

OPTIMIZATION AND PARAMETRIC ANALYSIS OF TITANIUM GRADE 2 IN EDM USING GRAPHITE TOOL AS AN ELECTRODE

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in

Mechanical Engineering

by

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DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade "A" by NAAC

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APRIL 2021



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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **GADIRAJU CHARAN KRISHNA (Reg. No.37150060)** and **KARRI DUSHANTA VIDYA SAGAR (Reg.No.37150088)** who carried out the project entitled **“OPTIMIZATION AND PARAMETRIC ANALYSIS OF TITANIUM GRADE 2 IN EDM USING GRAPHITE TOOL AS AN ELECTRODE”** under our supervision from September 2020 to April 2021

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We, Gadiraju Charan Krishna (Reg. No.37150060) and Karri Dushanata Vidya Sagar (Reg.No.37150088) hereby declare that the Project Report entitled "Optimization And Parametric Analysis Of Titanium Grade 2 In EDM Using Graphite Tool As An Electrode" is a record of an original work done by us under the guidance of Mr. G. Britto Joseph, Me,(Ph.D.), at **SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY** is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.

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ABSTRACT

The current project is on modelling and parametric analysis of TITANIUM GR-2 on EDM using Graphite as an electrode. One of the most often used non-conventional machining processes is electric discharge machining. In EDM material removal happens by rapidly produced electric spark between tool and work piece. EDM is chosen to machine difficult-to-cut materials because of its high precision and performance. EDM can machine any electrically conductive material without regard to its strength or hardness. Current, pulse on-time, pulse off-time, gap voltage, feed, and flushing pressure are commonly used as machining parameters. Significant parameters include metal removal rate, tool wear rate, taper, and surface roughness. This process can be employed to make complicated profiles. Graphite electrode was machined in order to test in EDM on Titanium Grade 2 workpiece. Experimental procedure was planned using the Taguchi L_{16} orthogonal array based grey relational analysis. EDM oil was used as the dielectric fluid for the experiment. ANOVA has been used to calculate the response of output parameters to input parameters. SEM images were taken to analyze optimum parameter values derived using grey relational analysis.

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LIST OF ABBREVIATIONS

EDM	Electric Discharge machining
MRR	Material Removal Rate
TWR	Tool Wear Rate
R _A	Surface Roughness
GRG	Grey Relational Grade
S/N	Signal to noise Ratio
OA	Orthogonal Array
Gr	Grade
SR	Surface Roughness
T _{ON}	Pulse on Time
DOE	Design of Experiments
ANOVA	Analysis of variance
ECM	Electrochemical machining
CHM	Chemical machining
AJM	Abrasive Jet Machining
USM	Ultrasonic Machining
PAM	Plasma Arc Machining
LBM	Laser Beam Machining
CNC	Computer Numerical Control

CHAPTER 01

INTRODUCTION

1.1 HISTORY OF EDM

EDM machining techniques were discovered far back in the 1770s by an English Scientist Joseph Priestley. EDM machining was imprecise and prone to errors when it was first observed by Joseph Priestly. B. Lazarenko and N. Lazarenko, Soviet physicists, exploited the destructive effect of an electrical discharge in 1943 and created a safe method for machining materials that are electrical conductors.

With the technological and industrial growth, devolvment of hard to machine materials takes place, which have lots of applications in nuclear plants, missile technology, aerospace and space research equipment and other industries due to their high strength to weight ratio, heat resistance and hardness qualities. Figure 1.1, shows the gradual increase in strength of material with year wise development of material in aerospace industry.

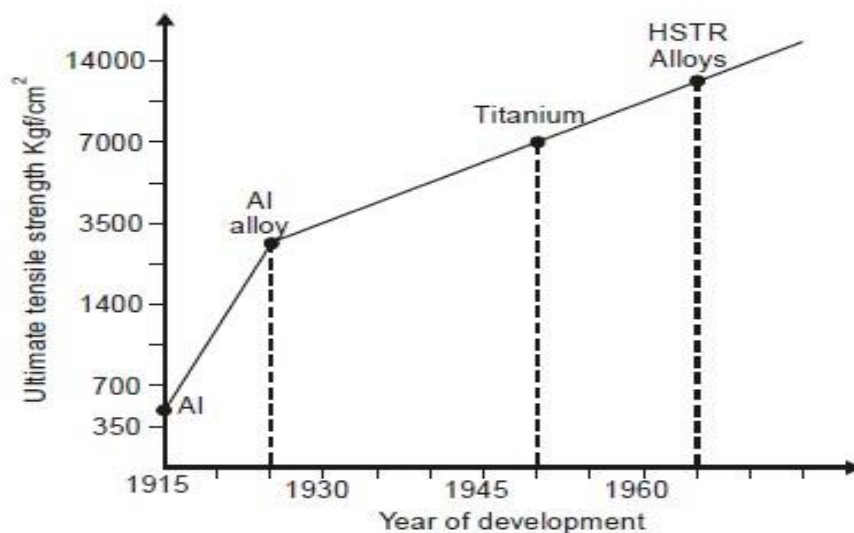


Fig. 1.1: Trend of increase of material strength

Conventional machining processes normally utilize the energy from electric motors, hydraulics and gravity, etc. and are based on the tool's direct contact with the workpiece. Hence machining these newer hard materials with conventional machining processes has become uneconomical and unviable. The non-conventional machining on the other hand uses energy from sources such as electrochemical reactions, high temperature plasma, high velocity jets and loose abrasives in a different carrier. So, the non-conventional machining processes are used to machine these newer hard materials and are capable of producing complex shapes, with good quality and surface finish. Except for volumetric material removal speeds, non-conventional processes currently have limitless process capabilities. As material removal rate increases, the cost effectiveness of nonconventional processes also increases, which encourage greater use of these processes

1.2 COMPARATIVE ANALYSIS OF NON-CONVENTIONAL MANUFACTURING PROCESSES

A comparative analysis of the different non-conventional manufacturing processes should be made so that a guide-line may be drawn to find the suitability of application of different machining processes.

A particular manufacturing process may be suitable under the given conditions and may not be equally efficient under other conditions. Therefore, a careful selection of the manufacturing process for a given manufacturing problem is essential. The analysis has been made from following point of view

1.2.1 Physical parameters involved in manufacturing processes

The physical parameters of non-conventional machining processes have a direct effect on the metal removal as well as on the energy consumed in different processes as given in Table-1.1. Figure 1.2 shows a comparison of the impact of metal removal rate on the electricity consumption by several nonconventional machining processes.

Processes that are above the mean power consumption line consume more energy than those that are below the average power consumption line. As a result, the capital cost of processes above the average line is high, while processes below the mean line have a low capital cost.

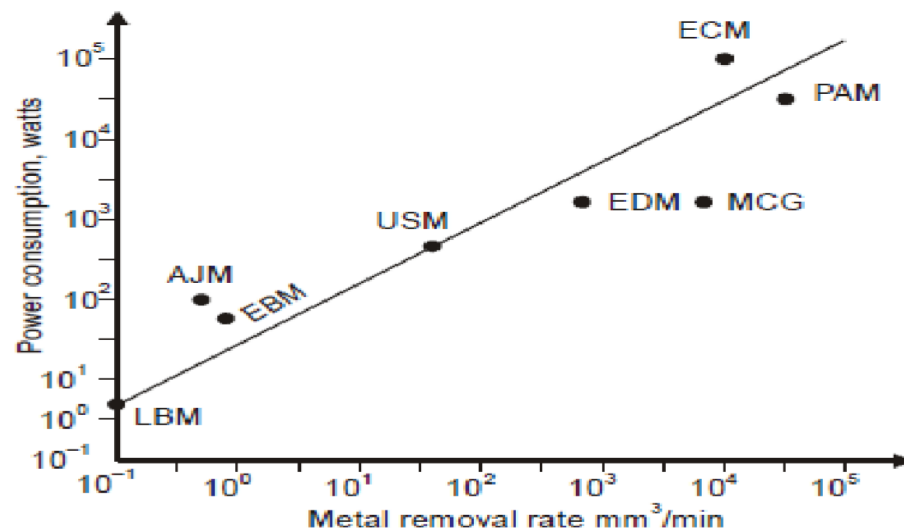


Fig: 1.2: Effect of metal removal rate on power consumption

From Figure 1.2, it can be seen that processes like EBM, ECM, AJM and USM lies above while processes like EDM, PAM, ECG and LBM lies below the mean power consumption line. Hence capital cost involved in the processes like EBM, ECM, AJM and USM is comparatively high as compared to the processes like EDM, PAM, ECG and LBM.

Table: 1.1: Physical parameters of the non-conventional processes

Parameters	USM	AJM	ECM	CHM	EDM	EBM	LBM	PAM
Potential (V)	220	220	10	-	45	150000	4500	100

Current (Amp)	12 (A.C.)	1.0	10000 (D.C.)	-	50 (Pulsed D.C)	0.001 (Pulsed D.C.)	2 (Average 200peak)	500 (D.C.)
Power (W)	2400	220	100000	-	2700	150	-	50000
Gap (mm)	0.25	0.75	0.20	-	0.025	100	150	7.5
Medium	Abrasive in Water	Abrasive in Gas	Electrolyte	Liquid Chemical	Liquid Dielectric	Vacuum	Air	Argon or Hydrogen

Laser beam machining is the only method that can micro drill holes with a slenderness ratio of less than 20, whereas USM, ECM, and EDM are the best options for drilling holes with a slenderness ratio of less than 20. EDM and ECM processes are capable of conducting pocketing operations. Surface contouring is best accomplished using the Electro Chemical Machining technique, but other methods, apart from EDM, have no use for this procedure.

1.2.2 Applicability of processes to various types of material

Tables 3 and 4 demonstrate the materials applications for the various machining methods.

From these tables it can be seen that ECM and EDM are unsuitable for the machining of electrically non-conducting materials, while mechanical methods used in materials that aren't electrically conductive can be machined using non-conventional machining. USM is well suited to machining refractory materials, while AJM is well suited to super alloys and refractory materials.

Table: 1.2: Shape application of non-conventional processes

Process	Holes				Through Cavities		Surfacing		Through Cutting	
	Precision small holes		Standard		Precision	Standard	Double contouring	Surface of Revolution	Shallow	Deep
	Dia <0.25	Dia >0.25	Length <20 mm	Length >20 mm						
USM	-	-	Good	Poor	Good	Good	Poor	-	Poor	-
AJM	-	-	Fair	Poor	Poor	Fair	-	-	Good	-
ECM	-	-	Good	Good	Fair	Good	Good	Fair	Good	Good
CHM	Fair	Fair	-	-	Poor	Fair	-	-	Good	-
EDM	-	-	Good	Fair	Good	Good	Fair	-	Poor	-
LBM	Good	Good	Fair	Poor	Poor	Poor	-	-	Good	Fair
PAM	-	-	Fair	-	Poor	Poor	-	Poor	Good	Good

1.2.3 Machining Characteristics

The following variables can be used to analyze the machining characteristics of various non-conventional machining methods, as shown in Table-5:

- Metal removal rate
- Tolerance maintained
- Surface finish obtained
- Depth of surface damage
- Power required for machining

Table: 1.3: Materials applications of the different machining methods for metal alloys

			Metal Alloys		
Process	Aluminum	Steel	Super Alloys	Titanium	Refractory Material
USM	poor	fair	poor	fair	good
AJM	fair	fair	good	fair	good
ECM	fair	good	good	fair	fair

CHM	good	-	fair	fair	poor
EDM	fair	good	good	good	good
EBM	fair	fair	fair	fair	good
LBM	fair	fair	fair	fair	poor
PAM	good	good	good	fair	poor

Table: 1.4: Materials applications of the different machining methods for non-Metals

	Non-Metals		
Process	Ceramics	Plastics	Glass
USM	good	fair	good
AJM	good	fair	good
ECM	-	-	-
CHM	poor	poor	fair
EDM	-	-	-
EBM	good	fair	fair
LBM	good	fair	fair
PAM	-	poor	-

Table: 1.5: Process capability of different non-conventional manufacturing processes

Process	MRR (mm³/min)	Tolerance (μ)	Surface CLA	Depth of Surface Damage	Power (Watts)
USM	300	7.5	0.2-0.5	25	2400
AJM	0.8	50	0.5-1.2	2.5	250
ECM	15000	50	0.1-2.5	5.0	100000
CHM	15	50	0.5-2.5	50	-

EDM	800	15	0.2-1.2	125	2700
EBM	1.6	25	0.5-2.5	250	150 (average) 2000 (peak)
LBM	0.1	25	0.5-1.2	125	2 (average)
PAM	75000	125	Rough	500	50000
Conventional Machining	50000	50	0.-5.0	25	3000

1.2.4 Economics of the processes

The economics of the various processes are analyzed with respect to following factors and shown in Table 1.6.

- a) Capital cost
- b) Tooling cost
- c) Consumed power cost
- d) Metal removal rate efficiency
- e) Tool wear.

Table 1.6 reveals that ECM has a very high capital cost as compared to traditional mechanical contour grinding and other non-conventional machining methods, whereas AJM and PAM have relatively low capital costs. The cost of EDM tooling is higher than that of other machining methods. The power consumption of the PAM and LBM processes is very low, while the power consumption of the ECM process is much higher. EBM and LBM have a much higher metal removal performance than other methods.

Table: 1.6: Economics of the various processes

Process	Capital cost	Tooling cost	Power consumption cost	Material removal rate efficiency	Tool wear
USM	L	L	L	H	M
AJM	VL	L	L	H	L
ECM	VH	M	M	L	VL
CHM	M	L	H (cost of Chemical)	M	VL
EDM	M	H	L	H	H
EBM	H	L	L	VH	VL
LBM	L	L	VL	VH	VL
PAM	VL	L	VL	VL	VL

To summarize, the suitability of any of the methods for implementation is based on a number of variables, all of which must be observed before using any non-conventional procedure.

The Electrical Discharge Machining (EDM) method is widely used for manufacturing axes, dies, and other precision parts since it is capable of machining geometrically complicated or hard material components consisting of heat-treated tool steels, composites, super alloys, ceramics, carbides, highly durable steels, and other precise parts.

The EDM process can be compared with the conventional machining processes like milling and turning as shown in Table 1.7.

Table: 1.7: EDM Compared to Conventional Machining

Characteristics	Conventional Machining (Milling/Drilling)	EDM
Contact between workpiece and cutting tool	Yes	No
Force	Yes	No
Tool/ Workpiece Rotation	Yes	Not Normally
Tool/ Workpiece Conductive	Not Required	Yes
Material Removal Method	Shear	Melt/ Vaporize

1.3 INTRODUCTION OF EDM

Electrical Discharge Machining (EDM) is a thermal erosion method that removes material by a series of short-duration, high-current-density electrical discharges between the workpiece and the tool. This is shown in Fig. below.

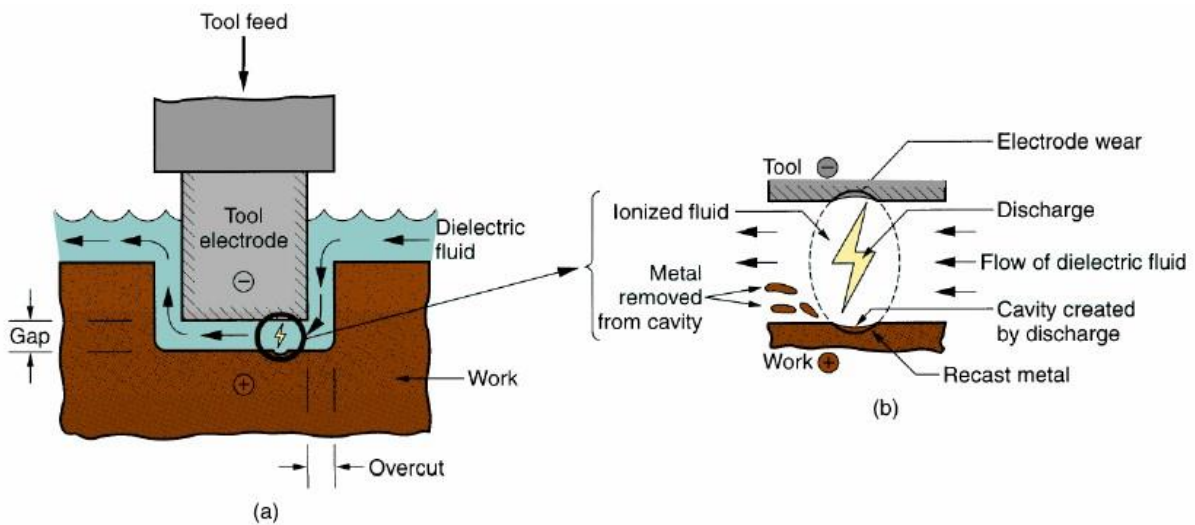


Fig: 1.3: EDM process depicting discharge and metal removal

EDM is mostly used to machine high-strength, temperature-resistant alloys and difficult-to-machine materials. In limited quantities or on a job-shop basis, EDM may be used to machine odd geometries. Since there is no physical contact between the

workpiece and the electrode in EDM, there are no physical forces between the workpiece and the electrode. However, in order to be machined by EDM, the work material must be good conductor of electricity.

1.4 PRINCIPLE OF EDM

In EDM, a potential difference between the instrument and the workpiece is used. Both the tool and the work material must be electrically conductors. EDM oil, kerosene, and deionized water are typical dielectric fluids used to immerse both the work piece and the tool. With the aid of Servo control, a constant gap between the tool and the workpiece is maintained, as shown in Figure 1.4.

The applied potential variation and the distance between the tool and the workpiece create an electric field. The work piece is normally anode, and the tool is cathode. If the electric field between the tool and the workpiece is created, the free electrons on the tool are subjected to electrostatic forces. If the work capacity or bonding energy of the electrons was tiny, they would be released from the tool. Such emissions of electrons are called as cold emission.

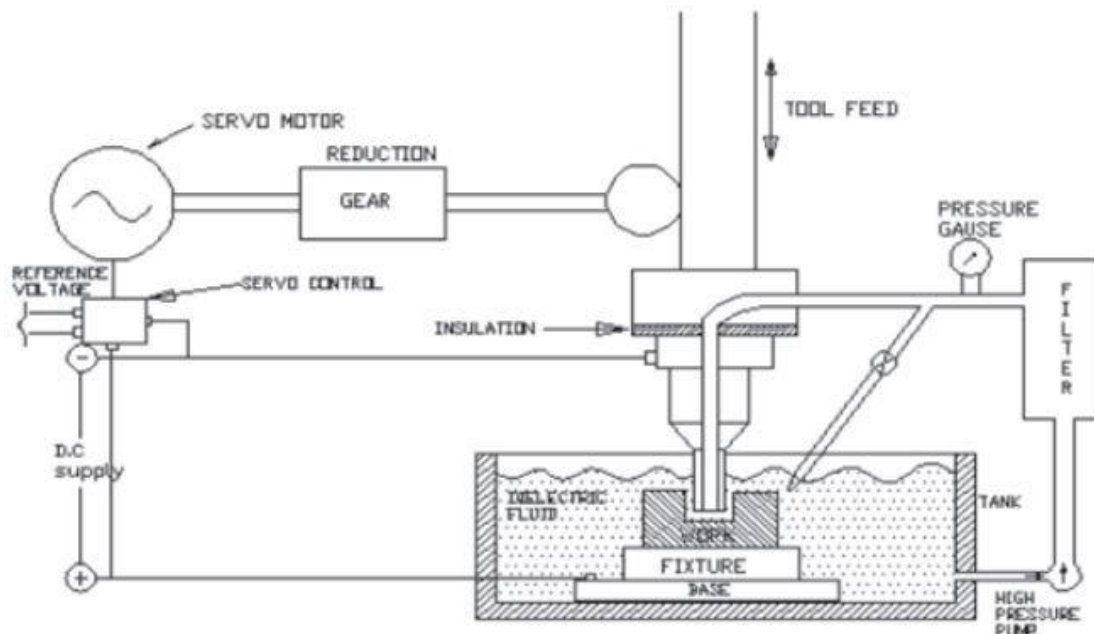


Fig: 1.4: Electric Discharge Machining set up

The dielectric medium then accelerates the "cold released" electrons towards the job. As they gain momentum and energy and begin moving towards the job, collisions

between electrons and dielectric molecules may occur. Such a collision will result in ionization of the dielectric molecule based on the work function or ionization energy of the dielectric molecule and the energy of the electron. Collisions between the electrons create more positive ions and electrons as they accelerate. The concentration of electrons and ions in the dielectric liquid between the tool and the job at the spark gap will increase as a result of this cyclic operation. The concentration would be so high that the matter existing in that channel could be characterized as “plasma”. Such a plasma channel will have a very low electrical resistance. As a consequence, a large number of electrons and ions can migrate from the instrument to the job at the same time. This is referred to as electron avalanche motion. The movement of electrons and ions can be interpreted as a spark, as shown in Figure 1.5. As a result, the spark's thermal energy dissipates the electrical energy.

The job and ions on the instrument are then barraged by high-speed electrons. The kinetic energy of the electrons and ions will be transformed into thermal energy or heat flux when they collided with the job and tool surfaces, respectively. The extreme immediate restricted temperature rise caused by such intense localized heat flux would exceed 10,000°C.

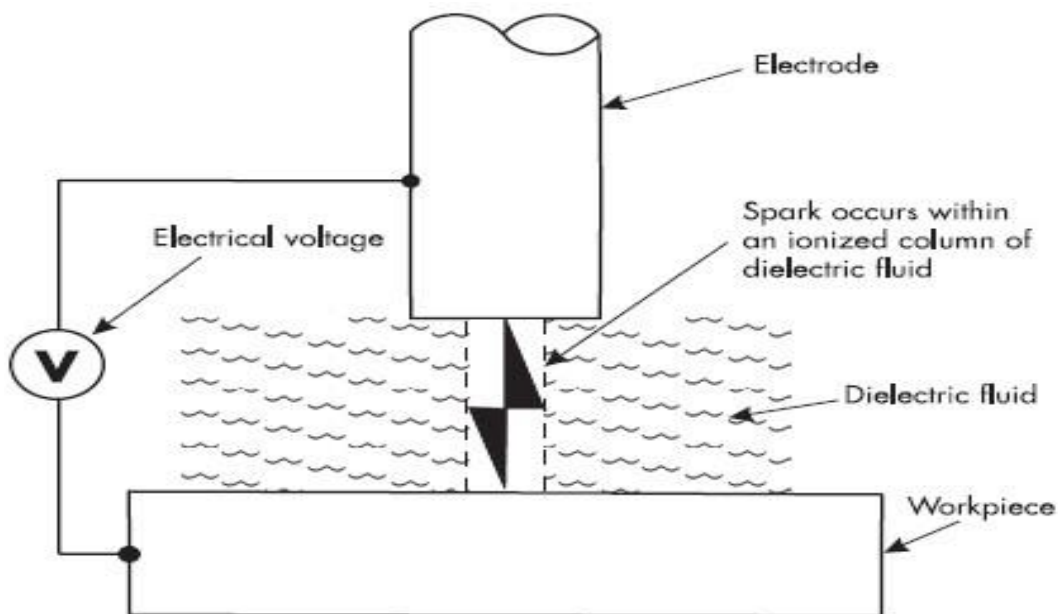


Fig: 1.5: Spark occurs within a column of ionized dielectric fluid

A small portion of the electrode and workpiece material is vaporized as a result of the localized extreme temperature increase. In the sparking distance between the electrode and the workpiece, the vaporized substance appears as a cloud. The theoretical gap is eliminated, the plasma channel is no longer maintained, and the flame is cut off, causing the vaporized cloud to solidify, as seen in Figure 1.6.

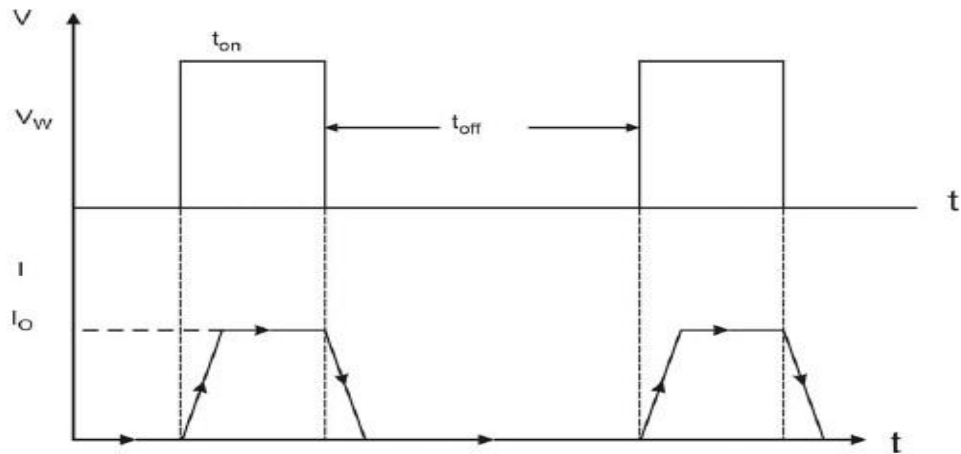


Fig: 1.6: Waveforms used in EDM

V_w -Working voltage, I_o - Maximum current

Each spark at that point creates an EDM chip or a minuscule empty circle of material comprised of the electrode and workpiece material. The EDM chip must be separated from the sparking area for effective machining. To clear this chip, dielectric fluid is pumped through the sparking gap. Figures 1.7, 1.8, and 1.9 depict the spark that generates the vapor cloud, the cloud in suspension, and the vaporized cloud cooling and shaping into an EDM chip.

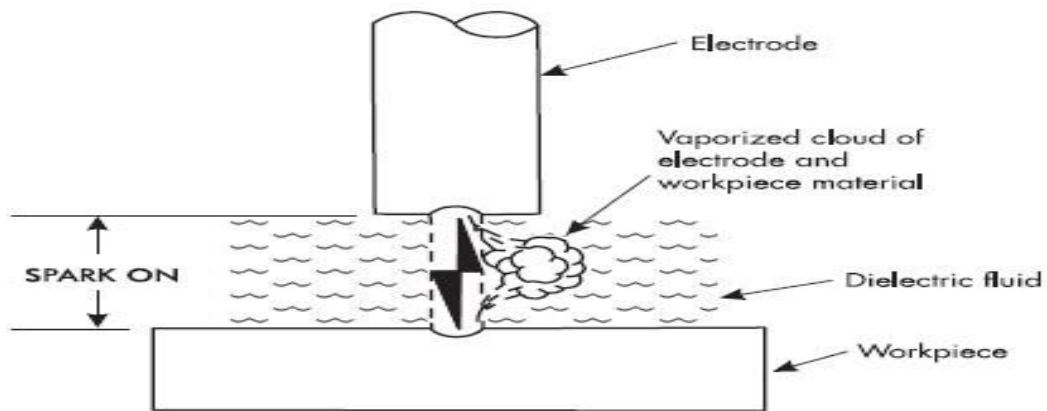


Fig. 1.7: Spark ON: Electrode and workpiece material vaporized

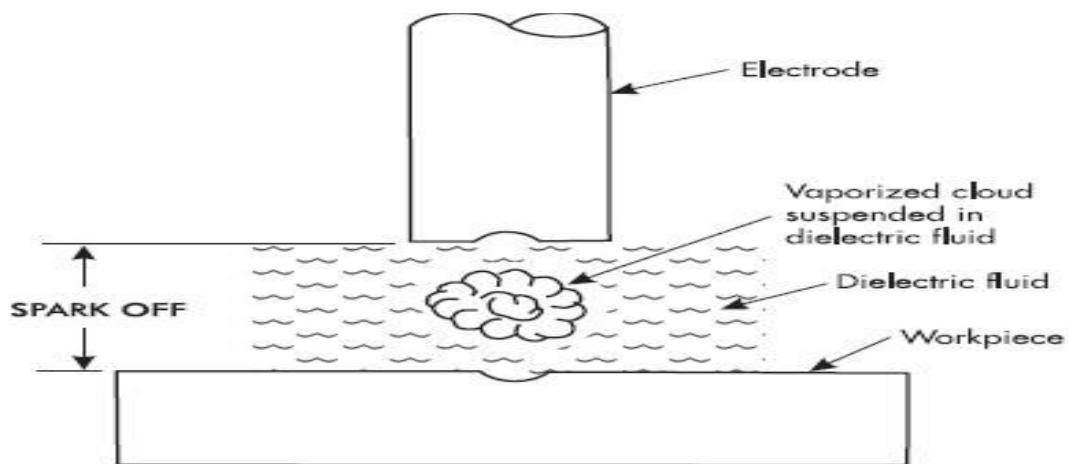


Fig. 1.8: Spark OFF: Vaporized cloud suspended in dielectric fluid

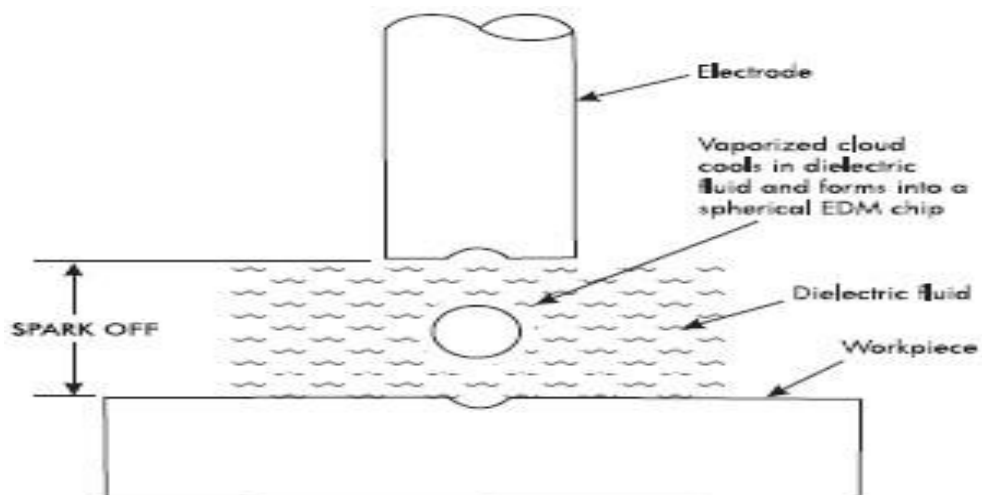


Fig. 1.9: Spark-OFF: Vaporized cloud solidifies to form EDM chip

As seen in Figure 1.6, the generator is used to apply voltage pulses between the tool and the workpiece in EDM. Since only sparking, not arcing, is needed in EDM, a constant voltage is not used. Arcing removes localized substance in a single step, while sparks are spread evenly across the tool surface, resulting in uniformly distributed material removal underneath the tool. When sparking occurs in EDM, the sparks pass from one electrode point to the next. Each spark occurs in between electrode's closest points and the workpiece, as seen in Figure 1.10 and 1.11.

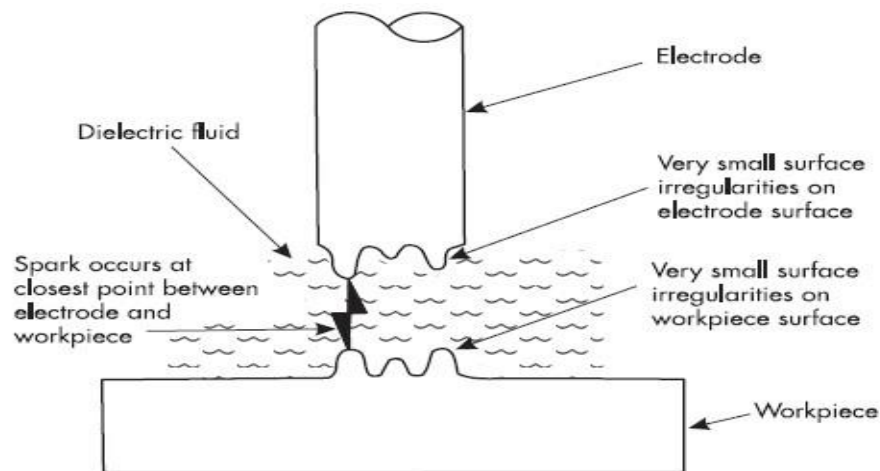


Fig: 1.10: Sparking occurs at closest points between electrode & workpiece

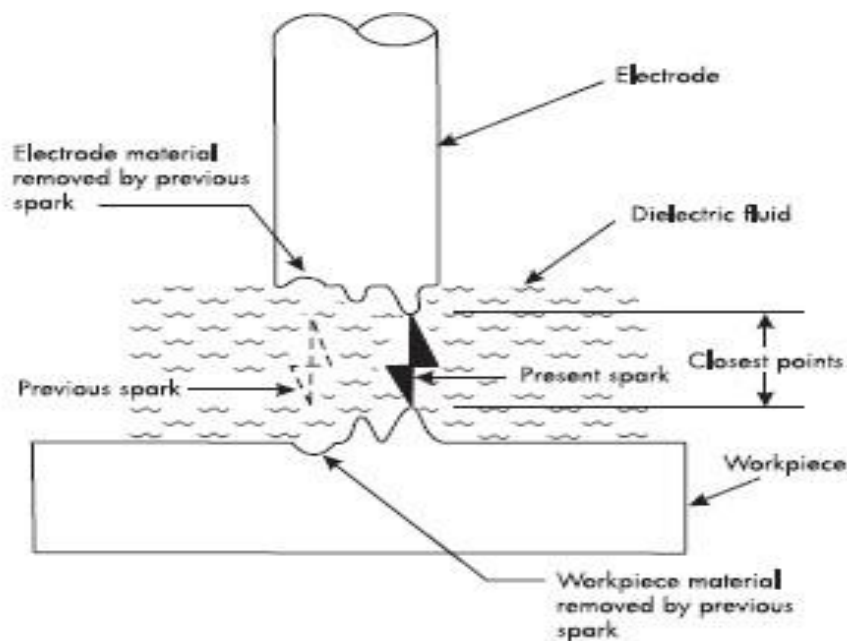


Fig: 1.11: Next spark occurs at closest points between electrode & workpiece

To summarize, material removal in EDM is primarily caused by the creation of shock waves caused by the collapse of the plasma channel due to the discontinuation of the applied potential difference.

1.5 TYPES OF EDM PROCESS

Basically, there are two types of EDM:

1.5.1 Die Sinking EDM

Die-sinking EDM is also referred to as cavity style EDM or volume EDM. The workpiece and electrode are immersed in dielectric oil during the EDM operation, which is an electrical insulator that helps regulate the arc discharge. Dielectric oil is pumped into the arc gap to provide a means of flushing. This clears the work cavity of suspended fragments of workpiece material and electrode.

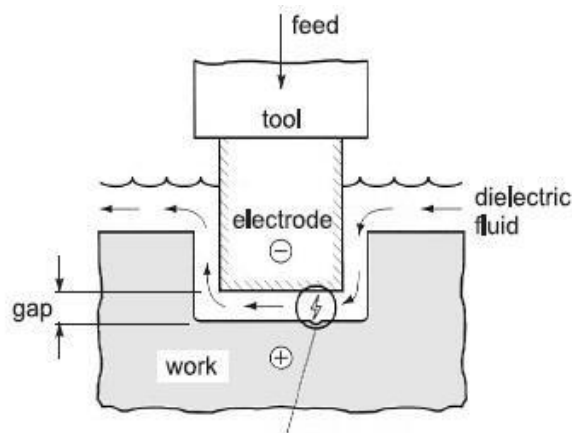


Fig: 1.12: Die sinking EDM process

1.5.2 Wire Cut EDM

Spark EDM is another term for wire-cut EDM. The wire-cut EDM is a discharge machine that produces the desired curve or design using CNC movement. Instead of a specially shaped electrode, it uses a cyclic vertical wire under tension. In wire-cut EDM, the electrode is about the thickness of a small diameter needle, and its path is operated by the machine computer to create the desired form.

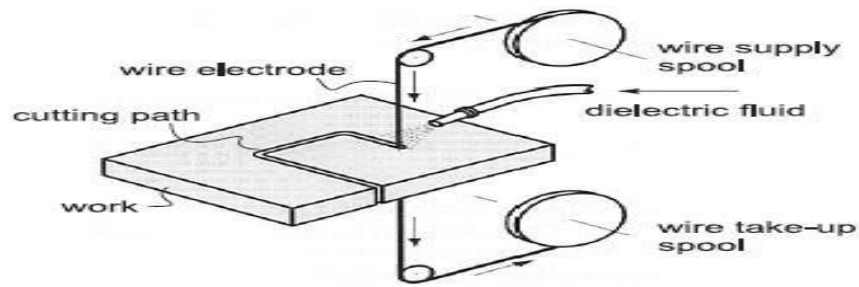


Fig: 1.13: Process of wire cut EDM

1.6 IMPORTANT PARAMETERS OF EDM

1.6.1 Pulse on-time (T_{on})

As shown in Figure 1.6, the pulse on-time indicates the period of time in microseconds (μs) during which the voltage pulse is applied in each step. The amount of material extracted is equal to the amount of energy added during the on-time pulse. The peak current and the duration of the pulse on-time decide the sum of energy released. The pulse discharge energy increases as the pulse on time increases, increasing the machining rate. However, using higher T_{on} values can increase surface roughness.

1.6.2 Pulse off Time (T_{off})

The pulse off-time, as shown in Figure 1.6, is the time in microseconds (μs) between two consecutive sparks. This gives the molten substance enough time to solidify and wash out of the arc void. At this part of the cycle, no voltage is present. If the pulse off time is set to a lower value, there will be more discharges in a specified amount of time, increasing sparking performance and thereby cutting efficiency. The spark will become unstable if the off-time is too short.

The pulse off-time, as shown in Figure 1.6, is the time in microseconds (μs) between two consecutive sparks. This gives the molten substance enough time to solidify and wash out of the arc void. At this part of the cycle, no voltage is present. The speed and stability of the cut are affected by this parameter.

1.6.3 Arc gap

During the EDM phase, the arc gap is the gap between the tool and the workpiece. It's also known as a spark gap.

1.6.4 Discharge current (I)

For a given pulse, the maximum current flowing through the electrodes is known as the discharge current. If the discharge current rises, the discharge energy rises, and the rate of material removal rises.

1.6.5 Duty cycle (τ)

It is expressed as a percentage of on-time compared to overall cycle time. The on-time is divided by the total cycle time to arrive at this value.

$$\tau = \frac{T_{on}}{T_{on}+T_{off}} \quad (1)$$

1.6.6 Voltage (V)

The potential gap between the electrode and the workpiece is what this term refers to. It also has an effect on the frequency of material removal.

1.6.7 Over cut

After the machining process, there is a clearance between the electrode and the workpiece on either side.

1.6.8 Flushing

One of the most critical aspects of a successful EDM method is the removal of metal particles from the working gap. Flushing these particles out of the distance between the workpieces to avoid short circuits by creating bridges.

1.6.9 Servo mechanism

The potential gap between the electrode and the workpiece is what this term refers to. It also has an effect on the frequency of material removal. It is important that the

electrode and the workpiece have no physical contact; otherwise, arcing could damage both the workpiece and the electrode. The servomechanism advances the electrode into the workpiece as the system proceeds and detects and monitors the work-electrode spacing to maintain the correct arc distance, which is crucial to an effective machining operation.

1.6.10 Application of EDM

- i) In the aerospace, automotive, and electronics industries, where output volumes are relatively low, the EDM process is becoming a common method of manufacturing prototype and production components.
- ii) It is used to machine extremely hard and difficult-to-machine materials such as alloys, tool steels, tungsten carbides, composites, ceramics, and so on.
- iii) It can be used to drill curved holes.
- iv) It is often used to cut internal threads and helical gears.
- v) It's used for machining rough edges and corners that other machining methods can't manage well.
- vi) Higher tolerance limits can be achieved with EDM machining. As a result, the EDM machining process is used in areas that require a higher degree of surface precision.
- vii) It is an efficient strategy for meeting the growing demand for smaller components in the field of microelectronics, which are typically highly complex, multi-functional parts.

1.6.11 Advantages of EDM

- i) The EDM method can be used to cut any electrically conductive material.
- ii) Hardened workpieces may be machined, and heat treatment deformation is removed.
- iii) The X, Y, and Z axes can be moved to program complex profiles with simple electrodes.
- iv) Complex die sections and moulds can be manufactured with greater accuracy, speed, and cost savings.

- v) Webs and fins, which are thin and delicate, can be easily machined without deforming the component.

1.6.12 Limitations

- i) The work piece must be conductive in order to achieve discharges. Plastics, glass, and most ceramics are not appropriate for EDM machining. Partial conductors, such as Si semiconductors, partially conductive ceramics, and even glass, can be machined.
- ii) The EDM-process has a low material removal rate, particularly in the case of die-sinking EDM, which requires melting and evaporating the metal to remove the entire volume of a cavity. Due to its low material removal rate, EDM is mostly used for small-series processing, though it has a few specific mass-production applications.
- iii) A heat-affected zone exists underneath the recast sheet, which may be softer than the parent material.
- iv) Dielectric vapor is hazardous.
- v) Holes with a slight taper, particularly if blind.

1.6.13 Disadvantages of EDM

- i) The electrode wear rate is significantly higher. To complete the job, it may be appropriate to use more than one electrode.
- ii) To be machined using the EDM method, the workpiece must be electrically conductive.
- iii) The energy required for the operation is more than that of the conventional process and hence will be more expensive.

1.7 DESIGN OF EXPERIMENTS

The design of experiments (DOE) or experimental design is the process of creating any information-gathering activity that involves variance, whether or not the experimenter

has complete control over the outcome. In statistics, however, these words are commonly used to refer to a managed situation. For deriving clear and reliable conclusions from experimental findings, a well-planned and conducted experiment is essential. For completing these tasks, the design of experiments is thought to be a very useful technique. Sir Ronald Fisher's work in the 1920s in England gave birth to the science of statistical experimental design. During his efforts to increase agricultural crop yields, Fisher developed the basic theory of experimental design and the related data-analysis methodology known as Analysis of Variance (ANOVA). Many statisticians, including Box and Hunter, Box and Draper, and Hicks, have advanced the philosophy and implementations of experimental design, as well as the associated technique of response surface methodology. Taguchi's Method, for example, makes extensive use of orthogonal arrays.

The following are some of the benefits of experiment design:

- i) Numbers of trials is significantly reduced.
- ii) Important decision variables which control and improve the performance of the product or the process can be identified.
- iii) The best parameter settings can be discovered.
- iv) Parameter estimation can be done qualitatively.
- v) It is possible to quantify the experimental error.
- vi) Inference regarding the effect of parameters on the characteristics of the process can be made.

1.7.1 Taguchi's experimental design and analysis

The Taguchi method entails using a robust design of experiments to reduce variance in a phase. The method's ultimate aim is to deliver a high-quality product at a low cost to the producer. Dr. Genichi Taguchi of Japan invented the Taguchi system. Taguchi devised a method for designing experiments to see how various parameters influence the mean and variance of a process output metric, which shows how well the process is working. Taguchi's experimental design involves organizing the parameters

influencing the mechanism and the levels at which they should be varied using orthogonal arrays. Rather than checking all possible combinations as the factorial architecture does, the Taguchi method tests pairs of combinations. This saves time and money by allowing for the collection of the required data to decide which variables have the greatest impact on product quality with the least amount of experimentation. Where there are an intermediate number of variables (3 to 50), few interactions between variables, and only a few variables add greatly, the Taguchi method is a good solution.

1.7.2 Philosophy of Taguchi method

Quality should be built into a commodity rather than inspected. Via system design, parameter design, and tolerance design, quality is built into a process. Parameter design, the topic of this article, involves deciding the process parameters have the greatest effect on the product and then developing them to achieve a particular product quality goal. Quality "inspected into" a commodity means that it is made at random quality levels, with those that deviate too far from the mean being discarded.

Holding the deviation from a target as minimal as possible is the best way to achieve efficiency. The product should be designed to withstand uncontrollable environmental conditions. To put it another way, there should be a high signal to noise ratio.

Quality costs should be calculated as a function of deviation from the norm, and losses should be calculated over the entire system. This is the principle of the loss function, or the net loss caused by a poor-quality product on the consumer and community. Since the manufacturer is also a member of society, and since consumer disappointment will deter potential loyalty, the producer will bear the expense of the customer and society.

1.7.3 Taguchi method designs of experiments

The Taguchi Method consists of the following steps:

- i) Define the process goal, or, more precisely, a target value for a process output metric. This could be flow rate, temperature, or something else entirely. A process's goal may also be a minimum or maximum; for instance, the goal may be to maximize

the production flow rate. The loss function for the process is defined by the deviation in the output characteristic from the target value.

- ii) Define the design parameters that influence the operation. Temperatures and pressures, for example, are easily controllable variables within a process that affect the performance measure. It is important to determine the number of levels at which the parameters can be differed. For example, a temperature could be adjusted between 400 and 800 degrees Celsius. If the number of thresholds increases, the number of experiments required to change a parameter increases.
- iii) Build orthogonal arrays for the parameter configuration, representing the constraints for each test. Orthogonal arrays are chosen based on the number of parameters and the degrees of variance for each parameter, as discussed below.
- iv) Collect data on the impact on the performance measure by conducting the experiments mentioned in the completed array.
- v) Complete data analysis to determine the effect of the different parameters on the performance measure.

1.7.4 Experimental design strategy

For lying out of experiments, Taguchi suggests orthogonal arrays (OA). These OAs are Graeco-Latin squares that have been generalized. The first step in planning an experiment is to choose the most fitting OA and assign the parameters and relations of significance to the appropriate columns. The use of linear graphs and triangular tables, as suggested by Taguchi, makes parameter assignment simpler. The array forces all experimenters to create experiments that are nearly identical.

The Taguchi method analyses the outcomes of experiments to accomplish one or more of the following goals:

- To figure out what the optimal or ideal condition for a product or process is.
- Assess the relative value of individual parameters and interactions.
- To calculate the response parameters in the best-case scenario.

By examining the key effects of each of the parameters, the optimal state is discovered. The key effects show the overall direction of each parameter's power. The ability to determine the contribution of individual parameters is crucial in determining the type of control that should be implemented on a production process. The analysis of variance (ANOVA) is the most commonly used statistical treatment for determining the percent contribution of each parameter to a given degree of confidence in experimental outcomes. The ANOVA table for a given analysis can be used to decide which parameters need to be regulated. Taguchi proposes two approaches to carrying out the full study of the experiments.

First, the conventional form, in which the outcomes of a single run or the average of repeated runs are evaluated using main effects and ANOVA.

Taguchi's second suggestion for multiple runs is to use the signal-to-noise (S/N) ratio for the same steps in the analysis. The S/N ratio is a loss function-related concurrent consistency metric. By maximizing the S/N ratio, the loss associated can be minimized. From the difference in the performance, the S/N ratio defines the most stable set of operating conditions. The experiment's S/N ratio is treated as a response parameter. Taguchi proposes using outer OA to introduce noise variation into the experiment, i.e., noise is purposefully introduced. Processes are subjected to a number of noise sources in general, which when combined have a major effect on response variance.

For extremely 'noisy' systems, it is not generally necessary to identify controllable parameters and analyze them using an appropriate S/N ratio. Both raw data analysis and S/N data analysis were done in this investigation. The effects of the selected EDM parameters on the selected quality characteristics have been investigated through the main effect's plots based on raw data. The optimum condition for each of the quality characteristics was determined using S/N data analysis. Instead of using an outer array, tests were replicated twice for each experimental condition.

1.7.5 Loss function and S/N ratio

The Taguchi approach is based on Taguchi's concept of the nebulous and elusive word "efficiency" as the attribute that prevents societal loss from the time the product is

delivered. Loss is expressed in monetary units and is linked to quantifiable product attributes. Taguchi's 'loss-function' determines consistency loss. Via a quadratic relationship derived from Taylor series expansion, he connects the financial loss with the functional specification.

$$(y) = (y - m)^2 \quad (2)$$

Where,

'L' denotes the monetary loss and 'm' denotes the value at which the characteristic should be set and 'y' denotes the characteristic's real value.

Depending on the magnitude of the characteristic and the monetary unit in question, $k = \text{constant}$. The following are two things to consider:

The greater the difference between the product's characteristic and the target value, the greater the loss. If the product's quality characteristic reaches its target value, the loss is zero.

The loss is a continuous function rather than a one-time occurrence as in the conventional approach.

This outcome of the continuous loss function shows that actually manufacturing a product within specification limits does not guarantee that it is of good quality. In a mass production process, the average loss per unit is expressed as:

$$(y) = k \sum (y_i - m)^2 \quad (3)$$

Where,

$i = 1, 2, \dots, n$

$n = \text{number of units in a given sample}$

$y_i = \text{values of characteristics for units } 1, 2, \dots, n$

$k = \text{constant based upon the magnitude of characteristic and the monetary unit involved}$

$m = \text{Target value at which characteristic should be set}$ Equation can be written as:

$$(y) = (MSD) \quad (4)$$

Where MSD stands for mean square variance, which displays the average squares of all deviations from the target value rather than the average value itself. Taguchi converted the loss function into a concurrent statistic known as the S/N ratio, which incorporates the quality characteristic's mean level and variance around it into a single metric. The S/N ratio combines multiple repetitions (at least two data points) into a

single value. A high S/N ratio means that the output is at its best with the least amount of variance. The following three types of S/N ratios are used in practise, based on the type of response.

Higher the better (HB) :

$$(S/N)_{HB} = -10 \log(MSD)_{HB} \quad (5)$$

Where,

$$(MSD)_{HB} = \frac{1}{2} \sum_{j=1}^R \frac{12}{y_j} \quad (6)$$

Lower the better (LB):

$$(S/N)_{LB} = -10 \log(MSD)_{LB} \quad (7)$$

Where,

$$(MSD)_{LB} = \frac{1}{R \sum_{j=1}^R y_{21}} \quad (8)$$

Nominal the bestx(NB) :

$$(S/N)_{NB} = -10 \log(MSD)_{NB} \quad (9)$$

Where,

$$(MSD)_{NB} = \frac{1}{R} \sum_{j=1}^R (y_i - y_0) \quad (10)$$

R = Number of repetitions

It should be noted that for nominal the best type of characteristic, the regular MSD description was used. The goal value for the smaller the better form is zero. The inverse of each large value becomes a small value for the greater the better kind, and the target value is zero once more. As a consequence, the smallest magnitude of MSD is sought for all three terms.

1.8 INTRODUCTION TO MINITAB

Minitab is statistical analysis software and is relatively easy to use. It can be used for both studying and conducting statistical analysis. Software programs for statistical

analysis have the advantage of being more precise, reliable, and usually quicker than manually calculating statistics and drawing graphs.

Steps to open Minitab

In the bottom left corner of the screen, click the Start button.

Select **Programs >Minitab 14>Minitab 19**.

Or

Double click the Minitab icon on the desktop.

Minitab will open.

You'll see two windows when you first open Minitab: a Session window and a Worksheet window.

Session Window: The area that displays the statistical results of data analysis. (Also used to enter commands and macros.)

Worksheet Window: The data is entered and manipulated using a grid of rows and columns. Note: While this area resembles a spreadsheet, it does not automatically update the columns as new entries are altered.

There are even other windows present, which are:

Project Manager: You can navigate, display, and control different aspects of your project, including session window performance, graphs, worksheets, and related project areas. Note: This window is minimized at start up.

Report Window: Found in the Project Manager for creating, arranging, and editing, reports of your work.

Graph Window: When you generate graphs, each graph is opened in its own window.

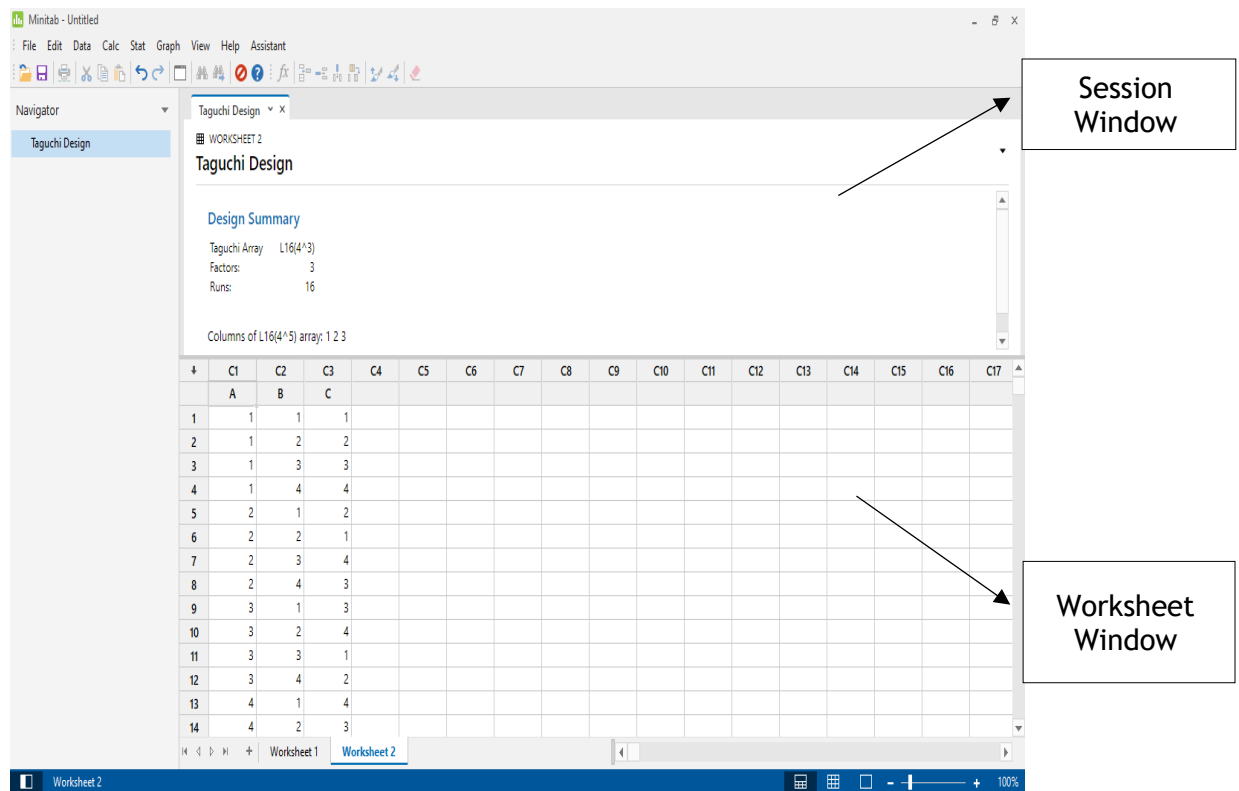


Fig: 1.14 : Worksheet and Session Window

1.9 ENTERING DATA

We can enter the data going down or across. A cell with an arrow in it can be found in the top left corner of the Worksheet pane. Alter the operation of the ENTER key by selecting this cell.

If the arrow is pointing down, pressing Enter will move the cursor down the column. If the arrow is pointing to the right, pressing Enter will move the cursor across the row to the next column.

Example:

During a three-hour cycle outdoors, a person recorded the temperature and the amount of water drank. The information provided below was gathered over the course of seven days during the summer.

1. **Enter the data.** In the relevant column, enter the corresponding temperatures and water consumption as shown. Do not rearrange the products in any way. Check that the things were entered as numbers rather than text.

1.10 GENERATING GRAPHS

We'll make a histogram and box plot of the temperature data, as well as a scatter plot of water consumption versus temperature, in this example.

1. Choose **GRAPH > HISTOGRAM** to construct a histogram.
2. Pick C1 in the Graph Variables box (Temperature).
3. Choose OK.
4. Compare the response to the histogram that results, which is shown below. (Note: The width of the bars in the histogram can be adjusted by selecting Options from the histogram dialogue box and making the necessary changes.)

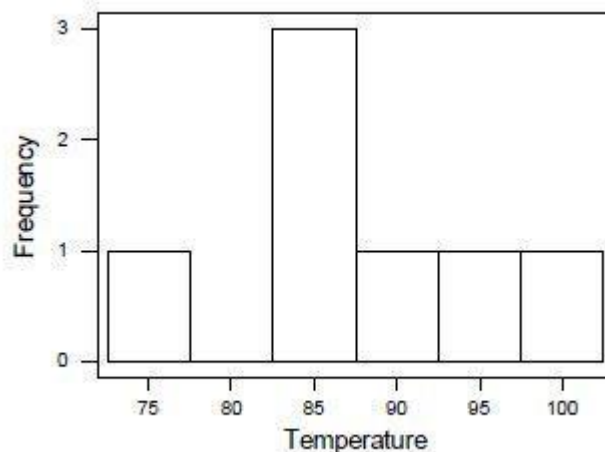


Fig: 1.15: Example of a graph drawn using Minitab

1. Choose **GRAPH > BOXPLOT** to develop a box plot.
2. Pick C1 in the Graph Variables box under the **Y. (Temperature)**. (Note: The X column denotes a category.) If you graphed GPA by Gender, for example, two box plots will be produced, one for each gender (Since our data isn't organized into categories, this choice isn't applicable in this case.)

3. Click OK.
4. Compare your answer with the resulting box plot shown below.

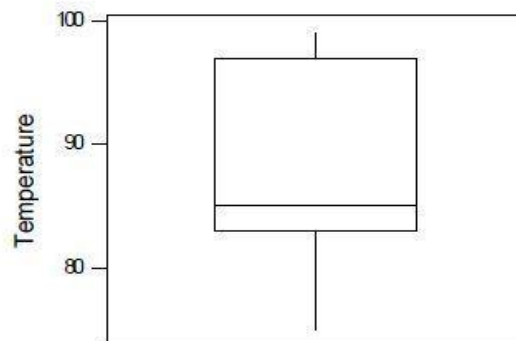


Fig: 1.16: Example of Box plot graph drawn using Minitab

- 5 To graph a **scatter plot** for the water consumption based on the temperature, select **GRAPH > PLOT**.
- 6 Select **C2 (Water Consumption)** under the Y axis and **C1 (Water Consumption)** under the X axis in the Graph Variables box (Temperature).
- 7 Click **OK**.
- 8 Compare your graph with the graph shown below.

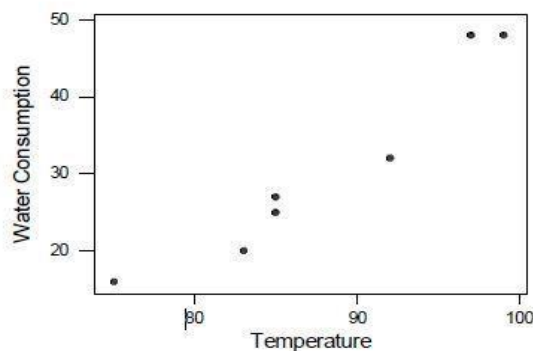


Fig: 1.17: Example graph drawn using Minitab

Save the project including graphs.

Select **FILE > SAVE PROJECT AS**.

Pick the 312 Floppy (A:) or the location of your diskette or USB unit using the arrow beside the Save in: area.

Type "Project Name" in the File Name area. Minitab can apply the MPJ extension to your Minitab project automatically.

Click **SAVE**.

CHAPTER 2

LITERATURE SURVEY

In this chapter research papers are selected, related to EDM which affects the workpiece material removal rate, electrode wear rate and surface roughness of workpiece material. Any electrically conductive material can be machined with EDM, regardless of its strength or hardness. Machining parameters include current, pulse on-time, pulse off-time, gap voltage, feed, and flushing pressure. Metal removal rate, tool wear rate, taper, and surface roughness are all important parameters. This method can be used to create complex profiles.

Yusuf Keskinetal in a study machined the parameters on the surface roughness region machined by EDM on steel with a copper tool electrode The data for response measures was evaluated using the multiple regression method of the Design of experiments method. Since there was more discharge energy released during this period, the surface roughness increased as the discharge length increased.

Chen and Madhavian proposed a computational model for forecasting the rate of material removal and surface roughness. Theoretical and experimental results were later compared and found to be virtually identical.

Shao, B., & Rajurkar, K. P. discussed the electro-thermal model of micro-EDM explored in detail in order to simulate the cavity forming mechanism. Pulse energy, pulse on time, and energy distribution fraction were all experimentally specified parameters that were implemented into the model and solved using the FEM.

Ved Prakash, P Kumar studied the summary of conventional and micro–electrical discharge machining processes, as well as categorization and a brief analysis of various aspects of micromanufacturing methods. Traditional and micro–electrical

discharge machining of nickel and its alloys, titanium alloys (Ti6Al): new research trends and developments, research gaps, and challenges.

Chen PW. examined the effects of electrode material in order to prevent residual stresses, surface roughness, and cracks (EDM). During all machining conditions, Dura graphite had a higher surface roughness on the DIN 1.2080 surface. As a result of the higher pulse current used in rough EDM machining, there were more micro-cracks.

Kao, J. Y., in this study used the Taguchi method and grey relational analysis to optimize the electrical discharge machining process for Ti–6Al–4V alloy, taking into account various performance characteristics. As a result, it is seen that this approach makes optimizing complex multiple output characteristics much easier.

Meena, V. K., & Azad, M. S. studied about micro-electric discharge machining of Ti-6Al-V alloy with tungsten carbide electrode was carried out in this study. The impact of various input parameters is investigated in this analysis. To optimize the levels of input parameters, grey relational analysis and analysis of variance (ANOVA) were used.

Kansal, H. K., Singh, S., & Kumar, P. in their research the Taguchi Method was used to figure out the best process conditions for Powder Mixed EDM (PMEDM) in the rough machining step. It was also seen that to influencing the efficiency of PMEDM, the peak current is by far the most critical process parameter. The impact of graphite powder on EDM output was also investigated.

Mhatre, M. S., Sapkal studied the grey relational theory-based parameter optimization in EDM of Ti-6Al-4V alloy. While all factors have a major impact on EDM performance to varying degrees, it is discovered that pulse current is the most important factor affecting material removal rate, dimensional accuracy, and drilled hole surface integrity.

Mishra, B. P., & Routara Using the Taguchi robust design approach and multi-Objective Grey Relational Grade with four input parameters such as (TON), (Toff), (I P), and Flushing pressure, researchers investigated the MRR and tool wear rate of EDM on EN-24 alloy steel (Fp). The research showed that optimum level setting of control factors.

S.H.Tomadi et al. studied the correlation between input parameters in EDM of Tungsten Carbide as workpiece and Copper Tungsten as the electrode was investigated. Ton, Toff and voltage, material removed rate and electrode wear rate are considered process performances, while voltage and peak current are considered input process parameters. The optimal state of process parameters was determined using a full factorial design of experiment. The most influential factor for surface roughness was voltage, followed by pulse off time, peak current, and material removal rate. The most influential factor for material removal rate was pulse on time, followed by voltage, peak current, and pulse off time.

Lee and Li the effect of operating parameters on tungsten carbide and its machining properties was investigated. To model and optimize the EDM mechanism, Wang used a hybrid artificial neural network and genetic algorithm methodology.

P.Narender et al. [16] investigated the relationship between process parameters in EDM of Al-10% SiCp as workpiece and Brass as tool material. On machining Al MMC with 10% SiCp reinforcement, the researcher said the effects of current, pulse on time, and flushing pressure on MRR, TWR, taper (T), radial overcut (ROC), and surface roughness (SR). It was seen that MRR is higher for larger current and pulse on time at the cost of taper-city, radial overcut, and surface finish, while TWR is also higher at higher current settings. It was also discovered that the dielectric flushing pressure has a significant impact on the MRR and TWR.

A.Majumder et al. depicted the process behavior of Die-Sinking Electrical Discharge Machining, a quadratic mathematical model was developed. Experiments were carried out with three process parameters: discharge current, pulse on time, and pulse off time, with the goal of relating them to process responses such as material removal rate (MRR) and electrode wear rate (EWR). The experiment was carried out with mild steel as the workpiece and copper as the electrode, and it was discovered that the effect of supply current on material removal rate is greater than the effect of the other.

S. Gopalakannan et al. The effects of process parameters such as pulse current, gap voltage, pulse on time, and pulse off time, as well as their interactions, on MRR, EWR, and SR were studied. Using copper as an electrode, experiments were carried out to machine a newly designed metal matrix composite of aluminium 7075 reinforced with 10% B4C particles. To create a mathematical model and construct empirical relationships between process parameters and process responses, Response Surface Methodology was used. The results of the study were validated using analysis of variance. Pulse current and pulse on time were found to be the two most important factors affecting the MRR. With rising pulse on time, the MRR first rises and then falls. The surface roughness increases as the pulse current and pulse on time increase, and the surface roughness decreases until 50 volts, then increases as the voltage is increased further.

Raj Mohan et al. The effect of process parameters and interactions, such as voltage, pulse on time, current, and pulse off time, on the material removal rate (MRR) in stainless steel (304) as a workpiece was investigated. The effect of the parameters on MRR was studied using the (S/N) ratio and (ANOVA), and the Taguchi method was used to find the best cutting parameters. Pulse current and pulse on time were found to be the two most important factors affecting the MRR.

Nikalje et al. discussed about process parameters such as discharge current, pulse-on time, and pulse-off time for their impact on process performance criteria such as

MRR, Tool Wear Ratio (TWR), Relative Wear Ratio (RWR), and surface roughness. The MDN 300 steel was used as workpiece material and copper as electrode. The Taguchi method was employed for optimization. The optimal levels of the factors for SR and TWR were discovered to be the same, but they varied from the optimum levels of the factors for MRR and RWR. For MRR and TWR, discharge current is more important than pulse on time, while for RWR and SR, pulse on time is more important than discharge current. Pulse off time, on the other hand, is less critical for all performance characteristics considered.

Nilesh M. Vohra et al. investigated the optimum cutting parameters for a work piece (SS-304) & tool material (Copper, Aluminum, Brass) combination on Fuzzy Logic Control based Electrical Discharge Machine to find out the effect of process parameters viz. tool material, current, spark gap voltage, pulse on time and pulse off time on material removal rate (MRR), tool wear ratio (TWR), surface roughness (SR). It was found that gap voltage is more significant for MRR and SR But tool material is more significant for TWR.

Chandramouli S et al. studied the relationship between process parameters in EDM using RENE80 Nickel Super Alloy as the workpiece and aluminum as the electrode was examined. Current, pulse on time, and pulse off time were used as input process parameters, with MRR, TWR, and SR as process performances. MRR increases with rising current, pulse on time, and pulse off time, but not as much as pulse on time; on the other hand, TWR increases with increasing current and pulse off time but decreases with increasing pulse on time. It was also discovered that as current and pulse on time increase, SR increases, but as pulse off time increases, SR decreases.

S. Suresh Kumar et al. found that during electric discharge machining of Al (6351)-SiC-B₄C hybrid composite, increase in pulse current increases the electrode wear ratio and the surface roughness. However, pulse on time and the pulse duty factor have a negative influence on electrode wear ratio. It was also found that lower the pulse duration and pulse duty factor better will be the surface finish, but pulse duty factor

doesn't contribute significantly. Increases in pulse current and pulse task factor decreased the amount of power used during machining. However, the pulse duration has to be low to minimize the machining cost.

Sohani et al. studied Using response surface methodology, the influence of tool shapes such as triangle, rectangle, rectangular, and circular, as well as other process parameters such as pulse duration, Ton, Toff, and tool area. According to the study, the best tool shape for higher MRR and lower TWR is circular, followed by triangular, rectangular, and square cross-sections. The interaction effect of discharge current and pulse on time is highly significant on MRR and TWR, according to the parametric analysis, while the key factors such as pulse off time and tool area are statistically significant on MRR and TWR. To check the lack of fit and adequacy of the established model, the ANOVA was used in conjunction with Fisher's test (F- test) at a 95% confidence interval.

Ashok Kumar et al. investigated the effect of process parameters like Pulse on time, discharge current and diameter of electrode on MRR, TWR and over cut. The experiment used AISI P20 tool steel as workpiece and U-shaped copper tool as electrode with internal flushing system. The S/N ratios used for minimizing the TWR and maximizing the MRR and Taguchi method used for optimization the process parameters. The diameter of the instrument was found to be the most influencing factor for MRR, followed by pulse on time and discharge current. MRR increased as discharge current increased, and in the case of tool wear rate, the most controlling factor is pulse on time, followed by discharge current, and finally tool diameter.

S. Rama Rao et al. investigated the fabrication and mechanical properties of aluminum-boron carbide composites is studied. In this case, liquid metallurgy processes were used to fabricate aluminium alloy-boron carbide composites of various particulate weight fractions (2.5, 5 and 7.5 percent). It was discovered that as the

volume of boron carbide in the composites increased, the density of the composites decreased while the stiffness improved. Increases in the weight proportion of boron carbide in the composites improved the ultimate compressive power of the composites.

Amol D. Sable et al. The stir-casting process was used to prepare metal-matrix composites. This paper focuses on the stir-casting process for producing metal-matrix Al-SiC composites, and it produced six samples with different percentile compositions of SiCp – 5 percent, 10 percent, 15 percent, 20 percent, 25 percent, and 30 percent with aluminium. The main goal of this paper is to develop a low-cost, solid, light-weighted metal-matrix Al-SiC composite material that can be used in industrial and advanced machineries.

KuangYuan Kung et al On an electrical discharge unit, the material removal rate and electrode wear ratio were investigated using a powder blended dielectric fluid for machining cobalt-bonded tungsten carbide. To schedule and evaluate the experiments, they used reaction surface methodology.

Prasad and Gopalakrishna in their study created a statistical model for material removal rate and surface roughness, which they optimised as a multi-objective optimization using evolutionary algorithms, and used a central composite rotatable configuration with five variables.

Chiang proposed mathematical models using reaction surface methods for simulation and assessment of the effects of machining parameters on the output characteristics of the electro discharge machining phase of Al₂ O₃ + TiC mixed ceramic to analyse the impact of four machining parameters on material removal rate, electrodischarge voltage the discharge current, pulse on time, duty factor and open discharge voltage on material removal rate, electrode wear ratio and surface roughness.

Mohd.AmriLajis et al. the relationship between process parameters in EDM with Tungsten Carbide as the workpiece and Graphite as the electrode was investigated. Metal removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR) are called process performances, while peak current, pulse off time, pulse on time, and current are considered input process parameters. To formulate the experimental layout, evaluate the effect of each parameter on machining characteristics, and predict the optimal EDM parameters, Taguchi methodology was used. It was found that the electrode wear and surface roughness are primarily affected by the peak current of EDM, while the pulse on time has a significant impact on the metal removal rate.

Shabgard and Shotorbani used Design of Experiments (DOE), multi linear regression techniques, and response surface methodology, the relationship between input parameters peak current, pulse-on time, and voltage and process outputs was defined. The work on titanium alloy is defined in this article, which used the input parameters of peak current, pulse on time, pulse off time, and tool lift time to construct a mathematical model using the regression method.

CHAPTER 3

AIM AND SCOPE

3.1 AIM

Based on the literature review of the research work, the objectives of the present research work are:

- i) Investigate the effect of input process parameters like current, pulse on time, voltage on the process performance like MRR, EWR and SR using Taguchi technique based Grey Relational analysis to predict optimum levels of input process parameters.
- ii) To formulate an equation for the output parameters using ANOVA.

3.2 SCOPE

After a comprehensive study of the existing literature survey, it reveals that large amount of research work has been carried out in the area of metal matrix composites. Titanium matrix composites have an advantage among MMCs, as Titanium is of light weight, high strength and easy to fabricate. But limited work has done on the machining of Titanium Gr 2 using EDM. Most of the researchers have investigated influence of input parameters like current, pulse on time, pulse off time, flushing pressure and gap voltage etc., using the conventional process but the effect of Graphite tool material on process performances viz. material removed rate (MRR), electrode wear rate (EWR) and surface roughness (SR) has not been investigated yet.

CHAPTER 4

MATERIALS AND METHODS

4.1 TOOL MATERIAL

When positive ions impinge on a tool, it should be made of a material that resists tool wear. Thus, by adjusting or carefully selecting the properties, the localized temperature increase can be minimized, and even as the temperature rises, there are less melting. EDM is used to machine intricately formed geometric features, so the tool should be easy to work with.

For performing experiments **Graphite** tool was used. In EAF operations, artificial graphite electrodes are now the norm. Petroleum coke (needle type preferred) and coal tar pitch are the raw materials. In some steps, they are mixed and processed at high temperatures.

The basic characteristics of electrode material are:

1. High electrical conductivity
2. High thermal conductivity
3. Higher density
4. High melting point
5. Easy manufacturability
6. Cheap.

4.2 WORKPIECE MATERIAL

EDM can machine geometrically complex or hard material components that are precise and difficult to machine, such as heat-treated tool steels, composites, super alloys, ceramics, carbides, and heat resistant steels, among other materials. In this experiment **Titanium Gr 2** material was used as workpiece.

Titanium Grade 2 has a lower density, making it ideal for applications where weight is an issue. Titanium alloys are widely used in biomedical and aerospace applications. The toughness resistance of titanium Grade 2 make it suitable for use in the marine, chemical refining, and desalination industries. Grade 2 titanium is widely used in

exploration and production parts, reaction and pressure vessels, pipe or tube devices, heat exchangers, liners, flue-gas purification systems, and a number of other industrial components. Temperatures in continuous service can reach 800°F, with occasional, intermittent service at 1000°F.

Table 4.1 – Composition of Titanium Grade 2

Element	Content (%)
Titanium, Ti	≥ 98.9
Iron, Fe	≤ 0.30
Oxygen, O	≤ 0.25
Carbon	≤ 0.080
Nitrogen	≤ 0.030
Hydrogen	≤ 0.015

4.3 TAGUCHI PROCEDURE FOR EXPERIMENTAL DESIGN AND ANALYSIS

The stepwise procedure for Taguchi experimental design and analysis is described in the following paragraphs.

4.3.1 Selection of orthogonal array

In selecting an appropriate OA, the following prerequisites are required:

- Selection of process parameters and/or their interactions to be evaluated.
- Selection of number of levels for the selected parameters.

Taguchi proposes several methods for deciding which parameters to use in an experiment. Those are:

- Brainstorming
- Flow charting
- Cause-effect diagram

To keep the experiment as small as possible, two levels for each parameter are suggested. At least three levels for each parameter should be considered if a curved or higher order polynomial relationship between the parameters under analysis and the answer is predicted. The standard level arrays are:

Two-level arrays: L4, L8, L12, L16, L32

Three-level arrays: L9, L18, L27

Four-level arrays: L16

The number as subscript in the array designation indicates the number of trials in that array. An OA has the following degrees of freedom (DOF):

$$f_{LN} = (N - 1) \quad (11)$$

Where,

F_{LN} = total degrees of freedom of an orthogonal array

L_N = Orthogonal array designation

N = number of trials

When a particular orthogonal array is selected for an experiment, the following inequality must be satisfied:

$$f_{LN} \geq \text{Total DOF required for parameters and interaction} \quad (12)$$

Depending on the number of levels in the parameters and total DOF required for the experiment, a suitable orthogonal array is selected.

4.3.2 Assignment of parameters and interactions to orthogonal array

An orthogonal array has several columns to which various parameters and their interactions are assigned. Linear graphs and Triangular tables are two tools, which are useful for deciding the possible interactions between the parameters and their assignment in the columns of orthogonal array. Each orthogonal array has its particular liner graphs and interaction tables

4.3.3 Experimentation and data collection

The experiment is performed against each of the trial conditions of the inner array. Each trial condition experiment is replicated either simply (if the outer array is not used) or according to the outer array (if used). To minimize bias in the experiment, randomization should be used.

4.3.4 Data analysis

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average responses, interaction graphs, etc. In the present work, following methods are used.

- Response table for S/N Ratios
- Main Effect Plot for Means
- Main Effect Plot for S/N Ratios
- ANOVA for S/N Data

The pattern is indicated by the plot of average responses at each stage of a parameter. It's a visual representation of how a parameter affects the answer. When noise factors are present, the S/N ratio is viewed as an experiment response, which is a measure of variance within a study. On the raw data, a standard ANOVA was used to identify the significant parameters.

4.3.5 Grey Relational Analysis

Grey relational analysis is a method in which measured performance characteristics will be normalized from zero to one. In this process first data pre-processing is done because different parameters have different units, e.g., Unit of MRR and TWR is mm^3/min and unit of SR is μm . In data pre-processing we normalize all values between zero to one. Next, we calculate Grey relational coefficient. This is calculated by using normalized values which we previously calculated. Using Grey relational coefficient,

Grey relational grade is calculated. This is done by calculating averages of grey coefficient values. Based on Grey relational grade, we can find out rank of optimized values. The value which has the highest rank is considered to be the most optimized value.

In our study, TWR and SR need to be smaller the better values. For this the mathematical calculation is as follows:

$$C_i(k) = \frac{Max\ ci(k) - ci(k)}{Max\ ci(k) - Min\ ci(k)} \quad (13)$$

MRR needs to be bigger the better value. For this the mathematical calculation is as follows:

$$C_i(k) = \frac{ci(k) - Min\ ci(k)}{Max\ ci(k) - Min\ ci(k)} \quad (14)$$

Here,

$C_i(k)$ = Value received after grey relational generation;

$Min\ ci(k)$ = Smallest value of $ci(k)$;

$Max\ ci(k)$ = Maximum value of $ci(k)$;

Grey relational coefficient is mathematically calculated as follows:

$$\xi_i(k) = \frac{\Delta\ min + \zeta\Delta\ max}{\Delta\ 0i(k) + \zeta\Delta\ max} \quad (15)$$

Here,

$\zeta \in [0 - 1]$ is the differentiating coefficient, 0.5 is accepted widely as this coefficient;

$c_0(k)$ is the reference sequence;

$c_j(k)$ is the comparability sequence;

$\Delta_{0i} = \|c_0(k) - c_i(k)\|$ is the difference between $c_0(k)$ and $c_i(k)$;

$\Delta_{min} = \min \min \|c_0(k) - c_j(k)\|$ is the smallest value of Δ_{0i} ;

$\Delta_{max} = \max \max \|c_0(k) - c_j(k)\|$ is the largest value of Δ_{0i} .

4.4 ANALYSIS OF VARIANCE

In this study, ANOVA was performed to investigate the statistical significance of the process parameters affecting the MRR, SR, TWR. The objective was to analyze the influence of peak current, pulse on time and voltage on the total variance of the results. This analysis was undertaken for a level of significance of .5%, i.e., for a level of confidence of 99.5%. The F-values and percentage contributions are also included in the ANOVA table. The importance of the variables can be understood by comparing the F-values to the tabulated ones. If a parameter's obtained F value is greater than its tabulated value, the parameter has a major influence on the response variable.

The main effects of process variables both for raw data and S/N data were plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics. The ANOVA of raw data and S/N data is carried out to identify the significant variables and to quantify their effects on the response characteristics. Analyzing the response curves and the ANOVA Tables 5.1–5.5 yields the most favorable values (optimal settings) of process variables in terms of mean response characteristics.

Table: 4.2: Design layout with actual parameters

Factors	Parameters	Levels			
		L1	L2	L3	L4
A	Peak current	10	20	30	40
B	Voltage	30	40	50	60
B	Pulse on Time	50	100	150	200

4.5 EXPERIMENTAL SET UP



Fig: 4.1: Experimental Setup

To undertake the experiments, an Electric Discharge Machine (die-sinking type) with servo-head (constant gap) and positive conductivity for electrode was used. As a dielectric liquid, industrial grade EDM oil (specific gravity= 0.763, freezing point= 94°C) was used. Internal flushing of square shaped graphite tool with 0.2 kgf/cm² pressure. Electrodes with a positive potential were used in the experiments. The pulsed discharge current was introduced in various steps in positive mode.

The EDM consists of following major part as shown in the below

4.5.1 Dielectric reservoirs pump and circulation system

For each run of the experiment, dielectric reservoirs and pumps are used to circulate the EDM oil as well as filter it. Dielectric reservoir is shown in Figure 4.2.



Fig: 4.2: Dielectric Reservoir pump

4.5.2 Power generator and control unit

The amount of energy consumed is regulated by the power supply. Second, it has a time control feature that governs how long current flows during each pulse; this is referred to as "on time." The amount of current allowed to flow during each pulse is then regulated. These pulses are measured in microseconds and have a very short duration. A basic rule of thumb for determining how much current to use for a certain size of electrode is that for an effective removal rate, each square inch of electrode needs 50 A. Low current levels for broad electrodes would unnecessarily prolong machine time. A high current load, on the other hand, will affect the electrode workpiece.

The control unit is in charge of all machining tasks, such as Ton, Ip, duty cycle, setting values, and maintaining the work piece's tool gap. Figure 4.3 depicts the control unit.



Fig: 4.3: Circulating pump and Control unit

4.5.3 Working tank with work holding device

All of the EDM oil in the working tank is used to supply fluid to the machine during the machining process.

4.5.4 x-y table accommodating the working table

They are used for the movement of the work piece in X and Y direction.

4.5.5 The tool holder

The tool holder holds the tool during the process of machining. The tool holder with work piece and tool is shown in Figure.4.4.

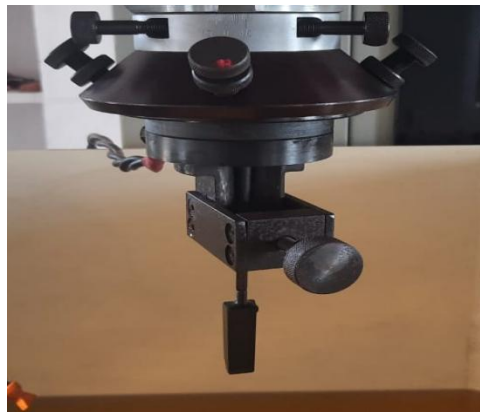


Fig: 4.4: Tool holder

4.5.6 The servo system to feed the tool

The servo control unit is provided to maintain the pre- determined gap. It detects the gap voltage and compares it to the current value, with the difference in voltage controlling the servo motor's movement to change the gap.

4.6 SELECTION OF THE WORK PIECE

Titanium today is the leading non-ferrous metal in use, finding ever more ingenious applications in sectors as varied as aeronautics, beverage containers, construction and energy transportation.

It can machine high - temperature tool steels, composites, super alloys, ceramics, carbides, and heat-resistant materials, among others. The base metal and amount of reinforcing material present in the composites will influence the strength of any composite material. Aluminium and Titanium alloys are the two most commonly used metal matrices because of their low specific gravities and are available in different alloy forms. Titanium Gr 2 alloy is a most commonly used as a matrix material because of its high strength and which can be further increased by suitable heat treatment process.

Table: 4.3 Mechanical properties of Titanium Gr 2

Yield Strength	345 Min Mpa
Tensile Strength	485 Min Mpa
Hardness Brinell	200 HB
Density	4.51 g/cm ³
Melting Point	1660°C
Thermal expansion	8.60 µm/m°C
Modulus of elasticity	105-120 Gpa
Thermal Conductivity	21.97 W/mK

Here we used the graphite as a work tool which is in square rod shape. The shape and figure of the work piece and the work tool are shown in the below Figure 4.5.

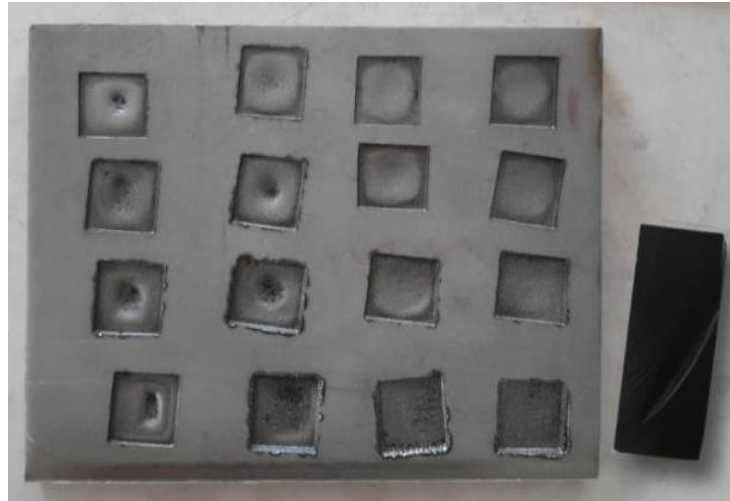


Fig: 4.5: Work piece and Tool

4.7 MECHANISM OF MRR

The method of transforming electrical energy to thermal energy. is the most commonly accepted theory for material removal in the EDM method. Sparks are created between the work piece and the tool during the machining process. As a result of melting and vaporization, each spark creates a tiny cavity in the material along the cutting line, as shown in Figure 1.3, eroding the workpiece to the shape of the instrument.

The Material Removal Mechanism (MRM) is a technique for moving material elements from the workpiece to the electrode. Roethel's work is well-known and illustrated by many EDM researchers. The transformations are transported as solids, liquids, or gases, and then alloyed with the contacting surface by a solid, liquid, or gaseous phase reaction.

4.7.1 Evaluation of MRR

The material MRR is determined by dividing the difference in work piece weight before and after machining by the machining time and density of the material.

$$\text{MRR} = \frac{\text{Weight before machining (Wb)} - \text{Weight after machining (Wa)}}{\text{Density of work piece (}\rho\text{a)} * \text{machining time (t)}} \quad (16)$$

Where,

Wb = weight of work before machining in grams

Wa = weight of work after machining in grams

t = machining time in minute

pa = density of Titanium GR 2

4.8 MECHANISM OF TWR

Tool wear is a significant factor because it has an impact on dimensional precision and the shape that is made. Tool wear is influenced by the melting point of the components. Tool wear is caused by carbon precipitation from the hydrocarbon dielectric on the electrode surface during sparking. The failure of carbon to precipitate at difficult-to-reach regions of the electrode also contributed to rapid wear on the electrode tip.

4.8.1 Evaluation of Tool Wear Rate

TWR is calculated by dividing the difference in tool weight before and after machining by the machining time. That can be explained by this equation;

$$TWR = \frac{\text{Tool Weight before machining (Wtb)} - \text{Tool Weight after machining (Wta)}}{\text{Density of work piece (pa)} * \text{machining time (t)}} \quad (17)$$

Where,

Wtb = Weight of the tool before machining.

Wta = Weight of the tool after machining.

t = Machining time

pa = density of Graphite tool

4.8.2 Evaluation of Surface Roughness



Fig: 4.6: Surface roughness Testing machine

The texture of a surface may be used to measure surface roughness, which is often deduced as roughness.

The spatial derivations of a real surface from its ideal shape are used to quantify it.

The surface is rough if these deviations are large; the surface is smooth if they are low.

4.9 OUTPUT PARAMETERS

The experiments are performed as per the L16 orthogonal array and the results are tabulated and the results are noted.

Table: 4.4: Experimental Results

S. No.	Current	Pulse on time	Voltage	TWR (mm³/min)	MRR (mm³/min)	SR (μm)
1	10	50	30	0.2670	0.6618	3.5470
2	10	100	40	0.2820	0.7001	4.2527
3	10	150	50	0.2950	0.9730	5.5365
4	10	200	60	0.4261	1.0551	3.8992
5	20	50	40	1.4530	3.8954	3.3623
6	20	100	30	1.0040	3.7352	5.2685
7	20	150	60	2.2970	1.7054	4.9305
8	20	200	50	3.5250	2.5443	4.8851
9	30	50	50	3.2912	2.9414	3.6427
10	30	100	60	0.5370	8.8691	4.4899
11	30	150	30	0.7902	3.9132	5.4177
12	30	200	40	1.2950	3.4336	8.3893
13	40	50	60	8.0540	2.0765	3.6926
14	40	100	50	0.9890	2.4451	5.7696
15	40	150	40	1.3422	6.0875	7.7279
16	40	200	30	1.1160	7.8231	6.3724

Table: 4.5: Normalization of values between 0 and 1

S. No.				Normalized Values			Deviation sequence		
	TWR	Ra	MRR	TWR	Ra	MRR	TWR	Ra	MRR
1	0.267	3.547	0.6618	1.0000	0.9633	0.0000	0.0000	0.0367	1.0000
2	0.282	4.2527	0.7001	0.9981	0.8229	0.0047	0.0019	0.1771	0.9953
3	0.295	5.5365	0.973	0.9964	0.5675	0.0379	0.0036	0.4325	0.9621
4	0.4261	3.8992	1.0551	0.9796	0.8932	0.0479	0.0204	0.1068	0.9521
5	1.453	3.3623	3.8954	0.8477	1.0000	0.3940	0.1523	0.0000	0.6060
6	1.004	5.2685	3.7352	0.9054	0.6208	0.3745	0.0946	0.3792	0.6255
7	2.297	4.9305	1.7054	0.7393	0.6880	0.1272	0.2607	0.3120	0.8728
8	3.525	4.8851	2.5443	0.5816	0.6971	0.2294	0.4184	0.3029	0.7706
9	3.2912	3.6427	2.9414	0.6116	0.9442	0.2778	0.3884	0.0558	0.7222
10	0.537	4.4899	8.8691	0.9653	0.7757	1.0000	0.0347	0.2243	0.0000
11	0.7902	5.4177	3.9132	0.9328	0.5911	0.3962	0.0672	0.4089	0.6038
12	1.295	8.3893	3.4336	0.8680	0.0000	0.3377	0.1320	1.0000	0.6623
13	8.054	3.6926	2.0765	0.0000	0.9343	0.1724	1.0000	0.0657	0.8276
14	0.989	5.7696	2.4451	0.9073	0.5211	0.2173	0.0927	0.4789	0.7827
15	1.3422	7.7279	6.0875	0.8619	0.1316	0.6611	0.1381	0.8684	0.3389
16	1.116	6.3724	7.8231	0.8910	0.4012	0.8726	0.1090	0.5988	0.1274

							Delta Min	0.0000	
Ma x	8.054	8.3893	8.8691	1.0000	1.0000	1.0000	Delta Max	1.0000	0.5
Min	0.267	3.3623	0.6618	0.0000	0.0000	0.0000			

Table: 4.6: Grey Relational Grade Calculation

S. No.	Grey relation coefficient			Grey relational grade	Rank
	TWR	Ra	MRR	GRG	
1	1.0000	0.9315	0.3333	0.7549	2
2	0.9962	0.7384	0.3344	0.6897	6
3	0.9929	0.5362	0.3420	0.6237	9
4	0.9607	0.8240	0.3443	0.7097	4
5	0.7665	1.0000	0.4521	0.7395	3
6	0.8408	0.5687	0.4442	0.6179	10
7	0.6573	0.6158	0.3642	0.5458	13
8	0.5444	0.6227	0.3935	0.5202	15
9	0.5628	0.8996	0.4091	0.6239	8
10	0.9352	0.6903	1.0000	0.8752	1
11	0.8815	0.5501	0.4530	0.6282	7
12	0.7911	0.3333	0.4302	0.5182	16
13	0.3333	0.8839	0.3766	0.5313	14
14	0.8436	0.5108	0.3898	0.5814	12
15	0.7836	0.3654	0.5960	0.5817	11
16	0.8210	0.4550	0.7969	0.6910	5

CHAPTER 5

ANALYSIS AND RESULTS

5.1 Analysis of variance for TWR

The regression equation is

$$\text{TWR (mm}^3/\text{min)} = 1.685 - 1.368 I(\text{amp}) - 0.891 V(\text{volts}) + 1.581 T_{\text{on}}$$

Table: 5.1: Regression Analysis: TWR (mm³/min) versus I(amp), V(volts), Ton

Predictor	Coefficient	SE coefficient	T	P
Constant	1.685	0.445	3.79	0.009
I(amps)	-1.368	0.771	-1.77	0.126
V(volts)	-0.891	0.771	-1.16	0.292
Ton	1.581	0.771	2.05	0.086

S = 1.78069 R-Sq = 67.26% R-Sq(adj) = 18.1%

The below table shows the results obtained in Taguchi analysis. It states that pulse on time and peak current stand as first and second in influencing TWR, whereas voltage stands on 3rd.

Table: 5.2: Response table for S/N ratio smaller is better (TWR)

Level	Current	Pulse on time	Voltage
1	0.3175	3.2663	0.7943
2	2.0697	0.7030	1.0931
3	1.4783	1.1811	2.0251
4	2.8753	1.5905	2.8285
Delta	2.5578	2.5633	2.0342
Rank	2	1	3

- **Main Plots for TWR (mm³/min)**

The below graph shows main plots of TWR for SN ratios.

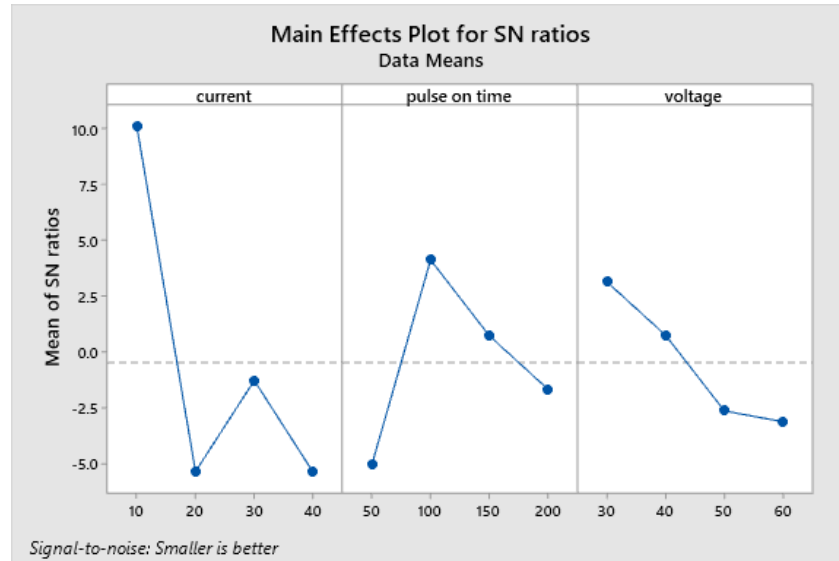


Fig: 5.1: Main Effects Plots for SN ratios TWR (mm³/min)

The main objective is to decrease the Tool wear/Electrode wear rate. The tables 15 shows the values pertaining to the equation. Table15 shows the rank obtained by the parameters in reducing the tool wear rate.

Those values are obtained by assuming smaller the better.

TWR decreases significantly with increase in pulse on time whereas voltage increases tool wear rate. Higher current also decreases the TWR.

By varying the parameters optimum combination of electrical parameters namely peak current and pulse on time TWR can be decreased.

5.2 ANALYSIS OF VARIANCE FOR MRR

The regression equation is

$$\text{MRR (mm}^3/\text{min)} = 3.304 - 2.46 I(\text{amp}) + 0.73 V(\text{volts}) - 0.091 T_{\text{on}}$$

The main objective is to increase the material removal rate by changing the parameters like peak current, voltage, pulse on time. The below table shows the values pertaining to the equation.

Table: 5.3: Regression Analysis: MRR (mm³/min) versus I(amp), V(volts), Ton

Predictor	Coefficient	SE coefficient	T	P
Constant	3.304	0.620	5.33	0.002
I(amps)	-2.46	1.07	-2.29	0.062
V(volts)	0.73	1.07	0.68	0.522
Ton	-0.91	1.07	-0.85	0.429

S = 2.48033 R-Sq = 58.91% R-Sq (adj) = 0.00%

To consider it we have to assume as larger is better for signal to noise ratio. The table 16 shows the results obtained after analyzing it in ANOVA. It states that peak current, voltage, pulse on time causes difference in the respective order.

Larger material removal rate decreases the cost and time of machining. The below table 17 shows the ranks achieved by the parameters after analyzing. It is assumed as **larger the better**.

Table: 5.4: Response Table for S/N Ratios Larger is better for MRR

Level	Current	Pulse on time	Voltage
1	-1.614	5.986	9.395
2	9.000	8.768	8.780
3	12.724	7.985	6.253
4	11.917	9.290	7.602
Delta	14.337	3.304	3.142
Rank	1	2	3

MRR increases significantly with increase in current, at first when the current is 10amps i.e., at level-1, the line is near 35(mean of SN ratios), when the peak current increased to 20amps the line reached 42.5 on the vertical line, by increasing further to 30 amps the line has reached to 45 on the vertical line. This shows by increasing the peak current MRR had increased. Whereas by increasing the voltage the MRR value has been decreased.

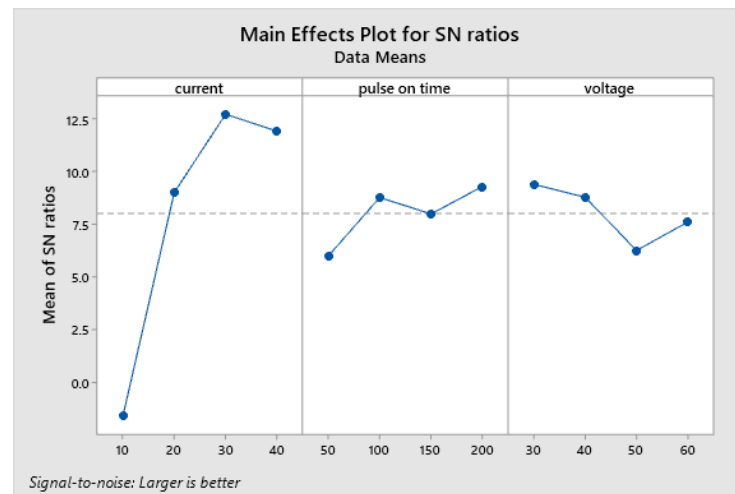


Fig: 5.2: Main effects plot for SN ratios MRR (mm³/min)

The other factors like pulse on time has large vertical value at the initial stage, but by increasing pulse on time decreased the value moderately, which shows it does not have a great affect in reducing MRR.

5.3 ANALYSIS OF VARIANCE FOR SN RATIOS FOR SR.

The regression equation is

$$SR (\mu m) = 5.074 - 0.765 I(\text{amp}) + 0.077 V(\text{volts}) - 1.513 T_{on}$$

Table: 5.5: Regression Analysis: SR (mm³/min) versus I(amp), V(volts), Ton

Predictor	Coefficient	SE coefficient	T	P
Constant	5.074	0.236	21.24	0.000
I(amps)	-0.765	0.410	-1.87	0.111

V(volts)	0.077	0.410	2.10	0.081
Ton	-1.513	0.410	-3.69	0.010

S = 0.945853 R-Sq = 83.35% R-Sq(adj) = 58.38%

The objective here is to reduce surface roughness after machining, higher roughness indicates low product quality. The tables 18 shows the results obtained after analysis. The smaller the roughness, better the quality. Hence smaller the better is selected for Signal to Noise ratios.

The below table 5.5 shows the results obtained after analyzing it in ANOVA. It states that peak current, voltage, pulse on time causes difference in the respective order. Ranks are obtained as follows.

Table: 5.6: Response Table for Signal to Noise Ratios Smaller is better

Level	I(amps)	Ton	Volts
1	-12.56	-11.03	-14.05
2	-13.15	-13.82	-14.84
3	-14.36	-15.29	-13.77
4	-15.10	-15.04	-12.52
Delta	2.54	4.26	2.32
Rank	2	1	3

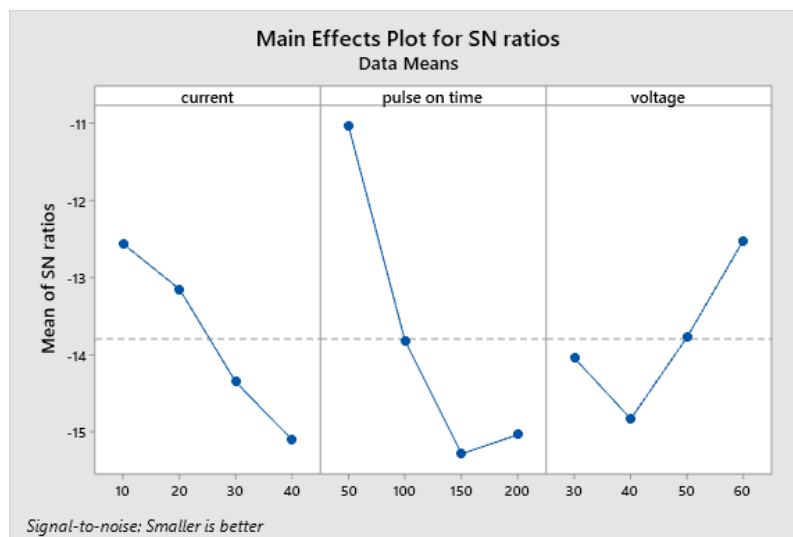


Figure: 5.3: Main Effects plot for SN ratios for SR (μm)

By considering **smaller the better**

The above graph in Fig.5.7 shows the main effects plot data for Surface Roughness. It represents that Current is most significant factor affecting surface roughness. Due to the high energy input to the machining zone, the surface finish deteriorates dramatically as the setting value of these process parameters is increased. At the optimal current environment, the best surface finishing can be achieved. Later, the voltage plays a major role in reducing the surface roughness. Whereas pulse on time has less effect on surface roughness.

5.4 SEM ANALYSIS

The following are the images of SEM analysis.

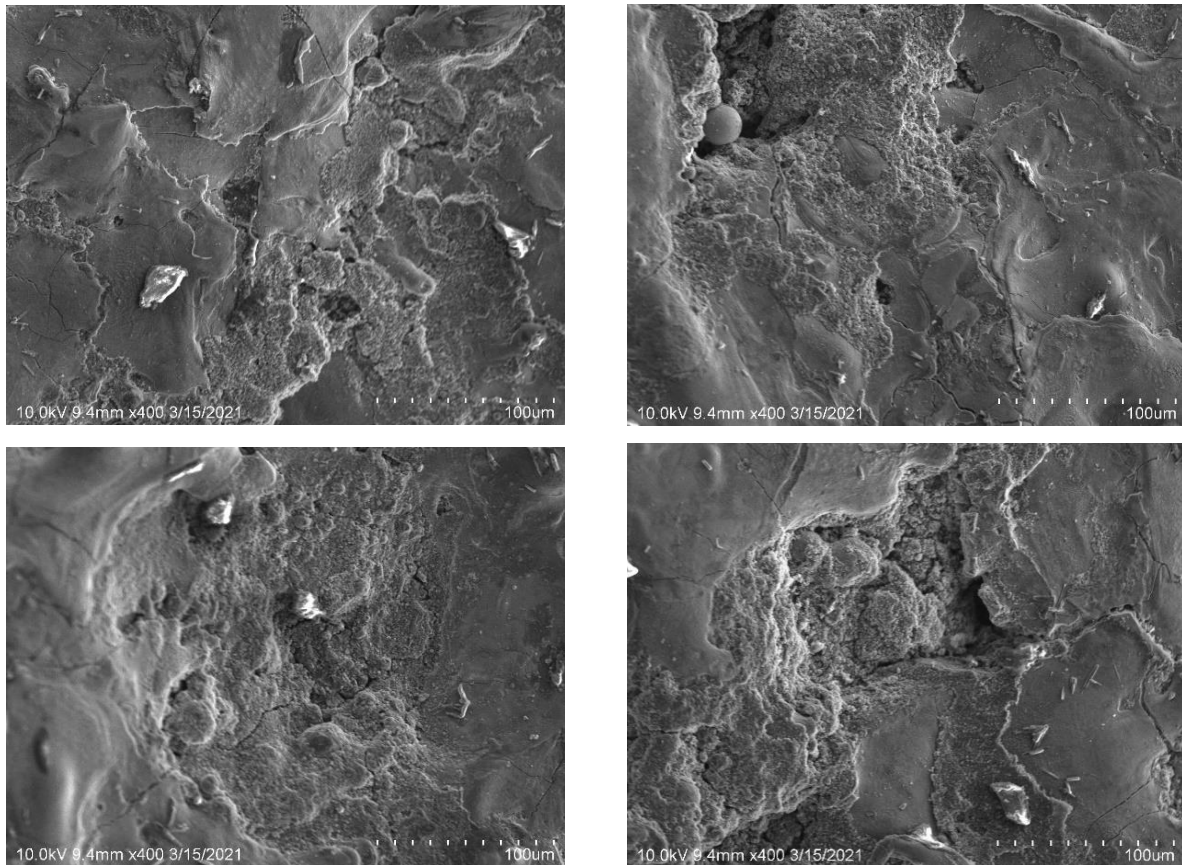


Fig: 5.4: SEM Analysis Images

These images show us that machining with Graphite gives us rough surface finish. The observation of high energy electrons released from the surface of a sample after it has

been subjected to an intensely concentrated beam of electrons from an electron gun is the basis of SEM. Using the SEM objective prism, this electron beam is focused on a small spot on the sample surface. To obtain the highest image quality, variables such as the accelerating voltage used, the size of the aperture used, and the distance between the sample and the electron gun can be optimized. The four SEM images show us how Titanium remains after machining with Graphite.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

EDM is a complicated machining process that is influenced by a large number of variables e.g., current, pulse on time, pulse off time, gap voltage, flushing pressure, electrode material and electrode size. But for current study the main factors considered are: current, voltage, pulse on Time (Ton), and electrode materials on EWR SR and MRR has been investigated. The result obtained from the experiment shows that current, voltage, pulse on time on electrode material has significant effect on MRR, EWR and SR. The current study's results suggest that input parameter selection plays a critical role in optimizing electric discharge machining.

6.2 CONCLUSIONS

After performing statistical analysis, the following findings were drawn from the ongoing investigations.

From the study we can infer that among all the input parameters, pulse on time and current has the most influence among all the parameters. The optimum input parameters are current of 30 amps, pulse on time 100 and voltage of 60 volts that yielded this optimal result for experiment No. 10. Grey relational analysis can be used to refine several parameters at the same time to produce the desired results. The accuracy of the results is determined by how well the parameters are set.

Based on the results of ANOVA analysis it has been seen that current and voltage were the most significant factors affecting material removal rate. MRR of the material increases with increase in current while it decreases with increase in voltage.

Based on the results of ANOVA analysis it has been seen that current is most significant parameter for electrode wear rate. Electrode wear rate decreases linearly with increase in current. EWR of the material is increasing gradually with increase in

voltage. It was found that EWR of the material lightly increases with increment in pulse on time.

Based on the results of ANOVA analysis it has been seen that current and voltage are the most significant parameters for surface roughness. Surface roughness of the material during machining decreases with increase in current and voltage. While it decreases initially with increment in pulse on time but increases with further increase in pulse on time.

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ABSTRACT The current project is on modelling and parametric analysis of TITANIUM GR-2 on EDM using Graphite as an electrode. Electric discharge machine is one of the most relatively used non-conventional machining process. In EDM material removal happens by rapidly produced electric spark between tool and work piece.

EDM is chosen to machine difficult-to-cut materials because of its high precision and performance. EDM can machine any electrically conductive material without regard to its strength or hardness. Current, pulse on-time, pulse off-time, gap voltage, feed, and flushing pressure are commonly used as machining parameters.

Significant parameters include metal removal rate, tool wear rate, taper, and surface roughness. This process can be employed to make complicated profiles. Graphite electrode was machined in order to test in EDM on Titanium Grade 2 workpiece. Experimental procedure was planned using the Taguchi L16 orthogonal array based grey relational analysis. EDM oil was used as the dielectric fluid for the experiment.