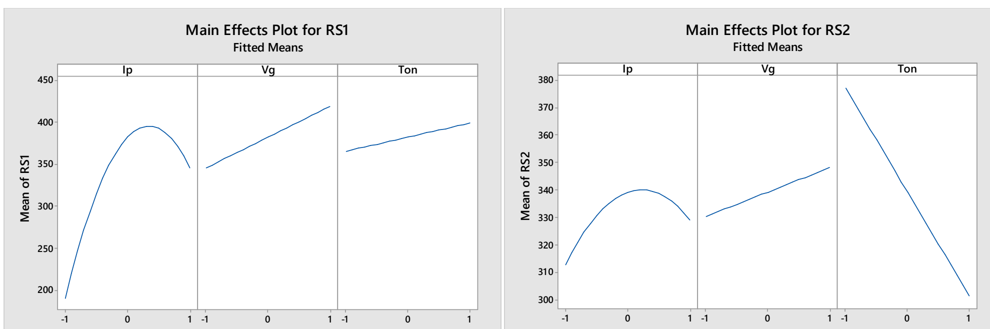
It is well known that surface geometry represents damage of machined sample namely microvoids and microcracks etc. This surface damage of machined sample appears due to melting in EDM operation. Therefore, material erosion is dependable for poor surface integrity upon electro-discharge machining. Surface roughness is observed to increase with all input process parameters due to more energy absorbed by the workpiece surface, and it generates large and deep craters on the EDMed surface. It is observed that negative polarity for graphite promoted very high values of MRR than observed with graphite at positive polarity (anode). It is due to the low density of graphite. The negative graphite tool shows more surface roughness than positive graphite tool because of the heating effect negative electrode allow electrons to absorb enough energy to escape results more crater formation and increase surface roughness.

3.6. Residual Stress (RS)

The residual stress is developed on EDMed surface due to non-uniformity of heat distribution and material phase changes. This stress is also found in thin upper surface of the machined sample. This induced residual stress is tensile for this thin surface. It also increases up to a peak value. After this peak value, the tensile residual stress decreases and convert to compressive residual stress. This compressive stress is observed at the core of the material. Also, it is observed that evacuation of the molten metal causes mechanical blast forming craters on both electrodes surface. This leads to impact by the blow away material particles which should cause compressive residual stress. The Eq. 3.25 and Eq.3.26 show the analysis of residual stress for both polarities of the copper tool. The main effect plot for a mean of residual stress observation is discussed in Figure 3.13 (a) and Figure 3.13 (b) for both polarities.

Figure 3.13 (a) depicts that the high residual stress is induced on the machined sample. This induced stress generates on the machined surface because of expansion and contraction of material occurred in the surface layer whereas the bulk material is not affected by the temperature gradient. The carbon content comes from the dielectric affects the properties of the surface layer. While the tensile residual stress of machined sample is more as compared to the material's ultimate tensile strength, cracks are formed and distributed in a WL of the machined sample. In this Figure, it is found that the residual stress increases with pulse current up to an absolute value and then it decreases. It occurs because the residual stress distribution at different pulse currents generates branches of the cracking network. This similar type of results was also noticed by Ekmekci *et al.*(2006). The residual stress shows linear nature with voltage. It appears due to new phase development in white layer because of pulse energy. This pulse energy variation shows a vital role for the residual stress distribution on machined surface. The mean values of surface stresses depended on the non-homogeneity of phase which was observed in the white layer. The residual stress is also directly improved with the pulse on time. It can be justified as discharge energy influence the depth of EDMed surface where more residual stress was observed. Therefore, pulse energy generates due to large pulse on time results existence of residual stress at a certain depth of machined surface.

On the contrary, Figure 3.13 (b) shows that the induces residual stress shows nonlinear relation with pulse current whereas it shows linear relation with voltage. Despite the change of polarity has changed, both pulse current and voltage variation have been explained in Figure 3.13 (a). But the residual stress drastically reduces with the pulse on time. It appears because as the higher value of pulse on time changes the thickness of the average WL. The relation between residual stresses with the pulse on time was also experimentally found by Lee *et al*. (2004) during the EDM of tool steel.



(a) (b)

Figure 3.13: Main effect plot for mean of residual stress (RS) using

(a) positive polarity copper tool & (b) negative polarity copper tool

$$RS_1 = 382.4 + 77.7\, I_p + 36.7\, V_g + 16.8\, T_{on} - 113.9\, I_p^2 - 23.0\, I_p . V_g + 1.0\, I_p . T_{on} - 42.5\, V_g . T_{on} \quad (3.25)$$

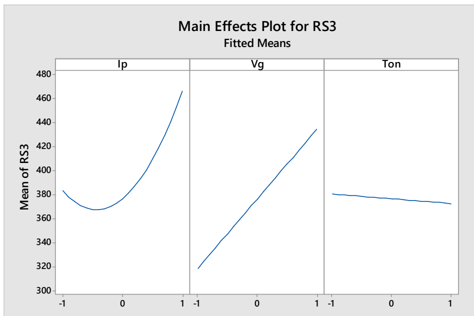
$$RS_2 = 339.2 + 8.1\, I_p + 8.9\, V_g - 37.9 T_{on} - 18.3\, I_p^2 - 32.9\, I_p . V_g + 17.4\, I_p . T_{on} - 47.4\, V_g . T_{on} \quad (3.26)$$

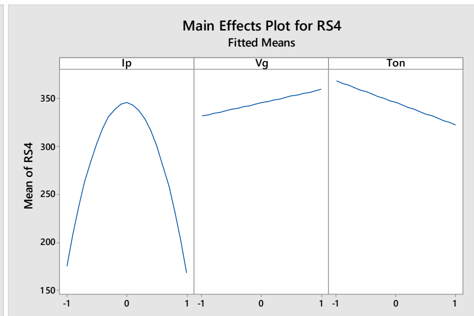
Except for pulse current all three EDM process parameters are insignificant because of high p- value observed in both linear and two-way interaction which has been described in Table A.25. The correlation coefficient is 81.27%. Table A.26 reveal that all the three EDM process parameters are insignificant in both linear and two-way interaction. But lack of fit is 0.735 which is very good for the analysis of residual stress using the negative copper tool.

The main effect plot for residual stress with all the process parameters using positive polarity have been depicted in Figure 3.14 (a). It is observed that the residual stress reveal irregular trend with pulse current. The increase of pulse current resulted in WLT. The improvement of WLT is observed with the spark energy in the machining process. Simultaneously, a branching of cracks is detected with the growth of residual stresses. It is observed that the higher value of pulse-on time generates more stress and raise the possibility of more cracks on the machined surface. Thus the improvement of pulse current induces generate the residual stress which may changes from tensile to compressive nature. This type of observation was also noticed by Lee *et al*. (2004) in the EDM of tool steel. But the improvement of voltage increases the residual stress. It occurs because of high voltage the spark energy increases, and it melts more material in machining zone. This melted material flushed away and generate more residual stress. To verify the relation between residual stress and pulse on time, it is noted that at high pulse on time and low energy levels, the residual stress decreases because of the electrolytic liquid diffuse into the subsurface from the cracked sectors which lead to the non-homogeneous removal of material from the surface in EDM process. This observation is quite similar to the result gained by Ekmekci *et al*. (2006) during the machining of stainless steel using both graphite and copper tool.

The residual stress increases with pulse current up to some specific value; then it starts to decrease. Because of more pulse current, the average WLT increases and a network of cracks also observed. This variation of WLT and crack network changes the residual stress. On the other hand, both voltage and pulse on time shows a similar trend with residual stress which already described in Figure 3.14 (a). The residual stress on the machined surface observed because of phase change. Simultaneously the volume of the altered phase also changes. Therefore, with the optimized value of input process parameters like pulse current, pulse on time and voltage reduce tensile residual stresses because of a decrease in volume of phase. But the reverse nature is observed, and compressive residual stress also generates. The significant difference is the polarity of the electrode which narrates pulse energy distribution on cathode or anode.

This amount of energy distribution decides the variation of residual stress. Also, it also depends on the supply of EDM process parameters (refer to Figure 3.14 (b)).





(a) (b)

Figure 3.14: Main effect plot for mean of residual stress (RS) using

(a) positive polarity copper tungsten tool & (b) negative polarity copper tungsten tool

$$RS_3 = 376 + 41.5\ I_p + 57.7\ V_g - 4.0\ T_{on} + 48\ I_p^2 - 21.3\ I_p.\ V_g + 21.5\ I_p.\ T_{on} - 65.7\ V_g.\ T_{on} \quad (3.27)$$

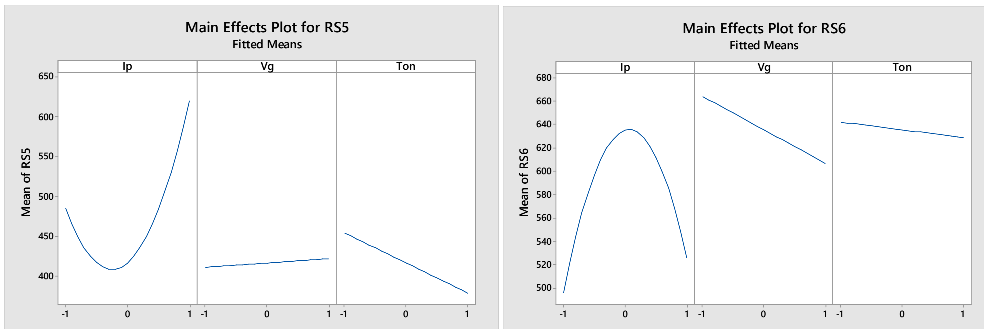
$$RS_4 = 346.0 - 3.4\ I_p + 13.9\ V_g - 22.9 T_{on} - 173.9\ I_p^2 - 0.1\ I_p.\ V_g - 2.4\ I_p.\ T_{on} - 16.1\ V_g.\ T_{on} \quad (3.28)$$

The Eq. 3.27 and Eq.3.28 show the analysis of residual stress for both polarities of copper tungsten tool. The ANOVA Table A.27 describe that all the three EDM process parameters are insignificant in both linear and two-way interaction. But lack of fit is 0.715 which is very good for the analysis of residual stress using positive polarity copper tungsten tool. Corresponding ANOVA as given in Table A.28 reveals that all the three EDM process parameters are insignificant in both linear and two-way interaction. But lack of fit is 0.846 which is suitable for the investigation of residual stress with negative polarity copper tungsten tool (refer appendix A).

In the current study, residual stresses observes in the machined surface due to the non-uniform heat flow on to the machined surface and sample surface modification. This observed residual stresses on machined structures are tensile. This tensile residual stress rises with increasing the spark energy. However, the residual stress values vary from the bulk material to the surface. While residual stress value becomes more than the fracture strength of the material, cracks are generated on the machined surface. The residual melted material which is no flushed in machining process also causes the formation of tensile stress. The present study shows that positive polarity copper tungsten tool provide more residual stress than the negative polarity copper tungsten tool.

The Eq. 3.29 and Eq.3.30 show the analysis of residual stress for both polarities of the graphite tool. The main effect of mean residual stress obtained in EDMed surface versus pulse current, pulse on time and voltage for both positive and negative polarity of graphite electrode has been depicted in Figure 3.15. (a). In this figure, it is found that residual stress decreases with the improvement of pulse current. This high pulse current breaks the dielectric fluid in the EDM process. Therefore more carbon content comes from dielectric fluid and graphite electrode deposit on the machined surface which reduces residual stress. Due to good wear quality of graphite tool, more amount of heat is absorbed by dying steel sample. This absorbed heat in the EDM process increases with voltage. Therefore the pulse energy helps to create different microstructure of machined surface which increases the residual stress. But more pulse on time decreases the residual stress because of the variation of pulse energy intensity towards the depth of the machined sample. Also, it is concluded that the surface is consist of craters, globules of debris, pockmarks voids because of consecutive discharges, which may diverge the residual stress distribution up to some extent on the machined surface.

The analysis of residual stress is shown in Figure 3.15 (b). Again the residual stress shows irregular trend with pulse current because of the variation of WLT thickness, depth of EDMed sample as well as the formation of cracks. Due to more voltage the pulse energy improves in the EDM process. While this spark energy increases with the depth of the machined sample, the residual stress reduces. This similar trend was observed by Rebelo *et al.* (1998). The value of residual stress is inversely related with a pulse on time because non-homogeneous of WLT. The induced residual stress which is observed on EDMed surface increase with the pulse on time and pulse current due to the high intensity of spark energy. This high intensity of spark energy evacuates of molten results craters on the machined surface. This crater formation also helps to wash the material particle from EDMed surface and induce residual stress.



(a) (b)

Figure 3.15: Main effect plot for mean of residual stress (RS) using

(a) positive polarity graphite tool & (b) negative polarity graphite tool

$$RS_5 = 416.8 + 67.4\ I_p + 5.4\ V_g - 37.6\ T_{on} + 136\ I_p^2 - 47.6\ I_p.\ V_g - 3.4\ I_p.\ T_{on} - 64.1\ V_g.\ T_{on} \quad (3.29)$$

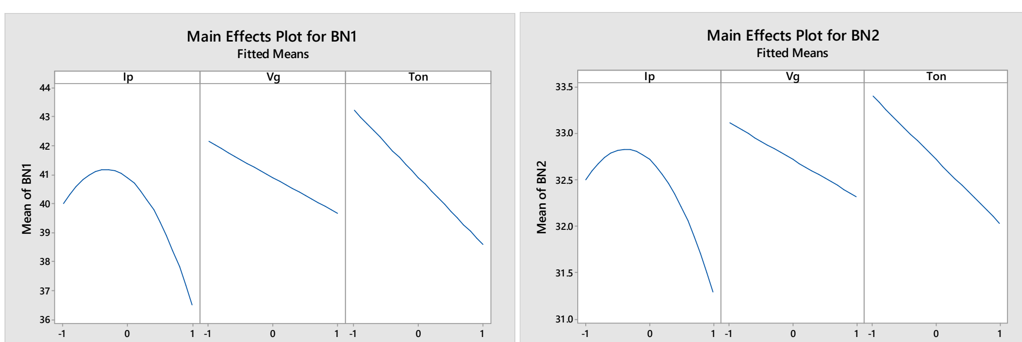
$$RS_6 = 635.4 + 15.1\ I_p - 28.6\ V_g - 6.6\ T_{on} - 124.3\ I_p^2 - 33.9\ I_p.\ V_g - 17.1\ I_p.\ T_{on} + 16.6\ V_g.\ T_{on} \quad (3.30)$$

The accompanying ANOVA as noted in Table A.29 show the influence of the pulse current, pulse on time and voltage on residual stress for positive polarity of graphite electrode during the machining process. From ANOVA, it is clear that pulse current, pulse on time and voltage which are quite insignificant in both linear and two-way interaction. The lack of fit is 0.804. This value higher lack fit indicates that the proposed model is appropriate to study the residual stress. It also indicates the statistical effects of the pulse current, pulse on time and voltage on residual stress for negative polarity of graphite electrode as having been described in Table A.30. But all the three EDM process parameters as shown this table are insignificant because of high p-value. Despite this insignificant p-value, the lack of fit is 0.418 which is quite right to use the study of residual stress (refer appendix A).

The primary reason for the residual stress observed in EDMed workpiece is the extreme thermal cycle and improper temperature distribution. In this current work, the negative polarity of the graphite electrode shows more residual stress than the positive polarity of the graphite electrode. In the EDM process, negative graphite electrode generates a white layer leads to more considerable residual stress.

3.7. Barkhausen Noise (rms)

To seek the root mean square (rms) value of Barkhausen Noise signal the second order regression model has been considering. The estimated main effect plot of rms value of Barkhausen Noise signal with process parameters like pulse current, pulse on time and voltage is shown in Figure 3.16.(a). From the experimental study, it is observed that the rms value of Barkhausen Noise signal nonlinearly decreases with increases of all process parameters. As discussed in the previous analysis, the MRR improves with all process parameters. In the EDM process, the MRR results in thermal damage to the EDMed surface, and it induces high tensile residual stress. Although the MRR shows a linear relation with all process parameters, the inverse relationship are observed among the rms value of the Barkhausen Noise signal and process parameters. Generally, the Barkhausen Noise signal is expressed by arms and peak value. But the rms value is a more well-known parameter as compared to peak value.



(a) (b)

Figure 3.16: Main effect plot for mean Bakhausen Noise (rms) using (a) positive polarity copper tool & (b) negative polarity copper tool

$$BN_1 = 40.9 - 1.740\ I_p - 1.238\ V_g - 2.318\ T_{on} - 2.65\ I_p^2 + 0.760\ I_p.\ V_g + 0.790\ I_p.\ T_{on} + 0.182\ V_g.\ T_{on} \quad (3.31)$$

$$BN_2 = 32.716 - 0.606\ I_p - 0.396\ V_g - 0.681\ T_{on} - 0.820\ I_p^2 + 0.151\ I_p.V_g + 0.321\ I_p.T_{on} + 0.076\ V_g.\ T_{on} \quad (3.32)$$

The Eq. 3.31 and Eq.3.32 show the analysis of rms value of Barkhausen Noise signal for both polarities of the copper tool. The Table A.31 also reveal the statistical effect of the pulse current, pulse on time and voltage on rms value for positive polarity of the copper electrode. The correlation coefficient of this regression model is around 76.42%. The ANOVA study represents that all the effect of EDM process parameters are quite insignificant in linear and two-way interaction. But the lack of fit is 0.870. This model is entirely appropriate for the investigation of rms value(refer appendix A).

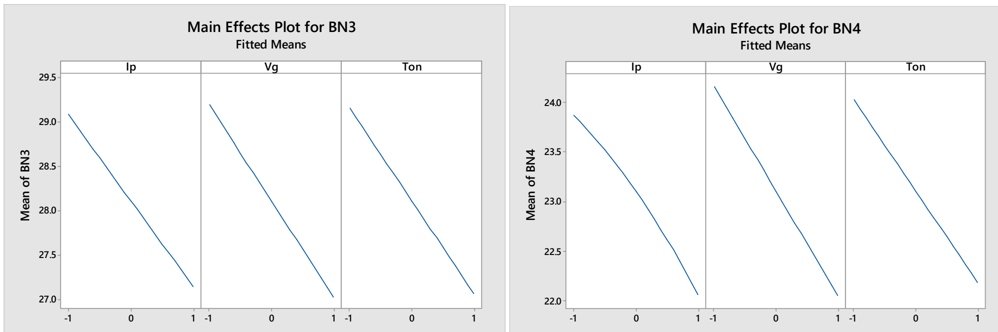
The estimation of main effect plot for the rms value of Barkhausen Noise signal versus pulse current, pulse on time and voltage is represented in Figure 3.16.(b). The rms value of Barkhausen Noise signal shows nonlinear relation all EDM process parameters under this study. The MRR of the workpiece was prime reliant on the spark energy generate plasma channel in the EDM process. But the MRR linearly increases with pulse current, voltage and pulse on time. In EDM operation, MRR also lead to the thermal destruction of the machine workpiece surface, and it may be the cause of initiation of high tensile residual stress. Although the linear trend is observed among the process parameters and MRR, the inverse relation is seen in case of variation of the rms value of Barkhausen Noise signal with process parameters. Usually, Barkhausen Noise signal profile is characterized using arms and peak value. The rms value is more recognized parameter as compared to the peak value.

ANOVA Table A.32 (refer appendix A) shows the statistical effects of the pulse current, pulse on time on rms for negative polarity of the copper electrode during the machining process. The correlation coefficient of this regression model is around 91.51%. The ANOVA study represented that the effect of the pulse current, pulse on time are quite significant in linear interaction. The two-way interaction shows that all the process parameters are insignificant due to the high p-value. The lack of fit is 0.337.

The micro-magnetic response of the workpiece material upon electro-discharge machining reveals a significant effect of process parameters on Barkhausen Noise parameters such as rms and peak value of the signal profile. The Barkhausen Noise parameters influenced by a change in state of stress, grain size, plastic deformation, and hardness. Typically, induction of tensile residual stress causes the higher amplitude of Barkhausen Noise signal.

On the other hand, the increase in hardness results in a reduction in Barkhausen Noise parameters. The more supply of current, voltage and pulse on time lead to a decrease in Barkhausen Noise parameters throughout the entire experimental domain of present investigation. It is quite interesting to note that Barkhausen Noise parameters reduces upon electro-discharge machining as compared to as received samples through the observed residual stress which is tensile in the entire experimental domain. This could be attributed to the increasing in the microhardness of samples upon electro-discharge machining, which produce the more dominant effect in comparison to tensile residual stress. The positive copper electrode generates a larger rms of Barkhausen Noise signal than the negative copper electrode.

The Eq. 3.33 and Eq.3.34 show the analysis of residual stress for both polarities of copper tungsten tool. Figure 3.17. (a) reveals the main effect plot of rms value of the Barkhausen Noise signal with process parameters like pulse current, pulse on time and voltage under positive polarity of copper tungsten electrode in the EDM process. It is noted that the rms value of the Barkhausen Noise signal decreases with increases of the pulse current, pulse on time and voltage. The highest MRR is attained in the EDM process due to more value of current intensity. The elevated temperature creates arcing in the machining process. It also deteriorates the electrode surface. The pulse energy in the EDM process generates some overlapped and dense surface craters in the recast layer. These networks of cracks were found on the EDMed surface due to the induction of high tensile residual stresses. The more significant value of pulse on time creates a conductive path between the electrodes. It also forms a thick and large number of craters on EDMed surface as more the material erosion occurs in the machining process. The stresses are estimated to begin mostly as the thermal contraction of the re-solidified metal, which is not removed from the craters. It also observes the parent metal is comparatively unaffected, inducing plastic deformation and tensile stress. As the gap voltage increases, the spark energy also increases. This caused the formation of cracks and induces residual stress which reduce the rms value of the Barkhausen Noise signal. The Barkhausen Noise signal is expressed by rms and peak value. But the rms value is a more well-known parameter as compared to peak value.



(a) (b)

Figure 3.17: Main effect plot for mean Bakhausen Noise (rms) using

(a) positive polarity copper tungsten tool & (b) negative polarity copper tungsten tool

BN_3=28.110- 0.966 I_p-1.079 V_g - 1.044 T_{on} + 0.006 I_p^2 + 0.184 I_p. V_g -0.061 I_p. T_{on}- 0.044 V_g. T_{on} (3.33)

BN_4=23.108-0.906 I_p-1.056 V_g-0.921T_{on}- 0.137 I_p^2+ 0.226 I_p.V_g 0.044 I_p.T_{on}+0.056 V_g. T_{on} (3.34)

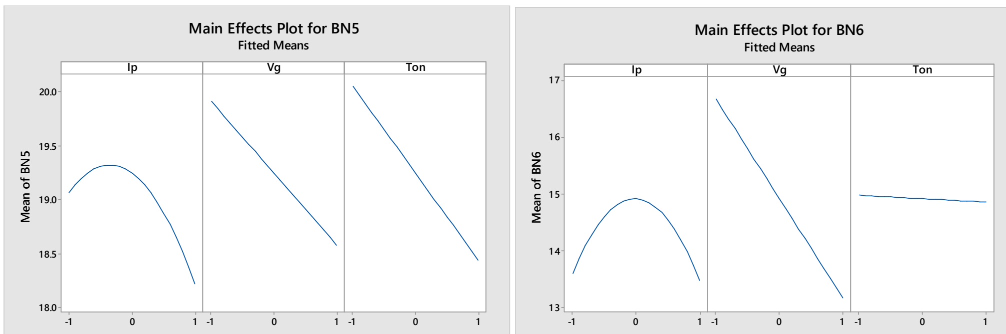
Table A.33 also reveals the statistical effects of the pulse current, pulse on time and voltage on rms for positive polarity of copper tungsten electrode during the machining process. The correlation coefficient of this regression model is around 75.81%. The ANOVA study represents that the all three EDM process parameters are quite insignificant because of high p-value. The lack of fit is 0.134. The proposed model is significant to investigate rms value(refer appendix A).

Similarly, Figure 3.17. (b) Shows the response surface of the rms value of the Barkhausen Noise signal versus all three process parameters. It is observed that the rms value of the Barkhausen Noise signal decreases with the improvement in all EDM process parameters under investigation. The MRR in the EDM process depends upon the spark energy in the machining zone. The MRR also reflects the intensity of thermal damage of the work surface and may be one of the reasons for the induction of highly tensile residual stress. Although the MRR increases with an increment in process parameters, the reverse is observed in case of variation of rms value of Barkhausen Noise signal. The Barkhausen Noise signal profile is generally characterized by rms value and peak value. The rms value is a more established parameter in comparison to peak value.

Corresponding ANOVA Table A.34 reveals the statistical effects of the pulse current, pulse on time and voltage on rms for negative polarity of copper tungsten electrode during the machining process. All three EDM process are insignificant. The correlation coefficient of this regression model is around 81.67%. The lack of fit is 0.108. This model is also more significant to find out the rms value (refer appendix A).

From the principal effect plot analysis, it is summarised that the rms value of the Barkhausen Noise signal reduces with a higher value of all EDM process parameters under investigation. The MRR in the EDM process is mostly reliant on the spark energy. The MRR also reflects the intensity of thermal damage of the work surface and may be one of the reasons for the induction of highly tensile residual stress. Although it is observed that MRR enhanced with an increase in process parameters, but the reverse was observed in case of variation of rms value of Barkhausen Noise signal. Barkhausen Noise signal profile is generally characterized by rms value and peak value. The rms value is a more established parameter in comparison to a peak value. The similar trend of variation of Barkhausen Noise peak value with process parameters was observed.

The Eq. 3.35 and Eq.3.36 show the analysis of rms of Barkhausen Noise signal for both polarities of graphite tool. The interaction of process parameters with response surface of rms value of Barkhausen Noise signal is shown in Figure 3.18 (a). From the experimental result, It was concluded that the rms value of the Barkhausen Noise signal decreases with a higher value in all three process parameters. In the EDM process, the MRR is depended on the discharge energy in the machining zone. It also increases with the increase in all these three process parameters such as pulse current, voltage, and pulse on time. The MRR also reveals the induction of thermal damage to the EDMed sample. It may cause for the initiation of extremely tensile residual stress. The higher value of all three EDM process parameters increases the MRR due to a high density of spark energy. Also, the thermal gradient occurred in EDM process causes the source of tensile residual stress. Barkhausen Noise signal profile is characterized by rms as well as the peak value. The rms value is the more recognized parameter as compared to the peak.



(a) (b)

Figure 3.18: Main effect plot for mean Bakhausen Noise (rms) using (a) positive polarity graphite tool & (b) negative polarity graphite tool

$$BN_5=19.250- 0.425\ I_p- 0.665\ V_g- 0.808\ T_{on}- 0.605\ I_p^2+0.080\ I_p.V_g+0.072\ I_p.T_{on}- 0.162\ V_g.\ T_{on} \quad (3.35)$$

$$BN_6=14.920 - 0.066\ I_p -1.751\ V_g -0.059\ T_{on} -1.379\ I_p^2 + 0.821\ I_p.\ V_g -0.876\ I_p.\ T_{on} +0.714\ V_g.\ T_{on} \quad (3.36)$$

The accompanying ANOVA Table A.35 reveals the statistically insignificant effects of the pulse current, pulse on time and voltage on rms for positive polarity of graphite electrode in linear interaction. The voltage is significant in linear interaction. However, all these process parameters are insignificant in two-way interaction. Therefore, pulse on time has less effect on the rms value of the Barkhausen Noise signal in the EDM process. The correlation coefficient of this regression model is around 90.77%. The lack of fit is 0.875.

The main effect for rms value of Barkhausen Noise signal with pulse current, pulse on time and voltage under negative polarity of a graphite electrode is shown in Figure 3.18.(b). The rms value of Barkhausen Noise signal decrease with the increase of pulse current. This can be described as the higher value of pulse current generates more spark energy in the EDM process. This high density of spark energy erodes more material and forms more quantity of a crater on the EDMed sample. With longer pulse on-time, a small amount of melted material is eroded from EDMed surface due to the weak and larger diameter of plasma channel and proper flushing action of the dielectric. Despite the erosion of material erosion, remained melted material re-solidifies. This re-solidified layer termed as a white layer. It is the combination of high tensile residual stress, a branch of microcracks and small holes occurred due to the high-temperature gradient. On the other hand, a higher value of supply voltage decreases the rms value of the Barkhausen Noise signal due to induced tensile stress in the EDM process.

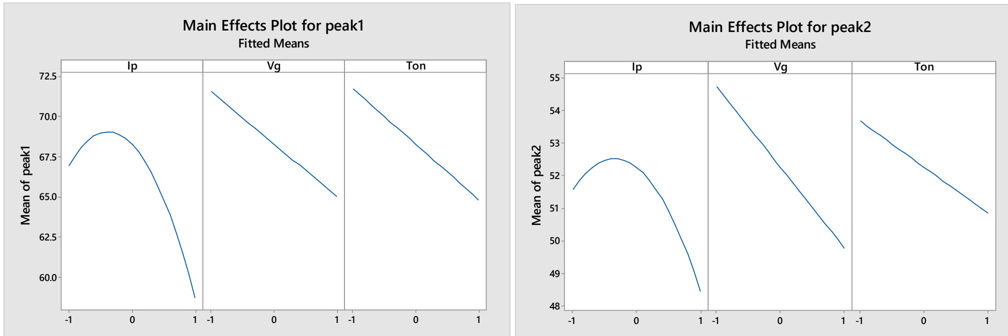
Table A. 36 also represent the statistical effects of the pulse current, pulse on time and voltage on rms for negative polarity of graphite. The only voltage is insignificant as mentioned in ANOVA Table A.36 in linear interaction. Whereas all the process parameters are significant in two-way interaction. The correlation coefficient of this regression model is around 96.62%. The lack of fit is also 0.597.

Generally, rms and peak value of Barkhausen Noise signal gets affected by the induction of residual stress, microhardness changes and changes in microstructure. The electro-discharge machining process is peculiar as all these simultaneously changes during the process. It was also observed that the variation of rms and peak value of Barkhausen Noise signal concerning residual stress, although the trend is scattered in nature. The Barkhausen Noise signal gets affected by the change in microhardness, microstructure, and induction of residual stress. Typically, all these features simultaneously occur during the EDM process. Hence, it is quite difficult to predict which feature is having a more dominant effect on Barkhausen Noise signal. The rms value of the Barkhausen Noise signal is a well-established parameter for the characterization of surface integrity. In this present work, the study of variation in peak value concerning EDM process parameter throughout the experimental domain. It can be observed that the variations of peak value occur similarly as the rms value varies with process parameters.

3.8. Barkhausen Noise (peak)

The peak value of Barkhausen Noise signal falls with an increase of process parameters were depicted in Figure 3.19.(a). The Barkhausen Noise parameters are responsive to residual stress, plastic deformation as well as hardness. Typically, the tensile residual stress induced in the workpiece is the source of large amplitude of Barkhausen Noise signal. The higher the value of hardness leads to decrease in rms and peak value of Barkhausen Noise signal. In the EDM process higher value of input parameters resulted in the drastic fall of rms and peak value of Barkhausen Noise signal through the entire experiment of the present study. The Eq. 3.37 and Eq.3.38 show the analysis of peak of Barkhausen Noise signal for both polarities of the copper tool.

The similar relation of variation of Barkhausen Noise peak value concerning process parameters was shown in Figure 3.19.(b). The micro-magnetic response of the machined sample in EDM process represents the significant influence of process parameters on Barkhausen Noise parameters namely rms and peak value of signal profile. Barkhausen Noise parameters are the function of residual stress variation, plastic deformation as well as hardness. Typically, the tensile residual stress observed in EDMed surface is one of the reasons for the larger amplitude of Barkhausen Noise signal, while the improvement of hardness results reduction in Barkhausen Noise parameters. While current, voltage and pulse on time are set at a higher value, these parameters consequence decrease in Barkhausen Noise parameters through the whole experiment of the present study. It is interesting to note that despite induction of tensile residual stress, Barkhausen Noise parameters are observed to decrease. This may be attributed to an increasing in hardness.



(a) (b)

Figure 3.19: Main effect plot for mean Bakhausen Noise (peak) using

(a) positive polarity copper tool & (b) negative polarity copper tool

$$peak_1 = 68.30 - 4.10\, I_p - 3.26\, V_g - 3.44\, T_{on} - 5.43\, I_p^2 + 0.25\, I_p.\, V_g + 0.58\, I_p.\, T_{on} + 0.91\, V_g.\, T_{on} \quad (3.37)$$

$$peak_2 = 52.26 - 1.56\, I_p - 2.46\, V_g - 1.41\, T_{on} - 2.23\, I_p^2 + 0.55\, I_p.\, V_g + 0.18\, I_p.\, T_{on} + 0.70\, V_g.\, T_{on} \quad (3.38)$$

The accompanying ANOVA Table A.37 also reveals the statistical effects of the pulse current, pulse on time are significant during linear interaction and but voltage for positive polarity of the copper electrode during the machining process. The pulse current, pulse on time is significant, and voltage is relatively insignificant during linear interaction of process parameters with a response. On the other hand, two-way interaction shows that all the process parameters are insignificant due to the high "p" value. The lack of fit is 0.454 and correlation coefficient is 86.02%. The lack of fit is 0.260.

The influence of the magnetic response of the machined workpiece material in EDM process represented the significant effect of input parameters on Barkhausen Noise parameters namely peak value of Barkhausen Noise signal profile. The peak value of Barkhausen Noise is sensitive to change of residual stress, grains structure, plastic deformation and hardness of EDMed workpiece. The induced tensile residual stress of EDMed surface generate high amplitude of Barkhausen Noise signal. On the contrary, the improvement of the hardness of a machined workpiece lead to a decrease in the peak value of Barkhausen Noise signal. Therefore, the higher value of all these three EDM process parameters resulted decrease the peak value of Barkhausen Noise signal during the whole experimental domain of the current experiment. It is also the noteworthy observation that the peak value of Barkhausen Noise signal decreases in EDM process as compared to obtained machined samples which show tensile residual stress in the whole experimental domain. This could be justified that an increase in microhardness of machined samples generates the more dominant effect in comparison to tensile residual stress.

The Eq. 3.39 and Eq.3.40 show the analysis of peak of Barkhausen Noise signal for both polarities of copper tungsten tool. Figure 3.20 (a) depicts the peak value of Barkhausen Noise signal reduces with the increase of process parameters under positive polarity of copper tungsten electrode. Barkhausen Noise parameters like peak value are sensitive to residual stress, plastic deformation, and hardness. In the EDM process, a higher value of pulse current generates to increase the residual stresses in EDM because of the non-uniform of heat flow and metallurgical transformations and plastic deformation. This stress observed on the workpiece surface is tensile and generate large amplitude of Barkhausen Noise signal leads to lower the peak value of Barkhausen Noise signal. On the contrary, a higher value of pulse on time improves the hardness of the EDMed sample due to more discharge energy causes material transformation and carbon diffusion on the machined surface. This more significant value of hardness results decreases the peak value of Barkhausen Noise signal. Furthermore, the more supply voltage also leads to a decrease in the peak value of Barkhausen Noise signal.

Figure 3.20 (b) also shows similar the variation in rms value of Barkhausen Noise signal with process parameters. It is observed that the rms value of the Barkhausen Noise signal decreases with enhancement in all EDM process parameters. But pulse current improvement causes a sharp decrease of the peak value of Barkhausen Noise signal. It occurs due to the excellent melting point of copper particle and wears characteristic; the energy absorbs quantity to affect the material erosion from workpiece surface as compared positive polarity copper tungsten tool.

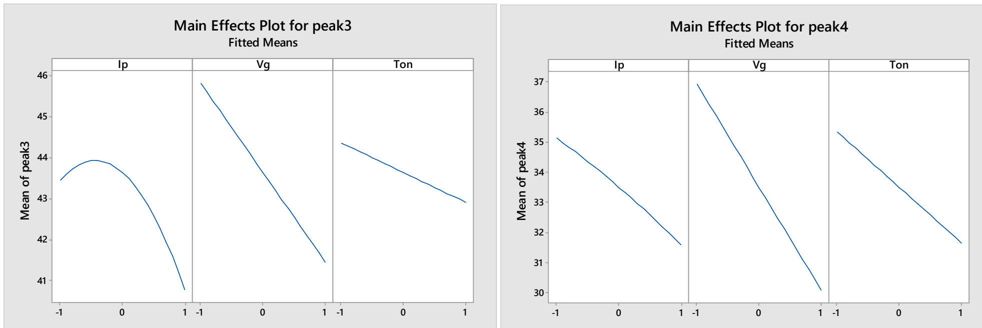


Figure 3.20: Main effect plot for mean Barkhausen Noise (rms) using (a) positive polarity copper tungsten tool & (b) negative polarity copper tungsten tool

$$peak_3 = 43.63 - 1.34\, I_p - 2.18\, V_g - 0.72\, T_{on} - 1.52\, I_p^2 + 0.38\, I_p.\, V_g + 0.28\, I_p.\, T_{on} - 0.36\, V_g.\, T_{on} \quad (3.39)$$

$$peak_4 = 33.51 - 1.771\, I_p - 3.429\, V_g - 1.841 T_{on} - 0.15\, I_p^2 + 0.614\, I_p.V_g + 0.246\, I_p.T_{on} + 0.304\, V_g.\, T_{on} \quad (3.40)$$

Table A.39 also reveals the statistical effects of the pulse current, pulse on time and voltage on the peak for positive polarity of copper tungsten electrode during the machining process. The lack of fit of this model is around 0.203. Table A.40 reveals the statistically significant effects voltage in linear interaction with response. But all three process parameters are insignificant because of more p-value. The lack of fit is 0.223 which indicates that this selected model is meant for the calculation of peak value. The correlation coefficient for this model is around 83.65%(refer appendix A).

It is quite interesting to note that a good correlation was observed between microhardness and Barkhausen Noise parameters. In the present work, the rms value of Barkhausen Noise signal was observed to decrease with increase in microhardness. It is quite known that increase in hardness indicates an increase in dislocation density due to the accumulation of dislocations. Generally, microhardness number at any point over the material surface can be accepted as a qualitative indication of the dislocation density at this point. During EDM, the formation of white layer typically occurs. It is generally considered a hard to magnetize phase as it restricts the motion of magnetic domain walls in the existence of an external magnetic field. The amplitude of Barkhausen Noise signal typically reliant on the travel length of magnetic domain motion. Dislocations and hard micro-structural phase act as a pinning site for domain wall motion. Hence increase in dislocations density and presence of white layer leads to a decrease in peak and rms value of Barkhausen Noise signal as well peak value with respect to microhardness .

The Eq. 3.41 and Eq.3.42 show the analysis of peak of Barkhausen Noise signal for both polarities of graphite tool. Figure 3.21 (a) shows the variation of the rms value of Barkhausen Noise signal with process parameters. The trend of rms value of Barkhausen Noise signal is found to be decreasing with increasing all three process parameters. In the EDM process, the MRR is depended on the discharge energy in the machining zone. It also increases with the increase in all these three process parameters such as pulse current, voltage and pulse on time. The MRR also reveals the induction of thermal damage of the EDMed sample. It may cause for the initiation of extremely tensile residual stress. Although, MRR linearly increased with the three process parameters, whereas the reverse trend was investigated in the variation of the rms value of Barkhausen Noise signal. The Barkhausen Noise signal profile is characterized by rms as well as the peak value. But the rms value is a more recognized parameter as compared to peak value.

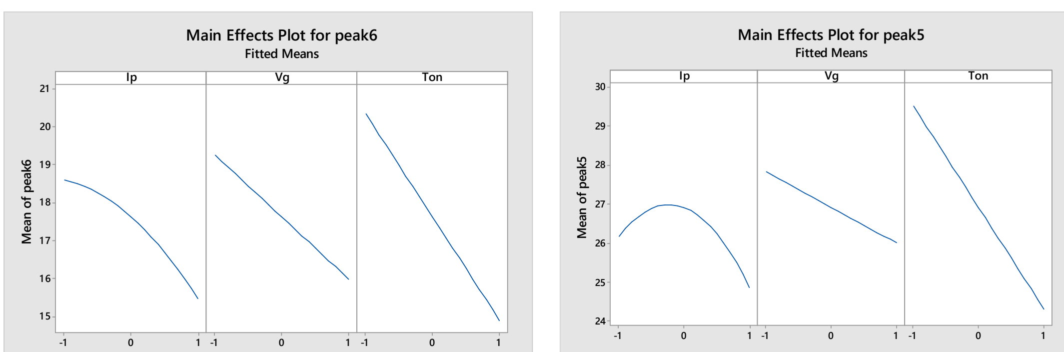


Figure 3.21: Main effect plot for mean Bakhausen Noise (peak) using (a) positive polarity graphite tool & (b) negative polarity graphite tool

$$peak_5=26.912- 0.656\ I_p- 0.909\ V_g- 2.599T_{on}-1.388\ I_p^2- 0.119\ I_p.V_g+0.621\ I_p.T_{on}- 0.086\ V_g.\ T_{on} \quad (3.41)$$

$peak_6$=17.602- 1.561 I_p-1.634 V_g-2.714T_{on}- 0.586 I_p^2+0.601 $I_p.V_g$-0.959 $I_p.T_{on}$-0.576 $V_g.\ T_{on}$ (3.42)

Table A.41 also reveals the statistical effects of the pulse current, pulse on time and voltage on the peak for positive polarity of graphite electrode during the machining process. The correlation coefficient of this model is around 94.13%. ANOVA Table A.47 indicates all three process parameters are significant in linear interaction but it shows insignificant in two way interaction.

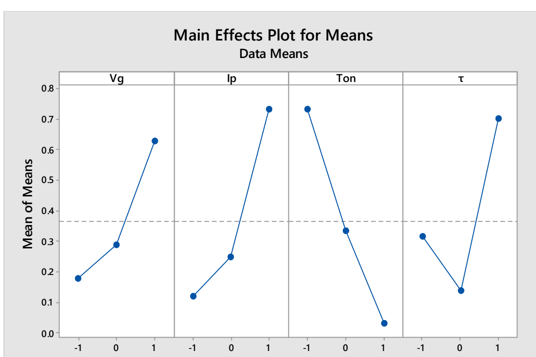
Figure 3.21 (b) depicts the variation of the peak value of Barkhausen Noise signal with pulse current, pulse on time and voltage for negative polarity of the graphite electrode. From the previous discussion, it was concluded that the MRR is a function of pulse current. With a suitable pulse duration, the intensity of energy improvement with the increase of pulse current. This high amount of MRR induces residual stress on the machined surface. Typically, this stress is tensile in nature leads to decrease the peak value of Barkhausen Noise signal. On the contrary, an increase of pulse on time also decrease the peak value of Barkhausen Noise signal due to material transformation and carbon deposition on EDMed surface. This causes the initiate of hardness on the workpiece surface. A higher value of voltage causes decreases in peak value due to induction of tensile residual stress. It can be described as the amplitude of Barkhausen Noise signal is more which indicates the decrease of the peak value of Barkhausen Noise signal.

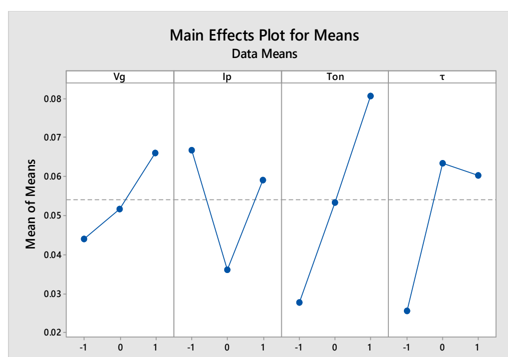
Table A.42 explain the statistical effects of the pulse current, pulse on time and voltage on the peak for negative polarity of graphite electrode during the machining process. The correlation coefficient of this regression model is around 88.88%. In this ANOVA, the effect of EDM process parameters is statistically significant for linear interaction. Whereas these parameters are non significant in two way interaction(refer appendix A).

The EDMed sample shows the significant correlation between the magnetic response of the like peak value of Barkhausen Noise profile and pulse current, pulse on time and voltage. From the previous work, it was concluded that the peak value of Barkhausen Noise signal gets influenced by a change in residual stress, grain size, plastic deformation as well as hardness. The residual stress observed in the machined sample is tensile in nature and it also creates high amplitude in Barkhausen Noise signal. Furthermore, the increased hardness of EDMed sample in machining process reduces the peak value of Barkhausen Noise profile. Therefore, the larger value of pulse current, pulse on time and voltage results decreases the peak value of Barkhausen Noise profile throughout the entire experimental domain of this study. Barkhausen Noise parameters decreased with an increase in all the EDM process parameters in machining. Although, tensile residual stresses and microhardness are get affected by Barkhausen Noise parameters in the entire experimental domain. But microhardness of EDMed samples shows a more dominant effect in comparison to tensile residual stress. Electro-discharge machining process creates more heat in the machining zone that results in elevated temperature condition. This condition followed by quick cooling of dielectric fluid induces plastic deformation at various degrees over the machined surface. Induction of varying degree of plastic deformation affects the surface roughness profile of the machined surface. Typically, Vickers hardness improves with permanent deformation. Electro-discharge machining with elevated temperature condition creates high plastic deformation on the surface and sub-surface layer, thus resulting to poor surface finish. The poor surface finish generated in the EDM process also results in a decrease in rms and peak value of Barkhausen Noise signal.

Figure 3.22 (a) shows the main effect plot for mean MRR of machined die steel using positive copper polarity. In this analysis, four input process parameters such as pulse current, pulse on time, voltage and duty cycle were varied for experimentation. This Figure depicts that the enhancement of pulse current generates more MRR because of more spark energy in the machining zone. This higher value of spark energy erodes more material from the workpiece. Similarly, the MRR also improved with more value of voltage because of higher spark energy. The increase in spark energy eases the melting and evaporation, which provide more material removal from the workpiece. The material erosion rate also shows a nonlinear trend with the pulse on time. Although MRR improves with the pulse on time up to optimum value, it decreases the MRR because of more expansion of plasma channel in machining zone. This more full plasma channel reduces the intensity of spark energy which results in a decrease of MRR. The duty cycle is an important parameter to consider in the EDM of die steel. Both pulses on time and pulse off include a single cycle of EDM. The duty cycle is the ratio of the pulse-on-time and the total cycle time. The pulse off selection in duty cycle is dependent on the pulse on time which is used in machining purpose. The suitable selection of the duty cycle also maintains the spark signal which results in the proper idle machining period. The more value of pulse on time leads to non-uniform spark signal. This non-uniformity of spark in EDM reduce the EDM efficiency. On the contrary, more pulse off time also create an uneven spark and short-circuiting. Therefore arcing and unstable machining process generate a nonlinear trend of MRR with duty cycle (refer to Figure 3.22. (a)).

This Figure 3.22 (b) shows the effect of these four input process parameters on MRR using negative polarity of the copper tool. The similar trend was also observed in the above Figure. During the EDM process, it was observed in plasma channel that more amount of electron liberated from the cathode and less number of cations strike on the anode surface. This movement of ions and electrons in the plasma channel decides the energy distribution in both cathode and anode. The more amount of energy generated in negative polarity which results in more MRR than positive polarity.





(a) (b)

Figure 3.22: Main effect plot for mean Material Removal Rate (MRR) using L9 orthogonal array (a) Copper positive polarity & (b) copper negative polarity

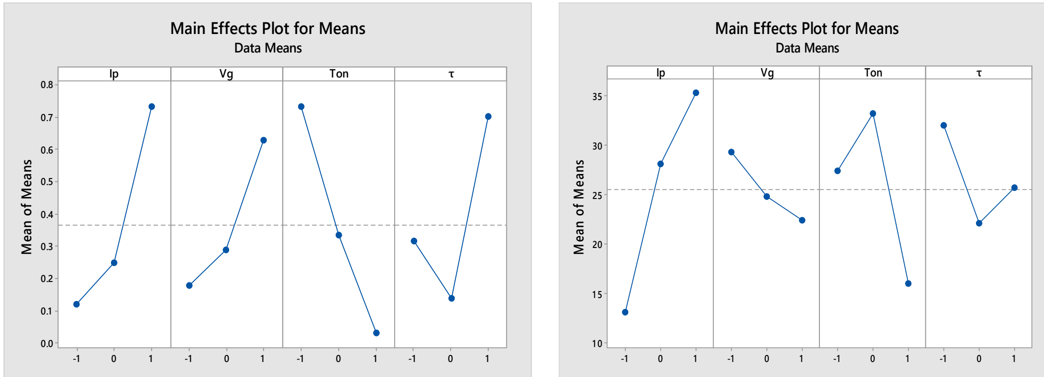


Figure 3.23: Main effect plot for mean Material Removal Rate (MRR) using L9 orthogonal array (a) positive polarity graphite tool & (b) negative polarity graphite tool

Figure 3.23 (a) depicts the MRR of the machined sample using positive polarity of graphite tool. In this Figure, it was observed that MRR is mostly affected by the pulse current. An increment in current results increase in pulse energy helps to erode more material in every discharge. The pulse on time shows less effect on MRR as compared to pulse current. The experimental results show that the improvement of MRR is not constant, it decreases as the expansion of the plasma channel in the EDM process. This expanded plasma channel reduce the intensity of spark energy which results in low MRR. Voltage improvement also increases the MRR. Also, the specific electric conductivity of graphite also describes that the small amount of electric energy lost at graphite tool as small electric resistance. Therefore a large amount of energy generates at the specimen which leads to more MRR.

Figure 3.23 (b) reveals that MRR enhances with pulse current because of more crater and erosion of material from EDMed surface for negative polarity Graphite tool. The pulse on time shows less effect on MRR as compared to pulse current. The experimental results show that the improvement of MRR is not consistency with the pulse on time, but it decreases as the expansion of the plasma channel in the EDM process. This expanded plasma channel reduce the intensity of spark energy which results in low MRR. On the other hand, voltage improvement also increases the MRR, but more voltage decreases the MRR as more spark gap or gap width observed in the inter-electrode gap. The higher value of duty cycle improves the MRR in the EDM process. In this factor, the pulse off time decreases while the pulse on time remained at consistent value. These setting of both pulses on time and pulse off time in duty cycle enhance the MRR.

All the experimental results for the machined sample using both polarities are shown in Table B.1 to B.6. The Table B.7 shows the conclusion Table for all three electrodes and two polarities (both positive and negative). The Table B.8 and Table B.9 depict the MRR for both copper and graphite tool using an orthogonal array.

3.9. Inferences

The performance of the EDMed surface is one of the essential subjects in widening its service life and surviving environmental effect. Therefore, surface morphology analysis is becoming a progressively more important topic. Electro-discharge machining initiate surface as well as subsurface deterioration on manufactured components. The substantial degrade of this EDMed component mostly relies on electrode discharge machining parameters. The majority of this damage is associated with high machining zone temperature. These surface modifications can be represented as a change in microstructural, microhardness, white layer development, induction of tensile residual stress and even formation of microcracks and voids.

In the current study, three different electrodes namely copper, copper tungsten and graphite and two polarities (straight and reverse) were taken on wide variation in machining parameters to study their relevant effects on various surface integrity indices. The die steel was commonly used as material in this experiment. It may be concluded that such machining process induces residual stress on the machined surface to a different degree along with other EDM damages.

The primary aim of the present research work is to assess the applicability of Barkhausen Noise technique for surface integrity assessment upon Electro-Discharge machining by investigating the correlation between the micromagnetic response of EDMed dies steel sample with surface integrity aspects. It is a well-known fact that micromagnetic response characterized by Barkhausen Noise parameters gets affected not only by the nature of residual stress but also by microstructure, hardness and surface roughness of the machined sample. Since electro-discharge machining process introduces all of these simultaneously, there lied the challenge of present research work.

Section 3.1 indicates that the electro-discharge machining process induces the high tensile residual stress through the experimental domain. Generally, the induction of tensile residual stress causes an increase in Barkhausen Noise signal parameters, i.e. rms and peak value of the signal. Figure 3.24 and Figure 3.25 represent the variation of rms and peak value of Barkhausen Noise signal with the residual stress induced upon electro-discharge machining. Although a scattered pattern was obtained between residual stress and Barkhausen Noise parameters, the linear fit between the scattered data indicates that both rms value and peak value reduced with improvement in the tensile residual stress.

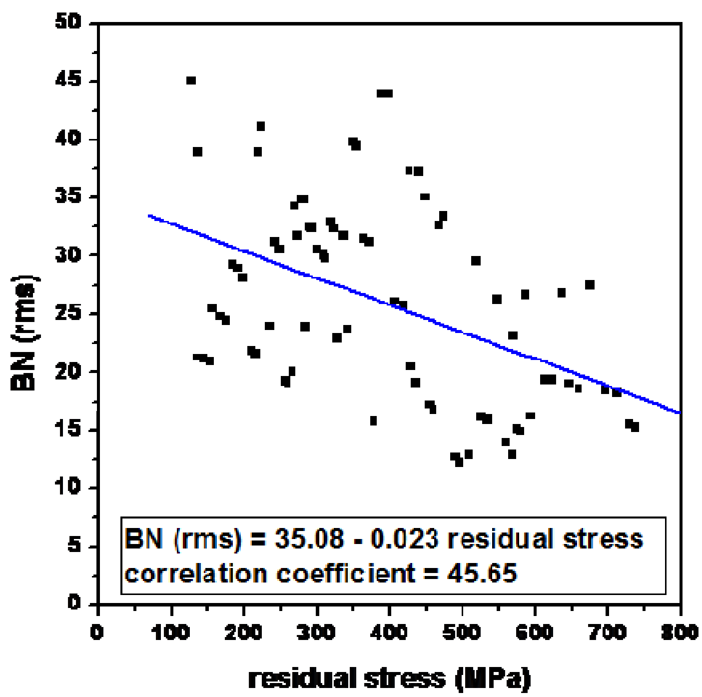


Fig 3.24 Variation of Barkhausen Noise (rms) with residual stress

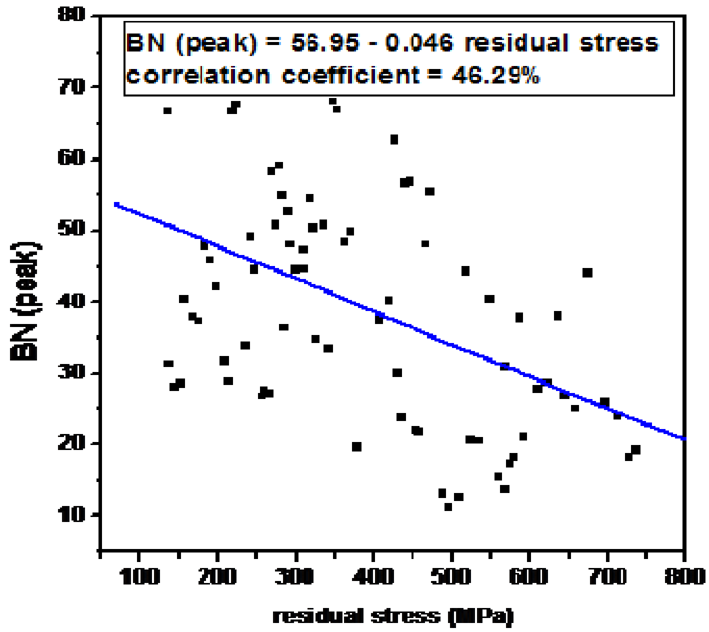


Fig 3.25 Variation of Barkhausen Noise (peak) with residual stress

The electro-discharge machining process is peculiar owing to the induction of high tensile residual stress, poor surface finish, microhardness variation, and changes in microstructure, the formation of a white layer with surface and subsurface cracks. In the present study, all these changes were observed throughout the entire experimental domain. Figure 3.26 shows the microstructure of die steel sample obtained upon electro-discharge machining in the present study. This clearly shows the formation of white layer followed by the dark band as well as surface cracks are also clearly visible.

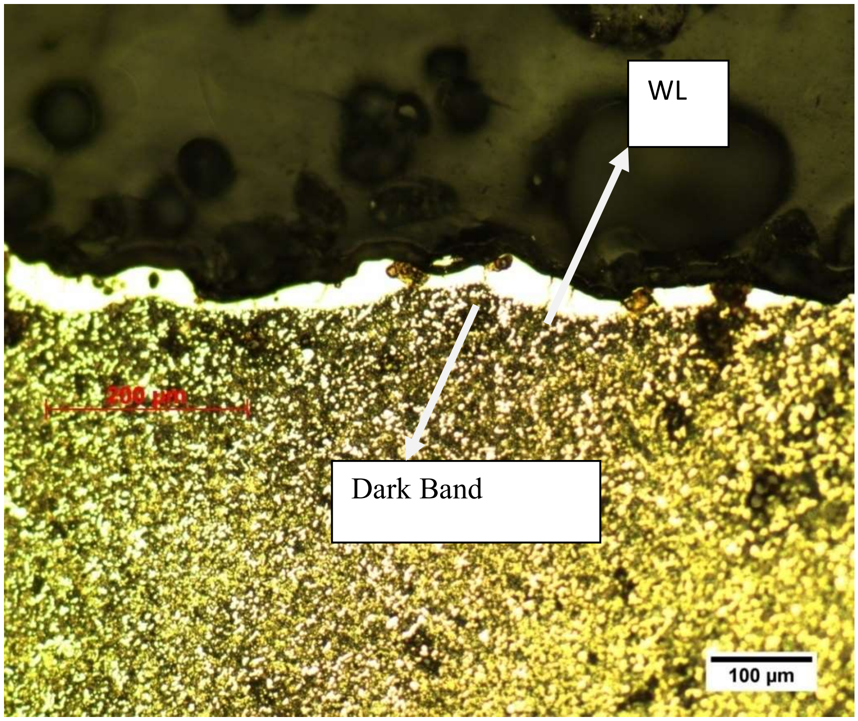


Figure 3.26. Optical micrograph of recast layer and heat effected zone machined sample obtained by standard EDM (Material: Die steel, 6A/400µs/39V)

Figure 3.27 and Figure 3.28 shows the variation of rms and peak value of Barkhausen Noise signal with microhardness obtained in the entire experiment domain.

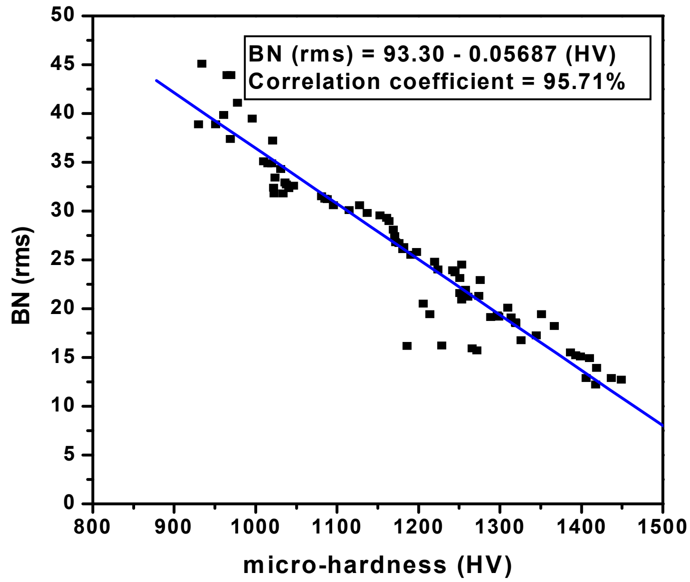


Figure 3.27. Variation of Barkhausen Noise (rms) with microhardness

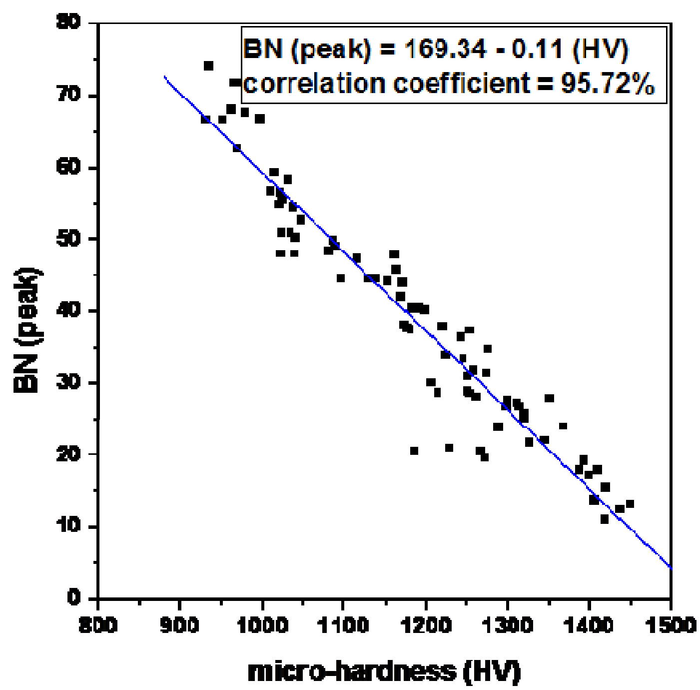


Figure 3.28 Variation of Barkhausen Noise (peak) with microhardness

Typically, induction of tensile residual stress causes the higher amplitude of Barkhausen Noise signal, on the other hand, increase in hardness results in a reduction in Barkhausen Noise parameters. Increase in current, voltage and pulse on time leads to a reduction in Barkhausen Noise parameters throughout the entire experimental domain of present investigation. It is quite interesting to note that Barkhausen Noise parameters reduced upon electro-discharge machining as compared to as received samples through the observed residual stress was tensile in the entire experimental domain. This may be attributed to the increasing in microhardness of samples upon electro-discharge machining, which produced more dominant effect in comparison to tensile residual stress.

Barkhausen Noise parameters (rms and peak value) gets affected by change in microhardness and variation in residual stress (nature of residual stress as well its magnitude). Electro-discharge machining is peculiar in nature as changes in microstructure, variation in microhardness and induction of residual stress takes place simultaneously. In the present research work, effect of variation in microhardness was more dominant on BN parameters in comparison to induced tensile residual stress, hence a fitting curve with good correlation coefficient was obtained between BN parameters and microhardness as shown in Figure 3.27 & 3.28. The correlation of experimental data of residual stress and BN parameters does not indicates a good fitting although a lot of method of fitting, i.e. linear fitting, non-linear fitting, exponential fitting were attempted to get a good fitting curve. Figure 24 and Figure 25 were included in the thesis to indicate the poor applicability of Barkhausen Noise technique for assessment of residual stress upon electro-discharge machining.