CHAPTER 5

DISCUSSION

DISCUSSION

5.1 ELECTRODES AND WORKPIECE

Three electrodes are used in this study; aluminium electrodes, copper electrodes and copper electroplated aluminium electrodes.

Aluminium Electrode

An aluminium rod available in the department was used as EDM electrode. Therefore, it was important to ascertain the composition of the rod. So, EPMA analysis of the material was performed, that gave the composition of the tool as in **Table 4.1**. It is evident that it was actually an Aluminium – Cobalt alloy with Aluminium 95.58 % and Cobalt 2.27 % and traces of other elements. The microstructure was also taken and shown in **Figure 4.1**. Two distinct phases can bee seen. It confirms that it is an alloy, not pure aluminium. However, interpretation of the phases is not going to help our study and hence it is considered beyond the scope of this work.

Copper Electrode

A pure forged copper rod was purchased. Therefore no compositional analysis was made. The rod diameter is 12.60 mm as compared to the aluminium rod diameter of 10.38 mm. Therefore it was decided that the MRR will be compared on the basis of depth machined in unit length of time.

Copper Electroplated Aluminium Electrode

The same Aluminium-Co alloy rod as above was electroplated with copper. The process of electroplating is described in **section 3.1.2.1**. The diameter of the rod was 10.64 mm.

Work Piece: The work material was hardened mould and die steel, SKD 11. Its hardness was checked in the laboratory. The average measured hardness of the work material was 64 HRC.

5.2 FIRST PHASE OF INVESTIGATIONS

Screening experiments was performed with a total of 24 experiments. Each experiments runs was repeated thrice, thus give 24 experiments. The longest machining time is 4 hours and 4 minutes and the shortest machining time is 3 minutes and 53 seconds.

SCREENING EXPERIMENTS

a) Metal Removal Rate

The Pareto ANOVA presented in **Table 4.4** shows that metal removal rate (MRR) is mainly dependent on discharge current and discharge voltage; discharge current having a contribution 87 % and discharge voltage 6.2 %. This can be observed from the pie chart given in **Figure 4.4**. This is in agreement with Shamila *(2003)*, Kausalya *(2002)*, Chen and Mahdavian *(1999)*, Puertas and Luis *(2003)* and George et al. *(2004a)* that discharge current is one of important parameters in determining MRR. Flushing pressure has less significant effect and pulse on time has the least effect on MRR. It may also be seen from **Table 4.4** that higher discharge current and higher voltage favor high metal removal rate. Higher pulse on time and higher flushing pressure give positive effect to some extent on MRR, but not very significant.

The optimum conditions for maximum metal removal rate may be taken as discharge current, 10 A and discharge voltage 120 V. The other parameters may be chosen on the basis of other considerations as suggested by Sung Park *(1996)*. For example, to keep tool wear at minimum level with the maximum metal removal rate, pulse on time may be chosen at higher level, 180 μsec (**Table 4.6**). Flushing pressure has very insignificant effect on metal removal rate. Therefore, if set at low level pressure on the tool will be low and overcut will be slightly lower (**Table 4.7**). Therefore, it may choose as 1 kg/cm^2. The average MRR at this optimum combination of process variables is 21.1190 x 10^{-3} mm/min (this can be observed from the **Figure 4.2**), surface roughness is 8.770 μm, diameteral overcut is 0.26 mm and electrode wear ratio is 11.84 %

However the error variance is 22.2, that is too high. Therefore, it is concluded that the experiments shall be planned again with the levels of the control parameters at the higher side and further study be conducted.

b) Surface Roughness

From the Pareto ANOVA presented in **Table 4.5** it is evident that surface roughness is influenced mainly by the discharge current, discharge voltage, pulse on-time and the interaction of pulse on time and the flushing pressure. Discharge current contributes about 70 % to surface roughness, discharge voltage 13.5 % and pulse on time about 6 %; while interaction between pulse on time and flushing pressure contributes 6.7 %. This is clear from the pie chart given in **Figure 4.5**. This is in agreement with Chen and Mahdavian *(1999)*, Puertas and Luis *(2004)*, Lee and Li *(2001)*, Lee and Tai *(2003)*, Kausalya *(2002)* and Shamila *(2003)* that discharge current has greatest influence on surface quality of the machined workpiece. This is also in agreement with Chen and Mahdavian *(1999)* that discharge voltage is an important factor to achieve the desired surface quality.

Optimum values of all the control parameters having significant effect for minimum surface roughness (i.e. better surface finish) are to be set low level and the less significant factor, flushing pressure, if set at low level will give lower electrode wear ratio (**Table 4.6**) and smaller diameteral overcut (**Table 4.7**). So overall optimum parameter setting for good surface finish is discharge current 2A, discharge voltage 60 V, pulse on time 30μsec and flushing pressure 1 kg/cm^2. The minimum surface roughness under this combination of parameters is 1.450 μm (this can be observed from **Figure 4.3**), the electrode wear ratio under this condition is 18.75 % and the diameteral overcut is 0.14 mm and metal removal rate is 0.4288 x 10^{-3} mm/min.

Again, in this case error variance is 3.13. Therefore it was decided to design the experiment again setting the levels of the control parameters at low levels.

Optimum combination of control parameters for minimum electrode wear ratio is discharge current of 2 A, pulse on time of 180 μsec, flushing pressure of 1 kg/cm^2 and discharge voltage of 120 V. Optimum combination of control parameters for minimum diameteral overcut is discharge current of 2 A, pulse on time of 180 μsec, flushing pressure of 1 kg/cm^2 and discharge voltage of 120 V. But these cannot be target functions. Main target functions are metal removal rate (MRR) and surface roughness. Therefore the actual values of electrode wear ratio (EWR) and diameteral overcut are given for maximum metal removal rate (MRR) and minimum surface roughness.

5.3 SECOND PHASE OF INVESTIGATIONS

The study was divided into two parts:

1. **Electric Discharge Machining with Aluminium Electrode**

   a) Roughing conditions: Target function in this study was the metal removal rate

   b) Finishing conditions: Target function in this study was the surface roughness.

   Experiments were conducted to arrive at a best combination of control parameters for optimum target functions and then the results compared with those observed with a forged pure copper tool and the copper electroplated aluminium tool under similar settings of control parameters.

2. **Electric Discharge Machining with Copper Electroplated Aluminium Electrode**

   a) Roughing conditions: Target function in this study was the metal removal rate

   b) Finishing condition: Target function in this study was the surface roughness

   Experiments were conducted to arrive at a best combination of control parameters for optimum target functions and then the results compared with those observed with a forged pure copper tool under similar settings of control parameters.

Total of 96 experiments was performed in this second phase of investigations; 24 experiments for rough machining with aluminium electrodes, 24 experiments for finish machining with aluminium electrodes, 24 experiments for rough machining with copper electroplated aluminium electrodes and 24 experiments for finish machining with copper electroplated aluminium electrodes. The longest machining time with aluminium electrodes is 5 hours and 36 minutes and the shortest machining time with aluminium is 3 minutes and 34 seconds. The longest machining time with copper electroplated aluminium electrodes is 17 hours and 20 minutes and the shortest machining time with copper electroplated aluminium electrodes is 2 minutes and 15 seconds.

5.3.1 Machining with Aluminium Electrode

a) Roughing conditions

The planning of levels of different control parameters in different experimental runs for rough machining is given in **Table 4.8**. The results are analyzed in **Table 4.12.** From the Pareto ANOVA analysis it is seen that in the narrow range of parameter settings only pulse on time shows highly significant effect on metal removal rate, contributing about 95 % to the metal removal rate. This is clear from the pie chart given in **Figure 4.8**. This is in agreement with Shamila *(2003)*, Kausalya *(2002)*, George et al. *(2004a)* and Puertas et al. *(2004)* that pulse on time is one of important parameters affecting the metal removal rate (MRR). In this study discharge current, discharge voltage and flushing pressure seem to have less significant effect. This may be because of very narrow range chosen for these parameters. In the screening experiments the discharge current is a highly significant factor affecting the MRR, but in this roughing the pulse on time is highly significant factor affecting the MRR. It can be seen from **Figure 5.1**, **Figure 5.2** and **Figure 5.3** that when the difference between the high level and low levels of the factors setting is very small, the effect does not appear to be much significant. The optimum combination of control parameters for maximum metal removal rate are discharge current 9.5 A, pulse on time 180 μsec, flushing pressure 2.0 kg/cm^2 and discharge voltage 120 V.

The estimated error variance in this study is only 0.03. So the optimum parameters given by this analysis were considered reasonably good. Confirmatory tests were performed three times and average values of MRR, surface roughness, electrode wear ratio and diameteral overcut observed under these conditions are as follows:

Metal removal rate: 26.0931 x 10^{-3} mm/min

Surface roughness: 8.2892 μm

Electrode wear ratio: 9.08 %

Diameteral overcut: 0.36 mm

This can be observed for MRR from **Figure 4.6.**

Under these conditions EDM was performed with forged copper electrode and results are compared in **Figure 4.10**, **4.11**, **4.12** and **4.13**. Then, the experiments were performed under the same conditions with copper electroplated aluminium electrodes. The results are compared in **Figure 4.10, 4.11**, **4.12** and **4.13**.

b) Finishing conditions

The planning of levels of different control parameters in different experimental runs for finish machining is given in **Table 4.10**. The results are analyzed in **Table 4.13**. From the Pareto ANOVA analysis it is seen that in the narrow range of parameter settings discharge voltage shows highly significant effect on surface roughness, contributing about 72 % to the surface roughness. This can be observed from pie chart given in **Figure 4.9**. This is in agreement with Chen and Mahdavian *(1999)* and Singh et al. *(1985)* that discharge voltage is influencing parameters in achieving desired surface finish. Discharge current and interaction between pulse on time and discharge voltage shows significant effect on surface roughness, contributing about 20 % and 5 %. In this study pulse on time and flushing pressure seem to show less significant effect. This may be because of very narrow range chosen for these parameters. In the screening experiments the discharge current and pulse on time were found to be highly significant factors affecting the surface roughness, but in this finish machining the discharge voltage is highly significant factor affecting the surface roughness. This can be explained by referring to **Figure 5.4**, **Figure 5.5** and

Figure 5.6 that when the difference between the high level and low levels of the factors setting is very small, the effect does not appear to be much significant. The optimum combination of control parameters for minimum surface roughness are discharge current 1.5 A, pulse on time 30 μsec, flushing pressure 1.0 kg/cm^2 and discharge voltage 60 V.

The estimated error variance in this study is only 0.23. So the optimum parameters given by this analysis were considered good. Confirmatory tests were performed three times and average values of surface roughness, MRR, electrode wear ratio and diameteral overcut observed under these conditions are as follows:

Surface roughness: 1.4559 μm (This can be observed in **Figure 4.7**)

Metal removal rate: 0.2556 x 10^{-3} mm/min

Electrode wear ratio: 28.12 %

Diameteral overcut: 0.15 mm

Under these conditions EDM was performed with forged copper electrode and results are compared in **Figure 4.14**, **4.15**, **4.16** and **4.17**. Then, the experiments were performed under the same conditions with copper electroplated aluminium electrodes. The results are compared in **Figure 4.14, 4.15, 4.16** and **4.17**.

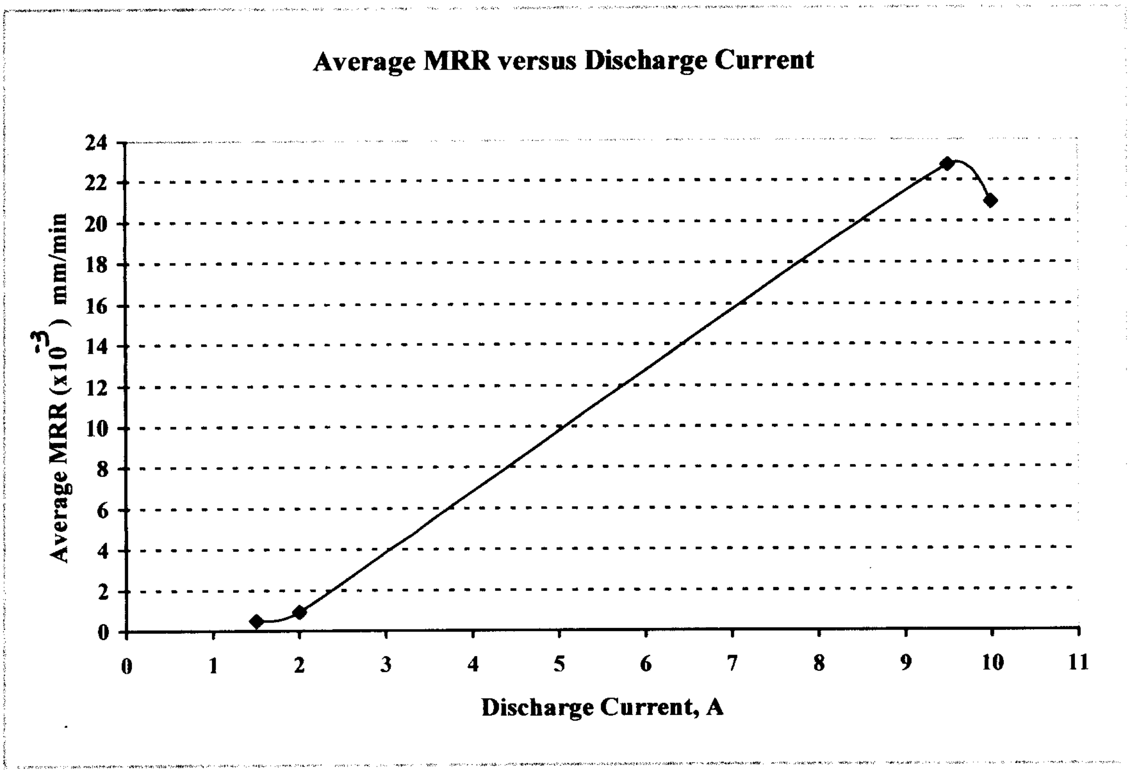

Figure 5.1 **Effect of Discharge Current on the Average Metal Removal Rate (MRR) with Aluminium Electrodes (From Table G1)**

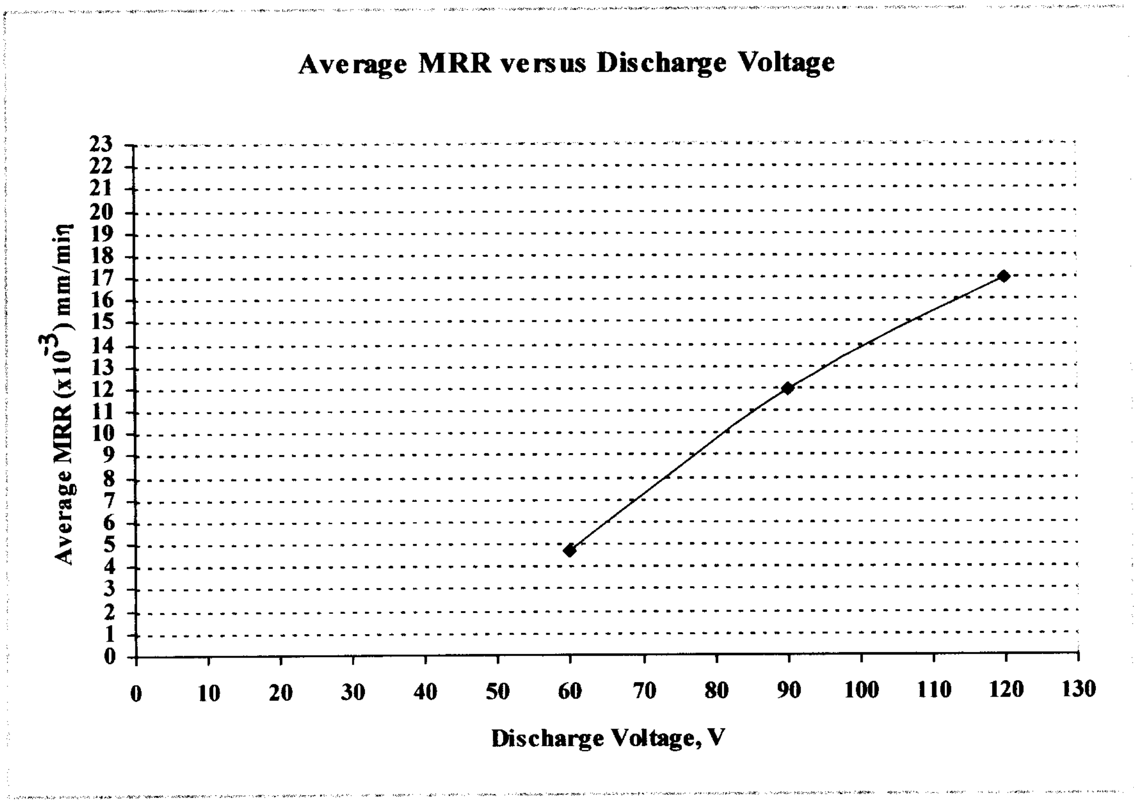

Figure 5.2 **Effect of Discharge Voltage on the Average Metal Removal Rate (MRR) with Aluminium Electrodes (From Table G2)**

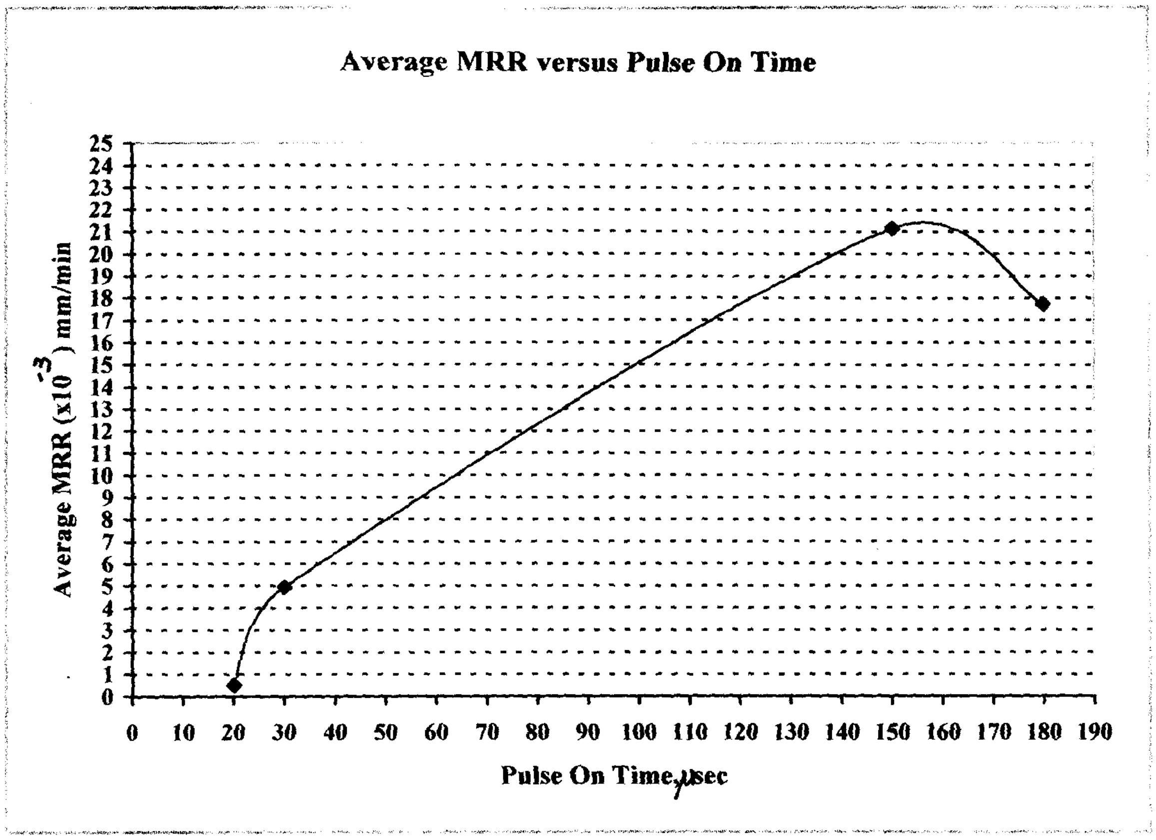

Figure 5.3 **Effect of Pulse On Time on the Average Metal Removal Rate (MRR) with Aluminium Electrodes (From Table G3)**

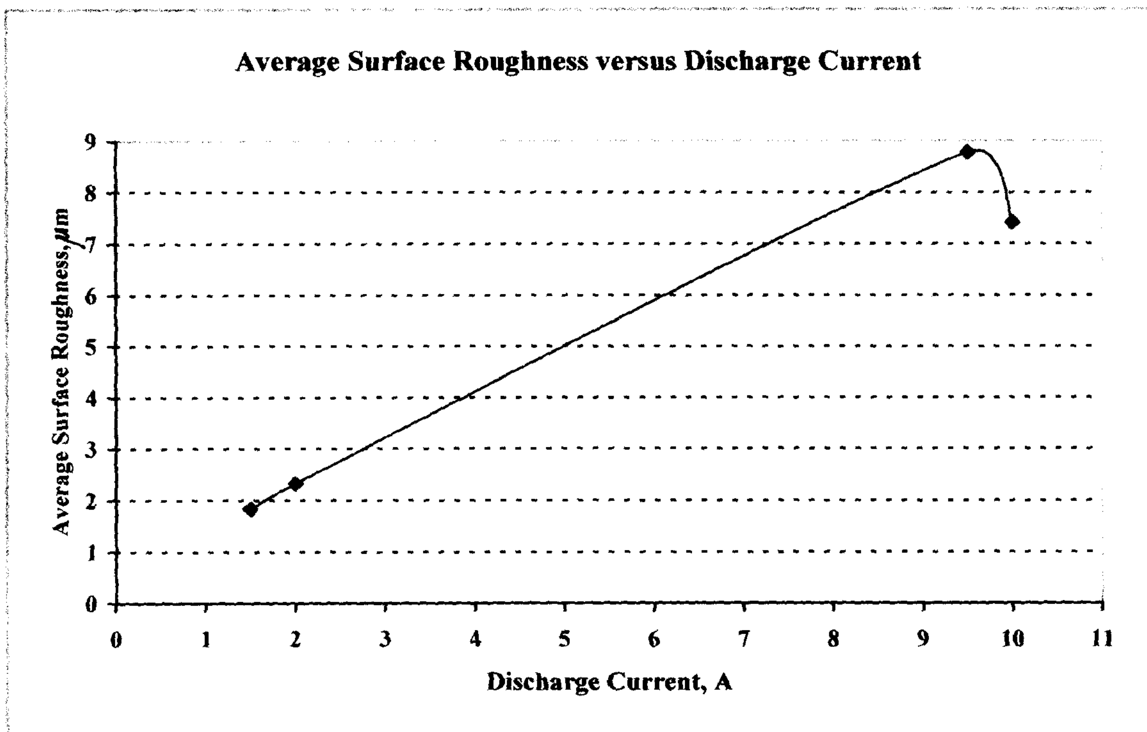

Figure 5.4 **Effect of Discharge Current on the Average Surface Roughness with Aluminium Electrodes (From Table G4)**

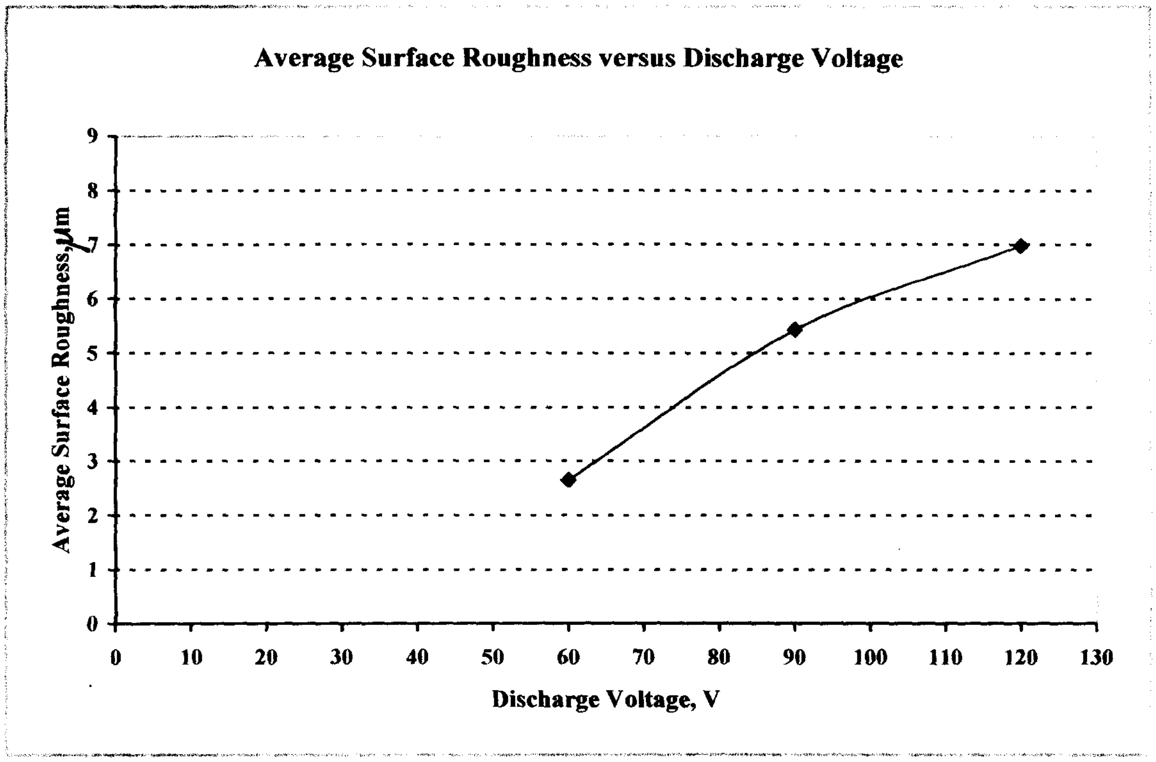

Figure 5.5 **Effect of Discharge Voltage on the Average Surface Roughness with Aluminium Electrodes (From Table G5)**

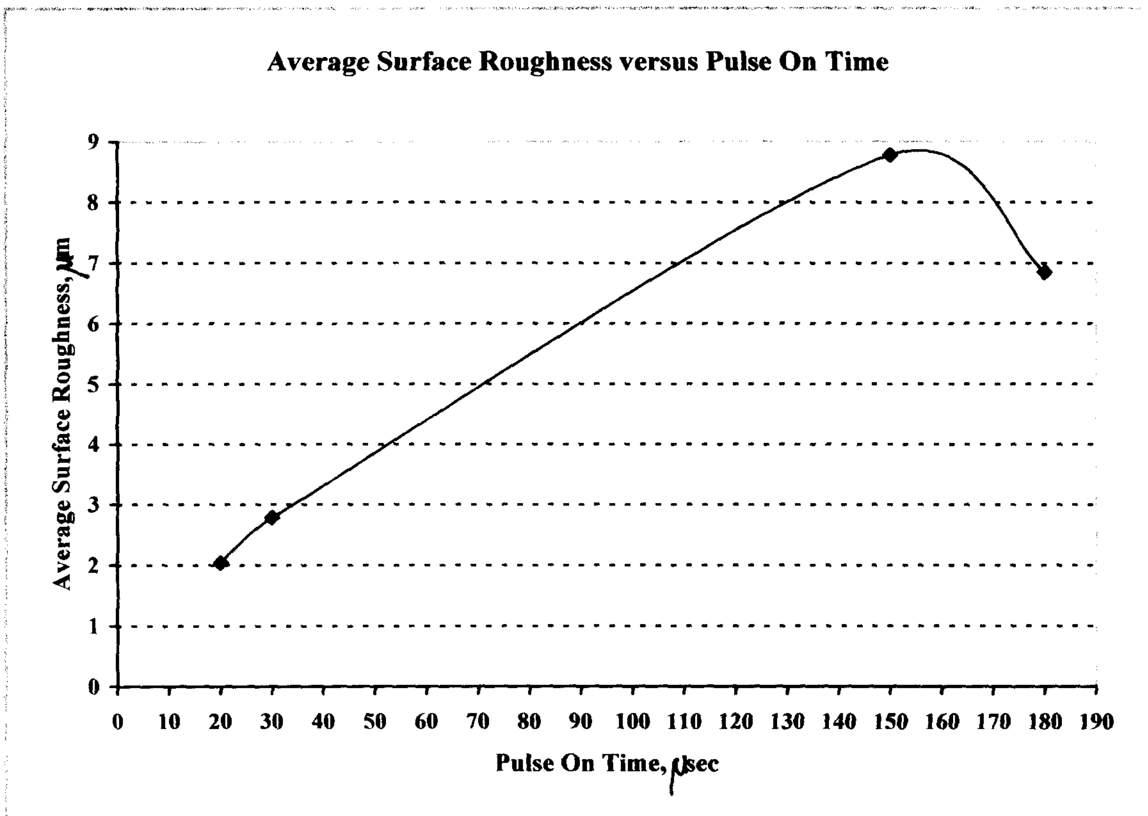

Figure 5.6 **Effect of Pulse On Time on the Average Surface Roughness with Aluminium Electrodes (From Table G6)**

5.3.1.1 Graphical Analysis

a) Roughing Conditions

Based on **Figure 4.10**, it can be observed that the copper electroplated aluminium electrode give the best metal removal rate (MRR) value of 49.6749 x 10^{-3} mm/min followed by the copper electrode which give the metal removal rate (MRR) value of 36.5651 x 10^{-3} mm/min. Aluminium electrode gives the lowest metal removal rate (MRR) value of 26.0931 x 10^{-3} mm/min. This observation agrees with the observations of Shanker Singh et al. *(2004)*, that the copper give slightly higher metal removal rate (MRR) than the aluminium electrode at high current of 9.5 A.

Based on **Figure 4.11**, it can be observed that all the three electrode results in poor machined surface at high currents, which is due to fact that higher metal removal rate (MRR) is accompanied by larger and deeper craters, resulting in a greater surface roughness *(Shanker Singh et al., 2004)*, *(Guu et al., 2004)* and *(Guu et al., 2003)*. Aluminium electrode (8.2892 μm) and copper electroplated aluminium electrode (8.4877 μm) gives better surface finish compare to copper electrodes (9.3588 μm). This observation agrees with the observations of Shanker Singh et al. *(2004)* ,that the aluminium electrodes gives lower surface roughness value than the copper at high current of 9.5 A.

Based on **Figure 4.12**, it is observed that copper electroplated aluminium electrodes gives the lowest electrode wear ratio (EWR) (1.3%) compares to copper (1.8%) and aluminium electrodes (9.08%). Aluminium electrode gives the highest electrode wear ratio (EWR). This observation agrees with the observations of Shanker Singh et al. *(2004)* that aluminium electrodes wear is more than the copper electrode at high current of 9.5 A. Electrode wear is dependent on the electrode materials and the energy of the discharge. Materials having good electrode wear characteristics are those that are also difficult to machine. These are materials that require large amount of energy to melt a given volume and usually have high melting temperature. The higher the melting temperature, the lower is the electrode wear (melting point of copper = 1356 K, aluminium = 933 K). The electrode wear rate is inversely proportional to melting point of the electrode *(Lee and Li, 2001)*. Aluminium has the lowest melting temperature and hence the highest electrode wear ratio. Due to the lower melting temperature of the aluminum electrode, its electrode wear ratio is highest and thus its material removal rate (MRR) is lowest, but the surface finish of the machined workpiece surface produced is the best among the three electrodes.

Based on **Figure 4.13**, it can be observed that, the copper electroplated aluminium electrodes produces high diameteral overcut (0.44 mm) compare to copper (0.363 mm) and aluminium electrodes (0.36 mm). Copper electrodes diameteral overcut is slightly higher than the aluminium electrodes, thus this observation agrees with observations of Shanker Singh et al. *(2004)* at high current of 9.5 A. The copper electroplated aluminium electrode results in high overcut due to its high dispersing effects.

Copper electroplated aluminium comparatively better choice of electrode material in rough machining even though the diameteral overcut is high, as it gives high metal removal rate (MRR), low electrode wear ratio (EWR) and reasonable surface roughness. Diameteral overcut is not important in rough machining because finally the dimensions will be adjusted in finish cutting.

b) Finishing Conditions

Based on **Figure 4.14**, it can be observed that the aluminium electrode give the best metal removal rate (MRR) of 0.2556 x 10^{-3} mm/min. There is a very small different in metal removal rate (MRR) between the copper *(0.0909 x 10^{-3} mm/min)* and copper electroplated aluminium (0.1003 x 10^{-3} mm/min) electrodes and therefore can be neglected.

Based on **Figure 4.15**, it can be seen that aluminium electrodes give the best surface finish (1.4559 μm) compare to copper (2.1216 μm) and copper electroplated aluminium (2.0031 μm) electrode. There is only a small difference in surface roughness value between the copper electrode and copper electroplated aluminium electrode.

Based on **Figure 4.16**, it is observed that copper electrodes give the lowest electrode wear ratio (EWR) (17.57%) compare to copper electroplated aluminium (19.81%) and aluminium (28.12%) electrodes. Aluminium electrode gives the highest electrode wear ratio (EWR). This observation agrees with the observations of Shanker Singh et al. *(2004)* that aluminum electrodes wear is more than the copper electrode. Electrode wear is dependent on the electrode materials and the energy of the discharge. Materials having good electrode wear characteristics are those that are also difficult to machine. These are materials that require large amount of energy to melt a given volume and usually have high melting temperature. The higher the melting temperature, the lower is the electrode wear (melting point of copper = 1356 K, aluminium = 933 K). The electrode wear rate is inversely proportional to melting point of the electrode *(Lee and Li, 2001)*. Aluminium has the lowest melting temperature and hence the highest electrode wear ratio. Due to the lower melting temperature of the aluminum electrode, its electrode wear ratio is highest.

Based on **Figure 4.17**, it can be seen that aluminium electrode gives the best diameteral accuracy (low diameteral overcut = 0.15 mm) followed by copper electrode (0.17 mm). Diameteral overcut for copper electroplated aluminium (0.23 mm) electrodes is the highest, thus gives the worst diameteral accuracy.

Among the three electrodes materials, aluminium electrodes is the better choice of electrode materials in finish machining as it give highest material removal rate (MRR), highest diameteral accuracy (lower diameteral overcut) even though the electrode wear ratio (EWR) is the highest. Next to aluminium electrode, copper electrode may be preferred as electrode material for finish machining. But this disagrees with Shanker Singh et al. *(2004)* conclusion that copper electrode gives the better surface finish than aluminium electrode. This is because they conducted the experiments in rough condition with high current values.

5.3.2 Machining with Copper Electroplated Aluminium Electrode

a) Roughing conditions

The planning of levels of different control parameters in different experimental runs for rough machining is given in **Table 4.18**. The results are analyzed in **Table 4.20**. From the Pareto ANOVA analysis it is seen that in the narrow range of parameter settings discharge voltage, pulse on time and interaction between discharge current and discharge voltage shows significant effect on metal removal rate, contributing about 76 % , 12 % and 7 % to the metal removal rate. This can be observed from pie chart given in **Figure 4.26**. This is in agreement with Chen and Mahdavian *(1999)* and Singh et al. *(1985)* that discharge voltage is influencing parameters in metal removal rate (MRR). In this study discharge current and flushing pressure seem to have less significant effect. This may be because of very narrow range chosen for these parameters. This is confirmed from **Figures 5.7** through **5.9**. However, from these experiments the optimum combination of control parameters for maximum metal removal rate are discharge current 9.5 A, pulse on time 180 μsec, flushing pressure 2.0 kg/cm^2 and discharge voltage 120 V.

The estimated error variance in this study is only 0.05. So the optimum parameters given by this analysis were considered reasonably good. Confirmatory tests were performed three times and average values of MRR, surface roughness, electrode wear ratio and diameteral overcut observed under these conditions are as follows:

Metal removal rate: 48.3785 x 10^{-3} mm/min (This can be observed in **Figure 4.24**)

Surface roughness: 7.4028 μm

Electrode wear ratio: 1.33 %

Diameteral overcut: 0.47 mm

Under these conditions EDM was performed with copper electroplated aluminium electrode and results compared in **Figure 4.28**, **4.29**, **4.30** and **4.31**.

b) Finishing conditions

The planning of levels of different control parameters in different experimental runs for finish machining is given in **Table 4.19**. The results are analyzed in **Table 4.21**. From the Pareto ANOVA analysis it is seen that in the narrow range of parameter settings discharge current, discharge voltage and pulse on time shows significant effect on surface roughness, contributing about 50 %, 33 % and 15 % to the surface roughness. This is clear from the pie chart given in **Figure 4.27**. This is in agreement with Lee and Tai *(2003)* and Puertas and Luis *(2004)*, Lee and Li *(2001)*, Kausalya *(2002)* and Shamila *(2003)*. This is also in agreement with Lee and Li *(2001)* that discharge voltage influencing parameters on surface finish. In this study flushing pressure seem to have less significant effect. These observations can be confirmed from the average surface roughness plot given in **Figures 5.10** through **5.12**. However, from these experiments the optimum combination of control parameters for minimum surface roughness are discharge current 1.5 A, pulse on time 20 μsec, flushing pressure 0.5 kg/cm^2 and discharge voltage 60 V.

The estimated error variance in this study is only 0.05. So the optimum parameters given by this analysis were considered good. Confirmatory tests were performed three times and average values of surface roughness, MRR, electrode wear ratio and diameteral overcut observed under these conditions are as follows:

Surface roughness: 1.7773 μm (This can be observed in **Figure 4.25**)

Metal removal rate: 0.0793 x 10^{-3} mm/min

Electrode wear ratio: 28.58 %

Diameteral overcut: 0.14 mm

Under these conditions confirmation tests EDM were performed with copper electroplated aluminium electrode and results are compared in **Figure 4.32**, **4.33**, **4.34** and **4.35**.

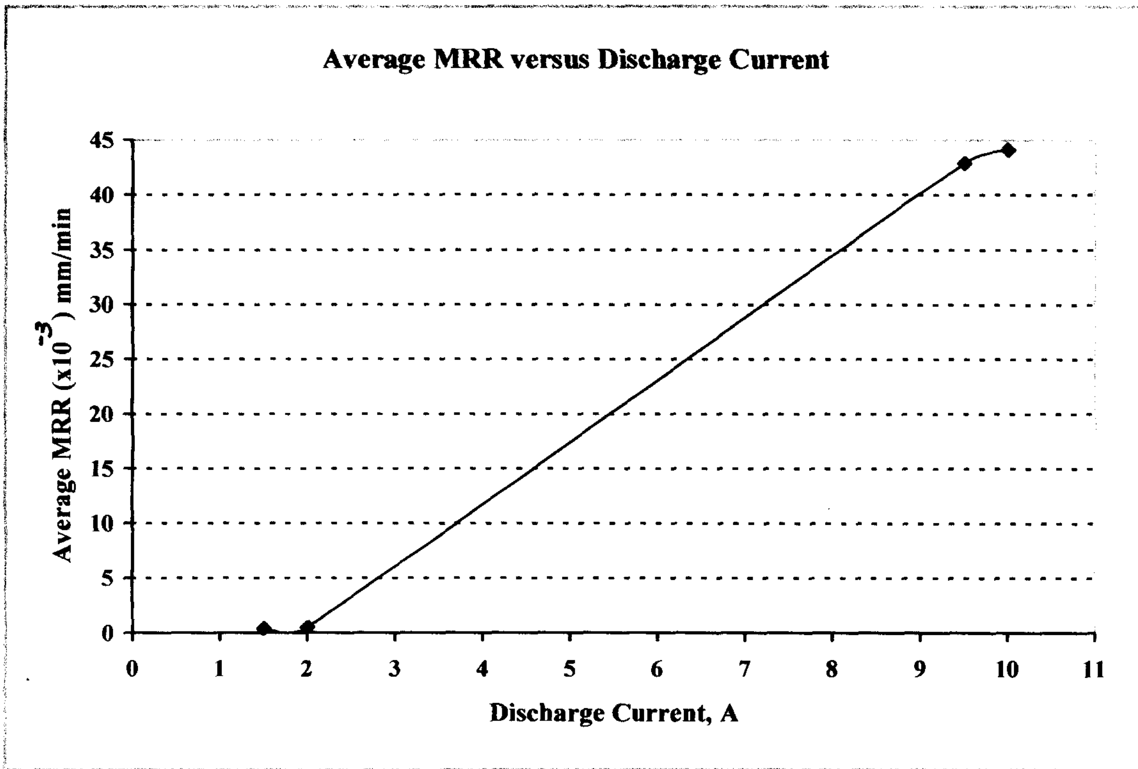

Figure 5.7 **Effect of Discharge Current on the Average Metal Removal Rate (MRR) with Copper Electroplated Aluminium Electrodes (From Table G7)**

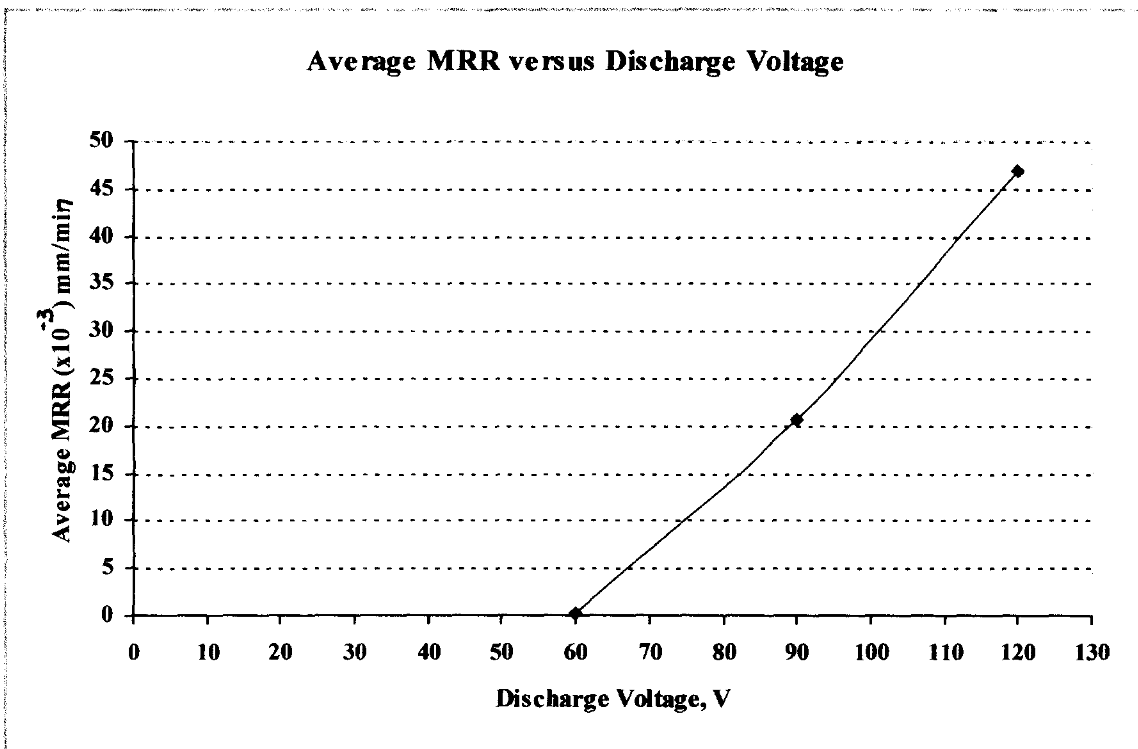

Figure 5.8 **Effect of Discharge Voltage on the Average Metal Removal Rate (MRR) with Copper Electroplated Aluminium Electrodes (From Table G8)**

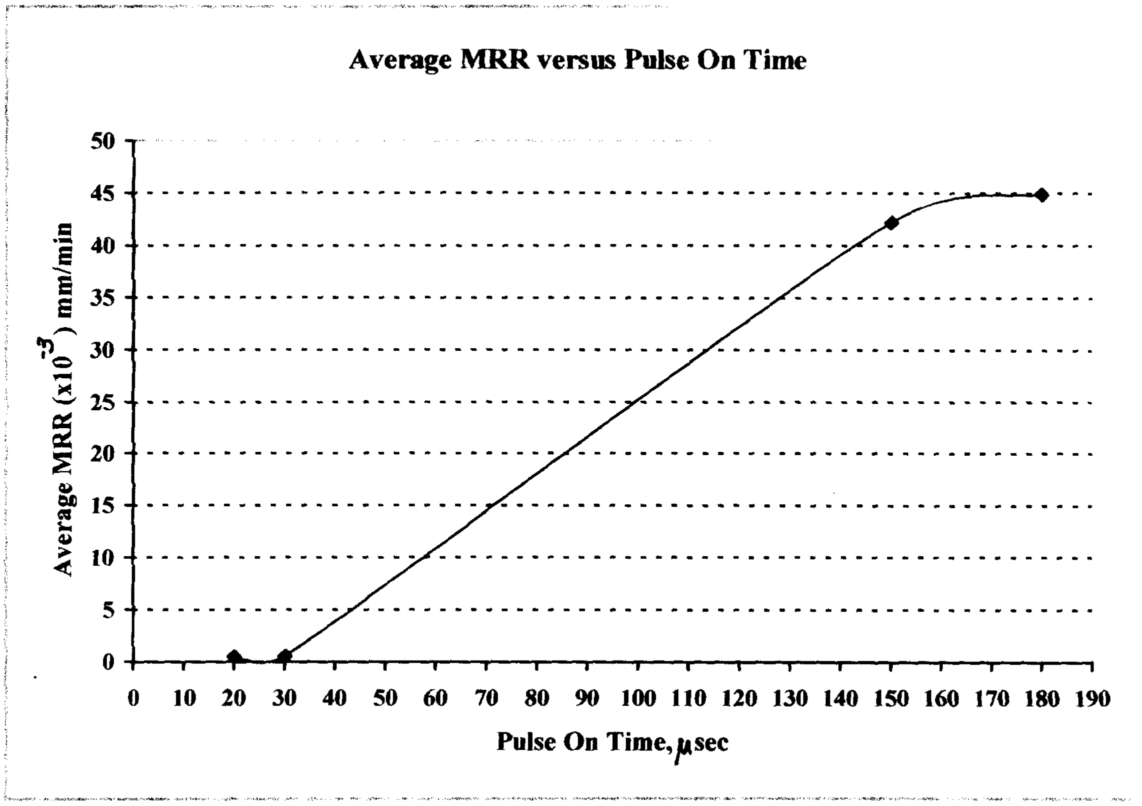

Figure 5.9 **Effect of Pulse On Time on the Average Metal Removal Rate (MRR) with Copper Electroplated Aluminium Electrodes (From Table G9)**

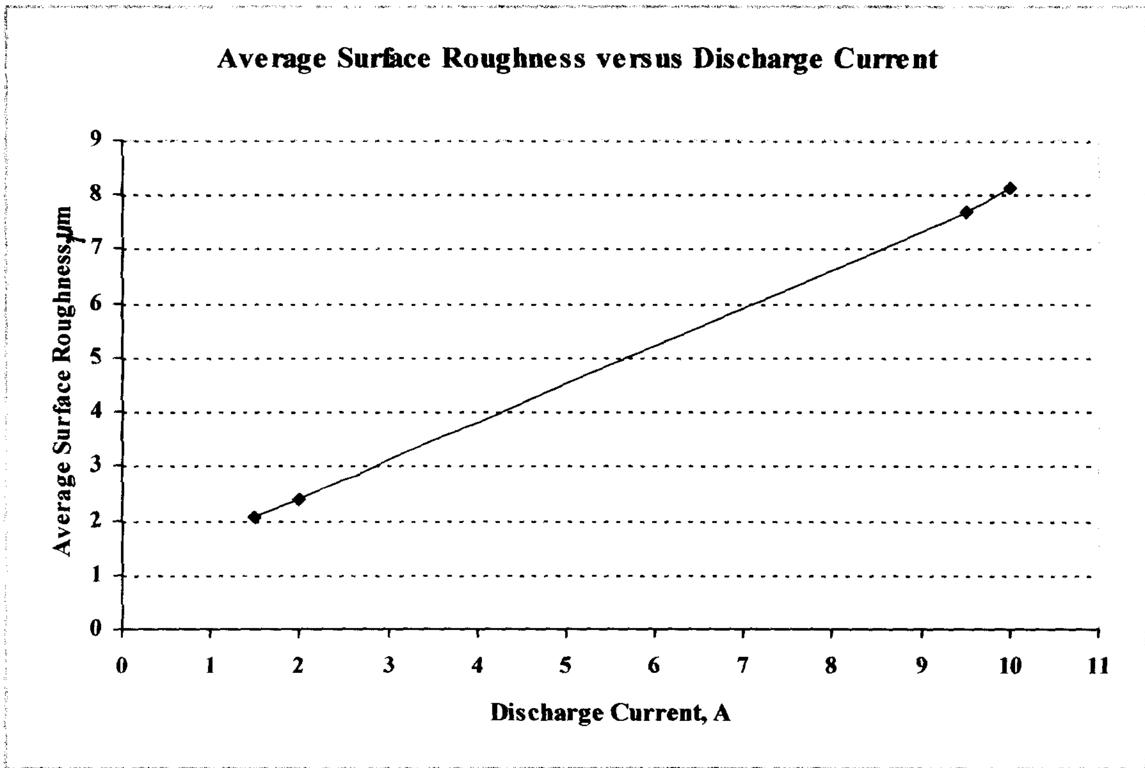

Figure 5.10 **Effect of Discharge Current on the Average Surface Roughness with Copper Electroplated Aluminium Electrodes (From Table G10)**

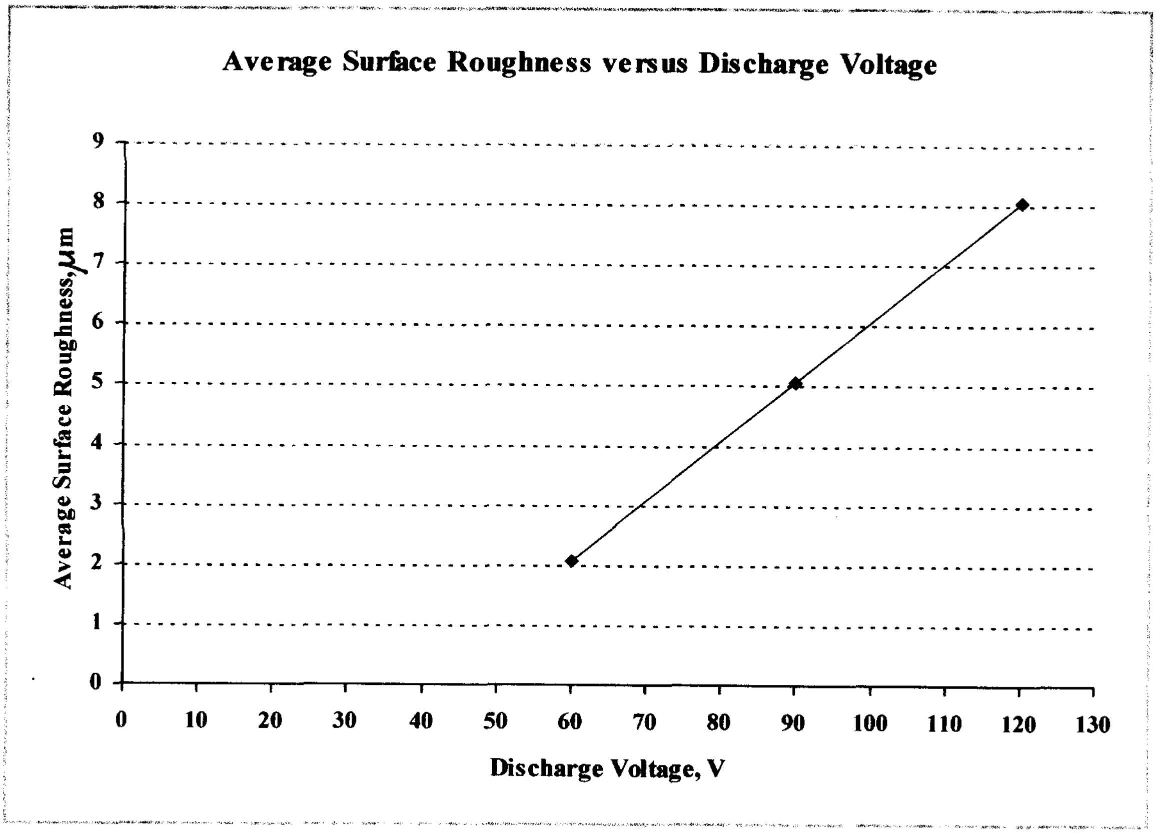

Figure 5.11 **Effect of Discharge Voltage on the Average Surface Roughness with Copper Electroplated Aluminium Electrodes (From Table G11)**

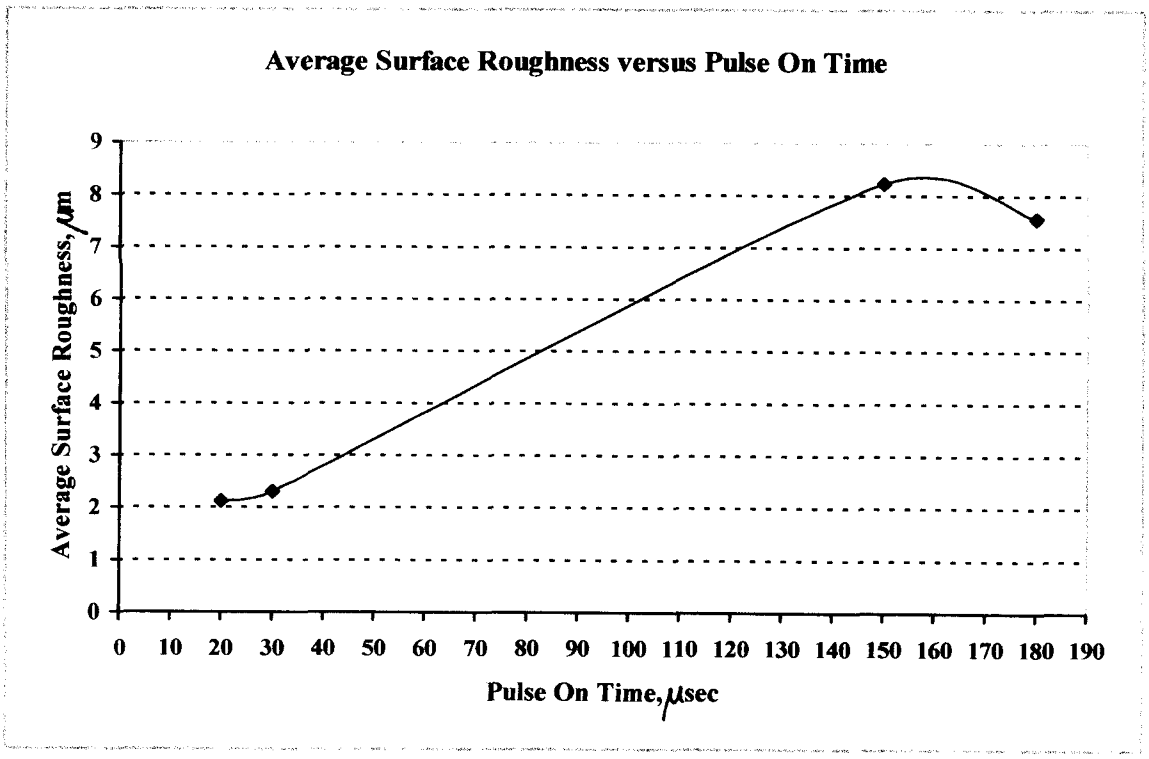

Figure 5.12 **Effect of Pulse On Time on the Average Surface Roughness with Copper Electroplated Aluminium Electrodes (From Table G12)**

5.3.2.1 Graphical Analysis

a) Roughing Conditions

Based on **Figure 4.28**, it can be observed that the copper electroplated aluminium electrode give the highest metal removal rate (MRR) (48.3785 x 10^{-3} mm/min) than the copper electrode (36.5651 x 10^{-3} mm/min).

Based on **Figure 4.29**, it can be observed that all the three electrode results in poor machined surface at high currents, which is due to fact that higher metal removal rate (MRR) is accompanied by larger and deeper craters, resulting in a greater surface roughness *(Shanker Singh et al., 2004)*, *(Guu et al., 2004)* and *(Guu et al., 2003)*. Copper electroplated aluminium electrode gives the better surface finish (7.4028 μm) than the copper electrode (9.3588 μm).

Based on **Figure 4.30**, it can be observed than the copper electroplated aluminium electrode give the lower electrode wear ratio (EWR) (1.327%) compare to copper electrode (1.8%).

Based on **Figure 4.31**, it can be observed that the copper electrode give lower diameteral overcut (0.363 mm) than the copper electroplated aluminum electrode (0.47 mm).

Among the two electrode material, copper electroplated aluminium electrode is the better choice of electrode for rough machining as it gives high metal removal rate (MRR), better surface finish and low electrode wear ratio (EWR). But because of high diameteral overcut, one should consider to reduce the electrode dimension so that the machine workpiece can be produce to the desired dimension.

b) Finishing Conditions

Based on **Figure 4.32**, it can be seen that copper electroplated aluminium give the higher metal removal rate (MRR) (0.0793 x 10^{-3} mm/min) compare to copper electrode (0.0429 x 10^{-3} mm/min).

Based on **Figure 4.33**, it can be observed that copper electroplated aluminium electrode give the better surface finish (1.7773 μm) compare to copper electrode (2.1016 μm).

Based on **Figure 4.34**, it can be observed that copper electroplated aluminium electrode give the lower electrode wear ratio (EWR) (28.58%) to copper electrode (29.61%).

Based on **Figure 4.35**, it can be seen that copper electroplated aluminium electrode the low diameteral overcut (0.14 mm) compare to copper electrode (0.21 mm).

Among this two electrode material, copper electroplated aluminium electrode is the best choice of electrode material for rough machining and finish machining.

5.3.3 SEM Analysis

a) Roughing Conditions

The surface topography presented in **Figure 4.18**, **4.19** and **4.20** reveals that the surface roughness is caused by an uneven fusing structure, globules of debris, shallow craters, pockmarks, void and cracks. Based on **Figure 4.36** and **4.37**, it is noticed that there is a larger and bigger craters, globules of debris, pockmarks and more cracks. This is due to higher discharge voltage, higher pulsed current and longer pulse on time. This is in agreement with the finding of Shanker Singh et al. *(2004)* that state that the workpiece surface after EDM is distinguished by the presence of the recast white layer, micro structural changes, surface roughness, residual stresses, micro-cracks, micro hardness and deposition of carbon contents.

Lee et al. *(1988)* reported that for tool steels, it has been shown that the top-most surface layer is an uneven, non-etchable layer, namely the recast layer. Lee et al. *(2004)* reported that this is a recast layer and is referred to as the white layer since it is very difficult to etch and because its appearance when observed through an optical microscope is white. This recast layer formed by the molten metal solidifying at an extremely high rate after the discharge process. Immediately beneath the 'white layer' there is an intermediate layer, a heat-affected zone, where the heat is not high enough to cause melting but is sufficiently high to induce micro-structural transformation in the material.

During each electrical discharge, intense heat is generated, causing local melting or even evaporation of the workpiece material. With each discharge, a crater is formed on the workpiece and a smaller crater is formed on the tool electrode. Of the molten material produced by the discharge, only 15% or less is carried away by the dielectric *(Lim et al., 1991)*. The remaining melt re-solidifies to form an undulating terrain. After magnification, the surface is observed to be observed to be covered with overlapping craters, globules of debris and pockmarks or 'chimneys', formed by entrapped gases escaping from the re-deposited material *(Rebelo et al., 1998)* and *(Lee and Li, 2003)*. This is confirmed from **Figure 4.18**, **4.19**, **4.20**, **4.36** and **4.37**.

Crack formation is caused by the stress induced by the EDM process. When the degree of induced stress exceeds the maximum tensile strength of the material, cracking will occur *(Lee and Tai, 2003)*. This is because that cracks and integrity of the machined surface are directly related to material removal rate mechanism *(Lee et al., 1990)*. The formation of the craters in EDMed surfaces is due to sparks that form at the conductive phase generating melting or possible evaporation. Larger crater sizes result in a rough machining. Surface roughness during EDM is a result of workpiece erosion which results in the formation of spark-induced. Larger material removal rate results in more and larger craters, thus leading to a rougher surface *(Lee et al., 1990)*, *(Lee and Li, 2001)*, *(Singh, 1985)* and *(Mamalis et al., 1987)*. The cracks can be clearly seen in **Figure 4.18** to **4.20**

b) Finishing Conditions

Based on **Figure 4.21**, **4.22**, **4.23**, **4.38** and **4.39** it can be observed that the crater formed on the workpiece after EDM under finishing conditions is smaller and less compared to the crater formed on workpiece after EDM under rough conditions. This is in agreement with Erden and Bilgin *(1980)*, who reported that smaller craters form, results in good surface finish. Good surface finish can be obtained by setting the machine parameters at a low pulsed current and a small pulse on time duration. These trends agree with results reported by Lee et al. *(1988)* and Guu *(2004)*. The damaged layer and micro-cracks seem to disappear when the peak current and pulse duration were set at very low values *(Lee and Li, 2003)*.