CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 CONSTANT PARAMETERS

The following shows the constant parameters that have been used for the experiment.

3.1.1 Workpiece

The workpiece used for this experiment is tool steel (Designation: SKD 11). Average hardness of this material is 64 HRC. Calculated density for this material is 0.0767023 g/mm^3. This is a cold work tool steel. The workpiece is first machined to 100 mm length and 50 mm width. The wire-EDM is used to perform this machining. To make sure the surfaces are parallel to each other, surface grinder is used to even the surface and to maintain 20 mm thickness throughout the length. Two pieces of workpiece were used. The chemical composition of SKD 11 is given below in **Table 3.1** by weight.

Table 3.1 **Chemical Composition of SKD 11 (wt.%) ***

Element	C	Si	Mn	Ni	Cr	Mo	V	Fe
Wt.%	1.4/1.6	≤ 0.40	≤ 0.60	≤ 0.50	11.00	0.8	0.20	Balance

* (Based on information supplied by the supplier)

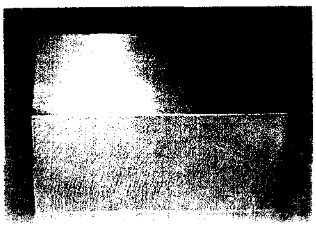


Figure 3.1 **Work Material SKD 11 Tool Steel (Hardness 64 HRC)**

3.1.2 Electrodes

Aluminium, copper and copper coated aluminium is used in this study. **Table 3.2** shows the detail of each electrode. The electrodes are cut to 40 mm length by using sawing machine. The electrodes were further machined by turning to make both ends parallel.

Table 3.2 **Detail of Each Electrode**

Materials	Copper	Aluminium	Copper electroplated aluminium
Shape	Rod	Rod	Rod
Diameter (mm)	12.60	10.38	10.64
Length (mm)	40	40	40

Figure 3.2 **Aluminium Electrodes**

Figure 3.3 **Copper Electrodes**

Figure 3.4 **Copper Electroplated Aluminium Electrodes**

Table 3.3 **Physical Properties of the Copper and Aluminium Materials (*)**

Physical property	**Copper**	**Aluminium**
Density [g/cm^3]	8.96	2.70
Electrical conductivity [$x10^5/\Omega$ cm]	5.88	3.65
Thermal conductivity [W/ (cm K)]	3.98	2.37
Melting point [K]	1356	933
Boiling point [K]	2868	2723

* *(Williams, 1970)*

3.1.2.1 Preparation of Electrode for EDM–Electroplating of Copper on Aluminium Electrode

The aluminium electrode was electroplated with copper. The copper electroplating procedure is given below:

a) **Degreasing process**

The aluminium electrode was polished by using UP-142 chemicals (alkaline base soap) to remove the grease. The chemicals concentration and the temperature was 60 g/l and 65 ^{0}C. This process was done for 2-3 minutes.

b) **Etching process**

After the degreasing process, the aluminium electrode was etched using sodium hydroxide (NaOH) as an etching solution. The concentration of the NaOH solution is 50 g/l. This process was done at room temperature for less than 1 minute.

c) **Bright dip process**

This process was done to give the aluminium a bright colour. The aluminium electrode was then dip into the nitric acid (HNO_3). The concentration of the HNO_3 acid solution was 30 g/l. This process was done at room temperature for less than 1 minute.

d) **Zincate (zinc coating) process**

The chemical used for this process was ZnO = 100 g/l, NaOH = 300 g/l, $KNaC_4H_4O_6.4H_2O$ = 10 g/l, $FeCl_3$ = 1 g/l, $NaNO_3$ = 2 g/l and HF = 3 ml/l. All this chemicals was diluted together. Then the aluminium electrode was dipped for 1-4 times at room temperature for 1 – 2 minutes. Zinc coating has to be done because copper cannot be coated on aluminium directly.

e) **Cyanide copper plating process (alkaline base copper)**

The chemical used was CuCN = 22.5 g/l, NaCN = 34 g/l and Na_2CO_3 = 15 g/l. In this electroplating process the temperature of the chemical was at 25-40 ^{0}C. The current density used was 1 ASD and the voltage used was 3 Volt. This electroplating process was done for less than 1 minute. Zinc easily dissolves in acidic solution, so we need to use the alkaline base copper solution. This is to cover the zinc before go to acidic copper solution.

f) **Copper plating (acidic)**

The chemical used for this plating process was $CuSO_4$ = 200g/l, H_2SO_4 = 55 g/l and brightener (UBAC No.1A) = 3 ml/l. This was the final electroplating process. The temperature of the electrolytic was set at 25 ^{0}C. The current density used was 3 ASD and the voltage used was 3.5 Volt. This process was done for less than 1 hour. The thickness of the coating was 40 micron.

3.1.3 Dielectric Used in EDM

Vitol 2 is used as the dielectric in this study. The properties of vitol-2 are as follows:

Specific Gravity : 0.754

Viscosity Index : 1.885

Inflammation Point : 100^{0}C

Total acid number : 0.01

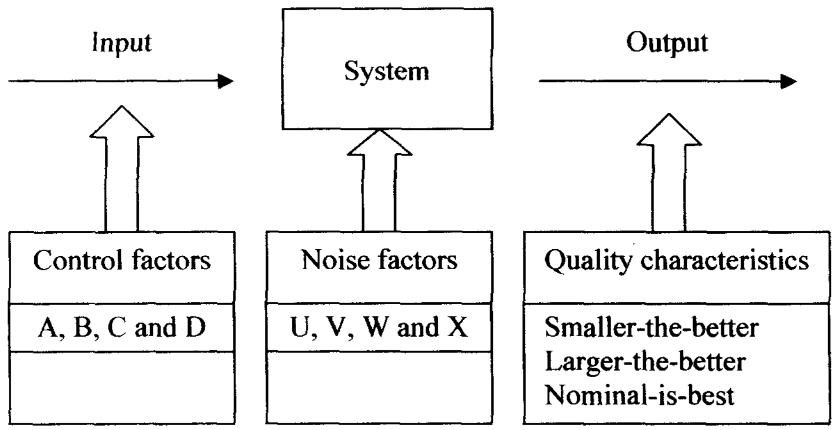
Appearance : colourless, transparent and odourless

3.2 VARIABLE PARAMETERS

In this experiment four factors; discharge current, discharge voltage, pulse on time and flushing pressure are varied at two different levels.

3.2.1 Factor Characteristics Relation Diagram

The factor characteristics diagram is prepared as suggested by Sung (1996). The diagram is given in figure below.



Control factors

A = discharge current, A

B = pulse on time, μsec

C = flushing pressure, kg/cm²

D = discharge voltage, V

Noise factors

U = temperature of the dielectric

V = concentration of the machine particle in the electrolyte

W = voltage fluctuation

X = electrode surface condition

Figure 3.5 **Factor Characteristics Relation Diagram**

3.2.2 Planning of Screening Experiments

Basic structure of Taguchi Parametric Robust Design given in **Table 1.2** is used for planning of experiments. The four factors that are varied at two different levels for screening experiments are shown in **Table 3.4**.

Table 3.4 **Levels of Input Variables for Screening Experiments**

Input variable	Levels	
	1 (-)*	2 (+)*
Discharge current (A)	2 A	10 A
Pulse on time (B)	30 μsec (009)	180 μsec (016)
Flushing pressure (C)	1 kg/cm^2	2 kg/cm^2
Discharge voltage (D)	60 V (00)	120 V (02)

* (-) sign represents low level of the factor

(+) sign represents high level of the factor

Actual experiments condition in each trial is given in **Table 3.5**.

Table 3.5 **Actual Experimental Conditions in Screening Experiments**

Experiment number	Discharge current (A), A	Pulse on time (B), μsec	Flushing pressure (C), kg/cm^2	Discharge voltage (D), V
1	2	30	1	60
2	2	30	2	120
3	2	180	1	120
4	2	180	2	60
5	10	30	1	120
6	10	30	2	60
7	10	180	1	60
8	10	180	2	120

3.2.3 Final Planning of Experiments

Basic structure of Taguchi Parametric Robust Design given in **Table 1.4** is used for planning the experimental condition. The four factors are varied at two different levels for different condition.

Finishing Condition

The levels of input variables used in finishing condition are shown in **Table 3.6**.

Table 3.6 **Levels of Input Variables for Finishing Condition**

Input variable	**Levels**	
	1 (-)	2 (+)
Discharge current (A)	1.5 A	2 A
Pulse on time (B)	20 μsec (008)	30 μsec (009)
Flushing pressure (C)	0.5 kg/cm^2	1.0 kg/cm^2
Discharge voltage (D)	60 V (00)	90 V (01)

* (-) sign represents low level of the factor

(+) sign represents high level of the factor

Actual experiments condition in each trial is given in **Table 3.7**.

Table 3.7 **Actual Experimental Conditions in Final Finish Machining Experiments**

Experiment number	Discharge current (A), A	Pulse on time (B), μsec	Flushing pressure (C), kg/cm^2	Discharge voltage (D), V
1	1.5	20	0.5	60
2	1.5	30	1.0	60
3	1.5	20	0.5	90
4	1.5	30	1.0	90
5	2.0	20	1.0	60
6	2.0	30	0.5	60
7	2.0	20	1.0	90
8	2.0	30	0.5	90

Roughing Condition

Levels of input variables used in roughing conditions are given in **Table 3.8**.

Table 3.8 **Levels of Input Variables for Roughing Condition**

Input variable	Levels	
	1 (-)	2 (+)
Discharge current (C)	9.5 A	10 A
Discharge voltage (V)	90 V (01)	120 V (02)
Pulse on time (O)	150 μsec (015)	180 μsec (016)
Flushing pressure (F)	1.5 kg/cm^2	2.0 kg/cm^2

* (-) sign represents low level of a factor

(+) sign represents high level of the factor

Actual experiments condition in each trial is given in **Table 3.9**.

Table 3.9 **Actual Experimental Conditions in Final Rough Machining Experiments**

Experiment number	Discharge current (A), A	Pulse on time (B), μsec	Flushing pressure (C), kg/cm^2	Discharge voltage (D), V
1	9.5	150	1.5	90
2	9.5	180	2.0	90
3	9.5	150	1.5	120
4	9.5	180	2.0	120
5	10.0	150	2.0	90
6	10.0	180	1.5	90
7	10.0	150	2.0	120
8	10.0	180	1.5	120

Other parameters are kept constant throughout the experiment as shown in **Table 3.10**.

Table 3.10 **Constant Parameters**

OFF Quiescent pulse duration	**MA Quiescen time**	**SV Servo voltage**	**PL Polarity**	**HP Pikaden pulse**	**PP Pulse control**	**C Capasitor**	**S Servo speed**
010	01	05	+	051	10	00	02

3.3 PERFORMANCE PARAMETERS

The following are the calculation of the parameters for this experiment:

a) Metal Removal Rate (MRR)

The metal removal rate is determined by the following equation:

$$\text{Volume of workpiece machined} = \frac{\text{Mass of workpiece machined}}{\text{Density of workpiece}}$$

Mass of workpiece machined

= weight of workpiece before machining – weight of workpiece after machining

$$\textbf{MRR} = \frac{\text{Volume of workpiece machined (mm}^3\text{)}}{\text{Machining time (min)}}$$

Because of the diameter of aluminium, copper and copper electroplated aluminium electrodes are not same; the MRR can be compared if represented as mm/min.

$$\textbf{MRR} = \frac{\dfrac{\text{Volume of workpiece machined (mm}^3\text{)}}{\text{Machining time (min)}}}{\text{Area of cross section of the electrode (mm}^2\text{)}} = \text{mm/min}$$

b) Electrode Wear Ratio

Electrode wear ratio is calculated by the following equation.

EWR

$$= \frac{\text{Weight of electrode before machining - Weight of electrode after machining}}{\text{Weight of workpiece before machining - Weight of workpiece after machining}} \text{ x } 100\,\%$$

c) Surface Roughness (Ra)

Surface roughness (Ra) was measured using perthometer at the bottom surface of the cavity. The measurement is averaged over several readings in different directions for reasonable accuracy.

d) Diameteral Overcut

Figure below shows the cavity that is measured. The diameter of the cavity is measured after each experiment. The measurement is averaged over several readings in different directions for reasonable accuracy. A circular cavity is formed according to the shape of the electrode. The depth of the cavity is 1 mm.

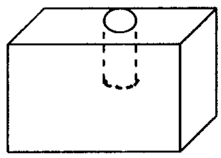


Figure 3.6 **Cavity formed in the workpiece**

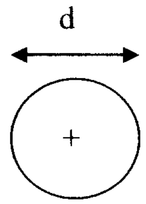


Figure 3.7 **Diameter of the cavity formed**

The difference between the electrode diameter and the cavity formed diameter is the diameteral overcut value. Diameteral overcut is how accurate a cavity can be formed with respect to the electrode.

3.4 EXPERIMENTAL SET-UP

The experiments were done on the Sodick Electrical Discharge Machine. Inspection on the final product was done using digital vernier, Mahr perthometer and digital precision balance.

3.5 EQUIPMENT USED

Throughout this work several equipments ranging from large equipment like EDM machine to small equipment like caliper were used. The brief descriptions of the equipment are as the following.

3.5.1 EDM Machine

Sodick A30R EDM electrical installation Mark-20 series is used for this work. Figure below shows the appearance of an EDM machine. Some specification about the machining geometry and operating instructions is attached in Appendix H.

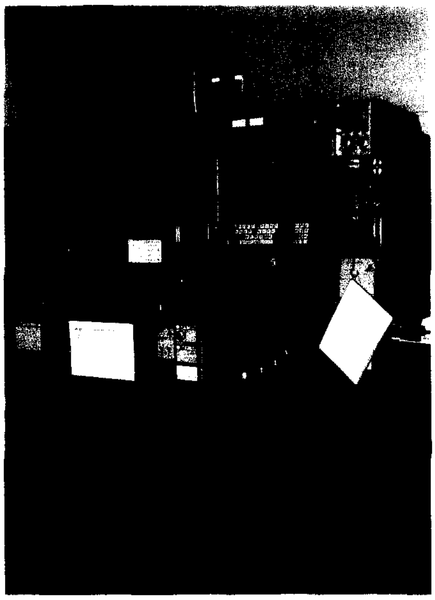


Figure 3.8 **EDM Die Sinking Machine A30R**

Basic component of the EDM:

a) Axis designation and direction.

   Determine the travel of each axis and is defined using [+] and [-]. The electrode holder can move in Y, Z and C direction. The table can move in X direction.

b) NC power supply unit "Mark 20".

   The power supply unit controls all the operations of the machine including its machining condition and movement. The description of the switches is shown in the Appendix H.

c) Remote control box

   On the box are collectively provided switches necessary to prepare for machining on the machine side.

d) Machining tank.

The machining tank consists of a machining bath, fluid level control section and fluid pressure control section.

e) Service tank.

Tank consists of feed pump, filter, filter pump, filter pressure gauge, R axis spindle coolant connecting coupler and R axis spindle coolant discharge port.

f) Electrode holder replacement

Electrode holder replacement is used when necessary.

g) Spindle rotation mechanism

This is to set the C axis rotation and angle indexing by input of the necessary codes by manual and programmed operation (see Appendix H).

Figure 3.9 **Filter System in EDM A30R**

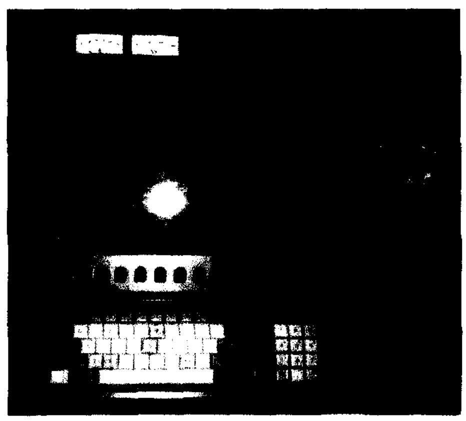


Figure 3.10 **NC Power Supply Unit**

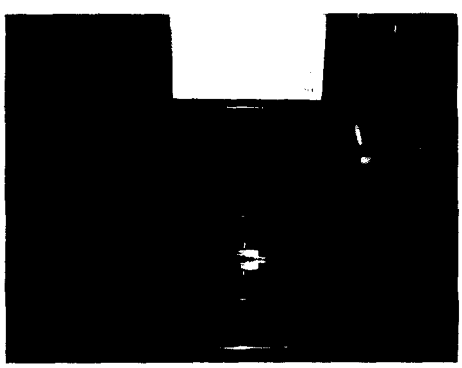


Figure 3.11 **Electrode Holder and Table**

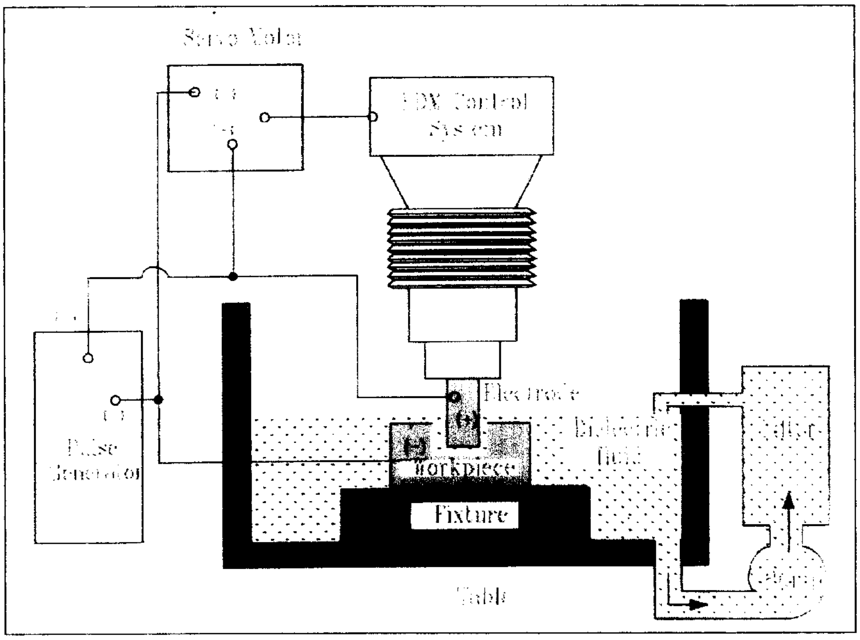


Figure 3.12 **Schematic Diagram of the EDM Process** *(Lin and Lin, 2002)*

3.5.2 Mahr Perthometer

Perthometer is a roughness measuring instrument. Measurements are taken using stylus method: a pick up is drawn straightly and at constant speed over the surface to be traced. The maximum tracing length is 17.5 mm. The maximum measuring range is 150 μm. The rugged housing and membrane keypad make the perthometer ideally suited for operation under severe conditions. The perthometer M1 is used to determine the most used parameters in accordance with ISO (Ra, Rz, Rmax and Pc) standard or JIS Japanese standard (Ra, Rz and Ry).

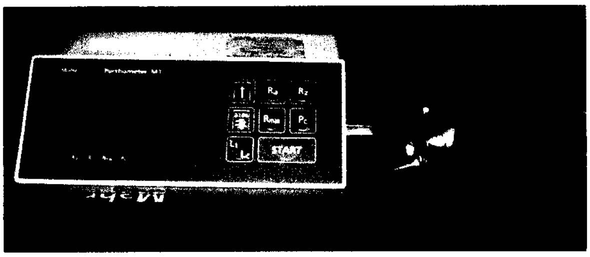


Figure 3.13 **Mahr Perthometer (Model: Mahr Perthometer M1)**

3.5.3 Microscope Optiphot

The image of microstructure of the workpiece and the electrodes is taken using this microscope. For best reveal the microstructure of the aluminium electrode, sodium hydroxide was used as etching solution.

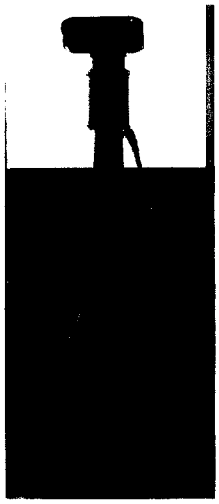


Figure 3.14 **Microscope Optiphot (Model: Nikon HFX-II)**

3.5.4 Scanning Electron Microscope (SEM)

Scanning electron microscope is used to take the image of the surface of the cavity. The Scanning Electron Microscope (SEM) is a microscope that uses electrons rather than light to form an image. There are many advantages to using the SEM instead of a light microscope. The SEM has a large depth of field, which allows a large amount of the sample to be in focus at one time. The SEM also produces images of high resolution, which means that closely spaced features can be examined at a high magnification. Preparation of the samples is relatively easy since most SEMs only require the sample to be conductive. The combination of higher magnification, larger depth of focus, greater resolution, and ease of sample observation makes the SEM one of the most heavily used instruments in research areas today.

(http://www.mse.iastate.edu/microscopy/whatsem.html)

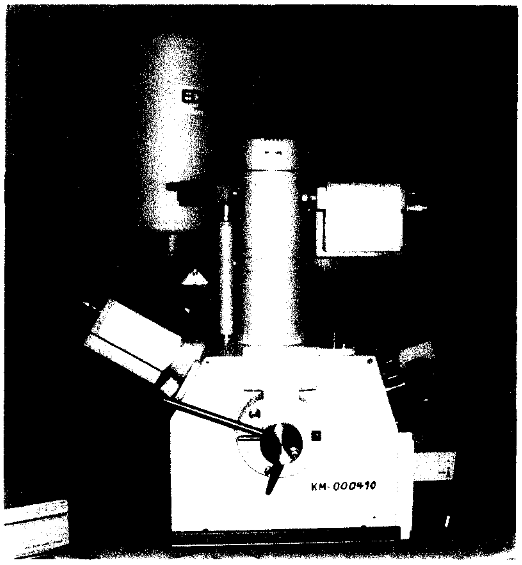


Figure 3.15 **Scanning Electron Microscope (Model: Philip XL40)**

3.5.5 Digital Vernier Caliper

A digital vernier caliper of least count 0.01 mm is used to take the dimension of the electrode and the workpiece.

3.5.6 Digital Precision Balance

A digital precision balance of precision 0.01 g is used to take the weight of the workpiece and the electrodes before and after the experiments.

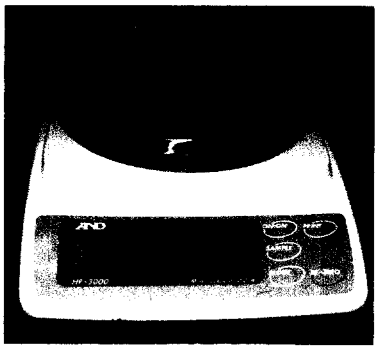


Figure 3.16 **Digital Precision Balance (Model: AND, HF-3000)**

3.6 EXPERIMENTAL PROCEDURE

3.6.1 Preparation of the Electrodes for Experimental Runs

The copper and aluminium electrodes were used in as received condition and electroplating copper on aluminium process was done as described in section 3.2.1.1

3.6.2 Screening Experiments

For each experimental run, the experimental conditions were set on the machine according to **Table 3.5** and the first experimental run was conducted as given below. Aluminium electrode was used in these screening experiments. The experiment was carried out by the following procedure:

a) The workpiece and the electrode was weighed using digital electronic balance.

b) Diameter of the electrode was measured using the digital vernier caliper.

c) Start machining.

- To start machining, the source switch is switch on.
- Power switch is pressed as soon as the CRT monitor displayed the initial screen.
- The electrode is mounted on the tool holder while the workpiece on the electromagnet table.
- As the tank was raised to a save level, the drain lever was closed.
- Pump switch was turned on. The tank is filled with dielectric until the word "float" is displayed on the screen.
- Go to edit mode and reload the file which is programmed before and the file are renamed as "THIL".
- Prepare for machining by input machining parameter into RUN mode.
- Set to appropriate flushing pressure.

- Press the enter button on the keyboard to start machining.
- Change the ON TIME, CURRENT and VOLTAGE according to the value needed.

d) After machining.

- The machining time is recorded.
- The dielectric fluid is let to subside.
- The workpiece and the electrode are unclamped and a tissue is used to wipe it.
- The workpiece and the electrode are weighted again using electronic balance.
- Diameter of the cavity is measured using digital vernier caliper.
- Surface roughness of the cavity is measured using Mahr perthometer.
- The whole process is repeated for other sets of conditions given in **Table 3.5**.

After analysed the results using Pareto ANOVA, it was observed that the error of variance is too high. So, the experiments were planned separately for roughing and finishing conditions as mentioned in section 3.2.2.

3.6.3 Experiments for Determining Optimum Machining Conditions in Finishing Conditions with Aluminium Electrodes

The experimental runs 1 through 8 were conducted for different combinations of input variables set according to **Table 3.7** using aluminium electrode. The procedure given in section 3.6.1 was repeated under every experimental condition. Each experimental run was repeated three times and data recorded in the format given in **Table 1.4**. The data was analysed using Pareto ANOVA and optimum combination of input variables for finish machining with aluminium electrode were determined. The S/N ratio was calculated based on smaller-the-better characteristics for surface roughness.

Then for these optimum conditions, machining was done with copper and copper-electroplated aluminium electrodes. The experimental run was replicated thrice and data recorded in the format given in **Table 1.4**. The results were compared.

3.6.4 Experiments for Determining Optimum Machining Conditions in Roughing Conditions with Aluminium Electrodes

Experiments were conducted for rough machining with aluminium electrodes according to the experimental conditions described in **Table 3.9**; each experimental runs being repeated three times. The data was recorded in the format of **Table 1.4** and analysed for optimum conditions for metal removal rate as in ANOVA Table. The S/N ratio was calculated based on larger-the-better characteristics for metal removal rate.

Under these optimum conditions, the experimental runs were conducted with copper and copper electroplated aluminium electrodes. The experimental run was replicated thrice. The results of metal removal rate are compared with the results with aluminium electrode.

3.6.5 Experiments for Determining Optimum Machining Conditions in Finishing Conditions with Copper Electroplated Aluminium Electrodes

The experimental runs 1 through 8 were conducted for different combinations of input variables set according to **Table 3.7** using copper electroplated aluminium electrode. The procedure given in section 3.6.1 was repeated under every experimental condition. Each experimental run was replicated thrice and data recorded in the format given in **Table 1.4**. The data was analysed using Pareto ANOVA and optimum combination of input variables for finish machining with copper electroplated electrode were determined. The S/N ratio was calculated based on smaller-the-better characteristics for surface roughness.

Then for these optimum conditions, machining was done with copper. The experimental run was replicated thrice and data recorded in the format given in **Table 1.4**. The results were compared.

3.6.6 Experiments for Determining Optimum Machining Conditions in Roughing Conditions with Copper Electroplated Aluminium Electrodes

Experiments were conducted for rough machining with copper electroplated aluminium electrodes according to the experimental conditions described in **Table 3.9**; each experimental runs being repeated three times. The data was recorded in the format of **Table 1.4** and analysed for optimum conditions for MRR as in ANOVA Table. The S/N ratio was calculated based on larger-the-better characteristics for metal removal rate.

Under these optimum conditions, the experimental runs were conducted with copper electrode. The experimental run was replicated thrice. The results of MRR are compared with the results with copper electroplated aluminium electrode.

3.7 MACHINING PROGRAM

The basic program for the experiment is shown below:

G80 Z - ;

G92 X0 Y0 Z0 ;

G00 M05 Z1.0 ;

G90 G54 G01 C340 Z-1.0 ;

M04 ;

M02 ;

Description of the program

G80 Z- ;	This brings the electrode into contact with the top surface of the workpiece.
G92 X0 Y0 Z0 ;	This sets the position of top surface as a"0" for the X, Y and Z actual position.
G00 M05 Z1.0 ;	This moves the electrode 1 mm above the surface of the workpiece.
G90 G54 G01 C340 Z-1.0 ;	This means machining to -1.0 mm level on the Z axis in the absolute coordinate system specified by G54. C340 calls the machining condition.
M04 ;	This returns to the machining start position.
M02 ;	This ends the machining process.