STUDY ON EFFECT OF WIRE EDM PROCESS PARAMETERS IN MACHINING OF INCONEL-625

A Project report submitted in partial fulfillment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY
In
MECHANICAL ENGINEERING
BY

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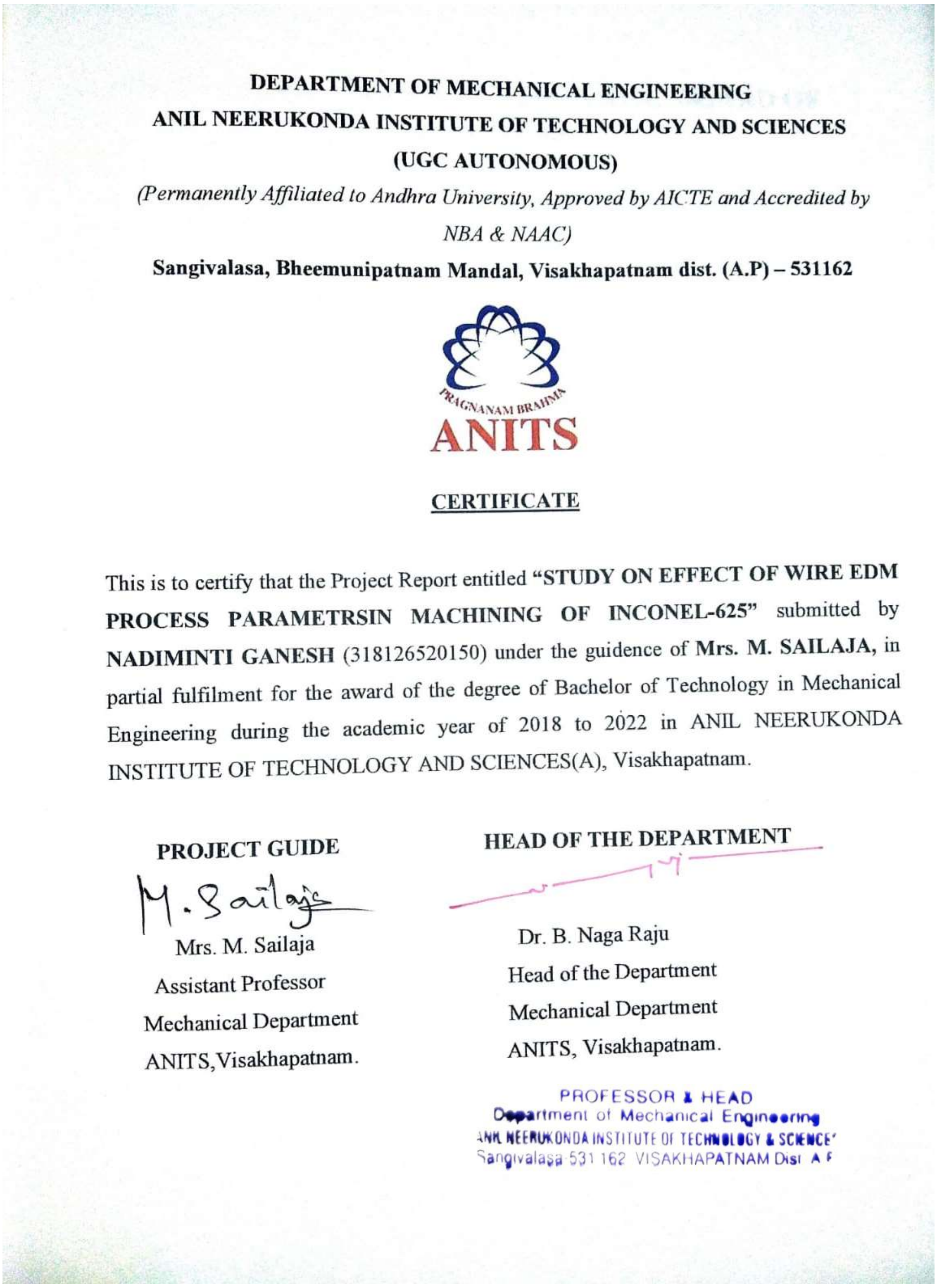

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CERTIFICATE

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ABSTRACT

Wire EDM machining of high-strength nickel-based super alloys has become a goal for researchers. In the present work, an experimental investigation has been conducted to study the effect of Wire-EDM process parameters on the responses of material removal rate and surface roughness characteristics. Inconel-625, which is commonly used for chemical, nuclear, and marine applications, has been selected as the work material. A number of experiments have been conducted using the L27 orthogonal array and the responses were analyzed using the single objective Taguchi method and ANOVA. The optimal combination for the higher-the-better characteristics is obtained at T_{ON}: 130 µs, T_{OFF}: 50 µs, SV: 20 volts, WF: 6 m/min, and WT: 3 kg/f, respectively. Similarly, for the lower-the-better characteristic, it was obtained at T_{ON}: 110 µs, T_{OFF}: 55 µs, SV: 25 volts, WF: 6 m/min and WT: 5 kg/f, respectively. An analysis of variance has been employed, and it is found that pulse-on-time (T_{ON}) is the predominant factor for both the responses. The regression models prepared were best fit and accurate as the residuals follow normality and constant variance, and hence they can be used for the best prediction of responses.

Keywords: *Wire-EDM, Material Removal Rate (MRR), Surface Roughness (SR), Orthogonal Array (OA), Taguchi method, ANOVA*

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CHAPTER 1

INTRODUCTION

In view of achieving higher production through consistent efforts by the manufacturing engineer, the manufacturing scenario has drastically changed in the present day metal cutting industry and focused towards an automated factory concept. Flexible Manufacturing System (FMS), Computer Integrated Manufacturing Systems (CIMS), a wide application of industrial robots, automated material handling and inspection systems has helped a lot in industrial automation and better productivity. All such progress in machine tools and metal machining is the outcome of the persistent effort, research work and logical thinking of scientists working in the area of metal cutting to understand what is happening when a cutting tool is fed into the work to cut the material.

1.1. Non-Conventional Machining Process

The conventional machining processes remove material by chip formation, abrasion or micro chipping. There are situations where these processes are not satisfactory, economical, or even impossible for the following reasons:

- The hardness and strength of the material is very high or the material is too brittle.
- The work piece is too flexible, slender, or delicate to withstand the cutting or grinding forces, or the parts are difficult to fixture- that is, to clamp in work holding devices.
- The shape of the part is complex, including such features as internal and external profiles or small-diameter holes.
- Surface finish and dimensional tolerance requirements are more rigorous than those obtained by other processes.
- Temperature rise and residual stresses in the work piece are not desirable or acceptable.

These requirements led to the development of chemical, electrical, laser, and other means of material removal, termed as un-conventional or non-traditional machining methods. There are a number of un-conventional machining processes having different characteristics as listed below in Table 1.1.

Table 1.1 Characteristics of Non-Conventional Machining Process

Process	Characteristics
Chemical Machining	Shallow removal on flat surfaces suitable for low production runs
Electro Chemical Machining	Complex shapes with deep cavities can be machined with highest material removal rates
Electric Discharge Machining	Shaping and cutting complex parts made of hard materials, some damage may occur due to spark erosion
Wire EDM	Contour cutting of flat or curved surfaces; expensive equipment
Electron Beam Machining	Cutting and hole making on thin materials. Very small holes and slots can be made expensive equipment. It requires vacuum.
Laser Beam Machining	Cutting and hole making on thin materials. Slots can be made; expensive equipment. But, does not require vacuum as in EBM.
Water Jet Machining	Cutting all types of metallic materials up to 25 mm thickness; no thermal damage; noisy
Abrasive Jet Machining	Cutting, slotting, deburring, etching of metallic and non-metallic materials; tends to round off sharp edges.

Out of the above-mentioned processes, the present research is restricted to the Wire Cut Electric Discharge Machining Process (WEDM).

1.2. Wire Cut Electric Discharge Machining

New materials created and/or demanded by space age technology sometimes cannot be economically cut using conventional cutting tools. Special, super-hard materials, normally quite expensive, are required. Synthetic diamonds or diamond compounds that are almost impossible to grind are very expensive, but are cut effectively by WEDM. The process wastes very little work piece material due to its small kerf size, coupled with the fact that the process can accurately cut unusual shapes. In modern manufacturing industry, WEDM has been extensively used to machine complicated shapes on advanced materials with high accuracy. WEDM is one of the most extended non-conventional machining processes. It is widely used to machine dies and moulds aimed at producing components for many industries. The main advantage of WEDM is its capability for the production of high complexity shapes with a high degree of accuracy, independently of mechanical properties of the material (especially, hardness, brittleness and resistance). Wire EDM uses brass, tungsten, or copper as its material for the electrode tool wire. Deionized water is used for the dielectric fluid. Almost like the standard EDM, the wire is eroded and slowly fed. Although it is similar to standard EDM, higher currents and lower rest times make this process much faster. Figure 1.1 shows the principle of WEDM process and Figure 1.2 shows the close view of machining zone.

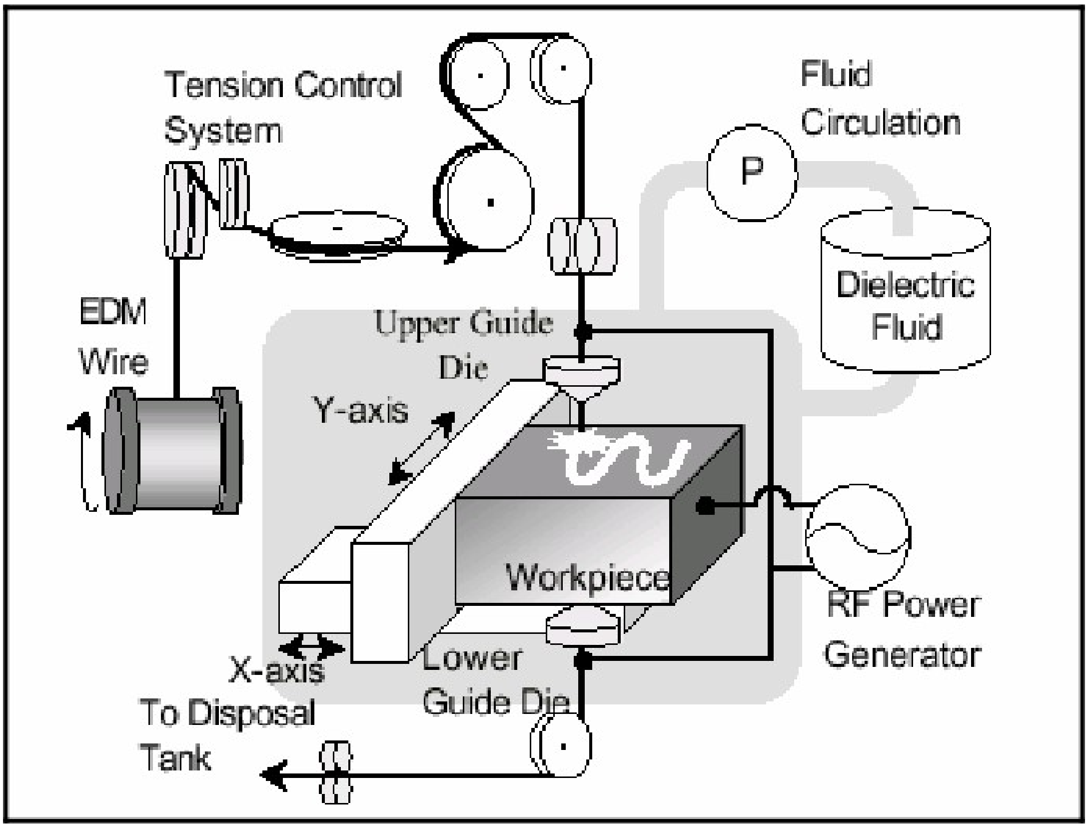

Figure 1.1 Wire Electrical Discharge Machining System

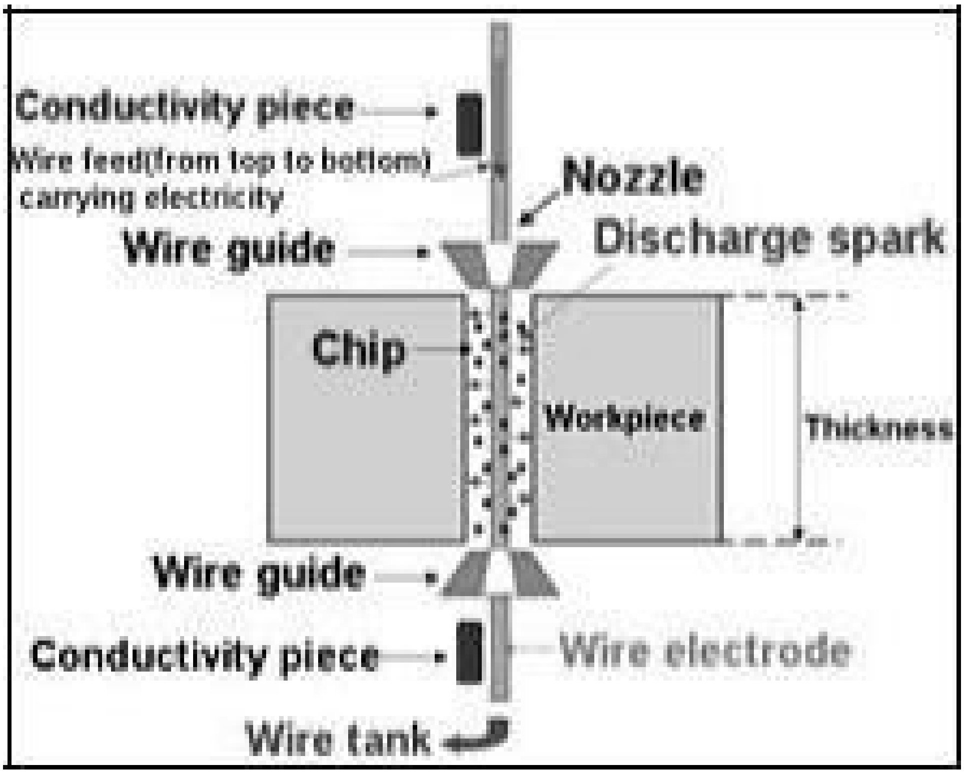

Figure 1.2 Close View of Cutting Zone in WEDM

1.3. How Wire EDM Works

WEDM is a special form of electrical discharge machining wherein the electrode is a continuously moving conductive wire. Material removal is effected as a result of spark erosion as the wire electrode is fed (from a spool) through the work piece. Figure 1.3 shows schematic view of generation of spark before the tool wire electrode starting the machining cycle.

Rapid DC electrical pulses are generated between the wire electrode and the work piece. Between the wire and the work piece is a shield of deionized water, called the dielectric fluid. Pure water is an insulator, but tap water usually contains minerals that cause the water to be too conductive for wire EDM. To control the water conductivity, the water goes through a resin tank to remove much of its conductive elements; this is called de ionized water.

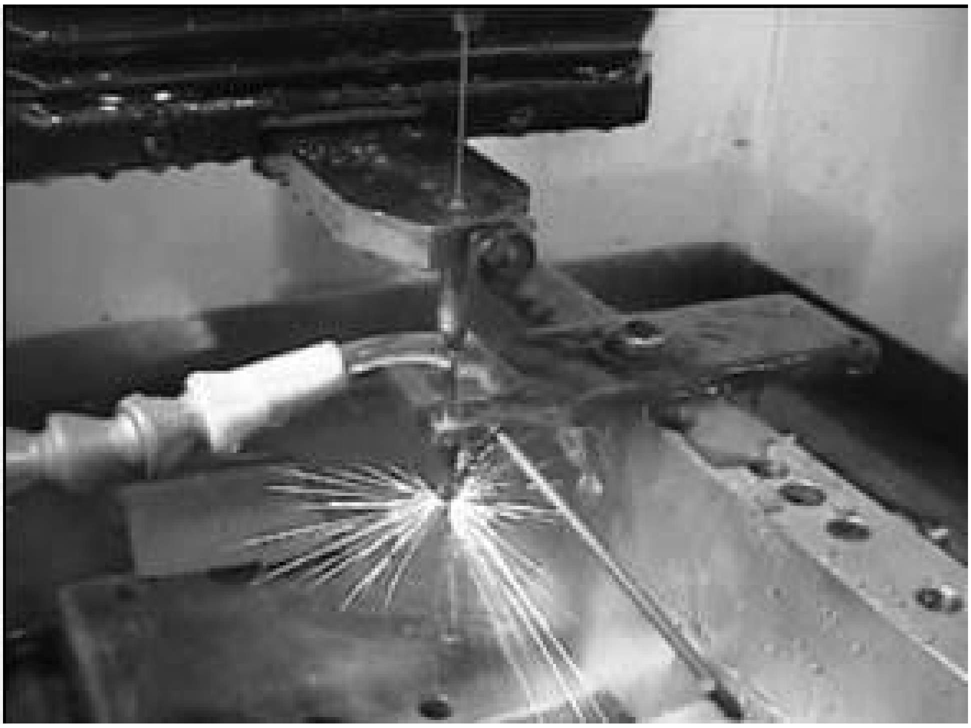

Figure 1.3 Generation of Spark in WEDM

When sufficient voltage is applied, the fluid ionizes. Then a controlled spark precisely erodes a small section of the work piece, causing it to melt and vaporize. These electrical pulses are repeated thousands of times per second. The pressurized cooling fluid, the dielectric, cools the vaporized metal and forces the re solidified eroded particles from the gap. The dielectric fluid goes through a filter which removes the suspended solids. Resin removes dissolved particles; filters remove suspended particles. To maintain machine and part accuracy, the dielectric fluid flows through a chiller to keep the liquid at a constant temperature.

The tool wire is usually made up of brass, copper or tungsten; zinc-or brass-coated and multi-coated wires are also used. The wire diameter is typically about 0.30mm for roughing cuts and 0.20mm for finishing cut. The wire should have sufficient tensile strength and fracture toughness, as well as high electrical conductivity and capacity to flush away the debris produced during cutting. The tool wire is generally used only once, as the wire gets deformed and loses its tensile strength. The wire travels at a constant velocity in range of 0.15 to 9.0 m/min, and a constant gap (kerf) is maintained during the cut. Figure 1.4 shows the path of wire generated by CNC automated computer system.

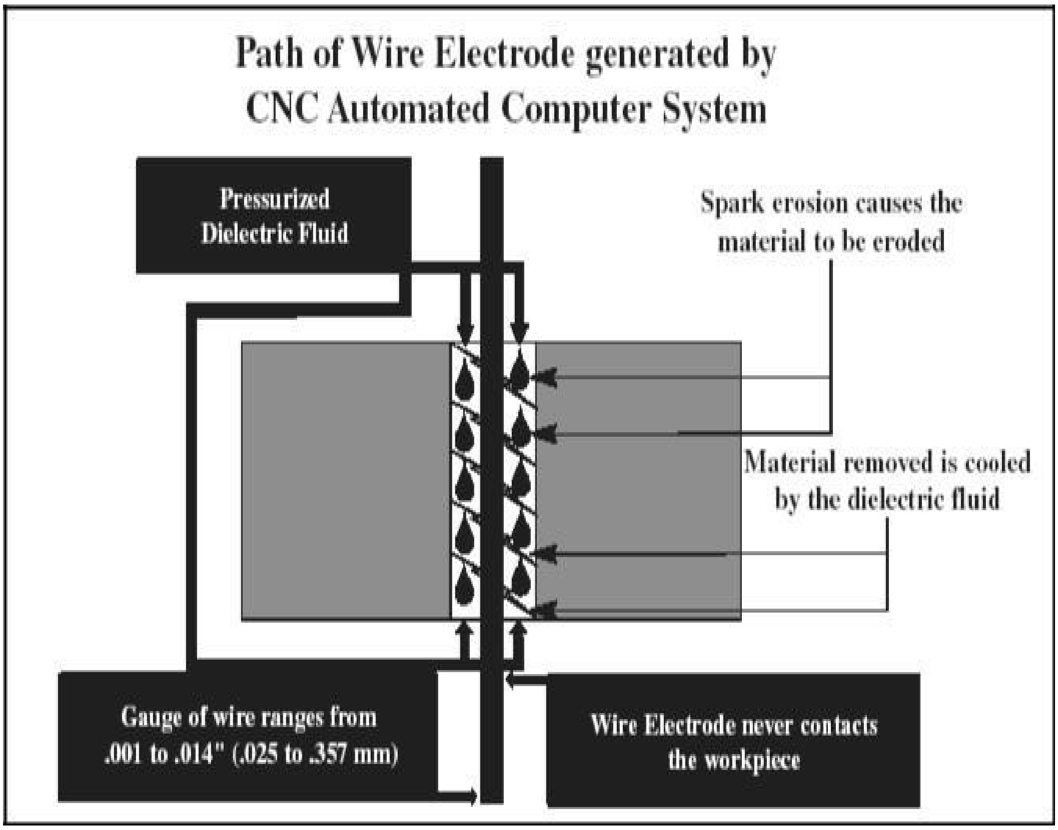

Figure 1.4 Path of Wire in WEDM

A DC or AC servo system maintains a gap from .002 to .003" (.051 to .076 mm) between the wire electrode and the work piece. The servo mechanism prevents the wire electrode from shorting out against the work piece and advances the machine as it cuts the desired shape. Because the wire never touches the work piece, wire EDM is a stress-free cutting operation.

1.4. Steps Involved In Wire EDM Process

Power Supply Generates Volts and Amps**:** Deionized water surrounds the wire electrode as the power supply generates volts and amps to produce the spark. Figure 1.5 shows how power supply generates volts and amps.

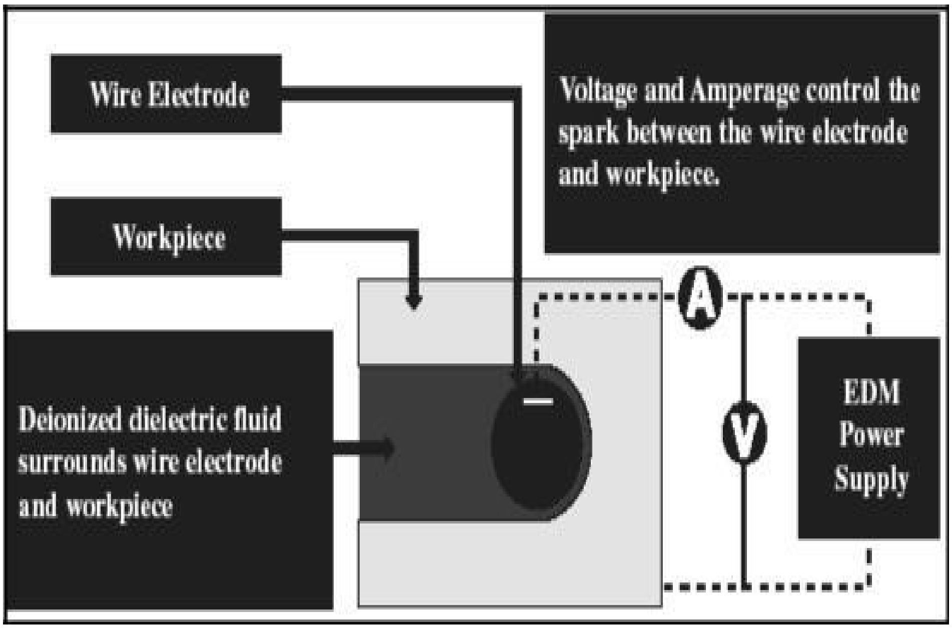

Figure 1.5 Power Generations in WEDM

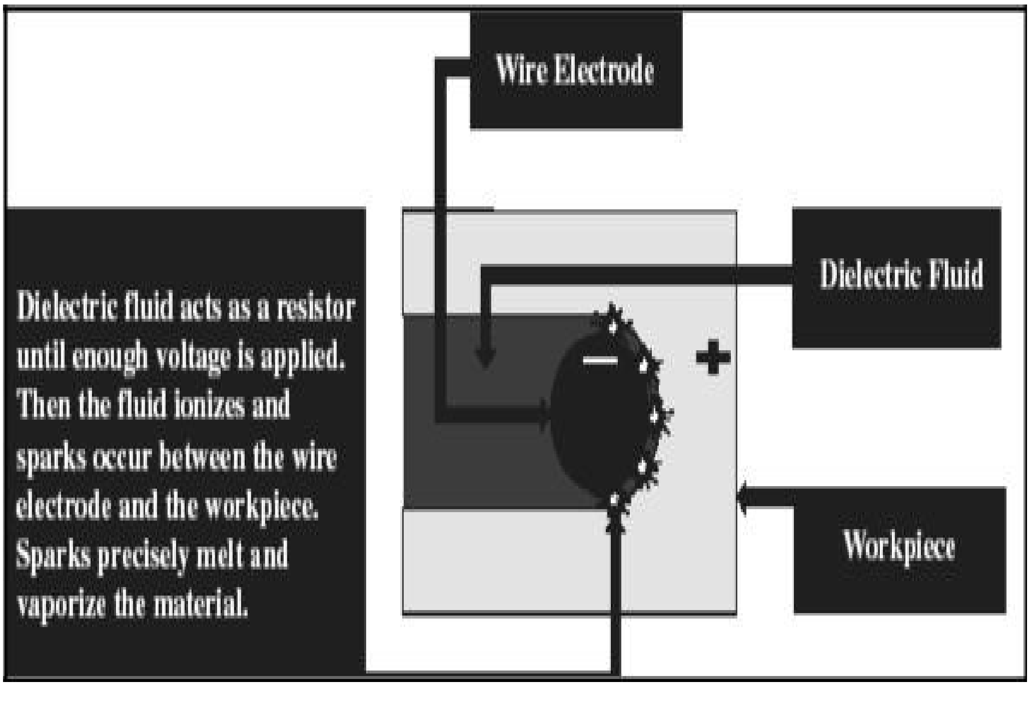

Figure 1.6 Erosion of Material in WEDM

During ON Time Controlled Spark Erodes Material**:** Figure: 1.6 shows how Sparks precisely melt and vaporize the material.

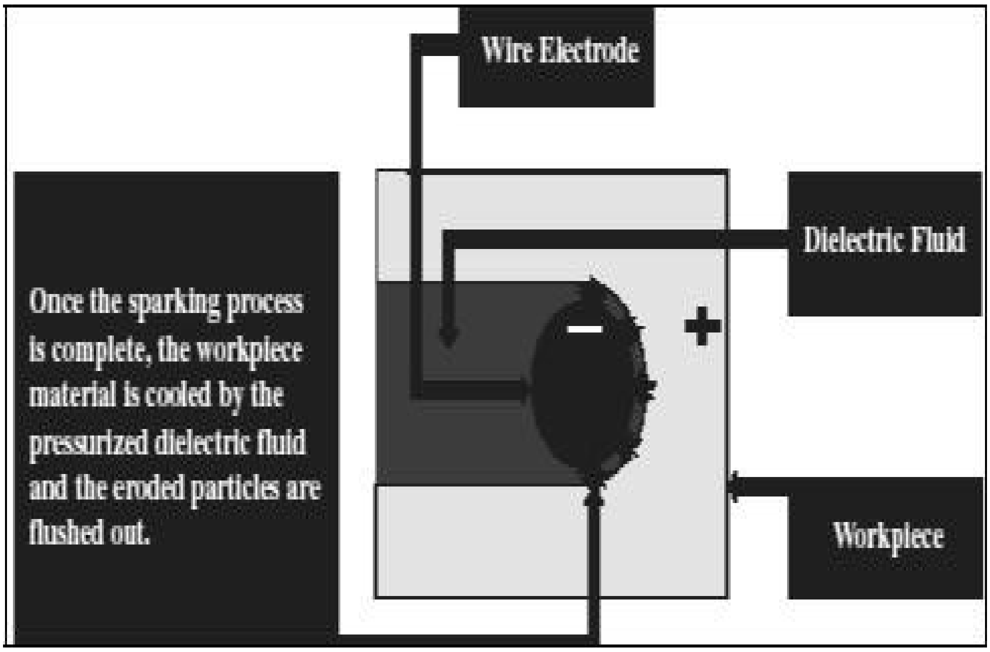

Figure 1.7 Spark Erosion during ON Time

OFF Time Allows Fluid to Remove Eroded Particles: During the off cycle, the pressurized dielectric fluid immediately cools the material and f1ushes the eroded particles as shown in Figure 1.7.

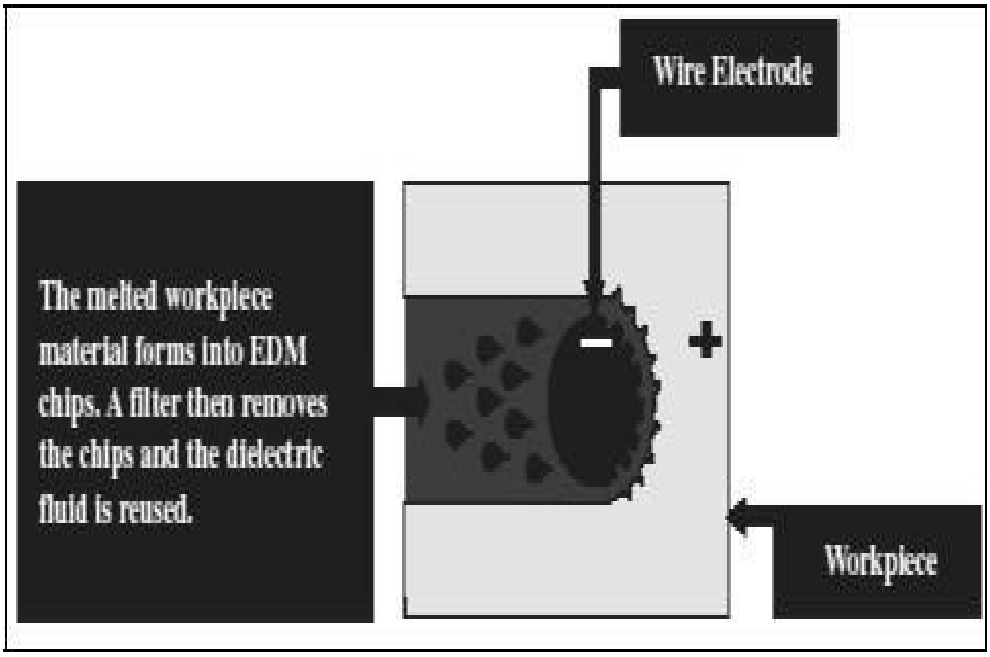

Figure 1.8 Chip Removal by Filtration

Filter Removes Chips While the Cycle is Repeated: The eroded particles are removed and separated by a filter system as shown in Figure 1.8.

1.5. Process Parameters and Their Influence

WEDM is complex in nature and controlled by large number of parameters. These parameters have to be controlled for effective working of the cutting process. The parameters may be grouped into input parameters and output parameters. Input parameters are those variables which are required to run the cutting process. The output parameters are those which are the outcome of the process and are observed on the finished work after cutting. Some of the process parameters in WEDM process are:

1.5.1 Influence of Wire Material Characteristics

As WEDM uses a thin wire as a single electrode, it is not necessary to make different shape of tool electrode to achieve the complex contours. However, to prevent the wire breaking, it becomes critical to obtain a continuous machining process. There has been a lot of effort by researchers over the years to improve the technology of the tool by overcoming the thermal effects to prevent the tool wire from breaking during the process. The optimal selection of wire properties would also determine its final performance.

1.5.2 Effect of Wire Tension

Within a considerable range, an increase in wire tension significantly increases the cutting speed. A higher tension decreases the wire vibration amplitude and hence decreases the cut width, so that the speed is higher for the same discharge energy. However, if the applied tension exceeds the tensile strength of the wire, it leads to wire breakage.

1.5.3 Effect of Frequency

This is a measure of the number of time the current is turned on and off. During roughing the ON time is increased significantly for high removal rates and there are fewer cycles per Second hence a lower frequency setting. Finish cycles will many cycles per second hence a larger frequency setting. Frequency should not be confused with the duty cycle as this is a measure of efficiency.

1.5.4 Heat Affected Zone

The Wire EDM process is a thermal process and, therefore, some annealing of the work piece can be expected in a zone just below the machined surface. In addition, not all of the work piece material melted by the discharge is expelled into the dielectric. The remaining melted material is quickly chilled, primarily by heat condition into the bulk of the work piece, resulting in an exceedingly hard surface. Since, the annealing effect is most common when unstable machining conditions exist, it can be reduced by choosing conditions that produce better stability.

1.5.5 Thickness of the Work Piece

In the WEDM process, cutting speed decreases as the thickness of the work piece increases. Normally, WEDM uses a transistor controlled capacitor circuit in which the cutting speed is controlled by a capacitor value. When using a fixed capacitor to machine a thicker work piece, the cutting speed is decreased.

1.5.6 Material of the Work Piece

Specific properties of the work piece material also influence the process. These properties include how well the metal is polished, its magnetic condition, and how the metal was removed from the heat treatment process when it was produced. One must also consider expansion and contraction according to the temperature of the materiel. For material processed by EDM or WEDM, the initial surface condition affects the results. A low melting point in the material increases the MRR, and improper heat treatment of the metal results in distortion and breakage of the mold.

1.5.7 Time ON

All the work is done during time ON. The spark gap is bridged, current is generated and the work is accomplished. The longer the spark is sustained more is the material removal. Consequently the resulting craters will be broader and deeper; therefore the surface finish will be rougher. Obviously with shorter duration of sparks the surface finish will be better. With a positively charged work piece the spark leaves the tool and strikes the work piece resulting in the machining. Except during roughing all the sparks that leave the tool result in a microscopic removal of particles of the surface. More sparks produce much more wear; hence this process behaves quite opposite to normal processes in which the tool wears more during finishing than roughing. Electrode material too plays a significant factor in tool wear.

1.5.8 Time OFF

While most of the machining takes place during time ON of the pulse, the time off during which the pulse rests and the reionization of the die-electric takes place, can affect the speed of the operation in a large way. More is the off time greater will be the machining time. But this is an integral part of the EDM process and must exist. The time off also governs the stability of the process. An insufficient off time can lead to erratic cycling and retraction of the advancing servo, slowing down the operation cycle.

1.5.9 Current

The average current is the average of the amperage in the spark gap measured over a complete cycle. This is read on the ammeter during the process. The theoretical average current can be measured by multiplying the duty cycle and the peak current (max. current available for each pulse from the power supply /generator). Avg. current is an indication of the machining operation efficiency with respect to MRR. The concept of maximum peak amperage that can be applied to the electrode is an important factor. Before determining the max. Peak ampere age the frontal area of the electrode minus the area of any flush holes must be determined. This setting can be fed into the CNC that controls the EDM operation.

1.5.10 Voltage

The voltage used is usually a DC power source of 40 to 400Volts. An AC power source can also be used but it is usually coupled with a DC rectifier. The pre-set voltage determines the width of the spark gap between the leading edge of the electrode and the work piece. High voltage settings increase the gap and hence the flushing and machining.

1.5.11 Gap Size

This is one of the most crucial parts of the EDM system. The size of the gap is governed by the servo control system whose motion is controlled by gap width sensors. They control the motion of the ram head or the quill, which in turn governs the gap size. Typical values of the gap size are between 0.010 to 0.050 mm, although gap sizes as small as of several hundred to several thousands of micrometre’s can be found depending on the application, current, voltage, and the die-electric media. To maintain a constant gap size the feed rate should be equal to the MRR. The gap size governs the possibility of sparking and arcing.

1.5.12 Surface Finish

The EDM process produces surface that contains a layer of recast-spattered metal, which is usually hard and cracked. Below this recast layer it is possible to have some surface alterations due to abusive machining. These are more pronounced when we use abusive machining conditions. The last layer is the heat-affected zone or the annealed layer, which has only been heated, not melted. The depth of the recast and the heat-affected zone is determined by the heat sinking ability of the material and the power used for the cut. The altered metal zone influences the quality of the surface integrity.

1.5.13 Polarity

Polarity refers to the electrical conditions determining the direction of the current flow relative to the electrode. The polarity of the electrode can be either positive or negative. Depending on the application, some electrode/work metal combination gives better results when the polarity is changed. Generally the graphite, a positive electrode gives better wear condition and negative gives better speed.

1.5.14 Material Removal Rate (MRR)

Achieving an efficient MRR is not simply a matter of good machine settings. It also includes direct energy dissipated in the EDM process. This energy can be dissipated in three ways:

1.5.15 The Work Piece

MRR is influenced by the thermal conductivity of the work piece. Copper for example has a low melting point but it also has a low MRR as it is a good conductor of heat. On the other hand steel has a high melting point but a low Thermal conductivity hence has a higher MRR.

1.5.16 In the Gap

Particles in the work gap will contribute significantly to slowing down the MRR.

1.5.17 In the Electrode

The MRR is also influenced by the electrode and the work piece selection.

1.5.18 Duty Factor

This is an important parameter in the EDM process. This is given by the ratio of the ON time to the total time. If we have a high duty factor then the flushing time is very less and this might lead to the short circuit condition. A small duty factor indicates a high off time and low machining rate. Therefore there has to be a compromise between the two depending on the tool used, the workpiece and the conditions prevailing.

1.5.19 Dielectric –Fluid Functions:

EDM dielectric fluids perform four functions necessary for spark machining. The fluids provide:

- A known electrical barrier between the electrode and work piece:
- Cooling for the electrode and work-piece
- Cooling for the vaporized material that becomes the EDM chip upon solidification
- A means for removal of the EDM-spark debris from the sparking gap.

1.5.20 De-Ionized Water

De-ionised water absorbs materials that make the water electrically conductive during the sparking process. As water absorbs materials the dielectric characteristics of the water change**.** This also changes the water’s ionization point and it affects the reliability and repeatability of the sparking process. Given these facts it would appear that deionised water is not an acceptable dielectric fluid. But wire-cut EDM uses dielectric fluid differently than diesinker EDM. In most instances, wire cut machining operations are not performed with the work piece submerged. Instead, a high velocity flow of fresh deionised water surrounds the electrode and covers the work piece in the sparking area, it then returns immediately to the collection system for reprocessing. This process ensures that the deionised water passing through the sparking area will stay within the acceptable range of the electrical characteristics required for precise EDM operations. In addition, it makes deionised water the dielectric fluid of choice for wire-cut operations.

1.5.21 De-Ionized water - Considerations

The following considerations are to be followed while using a deionized water dielectric system.

The deionizer unit removes dissolved material from water. This material then collects in the unity, diminishing the capability of the deioniser to produce acceptable water quality. At some point the deioniser material must be replaced.

- A process known as ion exchange deionises water. This process requires the use of a resin material. When replacing the deionizer unit, the used material must be disposed of accordance with environmental requirements.
- Water from the factory source may not be acceptable for filling or replacing water for the deionised water system. It may be necessary to obtain pre-deionised water.
- Bacteria and fungus can grow in the system and cause problems with the deionizer unit and filters. If this happens, the system might have to be purged and cleaned before acceptable water can be produced.
- Machine manufacturer recommendations should always be observed in setting up, using, and maintaining a deionised water dielectric system.

1.5.22 Filtration

Dielectric fluid needs to be filtered to remove EDM chips and by products that are produced during sparking. The filter assembly provided with the most EDM machines consists of a canister that contains the filter with a replaceable element. When the element becomes clogged and fluid flow through the filter is restricted, the element is removed and replaced. Disposal of the used filter must be in accordance with proper environmental considerations. It is a good policy for filter elements used with hydrocarbon fluids, to drain the fluid from the element prior to disposal. The salvaged fluid can be returned to the machine’s dielectric system. Filters do not completely remove all particles from the fluid. Filter elements are rated in microns according to their level of filtration.

1.5.23 Wire-Cut Chip Removal

Chip removal for a wire-cut machine is simple compared to a die-sinker machine. Wirecut machines include fluid-flow systems that provide dielectric-fluid flow with pressure to the top and bottom surfaces of the workpiece. The fluid is introduced into the sparking area by nozzles that direct flow into the machined opening. Figure 1.9 illustrates the positioning of the fluid-flow nozzles.

1.5.24 High Velocity Fluid Flow

Wire-cut machining normally requires high-velocity flow of fluid through the sparking area; the fluid must encapsulate the electrode wire and cover the entire sparking area, as fluid flows through the sparking area and out of the machined opening, the EDM chips are carried with it.

1.5.25 Positioning Fluid-Flow Nozzles

Fluid flow nozzles must be positioned very close to the top and bottom workpiece surfaces for effective fluid control and chip removal. If fluid escapes at either surface, less fluid will arrive in the sparking area.

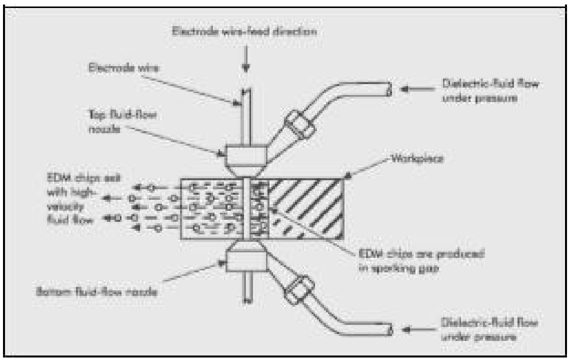

Figure 1.9 Wire Cut Fluid Flow Nozzles

Fluid must be supplied to the sparking area so that the electrode tool wire is completely surrounded with it. This provides the controlled sparking condition required for wire-cut machining. The dielectric fluid also cools the electrode tool wire that is heated by the wire's sparking and the passage of this spark electricity. Electrode tool wire breakage occurs if fluid does not properly surround the wire. Wire-cut machining is categorized into two classifications.

- Full-wire plunge machining.
- Partial-wire finish machining.

Full-wire plunge machining creates a sparking area on the electrode wire, Figure 1.10 illustrates this type of machining. In full-wire plunge machining centre enough care needs to be taken in controlling the fluid flow as it surrounds the electrode tool wire. After establishing the machined kerf slot, fluid flow is fairly consistent. But at the start of the machining operation fluid flow may be difficult to establish. If the electrode tool wire enters from a surface outside of the work piece. Fluid flow may be controllable enough to allow efficient machining conditions. In this case, reduced sparking energy should be used until the tool wire machines a slot into the workpiece. Otherwise, wire breakage is likely. A preferred method for starting a wire-cut machining operation is to provide a pre-drilled start hole in the workpiece to create positive fluid control by surrounding the electrode tool wire with fluid. In Partial wire finish machining wire plunge creates less than 180^0 sparking area as shown in Figure 1.11. In partial-wire machining, a curtain of fluid covers the workpiece in the sparking area and encloses the electrode wire. Chips are carried away with the fluid as it flows past the machined surface. Fluid flow for partial-wire machining is at a much lower velocity than fullwire machining. Controlling the dielectric fluid is a major consideration when using partial wire sparking. High velocity flow is used for full-wire plunge machining, but is not acceptable for partial-wire machining, which does not have enclosed sparking area.

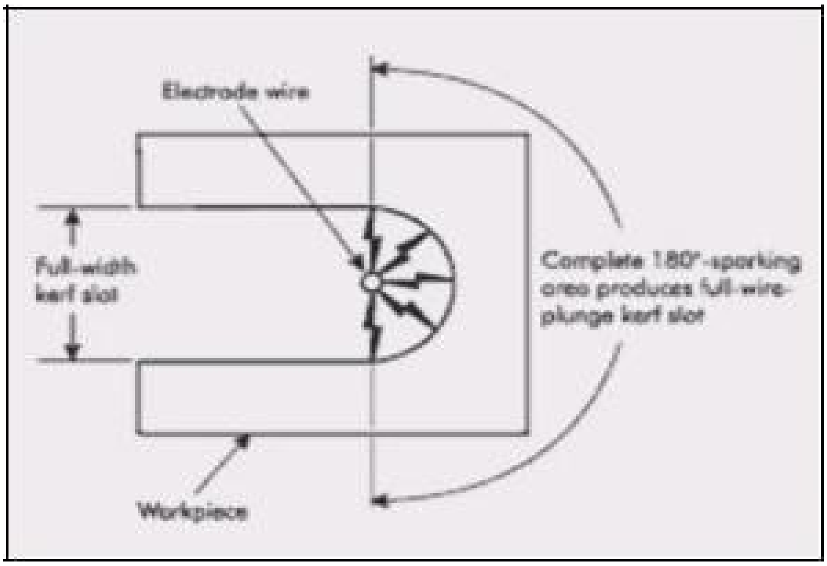

Figure 1.10 Full-Wire Finish Machining

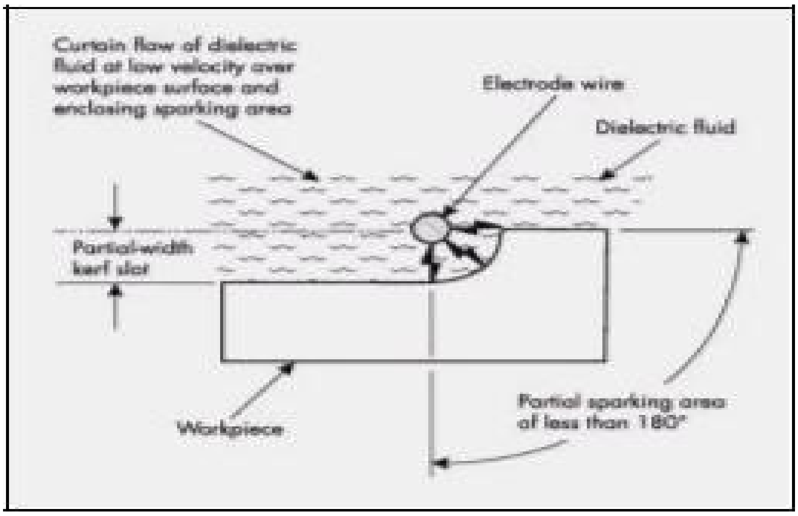

Figure 1.11 Partial-Wire Finish Machining

1.5.26 Minimum Wall Thickness for Fluid Control

Loss of fluid in the sparking area also occurs due to insufficient material at the sides of the machining operation. In most machining operation it is desirable to remove as little of workpiece material as possible. But in a full plunge machining, a certain wall thickness is required for efficient fluid control. A narrow wall does not allow the fluid-flow nozzle to seal the workpiece surface from fluid coming through the nozzle. Therefore a wall thickness of less than 0.25 inch (6.35mm) should be used with full-plunge machining. Any thinner wall thickness can result in escaping fluid, increased machining time and possible wire breakage.

1.5.27 Wire EDM Transport System

Wire EDM uses an electrically charged thin brass wire, which is moved by computer control, close to, but not touching, the part to be cut. The wire and the work piece are either fully submerged, or the part is vigorously flushed with a dielectric liquid. The small gap creates a spark, which vaporizes small particles of the work piece as the wire advances. The disintegrated particles are flushed away by dielectric fluid, and the wire is able to advance further. The wire itself is traveling – advancing from a large spool, and after use as an electrode, into a spent wire bin. The travel of the wire is determined by the machine’s computer program. The complexities of the wire transport system as shown in Figure 1.12 and automatic wire threader (AWT) both have a direct impact on performance. Since the wire used in the wire EDM is small and flexible, no more than two times larger than a human hair, threading reliably over long periods of time without extensive maintenance has been perceived as a problem. However, the most important feature of a wire EDM machine, in terms of real profitability to the end user, is the AWT- a reliable AWT system can add many hours of Available foe every week, month and year. The AWT makes it possible to schedule work more efficiently on the wire EDM machine based upon the importance rather than the length-time-of cut.

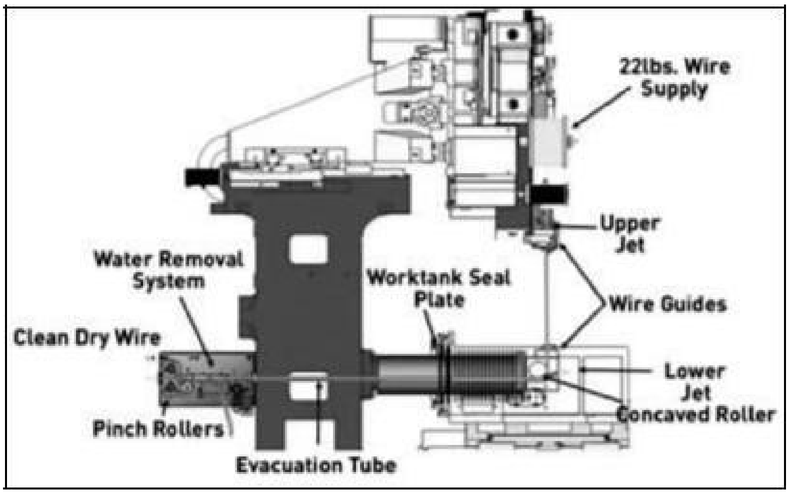

Figure 1.12 Wire EDM Transport System

Most AWTs use a high-pressure water jet as the main wire transport system between the upper and lower guides. The entire transport system must be maintained according to the manufacturer's recommendations. Wire guide types, the complexity of the jet, the cutting system, drive pulleys and tensioning all have an impact on reliability and performance. When it becomes possible, depending upon type of application, to operate in an unattended environment overnights, weekends and holidays, it is realistic to gain hundreds of machining hours per year. In fact, a highly reliable machining system, operating on a continuing basis will outperform a less reliable system cutting at high speed. Failure to properly maintain this valuable machine feature will affect production.

1.6. Materials That WEDM Can Cut:

1.6.1 Carbide

Tungsten carbide, third in hardness to diamond and boron carbide, is an extremely difficult material to machine. Except for diamond cutting tools and diamond-impregnated grinding wheels, EDM presents the only practical method to machine this hardened material. To bind tungsten carbide when it is sintered, cobalt is added. The amount of cobalt, from 6% to 15%, determines the hardness and toughness of the carbide. The electrical conductivity of cobalt exceeds that of tungsten, so EDM erodes the cobalt binder in tungsten carbide. The carbide granules fall out of the compound during cutting, so the amount of cobalt binder determines the wire EDM speed, and the energy applied during the cutting determines the depth of binder that is removed. When cutting carbide on certain wire EDM machines, the initial first cut can cause surface micro-cracks. To eliminate them, skim cuts are used. However, at our company, we have repeatedly cut carbide parts with a single cut. When precision carbide parts are needed, skim cuts are used. Some older wire EDM machines used capacitors. Since these machines applied more energy into the cut, there was a greater danger for surface microcracking. Then DC power supply machines without capacitors were introduced, and this helped in producing less surface damage when cutting carbide. Today, many machines come equipped with AC power supplies. These machines are especially beneficial when cutting carbide in that they produce smaller heat-affected zones and cause less cobalt depletion than DC powersupplied machines. To eliminate any danger from micro-cracking and to produce the best surface edge for stamping, it is a good practice to use sufficient skim cuts when EDMing highprecision blanking carbide dies. Studies show that careful skimming greatly improves carbide surface quality. Durability tests prove that an initial fast cut and fast skimming cuts produce very accurate high performance dies.

1.6.2 Polycrystalline Diamond

The introduction of polycrystalline diamond (PCD) on a tungsten carbide substrate has greatly increased cutting efficiency. PCD is a man-made diamond crystal that is sintered with cobalt at very high temperatures and under great pressure. The tungsten substrate provides support for the thin diamond layer. The cobalt in PCD does not act as a binder, but rather as a catalyst for the diamond crystals. In addition, the electrical conductivity of the cobalt allows PCD to be EDMed. When PCD is EDMed, only the cobalt between the diamonds crystals is being EDMed. EDM machining PCD, like EDM machining carbide, is much slower than cutting steel. Cutting speed for PCD depends upon the amount of cobalt that has been sintered with the diamond crystals and the particle size of PCD. Large particles of PCD require very high open voltage for it to be cut. Also, some power supplies cut PCD better than others.

1.6.3 Ceramics

Ceramics are poor conductors of electricity. However, certain ceramics are formulated to be cut with wire EDM.

1.6.4 Cost Savings with WEDM

There are twelve Criteria for Using Wire EDM in Production Applications:

1.6.5 Hard materials

The foremost benefit of wire EDM technology is its ability to cut hard material. The hardness of the material to be cut does not affect the EDM's speed or ability to cut it. Wire cutting can be performed on parts with finished dimensions after heat treating with no additional cost. Typical applications: large series production molds, jigs, fixtures, form tools, knives.

1.6.6 Exotic Metals

Wire EDM process can cut any material that conducts electricity, including Carbide, Inconel, Titanium, Haste Alloy, and many others. Typical applications: carbide knives and wear surfaces, Inconel molds, titanium high performance parts.

1.6.7 Stacking Plates

We can stack thin plates of a specific material and get multiple pieces with a single cut. Typical applications: custom collet wrenches, flat gears, copper shims.

1.6.8 Speed of EDM Delivery

Production Wire EDM delivery is very rapid as it usually requires little or no tooling or fixturing. Typical applications: medical and dental prototypes, prototype gears, prototypes for molded parts.

1.6.9 Racking of Parts

Wire EDM machining allows us to rack parts: this technique is used when only a particular portion of the work piece needs a complex geometry wire cut into or through it.

1.6.10 Raw Materials

Wire EDM saves time and money by making possible the use of raw materials straight from the mill. Bar stock, round stock and plates can all used with little added processing. A job that would normally require sawing, squaring and milling of stacked plates can be accomplished in much fewer operations with a wire EDM.

1.6.11 Complex Geometries

Wire EDM is especially beneficial when shapes such as gears, splines, and long thin slots are required. Any operation requiring such geometries is an excellent candidate for wire EDM.

1.6.12 Internal Contours

Pipes, gears, pultrusion molds all benefit from wire EDM.

1.6.13 Design Flexibility

Since programs are easily adjusted, prototypes and single parts are extremely well suited for Wire EDM machining. A part is manufactured very easily since no hard tooling is involved. Changes to part design can be handled simply and quickly.

CNC 5 Axis Wire Cutting Capability

Complex three dimensional programming systems enable EDM machines to independently control the top and bottom contour when wire cutting CNC 5 axis wire. Other applications: tapered pins for molds, extrusion molds.

1.6.14 Burr Free

Wire EDM eliminates secondary deburring operations, reducing the number of steps required to complete each part. Applications: go/no go gauges, custom tool inserts.

1.6.15 Splines

Wire EDM allows us to cut splines that would not be possible to cut with mechanical tools. We can make sharp angles with a radius as small as the diameter of the wire.

1.6.16 Applications

Machine tools with disposable blades also cut with a wire EDM.

1.7. Benefits of Wire EDM

1.7.1 Efficient Production Capabilities

Because of the precision and high-speed of wire EDM machines, manufacturers are increasingly discovering that many parts can be more economically produced with wire EDM, rather than with conventional machining.

1.7.2 Production Reliability

The constant reliability of wire EDM is one of the greater advantages of this process. Because the programs are computer generated and the electrode is constantly being fed from a spool (the tool wire electrode is used only once), the last part is identical to the first part. The cutter wear found in conventional machining does not exist. In addition, tighter machining tolerances can be maintained without additional cost.

1.7.3 Without EDM Impossible to Machine

As more and more engineers, tool designers, and machinists understand the wire EDM process, many unique machining processes can be performed that can only be done with wire EDM.

1.7.4 Reduced Costs

To be competitive in today's market it is important to take advantage of every costsaving procedure available. The high-speed cutting wire EDM machines of today have dramatically reduced costs for many manufactured parts. Conventional machining leaves sharp edges and often burrs when machined, but a radius can be made with wire EDM without any additional cost. This eliminates a filing or sanding operation.

1.7.5 Stress-Free and Burr-Free Cutting

Wire EDM is a non-contact, force-free, metal-removing process which eliminates cutting stress and resultant mechanical distortion. Extremely thin sections can be machined because the wire electrode never contacts the material being cut. Materials cut with wire EDM are totally burr-free, and the edges are perfectly straight. Thin parts can be stacked and cut without leaving any burrs.

1.7.6 Tight Tolerances and Excellent Finishes

The wire path is controlled by a CNC computer-generated program, with part accuracies up to +/- .0001" (.0025 mm). Dowel holes can be produced with wire EDM to be either press or slip fit. The extremely fine finish from the standard wire EDM process often eliminates the need for grinding or other finishing procedures.

1.7.7 Program Files Downloadable

If the parts to be machined are programmed on a CAD system, many job shops can accept the files directly into their systems. Electronically transmitting these files eliminates the need for reprogramming the parts.

CHAPTER 2

LITERATURE SURVEY

Electric discharge machining (EDM) is one of the most efficient manufacturing technologies used in highly accurate processing of all electrically conductive materials irrespective of their mechanical properties. It is a non-contact thermal energy process applied to a wide range of applications, such as in the aerospace, automotive, tools, molds and dies, and surgical implements, especially for the hard-to-cut materials with simple or complex shapes and geometries. Applications to moulds, tools, and dies are among the large-scale initial applications of this process. Machining these items is especially difficult as they are made of hard-to-machine materials, they have very complex shapes of high accuracy, and their surface characteristics are sensitive to machining conditions. This review provides an overview of the studies related to EDM with regard to selection of the process, material, and operating parameters, the effect on responses, various process variants, and new techniques adopted to enhance process performance. This chapter reviews research studies on the EDM of different grades of INCONEL materials. This chapter (i) pans out the reported literature in a modular manner with a focus on experimental and theoretical studies aimed at improving process performance, including material removal rate, surface quality, and tool wear rate, among others, (ii) examines evaluation models and techniques used to determine process conditions, and (iii) discusses the developments in EDM and outlines the trends for future research.

In recent years, rapid developments in aerospace, medical instruments, transportation, and many other industrial sectors increased the need for new materials with favourable characteristics. In addition to unique characteristics, most modern materials need special manufacturing processes to enable them to be machined with ease . Most of these materials are usually difficult to cut by conventional manufacturing processes. The unique characteristics of these hard-to-cut materials increase their applications, which further drive manufacturers to explore new machining processes with reasonable cost and high precision.

Inconel materials are nickel-chrome-based superalloys. Inconel has high corrosion resistance, oxidation resistance, strength at high temperatures, and creep resistance.

Inconel is able to withstand elevated temperatures and extremely corrosive environments. The chemical composition of Inconel material varies with grades. As this is a nickel allow, the Nickel percentage is more. Other elements present in Inconel alloy material are: Chromium, Iron, Cobalt, Molybdenum, Titanium, Niobium. The most widespread application of Inconel alloys is found in the aerospace industry. The space shuttle, Rocket engines, 3D printing technology, etc use Inconel. The nuclear industry also uses a lot of various Inconel grades.

Electric discharge machining (EDM) is one of the most advanced manufacturing methods used to successfully machine conductive hard-to-cut materials. EDM is the process of choice to machine hard-to-cut materials widely used in modern industries to facilitate accurate machining, complex shape machining, and better surface integrity. The process is utilized to machine electrically conductive materials by applying repetitive sparks between electrode and workpiece. Unlike in mechanical machining, no deforming force is required between the electrode and the workpiece, and the machining takes place without actual contact between them. There are a large number of variants of the EDM process such as sinking EDM, wire EDM, micro-EDM, powder-mixed EDM, and dry EDM; all of these possess work on the same mechanism of material removal. Developments of variants make the process more versatile and suitable for relatively big and micro-scale machining areas. Several review papers related to EDM were published in recent years such as references, among others. Furthermore, some other articles presented a discussion of specific objectives. The EDM remains one of the most popular processes used for their fabrication. Figure 2.1 shows the EDM processes and their main process parameters and output (performance) measures.

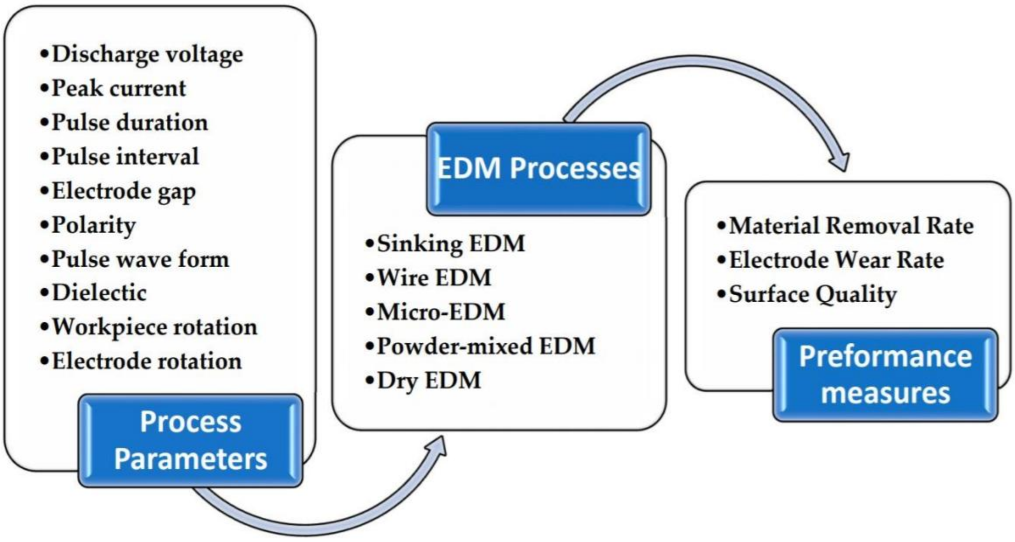

Figure 2.1. The processes of electric discharge machining (EDM) and their process parameters and performance measures.

2.1. Various Grades of INCONEL

Inconel is a registered trademark of Special Metals Corporation for a family of austenitic nickel-chromium-based superalloys. Inconel alloys are typically used in high temperature applications. Common trade names for

- Inconel Alloy 625 include: Inconel 625, Chronin 625, Altemp 625, Haynes 625, Nickelvac 625 and Nicrofer 6020.
- Inconel Alloy 600 include: NA14, N06600, BS3076, 2.4816, NiCr15Fe (FR), NiCr15Fe (EU) and NiCr15Fe8 (DE).

- Inconel 718 include: Nicrofer 5219, Superimphy 718, Haynes 718, Pyromet 718, Supermet 718, and Udimet 718.

Inconel material has a variety of grades varying in composition and properties developed for specific applications. The common Inconel grades are as follows:

- Inconel 188: Readily fabricated for commercial gas turbine and aerospace applications.

- Inconel 230: Alloy 230 Plate & Sheet mainly used by the power, aerospace, chemical processing and industrial heating industries. • Inconel 600: Solid solution strengthened
- Inconel 601:
- Inconel 617: Solid solution strengthened (nickel-chromium-cobalt-molybdenum), high-temperature strength, corrosion and oxidation resistant, high workability and weldability. Incorporated in ASME Boiler and Pressure Vessel Code for high temperature nuclear applications such as molten salt reactors c. April, 2020. • Inconel 625: Acid resistant, good weldability. The LCF version is typically used in bellows.
- Inconel 690: Low cobalt content for nuclear applications, and low resistivity[53]
- Inconel 713C: Precipitation hardenable nickel-chromium base cast alloy
- Inconel 718: Gamma double prime strengthened with good weldability
- Inconel X-750: Commonly used for gas turbine components, including blades, seals and rotors.
- Inconel 751: Increased aluminium content for improved rupture strength in the 1600 °F range
- Inconel 792: Increased aluminium content for improved high temperature corrosion resistant properties, used especially in gas turbines
- Inconel 907 • Inconel 909
- Inconel 706
- Inconel 939: Gamma prime strengthened to increase weldability.
- Inconel 925: Inconel 925 is a non-stabilized austenitic stainless steel with low carbon content.

In age hardening or precipitation strengthening varieties, alloying additions of aluminum and titanium combine with nickel to form the intermetallic compound $Ni_3(Ti,Al)$ or gamma prime (γ'). Gamma prime forms small cubic crystals that inhibit slip and creep effectively at elevated temperatures.

Earlier studies were also conducted to investigate the relationship between processes and performance parameters. The main researches in optimizing process parameters of EDM machining are summarized in Table 2.1.

Table 2.1 Researches in optimizing process parameters of EDM

S.No	Authors	Process	Process parameters	Machining performance	Remarks
1	Younis et al., 2015 [20]	EDM	Is, EM, and MC	CR and RS	SR was higher when using Dura graphite than when using Poco graphite. As pulse current increases, micro-cracks increase; soft machining exhibited higher residual stresses than medium and rough machining. Poco graphite exhibited higher residual stresses compared with Dura graphite electrode.
2	Valaki and Rathod 2015 [21]	Die sinking EDM machine	Is, Vg, Ton, and Tof	MRR, EWR, and TWR	The waste vegetable oil-based bio-dielectric fluid can be used as an alternate to hydrocarbon-, water-, and synthetic-based dielectric fluids for EDM.
3	Zhang et al. 2014[22]	EDM	PD and PoW	RE, D_plas, and RE	The MRR and energy efficiency were much higher with short pulse durations than with long pulse durations. The depth–diameter ratio of the crater was higher when the workpiece was positive.
4	Sudhakara and Prasanthi 2014 [23]	WEDM	Ton Toff, Vs, Ip, WT, and DP	SR	The ranges of process parameters for wire EDM were established as follows: pulse-on time 108–128 μs, pulse-off time 47–63 μs, peak current 11–13 A, voltage 18–68 V, wire tension 2–8 g, water pressure 8–14.
5	Aich and Banerjee	EDM	I, Ton, and Toff	MRR and SR	The optimal parameters (I, Ton, and Toff) to

	2014 [24]				maximize the MRR were 12.0 A, 153.9865 µs, and 50.0000 µs, respectively, and those to achieve the best SR were 3.0 A, 200.000 µs, and 126.8332 µs, respectively.
6	Balasubramanian and Senthilvelan 2014 [25]	EDM	Ip, Ton, DP and D_tool	MRR, TWR, and SR	For EN-8 material, the mean MRR value was (72.4 mm3 /min), it was higher for the cast electrode than for the sintered electrode. The TWR was (12.73 mm3 /min); it was lower for the cast electrode than for the sintered electrode. For die steel D3, the mean value of MRR was higher for the cast electrode than for the sintered electrode. The TWR was marginally lower for the cast electrode than for the sintered electrode. The mean value of SR was marginally lower for the sintered electrode than for the cast electrode.
7	Sahu, Mohanty et al. 2013 [26]	EDM	Ip, Ton, τ, and Dp	MRR, TWR, SR, and r1 /r2	The values of discharge current (Ip), pulse-on time (Ton), duty factor(τ), and flushing pressure (Fp) that achieved the best quality were 7 A, 200 µs, 90%, and 0.4 kg/m2, respectively. The optimal obtained response parameters were MRR = 13.9600 mm3 /min, TWR = 0.0201 mm3 /min, Ra = 4.9300 µm, and

					circularity = 0.8401.
8	Klocke et al. 2013 [27]	EDM	I, PD, and GG	MRR and TWR	The discharge current was the main parameter effect on the MRR and the discharge duration was the main parameter effect on the TWR. There was no direct link between the grain size and the two response parameters MRR and TWR. MRR increases as the current increases and it decreases as the pulse duration and electrical conductivity of graphite grade increase. Relative TWR slightly decreases as the current increase and slightly increases as the electrical conductivity of graphite grade increase, whereas it sharply decreases as pulse duration increases.
9	(Shabgard et al. 2013) [28]	EDM	Is and Ton	PFE	Plasma flushing efficiency increases as pulse current increases and it decreases as pulse-on time increases. Recast layer thickness increases as pulse-on time increases.
10	Fan, Bai et al. 2013 [29]	W EDM-HS	C	T and SR	Best surface roughness and the minimum achievable maximum processing thickness were obtained upon selecting a capacitance that achieved triple the charging time constant equal to pulse duration.
11	Srivastava	EDM	Is, Ton, τ,	MRR, EWR,	EWR and surface

	and Pandey, 2012 [30]		and Vg	and SR	roughness were significantly lower in the ultrasonic assisted cryogenically cooled copper electrode (UACEDM) process than in the conventional EDM process and MRR was approximately the same as for conventional EDM. Surface integrity of the workpiece machined by UACEDM was better than that machined by the conventional EDM process. In UACEDM, the density of cracks increases as the discharge current increases. Induced stress increases as pulse-on duration and crack formation increase.
12	(Teimouri and Baseri 2012) [31]	EDM	DE, H, and w	MRR and SR	The rotary tool electrode improved the machining performance. The magnetic field reduced the inactive pulses and helped the ionization. As rotational speed increases, Ra decreases.
13	(Kumar and Batra 2012) [32]	EDM	Ip, Ton, and Tof	μH	Machining conditions allowing material transfer (of tungsten and carbon to the workpiece surface) by EDM were at a discharge current less than 5 A, shorter pulse-on time less than 10 μs, and longer pulse-off time more than 50 μs with negative polarity of the tool electrode. The most

					significant factor for surface modification was peak current.
14	Sivapira et al. 2011 [33]	EDM	Ip, PD, DL, and DF	S_green	The optimal machining performance for green EDM was with peak current = 4.5 A, pulse duration = 261 µs, dielectric level = 40 mm, and flushing pressure = 0.5 kg/cm2 .
15	Çayda¸s et al. 2009 [34]	Wire EDM	PD, V, DP, and S-wire	TWL and Avr_SR	The developed approach greatly improved the surface roughness and white layer thickness in wire EDM.
16	Lin et al. 200) [35]	EDM	P, Ip, PD, IH, V, and Vs	MRR and SR	The MRR of magnetic force-assisted EDM was almost three times as large as the value for standard EDM. Employing magnetic force-assisted EDM improved the lower relative electrode wear ratio (REWR) from 1.03% to 0.33% and reduced the SR from Ra 3.15 to 3.04 µm on average. Discharge craters were bigger and deeper, and micro-cracks were more common in standard EDM than that magnetic force-assisted EDM. In the magnetic force-assisted EDM process, MRR was significantly affected by polarity and peak current and SR was significantly affected by peak current. The optimal

					parameters which maximized MRR were negative polarity, peak current = 5 A, auxiliary current = 1.2 A, pulse duration = 460 μs, no-load voltage = 120 V, and servo reference voltage = 10 V. The optimal parameters which achieved minimum SR were positive polarity, peak current = 20 A, auxiliary current = 0.8 A, pulse duration = 460 μs, no-load voltage = 200 V, and servo reference voltage = 10 V.
17	Wu et al. 2009 [36]	EDM	Ip, PD, V, and Vg	MRR and SR	Adding 30 g/L of Span 20 to kerosene increased the MRR by 40%. Selecting proper working parameters improved MRR by 85%. SR was not deteriorated even at MRR. Adding Span 20 (30 g/L) decreases both the concentrated discharge energy and the unstable discharge phenomenon. The thickness of recast layer on the workpiece of kerosene was less than the thickness of pure kerosene. The surfactant increased the conductivity of kerosene and shorted the delay time, thus improved the machining efficiency
18	Matoorian et al. 2008	EDM	IN, Ton, Toff, V, S,	MRR	The factors most influencing the cost-

	[37]		and W		effectiveness of the EDT process were intensity, spindle speed, servo, and pulse-on time in the following combination: 6 A, 50 µs, 20 µs, 120 V, 30 V, and 40 rpm, respectively. The actual and predicted values of MRR were 0.023 and 0.021, respectively.
19	Haron et al. 2008 [38]	EDM	I, EM, and D_tool	MRR	The copper electrode achieved higher MRR than the graphite electrode. It was recommended to use the copper electrode for rough cutting and the graphite electrode for finish cutting
20	Haddad and Tehrani 2008 [39]	Wire EDM	P, Toff, V, and w	MRR	The only influential design factors and interaction effects of machining parameters on the MRR in the cylindrical wire electrical discharge turning process were power, voltage, pulse-off time, and spindle rotational speed.
21	Kansal et al. 2008 [40]	Powder-mixed electric discharge machining (PMEDM)	I, Ton, Toff, DE, and PCH	TD	The simulation results showed that PMEDM produced smaller and shallower craters than EDM under the same set of machining conditions.
22	Kanlayasiri and Boonmung 2007	Wire EDM	Ton, Toff, Ip, and WT	SR	The main parameters of wire EDM affecting the SR of DC53 die steel were pulse-on time and

	[41,19]				pulse-peak current. The SR increases as the pulse-on time and pulse-peak current increase.
23	Kansal et al. 2007 [42]	Powder-mixed EDM	Ip, Ton, Toff, PCON, GN, and NF	MRR	MRR in powder-mixed EDM was significantly affected by peak current, concentration of the silicon powder, pulse-on time, pulse-off time, and gain. Among all, peak current and concentration of silicon powder were the parameters most influencing MRR. The optimum c parameters were peak current = 10 A, powder concentration = 4 g/L, pulse-on time = 100 µs, pulse-off time = 15 µs, and gain = 1 mm/s.
24	Kiyak and Cakır 2007 [43]	EDM	Is, Ton, and Tof	SR	The SR increases as pulsed current and pulse time increase. SR decreases as current and pulse time decrease and pulse pause time increases. For rough EDM machining, the machine power should be 25% of the produced power with current, pulse time, and pulse pause time of 16 A, 6 µs, and 3 µs, respectively. For finish machining, the machine had 50% of produced power with current, pulse time, and pulse pause time of 8 A, 6 µs, and 3 µs, respectively.
25	Tzeng and	EDM	V, Pd, τ, Ip,	Precision and	81.5% of the high-speed

	Chen 2007 [44]		PCON, regular distance for electrode lift, time interval for electrode lift, and powder size	accuracy of the high-speed EDM	EDM process variance was due to pulse time, duty cycle, and peak value of discharge current. The best parameter combinations achieving precision and accuracy of the high-speed EDM process were open-circuit voltage of 120 V, pulse duration of 12 µs, duty cycle of 66%, pulse-peak current of 12 A, powder concentration of 0.5 cm3 /L, regular distance for electrode lift of 12 mm, time interval for electrode lift of 0.6 s, and powder size of 40 µm
26	Zarepour et al. 2007 [45]	EDM	Ton, I, and V	TWR	Pulse-on time, current, and pre-EDM roughing as factors, along with pulse-on time/current, pulse-on time/pre-EDM roughing, and current/pre-EDM roughing as interactions, were found to have significant effects on electrode wear of the EDM process of DIN 1.2714.
27	Yilmaz et al. 2006 [46]	EDM	Is, PD, PI, FR, and GC	EWR, better SR, and ER	Providing a selection tool enables an unskilled user to select necessary parameters which achieve less electrode wear, better surface quality, and high erosion rate for both finish and rough machining.
28	Wu et al. 2005 [47]	EDM	P, PD, V, Vg, PCON,	SR	The surface roughness of the workpiece in the EDM

			and SCON		process was improved by adding surfactant and aluminum powder to the dielectric fluid. The EDM parameters which achieved optimal surface roughness (0.172 μm) were Al powder concentration of 0.1 g/L, positive polarity, peak current of 0.3 A, peak duration of 1.5 μs, and surfactant concentration of 0.25 g/L. The gap distance was increased by adding aluminum powder or surfactant to the EDM dielectric fluid. Dielectric mixed with both aluminum powder and surfactant achieved an optimally thin recast layer. The mixture also improved the SR by 60% compared to the SR under normal dielectric.
29	Kansal et al. 2005 [48]	Powder-mixed EDM	Ton, τ, Ip, and PCON	MRR and SR	MRR increases as the concentration of the silicon powder increases. SR decreases as the concentration of the silicon powder increases. Peak current and concentration of the silicon powder were the parameters most affecting MRR and SR. MRR increases and SR decreases as the combination of peak current and concentration increase.

30	Amorim and Weingaertner 2005 [49]	EDM	Is, PD, PI, V, P, and G_mod	MRR, WWR, and SR	The maximum MRR of 8 mm3 /min was obtained at a discharge current of 8 A and a discharge duration of 50 µs, with positive electrode polarity and a generator under iso-energetic mode. The minimum average SR of 0.6 µm was obtained at a discharge current of 3 A, discharge duration of 12.8 µs, negative electrode polarity, and generator under iso-energetic mode. The volumetric relative wear for EDM with a negative electrode polarity was much higher than that with positive electrode polarity
31	Hasçalýk and Çayda¸s 2004 [50]	W EDM	PD, V, S-wire, and DP	SR and MS	The thickness white layer was proportional to the magnitude of the energy impinging on that surface. The density of cracks in the white layer and SR increase as the pulse duration and open-circuit voltage increase. Dielectric fluid pressure and wire speed did not have much of an influence on SR. The surface of all workpieces was harder than the bulk material, while the heat-affected zone was softer in quenched and tempered workpieces
32	Kunieda et al. 2004	Dry EDM	G and Gain	MRR	The monotonous oscillation using a

	[51]				piezoelectric actuator was not useful in dry EDM.
33	Singh et al. 2004 [52]	EDM	Is and EM	MRR, D_over, EWR, and SR	Among copper, copper tungsten, brass, and aluminum, copper and aluminum electrodes offered higher MRR and SR during machining of En-31 work material in EDM, where the electrodes of these two materials produced low diametrical overcut. The copper–tungsten electrode offered low values of SR at high discharge currents. Copper and copper–tungsten electrodes offered low EWR. In contrast, brass resulted in the highest EWR. Among the four electrode materials, copper was the best to machine En-31 material.
34	Lin et al. 2000 [54]; Puri and Bhattacharyya 2003 [53]	W EDM	Ton, Toff, Ip, τ, Vp, S-wire, WT, Vs, DP, and F	Avg_CS and G-InI	The parameters most affecting the average cutting speed during rough cutting were pulse-on time, pulse-off time, and pulse-peak current, and those during trim cutting were pulse-on time and constant cutting. The parameter most affecting the SR during rough cutting was pulse-peak current, and those during trim cutting were pulse-on time, pulse-peak voltage, servo spark gap set voltage, dielectric flow

					rate, wire tool offset, and constant cutting speed. The factors most affecting geometrical inaccuracy due to wire lag during rough cutting were pulse-on time, pulse-off time, pulse-peak current, and pulse-peak voltage, and those during trim cutting were wire tension, servo spark gap set voltage, wire tool offset, and constant cutting speed.
35	Guu et al. 2003 [54]	EDM	Is, Ton, and Tof	T_RL, SR, and σ_{res}	The recast layer becomes thicker as the pulse current and pulse-on duration increase. As the peak current is achieved, the melting of the material and damage of the surface and subsurface area increase.
36	Ghoreishi and Atkinson 2002 [55]	EDM	A, w, LF, and HF	MRR, TWR, and SR	High-frequency vibration had a notable effect on the MRR. The combination of low-frequency vibration and electrode rotation did not give a satisfactory effect on MRR. The combination of ultrasonic vibration and electrode rotation led to an increase in MRR. The combination of high-frequency vibration and electrode rotation was the best for the finishing cut. In the semi-finishing cut, the vibro-rotary EDM increased MRR by 35% and 100% compared to

					vibratory and rotary EDM, respectively.
37	Kunieda and Furudate 2001 [56]	Dry EDM			The MRR and waviness could be improved by increasing the wire winding speed and decreasing the actual depth of cut.

After reviewing the research work using the EDM process, it can be found that the majority of studies investigated the effect of the operating parameters on the performance parameters of MRR, EWR, and surface quality. Other bodies of research were conducted to investigate, solve, or study other issues, such as the electrode shape and its movement, the effect of the EDM process on the machined surface, as well as combined and hybrid processes, and the effect of various dielectric fluid used in the process, among others. Researchers paid more attention to the sinking EDM and micro-EDM processes to obtain optimal and nearoptimal operating parameters, which may be attributed to the popularity of these two processes

This review on the state-of-the-art studies of the EDM processes led to the following conclusions:

- According to the general agreement of the results, the main factors influencing the MRR in EDM are the discharge current and the pulse-on time. The gas pressure and electrode rotation speed also have a significant influence on the MRR. Furthermore, the MRR can be improved by using an electrode material with high electrical conductivity. Using powder-mixed EDM significantly affects the MRR.
- According to major observations by the researchers, low SR is achieved at lower peak current and pulse-on duration. Furthermore, the medium value of peak current, along with minimum possible pulse-on time, can minimize surface crack density. The review revealed that the SR is increased with higher values of pulsed current and pulse-on time, whereas better surface finish is achieved with lower current, lower pulse-on time, and relatively higher pulse-off time. Long-duration pulses cannot meet the machining requirements during finish machining with high

requirements in SR. Furthermore, applying a magnetic field leads to an improvement in surface quality.

- The review revealed that surface cracks are influenced by the pulse current. Furthermore, a reduction in pulse-on duration suppresses the formation of surface cracks.
- The review revealed that waste vegetable oil-based bio-dielectric fluid can be used as an alternate to hydrocarbon-, water-, and synthetic-based dielectric fluids for EDM. Furthermore, the use of a powder-mixed dielectric in EDM reduces the SR, crater diameter, crater depth, and the white-layer thickness; it also significantly reduces the surface heterogeneity.
- The studies also divulged that a significant amount of material is transferred from the powder suspended in the dielectric medium to the work material. The most significant factor for this phenomenon of surface modification is the peak current.
- The review also revealed that ultrasonic action has a significant influence on the performance of the EDM process. The surface integrity is better in an ultrasonic-assisted process than in conventional EDM.
- Applying a magnetic field reduces inactive pulses, including arcing, short circuit, and open circuit, in addition to helping in the ionization. Using a magnetic field also leads to an improvement in surface quality.
- The review revealed that, for thermal profiling, the gauss heat source was closer to the actual EDM process than the point heat source, circular heat source, and other heat source types.
- The compositions of generated aerosol depend on the composition of the electrode materials and on the boiling points of its constituents.
- According to a general observation by the researchers, the particle size in the dielectric fluid affects the surface quality of the machined surface. More improvements in the SR can be achieved using a smaller particle size. However, particle size has the opposite effect on the recast layer, whereby a smaller particle size leads to a thicker recast layer in the EDM machined surface. Despite the existing studies on this topic, more studies are still needed to assess the effect of adding different available powder types in the EDM of different grades of tool steel.

- In the EDM process, particle agglomeration is reduced after surfactant molecules cover the surface of debris in the dielectric fluid. Adding a co-surfactant to the dielectric increases the conductivity of the dielectric and improves the machining efficiency. Furthermore, it improves the MRR of the EDM process.

CHAPTER 3

METHODOLOGY

In the present chapter the methodology used for obtaining better response parameters is briefly discussed. In modern industrial environment a numerous kind of Investigations have been done for the improvement of product quality in the field of manufacturing. Some have few factors to be considered, some have many. While there are others, that demand factors to have mixed levels. A vast majority of experiments however fall in the category where all factors possess the same number of levels. In the conventional technique of varying one factor at a time, lot of experimental data can be obtained. This way of experimentation not only consumes lot of time but also poses a challenge to the investigator for deriving appropriate conclusion from the huge experimental data. Design of Experiments (DOE) is at ever rescue for planning systematic experimentation and arriving at meaningful conclusion without being inundated in huge set of experimental data. DOE is an experimental strategy in which effects of multiple factors are studied simultaneously by running tests at various levels of factors. There are number of statistical techniques available for engineering and scientific studies. In the present investigation a Taguchi method and ANOVA are employed for optimizing the process parameters.

3.1. Design of Experiments (DOE)

Design of Experiments is a powerful statistical technique introduces by R.A. Fisher in England in the 1920’s to study the effect of multiple variables simultaneously. The DOE using Taguchi approach can be economically satisfy the needs of problem solving and product/process design optimization projects. DOE is a technique of defining and investigating all possible combinations in an experiment involving multiple factors and to identify the best combination. In this different factor and their levels are identified. Design of Experiments is also useful to combine the factors at appropriate levels, each with the respective acceptable range, to produce the best results and yet exhibit minimum variation around the optimum results. Therefore, the objective of a carefully planned designed experiment is to understand which set of variables in a process affects the performance most and then determine the best levels for these variables to obtain satisfactory output functional performance in products.

Advantages of Design of Experiments (DOE)

- Number of trails is significantly reduced.
- Important decision variables which control and improve the performance of the product or the process can be identified.
- Optimal setting of the parameters can be found out.
- Qualitative estimation of parameters can be made.
- Experimental errors can be estimated.
- The effect of parameters on the characteristics of the process can be found out.

The DOE techniques used for process parameter optimization

- Taguchi Orthogonal Array
- Taguchi Analysis
- Regression Analysis and ANOVA

3.2 TAGUCHI METHODOLOGY

The taguchi method is a one of the efficient robust technique, proposed by Denichi Taguchi in 1980's. Taguchi techniques are statistical methods developed by Genichi Taguchi to improve the Quality of manufacturing goods, and more recently also applied to engineering, bio-technology, marketing and advertising.

Basically, classical experimental design methods are to complex and not easy to use. A large number of experiments have to be carried out when the number of the process parameter increases. To solve this problem, the Taguchi method uses a special design called orthogonal arrays(OA) to study the entire parameter space with only a small number of experiments thereby reduces the overall cost and time of the experiments.

It is a set of methodologies like orthogonal array, Signal-to-Noise ratios, by which the inherent variability of materials and manufacturing processes can be considered at the design stage. It generally takes nominal design points that are responsible to variations in production and user environments to improve the productivity as well as quality of the product.

Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach

1. System Design
2. Parameter Design
3. Tolerance Design

1.System Design:-

In system design the engineer applies scientific and engineering knowledge to produce a basic functional prototype design, this design including the product design stage and process design stage.

In the product design stage, the selection of material components tentative product parameter values, etc., are involved as to the process design stage the analysis of processing sequences, the selection of production equipment, tentative process parameter values, etc., are involved. Since system design is an initial functional design it may be far from optimum in terms of quality and cost.

2.**Parameter Design:-**

The objective of parameter design is to optimize the settings of the process parameter values for improving quality characteristics and to identify the product parameter values under the optimal process parameter values. In addition, it is expected that the optimal process parameter values obtained from parameter design are insensitive to variation in the environmental conditions and other noise factors.

3.Tolerance Design:-

Tolerance design is used to determine and analyze tolerances around the optimal settings recommend by parameter design. Tolerance design is required if the reduced variation obtained by the parameter design does not meet the required performance. However, based on above discussion, parameter design is the key step in the Taguchi method to achieving high quality without increasing cost.

3.2.1Taguchi Method treats optimization problems in two categories,

1. Static problems

Generally, a process to be optimized has several control factors which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the the target value. Such a problem is called as a "Static Problem".

This is best explained using a P-Diagram which is shown below ("P" stands for Process or Product). Noise is shown to be present in the process but should have no effect on the output! This is the primary aim of the Taguchi experiments - to minimize variations in output even though noise is present in the process. The process is then said to have become ROBUST.

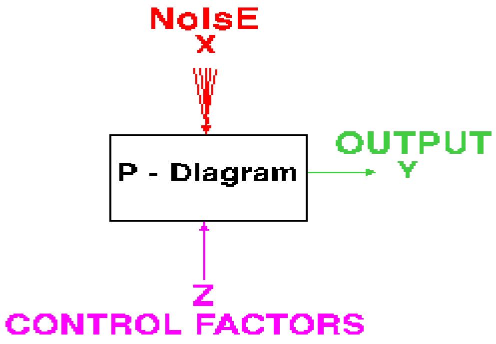

Figure 3.1 Diagram for STATIC Problems

2.Dynamic problems:-

If the product to be optimized has a signal input that directly decides the output, the optimization involves determining the best control factor levels so that the "input signal / output" ratio is closest to the desired relationship. Such a problem is called as a "Dynamic Problem".

This is best explained by a P-Diagram which is shown below. Again, the primary aim of the Taguchi experiments - to minimize variations in output even though noise is present in the process- is achieved by getting improved linearity in the input/output relationship.

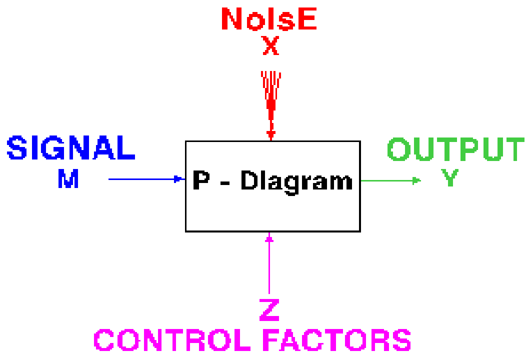

Figure 3.2 P-Diagram for DYNAMIC Problems

1.Static problem *(Batch process optimization)* **:**

There are 3 Signal-to-Noise ratios of common interest for optimization of Static Problems;

a. Smaller-The-Better :

n = -10 Log_{10} [mean of sum of squares of measured data]

This is usually the chosen S/N ratio for all undesirable characteristics like " defects " etc. for which the ideal value is zero. Also, when an ideal value is finite and its maximum or minimum value is defined (like maximum purity is 100% or maximum Tc is 92K or minimum time for making a telephone connection is 1 sec) then the difference between measured data and ideal value is expected to be as small as possible. The generic form of S/N ratio then becomes,

n = -10 Log_{10} [mean of sum of squares of {measured - ideal}]

b. Larger-The-Better :

n = -10 Log_{10} [mean of sum squares of reciprocal of measured data]

This case has been converted to Smaller-The-Better by taking the reciprocals of measured data and then taking the S/N ratio as in the smaller-the-better case.

c.Nominal-The-Best:

$$n=10\text{Log}_{10}\ \frac{\text{square of mean}}{\text{variance}}$$

This case arises when a specified value is MOST desired, meaning that neither a smaller nor a larger value is desirable.

Examples are;

(i) most parts in mechanical fittings have dimensions which are nominal-the-best type.

(ii) Ratios of chemicals or mixtures are nominally the best type. e.g. Aquaregia 1:3 of HNO3:HCL Ratio of Sulphur, KNO3 and Carbon in gun powder

(iii) Thickness should be uniform in deposition /growth /plating /etching..

2. Dynamic Problem *(Technology Development)* **:**

In dynamic problems, we come across many applications where the output is supposed to follow input signal in a predetermined manner. Generally, a linear relationship between "input" "output" is desirable.

For example : Accelerator peddle in cars, volume control in audio amplifiers, document copier (with magnification or reduction) various types of moldings etc.

There are 2 characteristics of common interest in "follow-the-leader" or "Transformations" type of applications,

(i) Slope of the I/O characteristics and.

(ii) Linearity of the I/O characteristics

(minimum deviation from the best-fit straight line)

The Signal-to-Noise ratio for these 2 characteristics have been defined as;

(I) Sensitivity {Slope}:

The slope of I/O characteristics should be at the specified value (usually 1).

It is often treated as Larger-The-Better when the output is a desirable characteristics (as in the case of Sensors, where the slope indicates the sensitivity).

$n = 10\ \text{Log}_{10}$ [square of slope or beta of the I/O characteristics]

On the other hand, when the output is an undesired characteristics, it can be treated as Smallerthe-Better. n = -10 Log_{10} [square of slope or beta of the I/O characteristics]

(II) Linearity (Larger-The-Better) :

Most dynamic characteristics are required to have direct proportionality between the input and output. These applications are therefore called as "Transformations". The straight line relationship between I/O must be truly linear i.e. with as little deviations from the straight line as possible.

$$n = 10\,\text{Log}_{10} \frac{\text{Square of slope or beta}}{\text{variance}}$$

Variance in this case is the mean of the sum of squares of deviations of measured data points from the best-fit straight line (linear regression).

3.2.2 8-Steps In Taguchi Methodology :

The procedure followed for Taguchi method is as follows

- Find the main functions, side effects
- Noise factors, testing conditions and quality characteristics has to be identified • Identify the objective function to be optimized
- Fix the control factors and their corresponding levels
- Select the orthogonal array matrix experiment
- Conduct the matrix experiment
- Predict the optimum levels and performance from the analysis
- Carryout the verification experiment and plan the future action

The following figure shows how the steps followed in each level

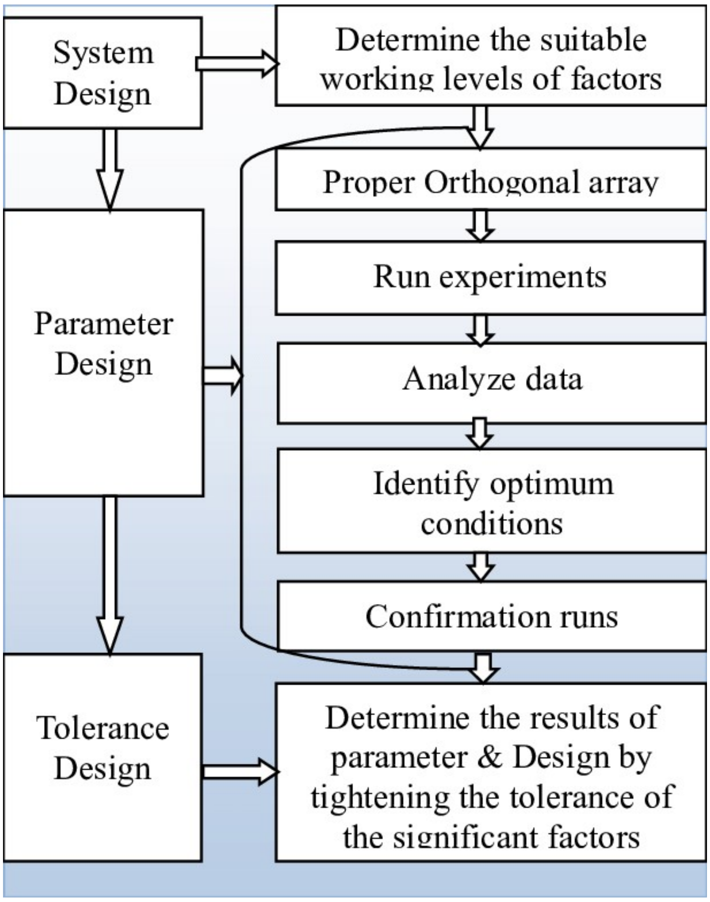

Figure 3.3 Stages of Taguchi Method

3.3 Analysis of Variance(ANOVA):-

3.3.1 ANOVA

Anova is a collection of statistical models and their associated estimation procedures (such as the "variation" among and between groups) used to analyze the differences among means. ANOVA was developed by the statistician Ronald Fisher. ANOVA is based on the law of total variance, where the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether two or more population means are equal, and therefore generalizes the *t*-test beyond two means. In other words, the ANOVA is used to test the difference between two or more means.

The analysis of variance has been studied from several approaches, the most common of which uses a linear model that relates the response to the treatments and blocks. Note that the model is linear in parameters but may be nonlinear across factor levels. Interpretation is easy when data is balanced across factors but much deeper understanding is needed for unbalanced data.

3.3.2 Characteristics:-

ANOVA is used in the analysis of comparative experiments, those in which only the difference in outcomes is of interest. The statistical significance of the experiment is determined by a ratio of two variances. This ratio is independent of several possible alterations to the experimental observations: Adding a constant to all observations does not alter significance. Multiplying all observations by a constant does not alter significance. So ANOVA statistical significance result is independent of constant bias and scaling errors as well as the units used in expressing observations. In the era of mechanical calculation it was common to subtract a constant from all observations (when equivalent to dropping leading digits) to simplify data entry.This is an example of data coding.

3.3.3 Logic:-

The calculations of ANOVA can be characterized as computing a number of means and variances, dividing two variances and comparing the ratio to a handbook value to determine statistical significance. Calculating a treatment effect is then trivial: "the effect of any treatment is estimated by taking the difference between the mean of the observations which receive the treatment and the general mean".

In this method, first the total sum of the squared deviations SS_T from the total mean of the S/N ratio η can be calculated as

$$SS_T = \sum_{i=1}^{m}\left(\eta_i - \bar{\eta}\right)^2 = \sum_{i=1}^{m}\eta_i^2 - \sum_{i=1}^{m}2\eta_i\bar{\eta} + \sum_{i=1}^{m}\bar{\eta}^2$$

$$= \sum_{i=1}^{m}\eta_i^2 - 2m\bar{\eta}^2 + m\bar{\eta}^2 = \sum_{i=1}^{m}\eta_i^2 - m\bar{\eta}^2$$

$$= \sum_{i=1}^{m}\eta_i^2 - \frac{1}{m}\left[\sum_{i=1}^{m}\eta_i\right]^2$$

Where 'm' is number of experiments in orthogonal array and η_i is the mean S/N ratio for the i^{th} experiment. The total sum of squared deviations SS_T is decomposed into two sources: the sum of the squared deviations SS_p due to each process parameter and the sum of the squared error SS_e.

$$SS_P = \sum_{j=1}^{t} \frac{(S\eta_i)^2}{t} - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_i\right]^2$$

Where p represents one of the experiment parameters, j the level number of this parameter p, t the repetition of each level of the parameter p, the S/N ratio of parameter p at level j is $s\eta j$.

The sum of squares SS_e is given as

$$SS_e = SS_T - SS_A - SS_B - SS_C$$

The total degree of freedom is D_T = m-1, where the degrees of freedom of the tested parameter D_P = t-1. The variance, $V_P = SS_P/D_P$. Then the F-Value for each design parameter is simply the ratio of the mean square's deviation to the mean of the squared error ($F_P = V_P/V_e$).

$$S_P = SS_P - D_P V_e$$

The percentage contribution p can be calculated as:

$$P = \frac{\hat{S}_P}{SS_T}$$

The P value gives the percentage that each process parameter is contributed for the response characteristic.

There are two methods of concluding the ANOVA hypothesis test, both of which produce the same result:

- The textbook method is to compare the observed value of F with the critical value of F determined from tables. The critical value of F is a function of the degrees of freedom of the numerator and the denominator and the significance level (α). If $F \geq F_{Critical}$, the null hypothesis is rejected.

- The computer method calculates the probability (p-value) of a value of F greater than or equal to the observed value. The null hypothesis is rejected if this probability is less than or equal to the significance level (α).

CHAPTER 4

EXPERIMENTATION DETAILS

4.1 Work Piece Material

The work material selected for the present study was **Inconel-625** and it is a highperformance nickel-chromium-molybdenum alloy known for its high level of strength, temperature resistance, and corrosion resistance. It has applications in marine, aerospace, nuclear industries and mainly used in production of vessels, heat exchangers, valves, and fluid distribution systems etc.

Inconel 625 was developed in the 1960s with the purpose of creating a material that could be used for steam-line piping. Some modifications were made to its original composition that have enabled it to be even more creep-resistant and weldable. Because of this, the uses of Inconel 625 have expanded into a wide range of industries such as the chemical processing industry, and for marine and nuclear applications to make pumps and valves and other high pressure equipment. Because of the metal's high Niobium (Nb) levels as well as its exposure to harsh environments and high temperatures, there was concern about the weldability of Inconel 625. Studies were therefore conducted to test the metal's weldability, tensile strength and creep resistance, and Inconel 625 was found to be an ideal choice for welding. Other well known names for Inconel 625 are Haynes 625, Nickelvac 625, Nicrofer 6020, Altemp 625 and Chronic 625.

4.1.1Key features of Inconel-625

- Good fatigue strength
- High tensile strength
- Good resistance to chloride-ion stress-corrosion cracking
- Good thermal-fatigue strength
- Good oxidation resistance
- Excellent weldability and brazeability

4.1.2 Properties of Inconel-625:

Some chemical properties of Inconel 625 include:

Table 4.1 Chemical properties of Inconel-625

Element	% Weight
Al	0.4max
C	0.1max
Co	1max
Cr	20-23
Fe	5
Mn	0.5max
Mo	8-10
Nb+Ta	3.2-3.8
Ni	58-71
P	0.015max
S	0.015max
Si	0.5max
Ti	0.4max

Balance Inconel-625 was designed as a solid solution strengthened material with no significant micro-structure. This holds true at low and high temperatures, but there is a region (923 to 1148 K) where precipitates form that are detrimental to the creep properties, and thus the strength, of the alloy. Under any creep conditions (high temperature with an applied stress), M23C6 -type carbides form at the grain boundaries. When tested at 973 K, γ” precipitates begin forming. These γ” phase precipitates are ordered A3 B type with a composition of Ni3 (Nb, Al, Ti) and a tetragonal crystal structure. They form a disk-shaped morphology and are coherent with respect to the matrix. When tested at 998 K, a δ-phase precipitate begins forming which consist of Ni3 (Nb, Mo) in an orthorhombic crystal structure. They form in a needle-like morphology and are incoherent with the matrix. Both of these precipitates can be completely dissolved back into the matrix when the sample is heated to 1148 K for 5 hours. This leads to the ability to recover creep properties of the alloy to prolong the materials lifetime.

The mechanical properties of Inconel-625 are shown in below table

Table 4.2 Mechanical Properties of INCONEL 625

Property	Density (g/cm3)	Tensile Strength (MPa)	Yield Strength (MPa)
Value	8.44	880	460

4.1.3 Markets for Inconel-625

Today Inconel-625 have a greater market due to their applications in industries The markets include the following:

- Offshore
- Marine
- Nuclear
- Chemical Processing
- Aerospace
- Glow plugs

4.1.4 Applications of Inconel-625

Due to their vast applications of this material, Inconel-625 is taken as work piece material for this current experiment.

Product and technology applications of Inconel-625 include:

- Seawater components
- Flare stacks
- Aircraft ducting systems
- Fabrication with Inconel-625
- Specialized seawater equipment
- Chemical process equipment
- Turbine shroud rings
- Engine thrust-reverser systems

- Jet engine exhausts systems
- Boiler furnaces

A cuboidal shaped Inconel-625 material has been used in this experimental study.The dimensions of the material are **150*150*25** mm of length, width and thickness respectively.The figure of the material that is used has been shown in below figure.

Figure 4.1 Inconel-625

Dimensions-150*150*25 mm^3

4.2 Wire Material

Selection of wire in wire EDM should be done by taking following criteria into consideration :

- Tensile strength
- Fracture resistance
- Conductivity
- Vaporization point (low is preferred)

4.2.1 Key physical properties that electrical discharge machine wires must incorporate are:

Conductivity: A high and good conductivity rating is imperative in light of the fact that, at any rate hypothetically, it implies wire may convey additional current, that compares to a hotter spark and improved cutting rate.

Tensile strength: This shows the capacity of wire to endure wire strain and tension, forced at wire amid cutting, keeping in mind and goal to make a vertically straight cut.

Elongation: Which portrays in what way wire "gives" or gets physically deformed before breaking.

Melting Point: The point in time when the wire electrode is impervious to be melted too rapidly buy electric sparks.

Memory: This property may favor the wire to remain straight.

Flush Ability: The better the flush ability or (flush-capacity), the quicker wire will cut, and the possibility of wear breakage will diminish.

Cleanliness: The wire can be filthy, because of pollution through residual metal powder available from the drawing procedure, paraffin or drawing lubricant is added to the wire by a few wire manufactures proceeding spooling.

The tool wire is usually made up of brass, copper or tungsten, zine-or brass-coated and multi-coated wires are also used.

4.2.2 Common Wire Materials used are:-

Zinc Coated: Zinc is mixed into the surface of the wire. Increased zinc level of the wire electrode will improve cutting speed of the WEDM. Also, the zinc-coated wire will experience a secondary heat treatment procedure in an oxygen environment. This creates a very thin layer of oxide on the zinc surface, thus enabling the wire to slide through the wire guide and stops gentler zinc from chipping. This kind of coated wire offers the largest amount of efficiency by increased cutting speed.

Solid Brass: Zinc + copper = brass. Brass wire is manufactured in many different tensile strengths and varying degrees of hardness. These properties are dependent upon the use and material that is being machined.

Coated Copper: This incorporates a core wire enduring moderately higher thermal conductivity with a shallow coating layer framed by a low-boiling point material.

Coated wires change the wire electrode using an alloy or metal bearing low vaporization temperature for example, zinc, lead, antimony, cadmium, bismuth, tin, and other alloys. This secures the center of the wire contrary to thermal shock, ensuring the rate of electrical discharge, which allows increments of frequency of electrical discharge decreasing the risk of wire breakage.

Coated Steel Wire: For accomplishing great rigidity and strength, steel wires are coated with zinc, lead, antimony, cadmium, bismuth, tin, and other alloys. For better electrical discharge machining, wire electrodes need to consume a high electrical conductance. this empowers a higher machining current over the wire electrode, and it needs to possess higher mechanical strength for increased force in the machining zone.

Diffusion Annealed Wire: This process is aimed at improving execution speed. Zinc has a lower melting point and of the aforementioned wires diffusion wire has a higher volume of zinc coating resulting in higher melting points. This drove the advancement of diffusion in coated wires, where the encased wire is strengthened at such temperature until the point that the alloy stretches out from the outer surface to the core, enhancing mechanical quality of the wire electrode and creating a heat shield from spark impact and short circuits.

4.2.3 Wire size to be used:

Standard EDM wire is 0.25mm in diameter. Microwires can range from 0.15mm down to 0.020mm. The wire diameter chosen depends on part features, such as corner radii, slot widths, thin-wall details and intricacy of geometries.

The wire diameter is typically about **0.30**mm for roughing cuts and **0.20**mm for finishing cut. The wire travels at a constant velocity in range of **0.15 to 9.0** m/min, and a constant gap (kerf) is maintained during the cut.

The tool wire is generally used only once, as the wire gets deformed and loses its tensile strength.

In this experiment, a **brass wire** of diameter **0.25 mm** has been used for cutting of work piece material.The following figure shows the electrode wire which was used in cutting process.

Figure 4.2 Brass wire   Diameter-0.25mm

4.3 Process Parameters

Process Parameters (also called a process variable) are certain measures that refer to status of the process (their values indicate whether the process meets the plan or it needs adjustment). In order to obtain effective execution of the process its parameters should stay under continuous control.

Anyone of these may have its desired value that is called a *set-point* that regulates proper functioning of process elements and operations, while if a parameter deviates from its set-point (goes beyond the acceptable level of variance), then probably a process tends to fail, hence special automatics or human operators should intrude into this process to adjust it and prevent upset.

Process parameters are extremely important in controlling a process, therefore should be accurately measured and monitored throughout process run – it is an essential part of process management and maintenance of its efficiency, therefore process parameters, as dynamically changeable features, are controlled with a help of technological sensors mounted at critical areas of a process, along with implementation of special methods and equipment to adjust them.

These process parameters are the input parameters that are given to be given to a WEDM machine. In this present study **5** input process parameters has been taken namely Pulse On time, Pulse Off time, Wire Feed, Wire Tension and Spark Gap Voltage which were taken in 3 different levels as shown in below table.

Table 4.3 WEDM Parameters and their Levels

Factor	Parameter	1	2	3
A	Pulse-on-Time (TON), μs	110	120	130
B	Pulse-off-Time (TOFF), μs	50	55	60
C	Spark Gap voltage (SV), Volts	20	25	30
D	Wire Feed (WF), m/min	2	4	6
E	Wire Tension (WT), Kg-f	3	4	5

From the above table we have seen clearly how the three levels of the five process parameters have been taken.

The Pulse-on-time was taken as 110, 120, 130 micro seconds respectively in each level. Similarly, Pulse-off-Time was taken as 50, 55, 60 micro seconds respectively in each level. In the same way other three parameters i.e., Spark Gap Voltage, Wire Feed and Wire tension were been taken accordingly.

4.4 ORTHOGONAL ARRAY DESIGN

The machining was then performed on the workpiece using Taguchi's standard L27 orthogonal array design.

Taguchi Orthogonal Array (OA) design is a type of general fractional factorial design. It is a highly fractional orthogonal design that is based on a design matrix proposed by Dr.Genichi Taguchi and allows you to consider a selected subset of combinations of multiple factors at multiple levels. Taguchi Orthogonal arrays are balanced to ensure that all levels of all factors are considered equally. For this reason, the factors can be evaluated independently of each other despite the fractionality of the design.

In the Taguchi OA design, only the main effects and two-factor interactions are considered, and higher-order interactions are assumed to be non-existent.In L27 OA the total number of the experiments to be conducted is 27. Here five factors which were in three levels have been designed in a matrix combination such that we can perform 27 number of experiments on the work piece material on WEDM machine. The formation L27 orthogonal array matrix table is shown below.

Table 4.4 L27 OA DESIGN

S.No.	A	B	C	D	E
1	110	50	20	2	3
2	110	50	20	2	4
3	110	50	20	2	5
4	110	55	25	4	3
5	110	55	25	4	4
6	110	55	25	4	5
7	110	60	30	6	3
8	110	60	30	6	4
9	110	60	30	6	5
10	120	50	25	6	3
11	120	50	25	6	4
12	120	50	25	6	5
13	120	55	30	2	3
14	120	55	30	2	4
15	120	55	30	2	5
16	120	60	20	4	3
17	120	60	20	4	4

18	120	60	20	4	5
19	130	50	30	4	3
20	130	50	30	4	4
21	130	50	30	4	5
22	130	55	20	6	3
23	130	55	20	6	4
24	130	55	20	6	5
25	130	60	25	2	3
26	130	60	25	2	4
27	130	60	25	2	5

In the above table we have seen how the combiation of different parameters have been formed.In the first three experiment we see that the first four parameters were kept constant and the fifth parameter is varying accordingly.

In the similar fashion all other parametrs were been varing keeping four of them as constant.With these 27 number of inputs, we will perform machining operation on WEDM machine.

Once the machining is completed with each input parameters then we have to calculate the Material Removal Rate(MRR) and Sourface Roughness(SR) each time for the work piece. The specifications of the WEDM machine which was used in present experiment is shown in following table.

Table 4.5 Specifications of WEDM machine

S.No	Particulars	Unit	Job Master D-zire
1	Table Size	mm	635 x 475
2	Work-tank	mm	800 x 650

	Internal Dimensions		
3	Main Table Travel X,Y	mm	400 x 300
4	Auxiliary Table travel U,V	mm	80 x 80
5	Z-Axis Travel	mm	250
6	Maximum Taper Angle	Deg/mm	± 30 / 50
7	Job Admit	mm	245
8	Maximum Work-piece weight	Kg	300
9	Machining Type		Flush
10	Jog Speed X,Y	mm/min	1000
11	Jog Speed U,V	mm/min	500
12	Jog Speed Z	mm/min	600
13	Wire Threading		SAWT
14	Machine Foot print	mm	2350 x 2100
15	Wire Diameter	mm	0.15 ~ 0.3
16	Wire Spool Size		DIN 125, DIN 160, P3R, P5R
17	Cutting Speed*	mm2/min	180
18	Best Surface Finish	µRa	0.6

The following figure is the WEDM machine which was used in machining of work piece.

Figure 4.3 WEDM MACHINE:- Job Master D -zire

4.5 Calculation of machine responses:-

Material Removal Rate and Surface Roughness are taken as machine responses in this current experiment.

4.5.1 Material Removal Rate(MRR):-

The material removal rate is defined as the amount of material removed from workpiece per unit time. After machining the samples were taken to analyze MRR. The material removal rate (MRR) for Wire cut EDM is calculated by using the equation(1)

$MRR = F \times Dw \times H$….. (1)

Where, F is the machine feed rate (mm/min),

Dw is wire diameter (mm),

H is the thickness of the workpiece (mm)

4.5.2 Surface Roughness(SR):-

Surface Roughness is the measure of the finely spaced micro-irregularities on the surface texture which is composed of three components, namely roughness, waviness and form. Surface roughness R_a is commonly used to indicate the level of surface roughness.

The average surface roughnesses (Ra) of the machined samples were measured by using surface roughness measurement device and the values are tabulated accordingly.

Figure 4.4 Roughness Surface Tester

CHAPTER 5

RESULTS AND DISCUSSIONS

In this chapter the experimental analysis of both the machine responses by taguchi method and ANVOA has been described and also mentioned about which process parameter is more predominant in each level in both the processes.

The results from Taguchi method are obtained from Main Effect Plots and the results from ANOVA are obtained from residual plots.

5.1 Taguchi Analysis:-

The experimental results of material removal rate and surface roughness measured were depicted in table 5.1, the corresponding signal-to-noise ratio values were given in table 5.2 .The analysis was carried out using MINITAB-17 software.

5.1.1 Minitab Software

Minitab is the statistical software which helps in taking out the complexities of statistical calculations. It provides easy to use interface to calculate and draw various graphs. Some of the complex topics such as MSA, Capability Analysis, Control Charts, Design of Experiments this software provides an easy to use Assistant.

Minitab is a statistics package developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in conjunction with Triola Statistics Company in 1972. It began as a light version of OMNITAB 80, a statistical analysis program by National Institute of Standards and Technology.

The effect of process parameters on responses(MRR, SR) were calculated and plotted. Taguchi results for the responses given in tables 5.3 and 5.4 where the ranks indicate the relative importance of each factor. The main effect plots were drawn to study the variation effects of parameters on the responses with their changes in levels. The plots were shown in figures 5.1 and 5.2

Table 5.1 Experimental Results of Responses

S.No.	MRR (mm3/min)	Ra (µm)
1	5.5	2.3
2	5.48	2.2
3	5.6	2.3
4	4.4	2.4
5	4.6	2.2
6	4.3	2.1
7	3.6	2.2
8	3.4	2.3
9	3.5	2.1
10	9.4	2.2
11	9.3	2.1
12	9.2	2.2
13	7.9	2.2
14	7.7	2.3
15	7.8	2.7
16	8.3	2.8
17	7.9	3.1
18	8.1	2.7
19	9.5	3.2
20	9.7	3.1
21	9.5	3.2
22	9.4	2.8

23	9.2	3.0
24	9.7	2.9
25	7.5	2.8
26	7.7	3.1
27	7.6	2.4

Table 5.2 S/N Ratios of Responses

S.No.	S/N of MRR	S/N of Ra
1	14.8073	-7.2346
2	14.7756	-6.8485
3	14.9638	-7.2346
4	12.8691	-7.6042
5	13.2552	-6.8485
6	12.6694	-6.4444
7	11.1261	-6.8485
8	10.6296	-7.2346
9	10.8814	-6.4444
10	19.4626	-6.8485
11	19.3697	-6.4444
12	19.2758	-6.8485
13	17.9525	-6.8485
14	17.7298	-7.2346

15	17.8419	-8.6273
16	18.3816	-8.9432
17	17.9525	-9.8272
18	18.1697	-8.6273
19	19.5545	-10.1030
20	19.7354	-9.8272
21	19.5545	-10.1030
22	19.4626	-8.9432
23	19.2758	-9.5424
24	19.7354	-9.2480
25	17.5012	-8.9432
26	17.7298	-9.8272
27	17.6163	-7.6042

The following table shows the Taguchi results for Marerial Removal Rate (MRR) versus Pulse-On time, Pulse-Off time, Servo Voltage, Wire Feed and Wire Tension.The values that obtained below are from Minitab software.

Table 5.3 Taguchi Results for MRR versus Ton, TOFF, SV, WF and WT

Level	TON	TOFF	SV	WF	WT
1	4.487	8.131	7.687	6.976	7.278
2	8.400	7.222	7.111	7.367	7.220
3	8.867	6.400	6.956	7.411	7.256
Delta	4.380	1.731	0.731	0.436	0.058
Rank	1	2	3	4	5

As we can see in the table that the value **Delta** is the difference between the maximum and minimum values.The ranking of these parameters are given according with the values of delta from higher value to lower values.

From the table it is clear that Pulse -On time has higher delta value.So, it is given with rank **1** in the table. In the similar way TOFF has second highest value. So, it is given with rank **2.** Similarly, all other parameters ranked accordingly.

Just like above ,the following table shows the Taguchi results for Surface Roughness(SR) versus Pulse-On time, Pulse-Off time, Servo Voltage, Wire Feed and Wire Tension, that obtained from Minitab software.

Table 5.4 Taguchi Results for Ra versus Ton, TOFF, SV, WF and WT

Level	TON	TOFF	SV	WF	WT
1	2.233	2.533	2.678	2.478	2.544
2	2.478	2.511	2.389	2.756	2.600
3	2.944	2.611	2.589	2.422	2.511
Delta	0.711	0.100	0.289	0.333	0.089
Rank	1	4	3	2	5

From the table it is clear that Pulse -On time has higher delta value.So, it is given with rank **1** in the table. In the similar way WF has second highest value. So, it is given with rank **2.** Similarly, all other parameters ranked accordingly.

5.1.2 Main Effect Plots For Means

A main effects plot is a plot of the mean response values at each level of a design parameter or process variable. One can use this plot to compare the relative strength of the effects of various factors. The sign and magnitude of a main effect would tell us the following:

- The sign of a main effect tells us of the direction of the effect, that is, whether the average response value increases or decreases.

- The magnitude tells us of the strength of the effect.

If the effect of a design or process parameter is positive, it implies that the average response is higher at a high level rather than a low level of the parameter setting. In contrast, if the effect is negative, it means that the average response at the low-level setting of the parameter is more than at the high level.

The main effects plots also give a rough idea about the relative significance of the parameters on the system response. In the main effects plots, if the line for a particular parameter is near horizontal, then the parameter has no significant effect. On the other hand, a parameter for which the line has the highest inclination will have the most significant effect.

The following are the main effect plots for means of MRR that were obtained from minitab software.

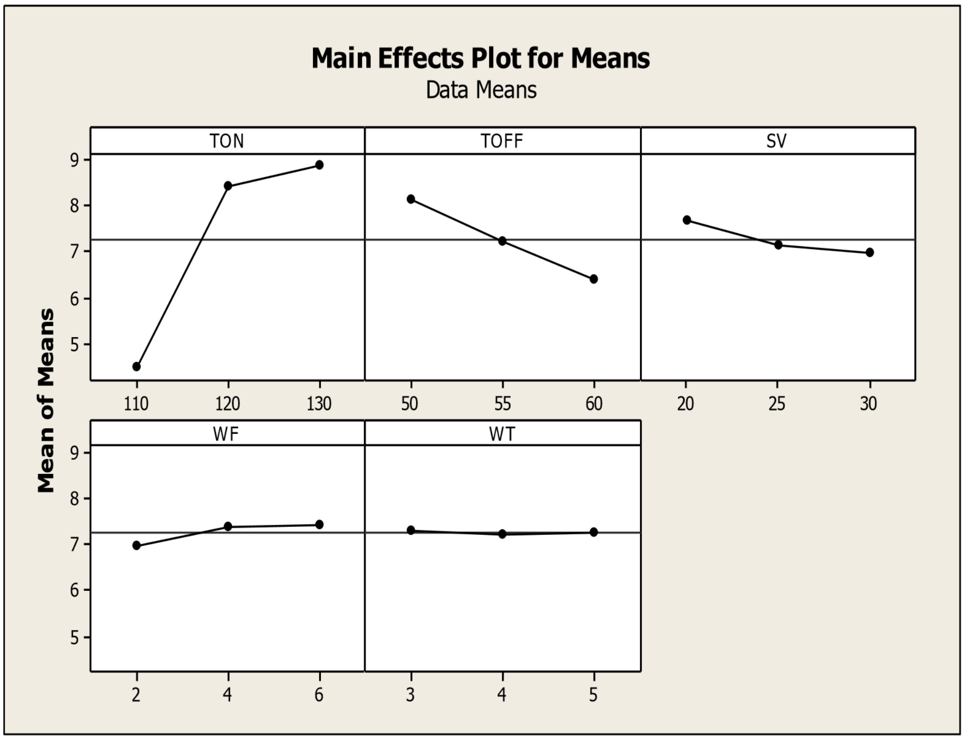

Figure 5.1. Main Effect Plots for Means of MRR

Since our goal is to get the maximum Material Removal Rate, the higher-the-better characteristic is used for optimal combination.

Therefore, from the above main effect plot analysis the optimal combination of process parameters for achieving maximum material removal rate is found at

Pulse-on-Time (T_{ON}): level 3;130µs
Pulse-off-Time (T_{OFF}): level1; 50µs
Servo Voltage: level1; 20 volts
Wire Feed: level3, 6 m/min
Wire Tension: level1; 3 Kg-f

Just like the above plots the following are the main effect plots for means of SR that were obtained from minitab software.

Figure 5.2 Main Effect Plots for Means of Ra

Since our goal is to get the minimum Surface Roughness, the lower-the-better characteristic is used for optimal combination.

Therefore, for achieving minimum surface roughness the optimal combination of process parameters is found at

Pulse-on-Time (T_{ON}): level 1;110µs

Pulse-off-Time (T_{OFF}): level2; 55µs

Servo Voltage: level2; 25 volts

Wire Feed: level3, 6 m/min

Wire Tension: level3; 5 Kg-f

5.2. Regression & ANOVA Results

Regression analysis is a reliable method of identifying which variables have impact on a topic of interest. The process of performing a regression allows you to confidently determine which factors matter most, which factors can be ignored, and how these factors influence each other.

Typically, a regression analysis is done for one of two purposes: In order to predict the value of the dependent variable for individuals for whom some information concerning the explanatory variables is available, or in order to estimate the effect of some explanatory variable on the dependent variable

Regression analysis has been employed to prepare first order models for the responses. ANOVA results of the responses were given in tables 5.5 and 5.6 respectively.

Table 5.5. ANOVA Results for MRR

Source	DF	AdjSS	AdjMS	F	P
TON	2	104.149	52.075	2360.47	0.000
TOFF	2	13.497	6.748	305.89	0.000
SV	2	2.670	1.335	60.51	0.000
WF	2	1.034	0.517	23.43	0.000
WT	2	0.015	0.008	0.35	0.712
Error	16	0.353	0.022		
Total	26	121.718			

$S = 0.148530$, $R^2=99.71\%$, R^2 (adj) = 99.53%

Table 5.6 ANOVA Results for R_a

Source	DF	AdjSS	AdjMS	F	P
TON	2	2.34963	1.17481	34.57	0.000
TOFF	2	0.04963	0.02481	0.73	0.497
SV	2	0.39407	0.19704	5.80	0.013
WF	2	0.57407	0.28704	8.45	0.003
WT	2	0.03630	0.01815	0.53	0.596
Error	16	0.54370	0.03398		
total	26	3.94741			

S = 0.184341, R^2 = 86.23%, R^2 (adj) = 77.62%

We know that the p-value for each term tests the null hypothesis that the coefficient is equal to zero (no effect). A low p-value (< 0.05) indicates that you can reject the null hypothesis. In other words, a predictor that has a low p-value is likely to be a meaningful addition to your model because changes in the predictor's value are related to changes in the response variable. Conversely, a larger (insignificant) p-value suggests that changes in the predictor are not associated with changes in the response.

As we see in both the tables, we observe that the p-value is less than 0.005 for pulseon-time.Therefore it is to be said that the pulse-on-time has the highest influencing factor for both the responses

Residual Plots:-

A residual plot is a graph that is used to examine the goodness-of-fit in regression and ANOVA. Examining residual plots helps you determine whether the ordinary least squares assumptions are being met. If these assumptions are satisfied, then ordinary least squares regression will produce unbiased coefficient estimates with the minimum variance.

They include the following residuals:

- **Histogram of residuals:-**Use the histogram of residuals to determine whether the data are skewed or whether outliers exist in the data.
- **Normal probability plot of residuals:-**Use the normal plot of residuals to verify the assumption that the residuals are normally distributed.
- **Residuals versus fits:-**Use the residuals versus fits plot to verify the assumption that the residuals have a constant variance.
- **Residuals versus order of data:--**Use the residuals versus order plot to verify the assumption that the residuals are uncorrelated with each other.

The residual plots for both MRR and SR were drawn and shown in figures5.3 and 5.4.

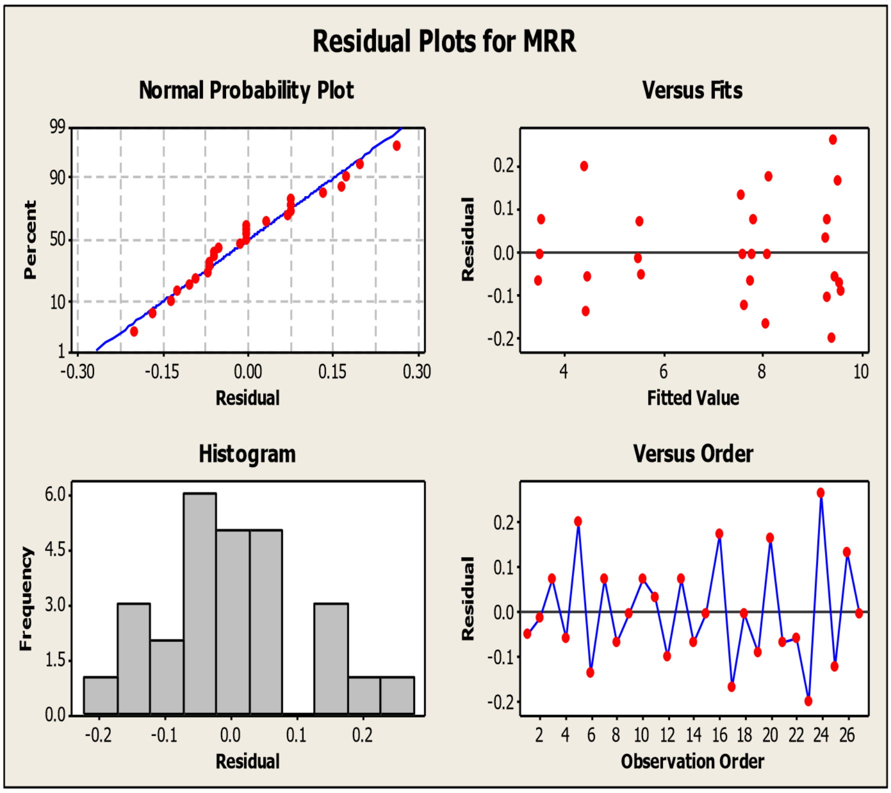

Figure 5.3 Residual Plots for MRR

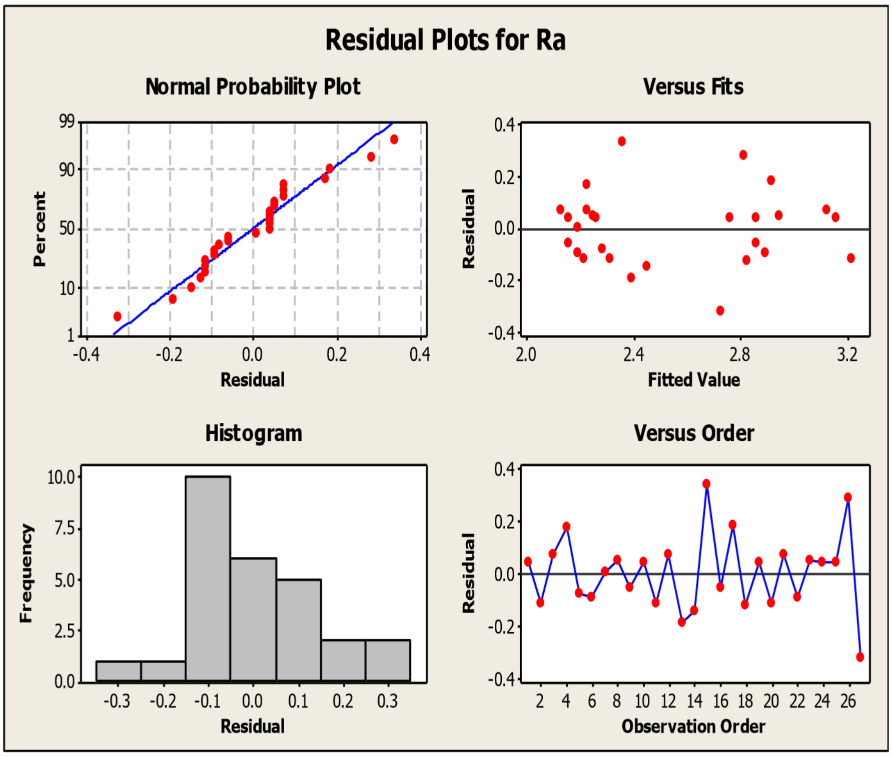

Figure 5.4 Residual Plots for R_a

From both the figures it is obseved that a very good agreement has been found between the predicted and experimental values hence the models prepared were best fit and accurate.

CHAPTER 6

CONCLUSIONS

From the Taguchi and ANOVA analysis results the following conclusions can be drawn:

1. The optimal condition for achieving maximum MRR is obtained at
   Pulse-on-Time (T_{ON}): level 3;130µs
   Pulse-off-Time (T_{OFF}): level1; 50µs
   Servo Voltage: level1; 20 volts
   Wire Feed: level3, 6 m/min
   Wire Tension: level1; 3 Kg-f
2. The optimal condition for achieving minimum R_a is obtained at
   Pulse-on-Time (T_{ON}): level 1;110µs
   Pulse-off-Time (T_{OFF}): level2; 55µs
   Servo Voltage: level2; 25 volts
   Wire Feed: level3, 6 m/min
   Wire Tension: level3; 5 Kg-f
3. ANOVA results showed that Pulse-on-time (T_{ON}) is the most predominant factor for both the responses.

The models prepared for both MRR and R_a are found to be in good agreement with the experimental results and they can be used for the prediction of responses

CHAPTER 7

FUTURE SCOPE

Future Research Directions

Even though a high amount of work in the field of EDM was conducted, there are challenges left which still require more research, and these are listed below.

- Optimizing Process Parameters: The EDM process has a multifarious nature due to the complex discharge mechanisms, which hinders its optimization. Additionally, the introduction of new materials constantly complicates the optimization of parameters. Even in TS, many grades are introduced frequently; thus, more studies are required.
- Extending to a Wide Range of Workpiece Materials: EDM is primarily used for conductive materials; however, the current trend is to investigate the potential of EDM for machining non-conductive or semi-conductive materials, such as ceramics.
- Powder-Mix EDM: Powders of different materials are mixed with dielectrics to improve the machining process. This is another area which requires further attention. Researchers need to pay more attention to the machining of different Inconel grades in different EDM types under dielectric fluids with different material powders. There is a lack of studies covering this point.
- Use of Di*ff*erent Electrodes: Investigators can examine the performance of the EDM process by using various electrode materials, shapes, sizes, and geometries. The use of tubular electrodes is in the initial stages, and it requires further attention to deliver promising results.
- Hybrid or Assisted EDM: The EDM process hybridized with some other processes provides better results. Magnetic force-assisted EDM, laser with EDM, etc. are becoming commonly used methods to overcome process limitations. The great improvement in the performance revealed in the reviewed research was related to EDM with ultrasonic action. Research trends may be directed toward the combination of these two processes.

- Electrode Cooling Methods: The electrode cooling mechanism represents another field of research. The cryogenic cooling of electrodes provided positive results in terms of a reduction in TWR.
- Electrical Discharge Turning (EDT) and Dry EDM: EDT is a very new concept and it requires more research. Dry EDM is also gaining interest in the research community.
- Miniaturization: More efforts are needed to extend the limits of miniaturization in microEDM. A smaller level of electric discharge energy is needed to overcome this limitation. Furthermore, new techniques to avoid the distortion of micro-workpieces are necessary in future research.
- Figure 7.1 shows a pictographic depiction of the future research directions.

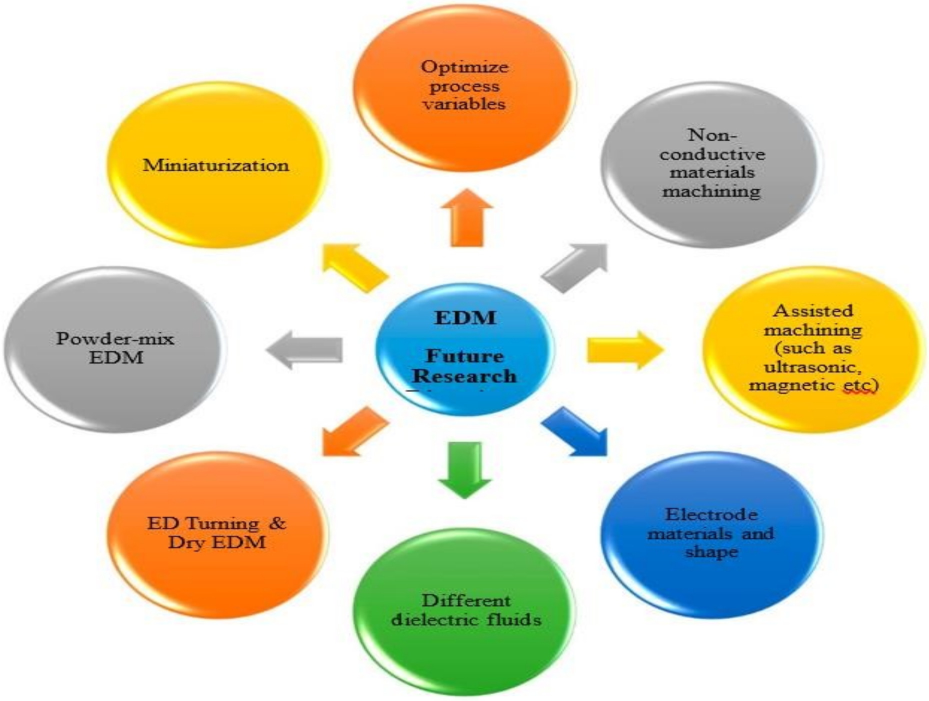

Figure 7.1. Future research areas in the EDM field

- The research directions can be categorized into four broad classes, which can be further allocated into sub-groups, as shown in Figure 7.2.

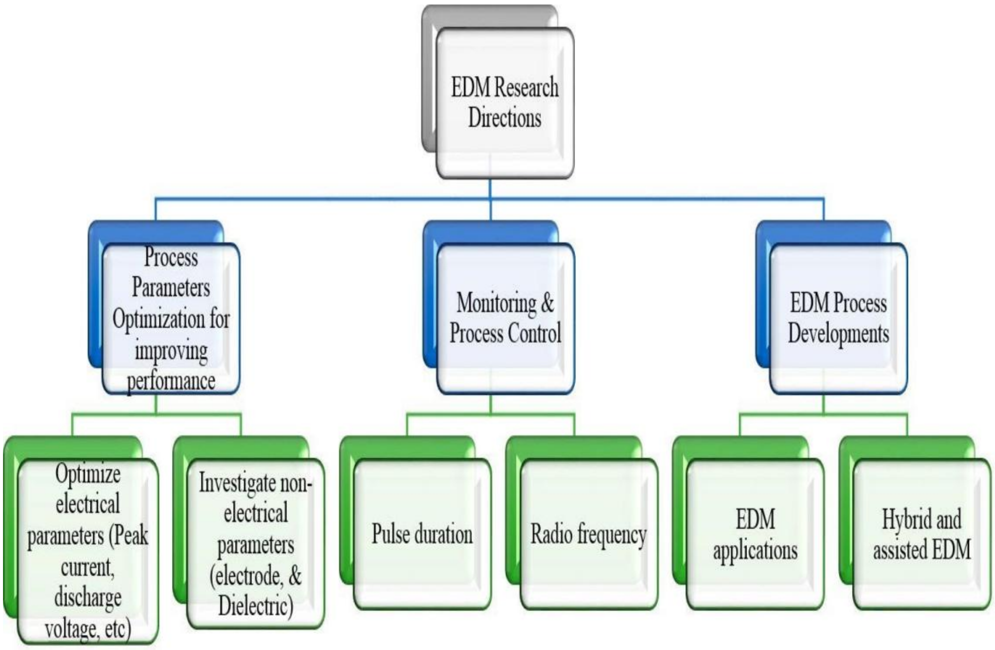

Figure 7.2. Classification of research directions

REFERENCES

1. Bilal, A.; Jahan, M.P.; Talamona, D.; Perveen, A. Electro-discharge machining of ceramics: A review. *Micromachines* **2019**, *10*, 10.
2. Qudeiri, J.E.A.; Mourad, A.-H.I.; Ziout, A.; Abidi, M.H.; Elkaseer, A. Electric discharge machining of titanium and its alloys. *Int. J. Adv. Manuf. Technol.* **2018**, *96*, 1319–1339. J.Pérez, J.; Llorente, J.I.; Sanchez, J.A. Advanced cutting conditions for the milling of aeronautical alloys. *J.Mater. Process. Technol.* **2000**, *100*, 1–11.
3. Komanduri, R.; Hou, Z.-B. On thermoplastic shear instability in the machining of a titanium alloy (Ti-6Al-4V). *Met. Mater. Trans. A* **2002**, *33*, 2995.
4. Cascón, I.; Sarasua, J.A.; Elkaseer, A. Tailored Chip Breaker Development for Polycrystalline Diamond Inserts: FEM-Based Design and Validation. *Appl. Sci.* **2019**, *9*, 4117.
5. Elkaseer, A.; Abdelaziz, A.; Saber, M.; Nassef, A. FEM-Based Study of Precision Hard Turning of Stainless Steel 316L. *Materials* **2019**, *12*, 2522.
6. Benes, J. Cutting Difficult-to-Machine Materials.
7. Available online:https: //www.americanmachinist. com/archive/cutting-tool-digest/article/21892040/cutting-difficulttomachine-materials
8. Abu Qudeiri, J.E.; Saleh, A.; Ziout, A.; Mourad, A.-H.I.; Abidi, M.H.; Elkaseer, A. Advanced electric discharge machining of stainless steels: Assessment of the state of the art, gaps and future prospect. *Materials* **2019**, *12*, 907.
9. Elkaseer, A.; Lambarri, J.; Ander Sarasua, J.; Cascón, I. On the development of a chip breaker in a metal-matrix polycrystalline diamond insert: Finite element based design with ns-laser ablation and machining verification. *J. Micro Nano-Manuf.* **2017**, *5*.
10. Lee, S.H.; Li, X.P. Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. *J. Mater. Process. Technol.* **2001**, *115*, 344–358.
11. Yu, Z.; Jun, T.; Masanori, K. Dry electrical discharge machining of cemented carbide. *J. Mater. Process. Technol.* **2004**, *149*, 353–357.
12. Hewidy, M.S.; El-Taweel, T.A.; El-Safty, M.F. Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. *J. Mater. Process. Technol.* **2005**, *169*, 328–336.

13. Chiang, K.-T.; Chang, F.-P. Optimization of the WEDM process of particle-reinforced material with multiple performance characteristics using grey relational analysis. *J. Mater. Process. Technol.* **2006**, *180*, 96–101.
14. Surleraux, A.; Pernot, J.-P.; Elkaseer, A.; Bigot, S. Iterative surface warping to shape craters in micro-EDM simulation. *Eng. Comput.* **2016**, *32*, 517–531.
15. McCown, B.H.; McCabe, D.E.; Russell, D.R.; Robison, D.J.; Barton, K.A.; Ra*ff*a, K.F. Stable transformation of Populus and incorporation of pest resistance by electric discharge particle acceleration. *Plant Cell Rep.* **1991**, *9*, 590–594.
16. Yan, B.H.; Huang, F.Y.; Chow, H.M.; Tsai, J.Y. Micro-hole machining of carbide by electric discharge machining. *J.Mater. Process. Technol.* **1999**, *87*, 139–145.
17. Lin, J.L.; Wang, K.S.; Yan, B.H.; Tarng, Y.S. Optimization of the electrical discharge machining process based on the Taguchi method with fuzzy logics. *J. Mater. Process. Technol.* **2000**, *102*, 48–55.
18. Kansal, H.K.; Singh, S.; Kumar, P. E*ff*ect of silicon powder mixed EDM on machining rate of AISI D2 die steel. *J.Manuf. Process.* **2007**, *9*, 13–22.
19. Kanlayasiri, K.; Boonmung, S. E*ff*ects of wire-EDM machining variables on surface roughness of newly developed DC 53 die steel: Design of experiments and regression model. *J. Mater. Process. Technol.* **2007**, *192*, 459–464.
20. Younis, M.A.; Abbas, M.S.; Gouda, M.A.; Mahmoud, F.H.; Allah, S.A.A. E*ff*ect of electrode material on electrical discharge machining of tool steel surface. *Ain Shams Eng. J.* **2015**, *6*, 977–986
21. Valaki, J.B.; Rathod, P.P. Assessment of operational feasibility of waste vegetable oil based bio-dielectric fluid for sustainable electric discharge machining (EDM). *Int. J. Adv. Manuf. Technol.* **2016**, *87*, 1509–1518
22. Zhang, Y.; Liu, Y.; Shen, Y.; Li, Z.; Ji, R.; Cai, B. A novel method of determining energy distribution and plasma diameter of EDM. *Int. J. Heat Mass Transf.* **2014**, *75*, 425–432.
23. Sudhakara, D.; Prasanthi, G. Application of Taguchi Method for Determining Optimum Surface Roughness in Wire Electric Discharge Machining of P/M Cold Worked Tool Steel (Vanadis-4E). *Procedia Eng.* **2014**, *97*, 1565–1576.

24. Aich, U.; Banerjee, S. Modeling of EDM responses by support vector machine regression with parameters selected by particle swarm optimization. *Appl. Math. Model.* **2014**, *38*, 2800–2818
25. Balasubramanian, P.; Senthilvelan, T. Optimization of machining parameters in EDM process using cast and sintered copper electrodes. *Procedia Mater. Sci.* **2014**, *6*, 1292–1302.
26. Sahu, J.; Mohanty, C.P.; Mahapatra, S.S. A DEA approach for optimization of multiple responses in electrical discharge machining of AISI D2 steel. *Procedia Eng.* **2013**, *51*, 585–591
27. Klocke, F.; Schwade, M.; Klink, A.; Veselovac, D. Analysis of material removal rate and electrode wear in sinking EDM roughing strategies using di*ff*erent graphite grades. *Procedia CIRP* **2013**, *6*, 163–167.
28. Shabgard, M.; Ahmadi, R.; Seyedzavvar, M.; Oliaei, S.N.B. Mathematical and numerical modeling of the e*ff*ect of input-parameters on the flushing e*ffi*ciency of plasma channel in EDM process. *Int. J. Mach. Tools Manuf.* **2013**, *65*, 79–87.
29. Fan, Y.; Bai, J.; Li, C.; Xu, W. Research on precision pulse power technology of WEDM. *Procedia CIRP* **2013**, *6*, 267–273.
30. Srivastava, V.; Pandey, P.M. E*ff*ect of process parameters on the performance of EDM process with ultrasonic assisted cryogenically cooled electrode. *J. Manuf. Process.* **2012**, *14*, 393–402.
31. Teimouri, R.; Baseri, H. E*ff*ects of magnetic field and rotary tool on EDM performance. *J. Manuf. Process.*
    2012, *14*, 316–322.
32. Kumar, S.; Batra, U. Surface modification of die steel materials by EDM method using tungsten powder-mixed dielectric. *J. Manuf. Process.* **2012**, *14*, 35–40.
33. Sivapirakasam, S.P.; Mathew, J.; Surianarayanan, M. Multi-attribute decision making for green electrical discharge machining. *Expert Syst. Appl.* **2011**, *38*, 8370–8374.
34. Çaydas¸, U.; Hasçalık, A.; Ekici, S. An adaptive neuro-fuzzy inference system (ANFIS) model for wire-EDM.
    Expert Syst. Appl. **2009**, *36*, 6135–6139.

35. Lin, Y.-C.; Chen, Y.-F.; Wang, D.-A.; Lee, H.-S. Optimization of machining parameters in magnetic force assisted EDM based on Taguchi method. *J. Mater. Process. Technol.* **2009**, *209*, 3374–3383.

36. Wu, K.L.; Yan, B.H.; Lee, J.-W.; Ding, C.G. Study on the characteristics of electrical discharge machining using dielectric with surfactant. *J. Mater. Process. Technol.* **2009**, *209*, 3783–37

37. Matoorian, P.; Sulaiman, S.; Ahmad, M. An experimental study for optimization of electrical discharge turning (EDT) process. *J. Mater. Process. Technol.* **2008**, *204*, 350–356.

38. Haron, C.H.C.; Ghani, J.A.; Burhanuddin, Y.; Seong, Y.K.; Swee, C.Y. Copper and graphite electrodes performance in electrical-discharge machining of XW42 tool steel. *J. Mater. Process. Technol.* **2008**, *201*, 570–573.

39. Haddad, M.J.; Tehrani, A.F. Material removal rate (MRR) study in the cylindrical wire electrical discharge turning (CWEDT) process. *J. Mater. Process. Technol.* **2008**, *199*, 369–378.

40. Kansal, H.K.; Singh, S.; Kumar, P. Numerical simulation of powder mixed electric discharge machining (PMEDM) using finite element method. *Math. Comput. Model.* **2008**, *47*, 1217–1237.

41. Kanlayasiri, K.; Boonmung, S. An investigation on e*ff*ects of wire-EDM machining parameters on surface roughness of newly developed DC53 die steel. *J. Mater. Process. Technol.* **2007**, *187*, 26–29.

42. Kansal, H.K.; Singh, S.; Kumar, P. Technology and research developments in powder mixed electric discharge machining (PMEDM). *J. Mater. Process. Technol.* **2007**, *184*, 32–41.

43. Kiyak, M.; Çakır, O. Examination of machining parameters on surface roughness in EDM of tool steel

44. Tzeng, Y.; Chen, F. Multi-objective optimisation of high-speed electrical discharge machining process using a Taguchi fuzzy-based approach. *Mater. Des.* **2007**, *28*, 1159–1168

45. Zarepour, H.; Tehrani, A.F.; Karimi, D.; Amini, S. Statistical analysis on electrode wear in EDM of tool steel DIN 1.2714 used in forging dies. *J. Mater. Process. Technol.* **2007**, *187*, 711–714

46. Yilmaz, O.; Eyercioglu, O.; Gindy, N.N.Z. A user-friendly fuzzy-based system for the selection of electro discharge machining process parameters. *J. Mater. Process. Technol.* **2006**, *172*, 363–371.

47. Wu, K.L.; Yan, B.H.; Huang, F.Y.; Chen, S.C. Improvement of surface finish on SKD steel using electro-discharge machining with aluminum and surfactant added dielectric. *Int. J. Mach. Tools Manuf.* **2005**, *45*, 1195–1201.

48. Kansal, H.K.; Singh, S.; Kumar, P. Parametric optimization of powder mixed electrical discharge machining by response surface methodology. *J. Mater. Process. Technol.* **2005**, *169*, 427–436

49. Amorim, F.L.; Weingaertner, W.L. The influence of generator actuation mode and process parameters on the performance of finish EDM of a tool steel. *J. Mater. Process. Technol.* **2005**, *166*, 411–416

50. Hasçalýk, A.; Çaydas¸, U. Experimental study of wire electrical discharge machining of AISI D5 tool steel.

51. Kunieda, M.; Furudate, C. High precision finish cutting by dry WEDM. *CIRP Ann.* **2001**, *50*, 121–124

52. Singh, S.; Maheshwari, S.; Pandey, P.C. Some investigations into the electric discharge machining of hardened tool steel using di*ff*erent electrode materials. *J. Mater. Process. Technol.* **2004**, *149*, 272–277

53. Puri, A.B.; Bhattacharyya, B. An analysis and optimisation of the geometrical inaccuracy due to wire lag phenomenon in WEDM. *Int. J. Mach. tools Manuf.* **2003**, *43*, 151–159

54. Guu, Y.H.; Hocheng, H.; Chou, C.Y.; Deng, C.S. E*ff*ect of electrical discharge machining on surface characteristics and machining damage of AISI D2 tool steel. *Mater. Sci. Eng. A* **2003**, *358*, 37–43.

55. Ghoreishi, M.; Atkinson, J. A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining. *J. Mater. Process. Technol.* **2002**, *120*, 374–384.

56. Kunieda, M.; Takaya, T.; Nakano, S. Improvement of dry EDM characteristics using piezoelectric actuator.

57. Arindam Mukhuti, Amruta Rout, S.Tripathy, “Optimization of Inconel 600 using Wire EDM by MOORA and Taguchi’s method”, International Conference of Electrical, Electronics and Optimization Techniques, 2016.
58. Ch. Maheswara Rao, K. Jagadeeswara Rao and K. Suresh Babu, “Optimization of Material Removal Rate and Surface Roughness Using Grey Analysis” International Journal of Engineering Research and Development, e-ISSN: 2278-067X, p-ISSN:2278-800X, Vol. 12, Issue 3, (Part-1), pp. 49-58, March 2016.
59. Ch.Maheswara Rao, K.Venkata Subbaiah, “Preference Number Based Taguchi-Utility Method for the Optimization of Multiple Responses”, Journal of Recent Activities in Production, e-ISSN: 2581-9771, Vol.3, Issue.2, pp. 1-7, 2018.
60. Ch. Maheswara Rao, K. Venkata Subbaiah and Ch. Suresh, “Prediction of Optimal Designs for Material Removal Rate and Surface Roughness Characteristics”, International Journal of Lean Thinking, Vol-7, Issue-2, pp.24-46, December-2016.

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