Study on Effect of Wire EDM Process Parameters Using MADM/MCDM Technique

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IN

MECHANICAL ENGINEERING

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This is to certify that the Project Report entitled **"STUDY ON EFFECT OF WIRE EDM PROCESS PARAMETERS USING MADM/MCDM TECHNIQUES"** being submitted by GOLIVI KUMAR (317126520082), SAMALA VAMSI (318126520L13), PURIYA SIVARAM (317126520110), BORA SURESH REDDY (317126520069), KUPPALA SAI VISWATEJA (317126520093) in partial fulfillments for the award of degree of **BACHELOR OF TECHNOLOGY** in **MECHANICAL ENGINEERING**. It is the work of bona-fide, carried out under the guidance and supervision of **MR.B.B.ASHOK KUMAR**, Assistant Professor, Department Of Mechanical Engineering, ANITS during the academic year of 2017-2021.

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Abstract

Wire-electro discharge machining (WEDM) has become an important non-traditional machining process, as it provides an effective solution for producing components made of difficult-to-machine materials like titanium, zirconium, etc., and intricate shapes, which are not possible by conventional machining methods. In the present work, an experimental investigation has been done to evaluate the effect of Wire EDM parameters on the performance characteristics. A medium carbon steel AISI 1040 has been taken as workpiece for the study due to its high ultimate tensile strength and hardness. The Wire EDM parameters are planned as per L18 0A for the experiments by taking brass wire as electrode and distilled water as dielectric medium. The results of AHP with utility analysis revealed that wire tension is the most influencing factor in achieving better multiple responses.

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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.

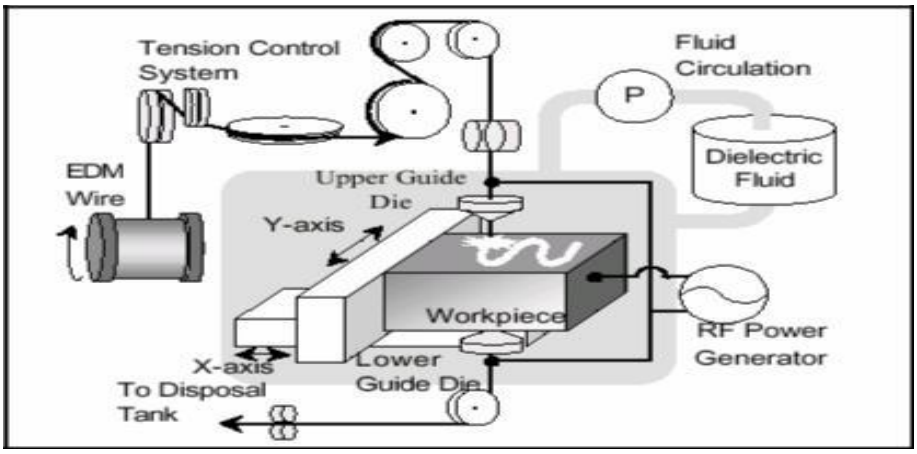

Figure 1.1 Wire Electrical Discharge Machining System

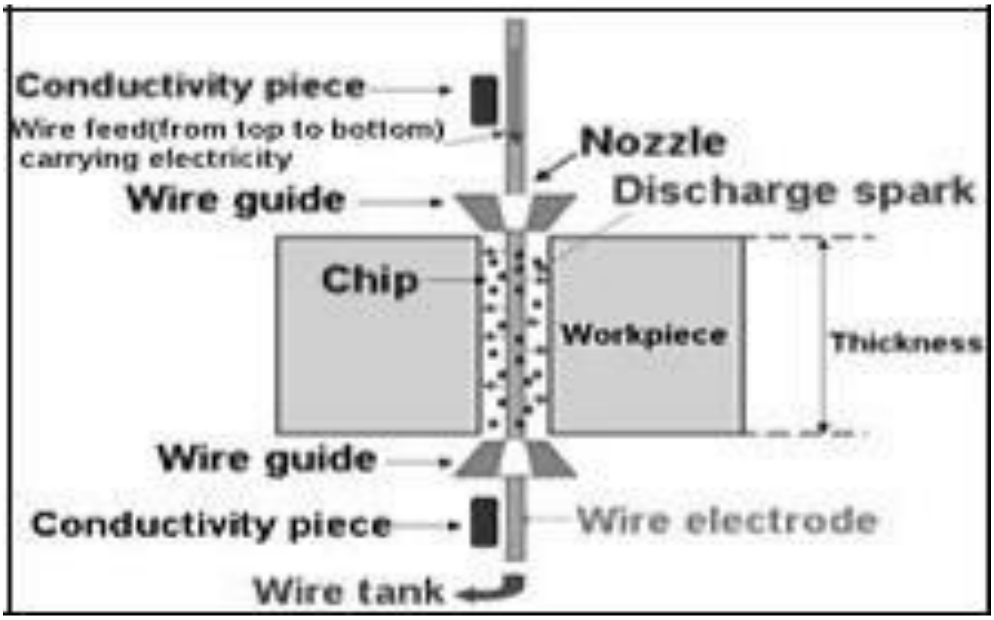

Figure 1.2 Close View of Cutting Zone in WEDM

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.

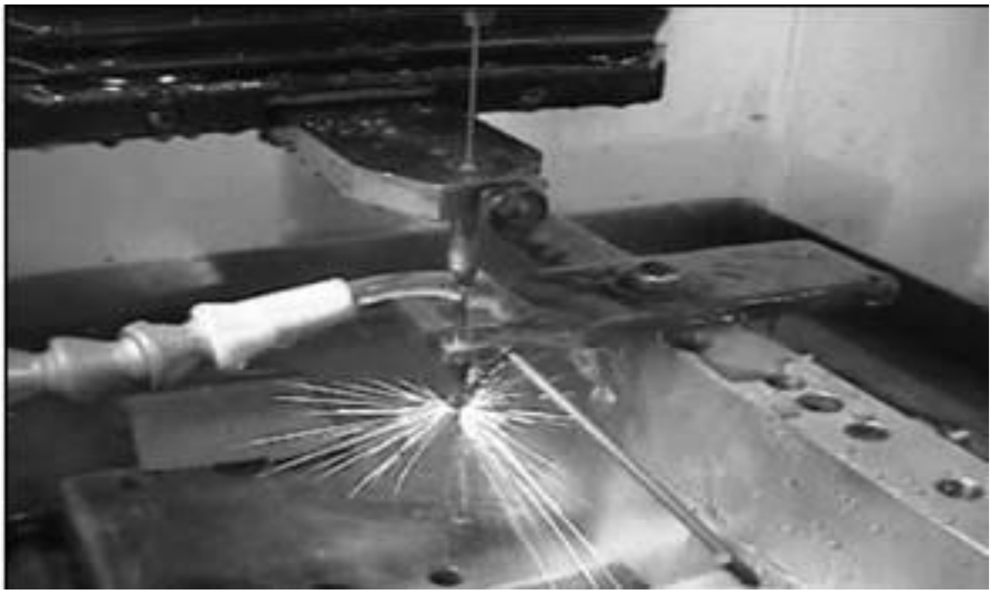

Figure 1.3 Generation of Spark in WEDM

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.

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.

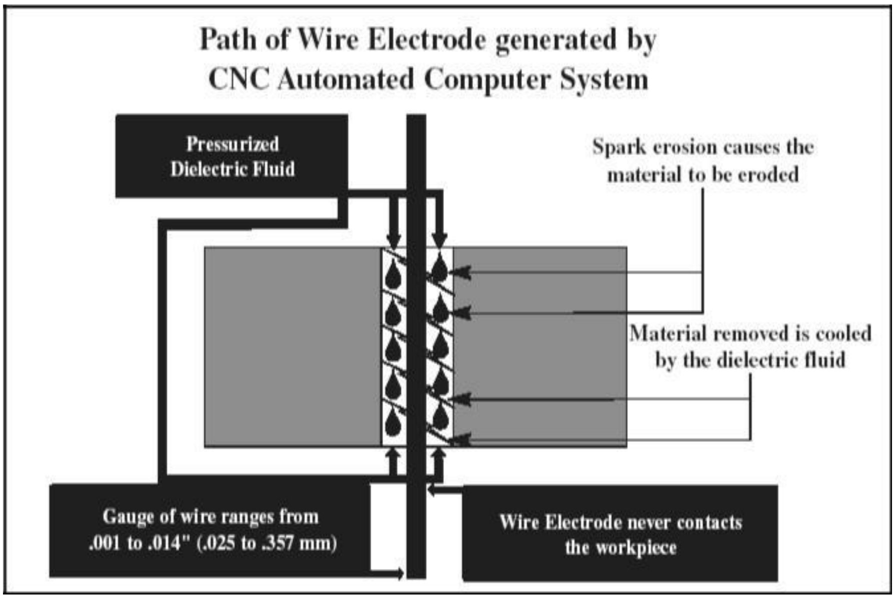

Figure 1.4 Path of Wire in WEDM

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

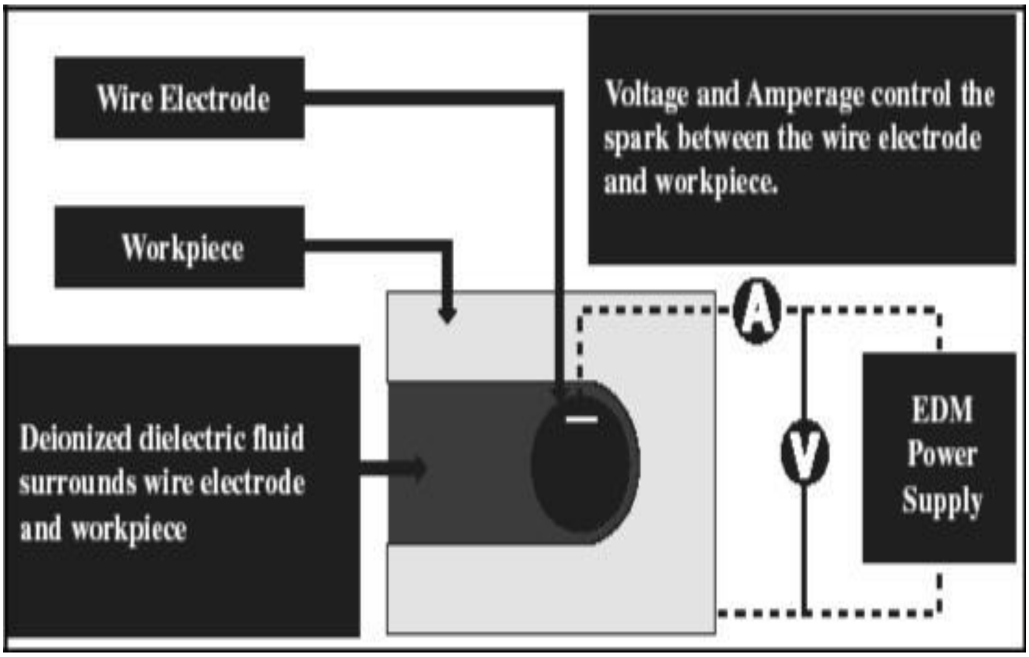

Figure 1.5 Power Generation in WEDM

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.

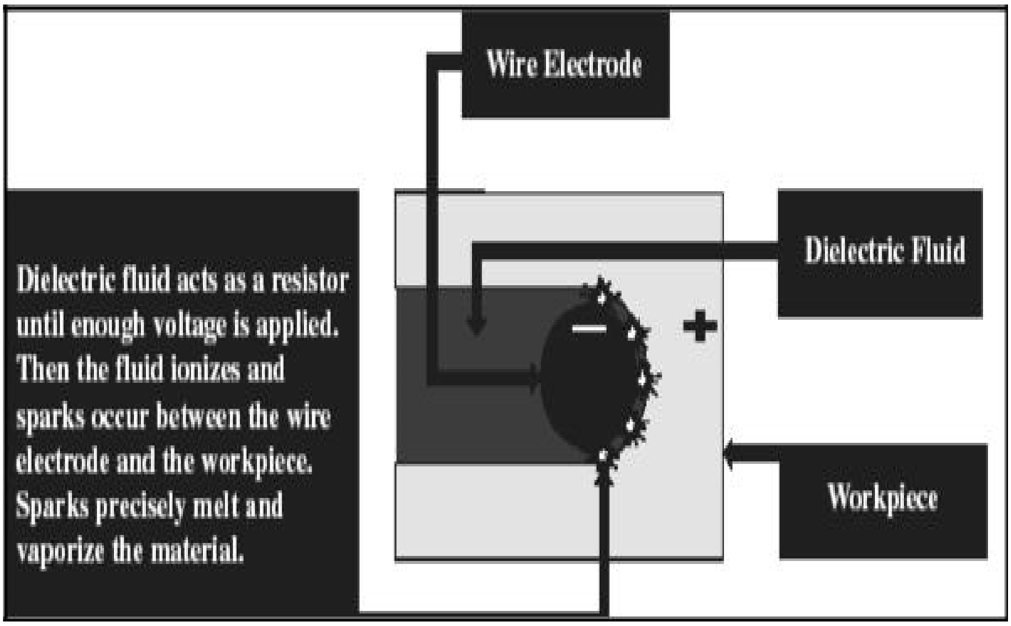

Figure 1.6 Erosion of Material in WEDM

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

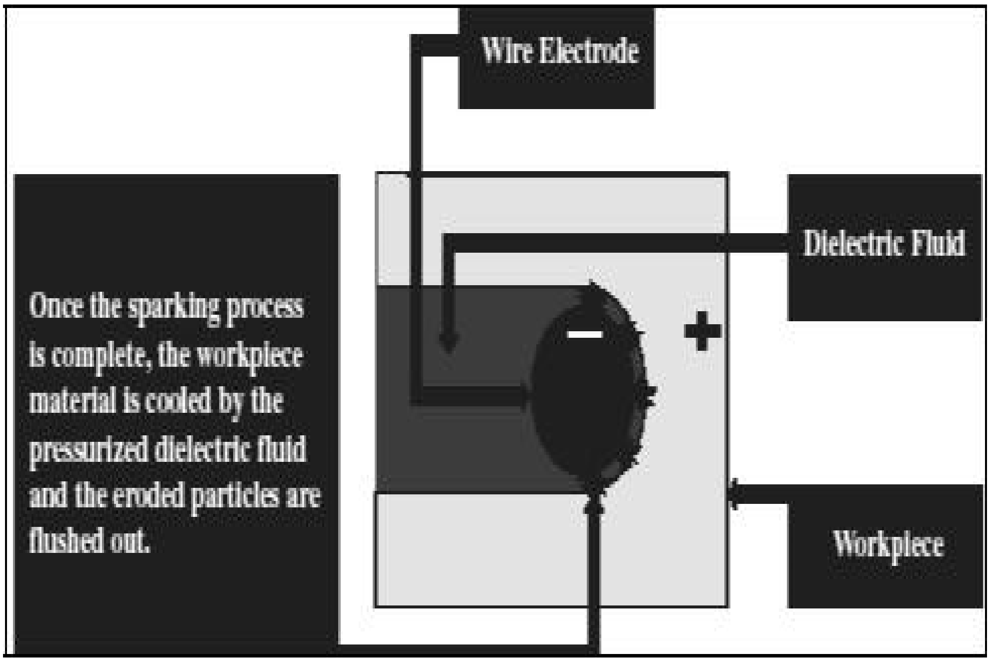

Figure 1.7 Spark Erosion during ON Time

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.

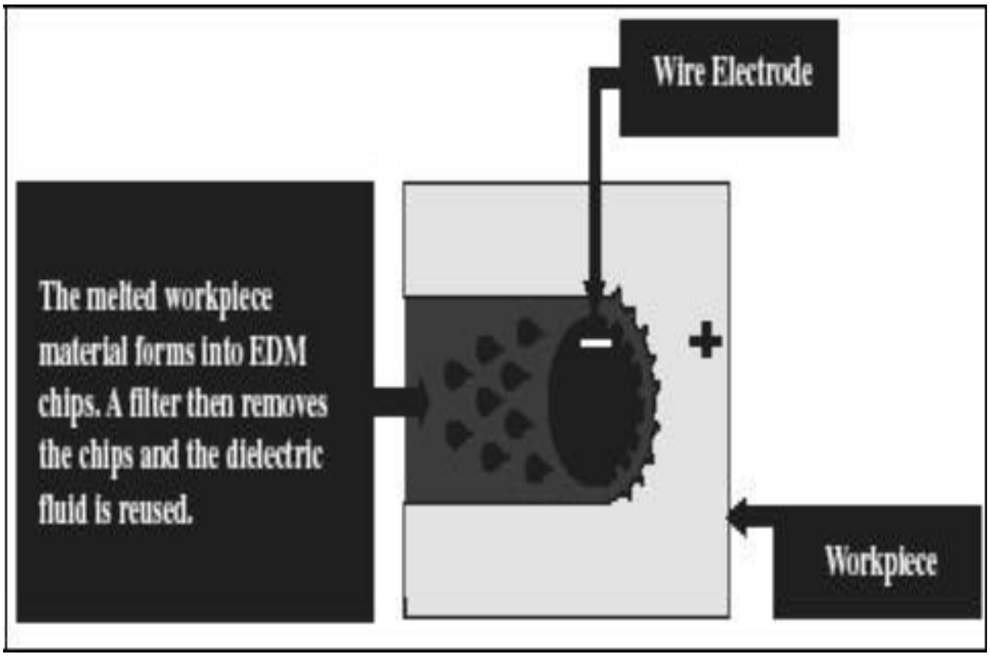

Figure 1.8 Chip Removal by Filtration

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:

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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:

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.

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

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

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.

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.

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 die-sinker 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.

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.

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.

Wire-Cut Chip Removal

Chip removal for a wire-cut machine is simple compared to a die-sinker machine. Wire-cut 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.

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.

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.

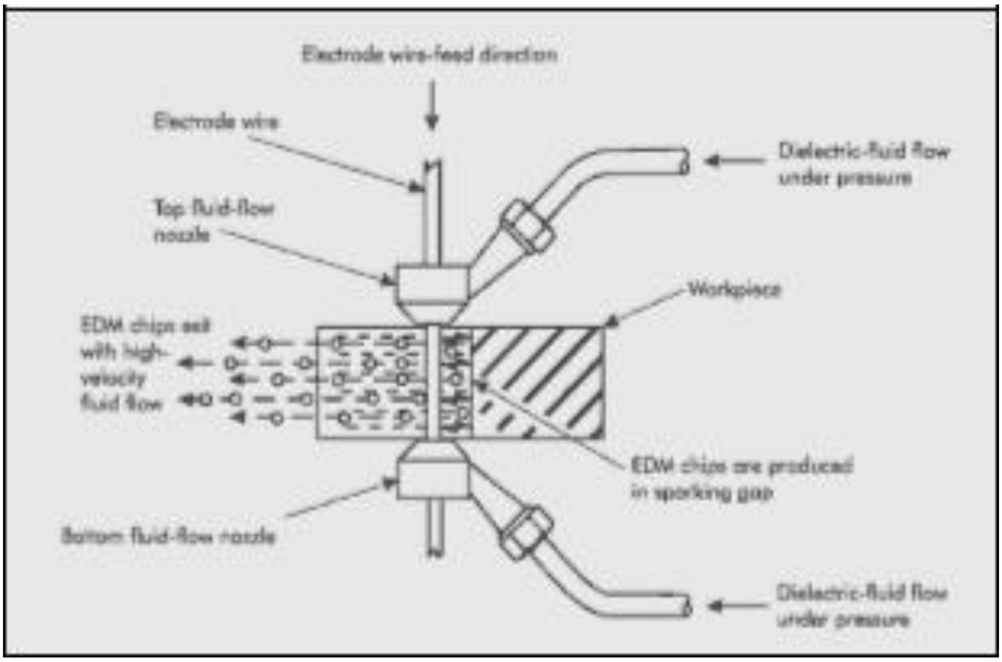

Figure 1.9 Wire Cut Fluid Flow Nozzles

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 full-wire 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.

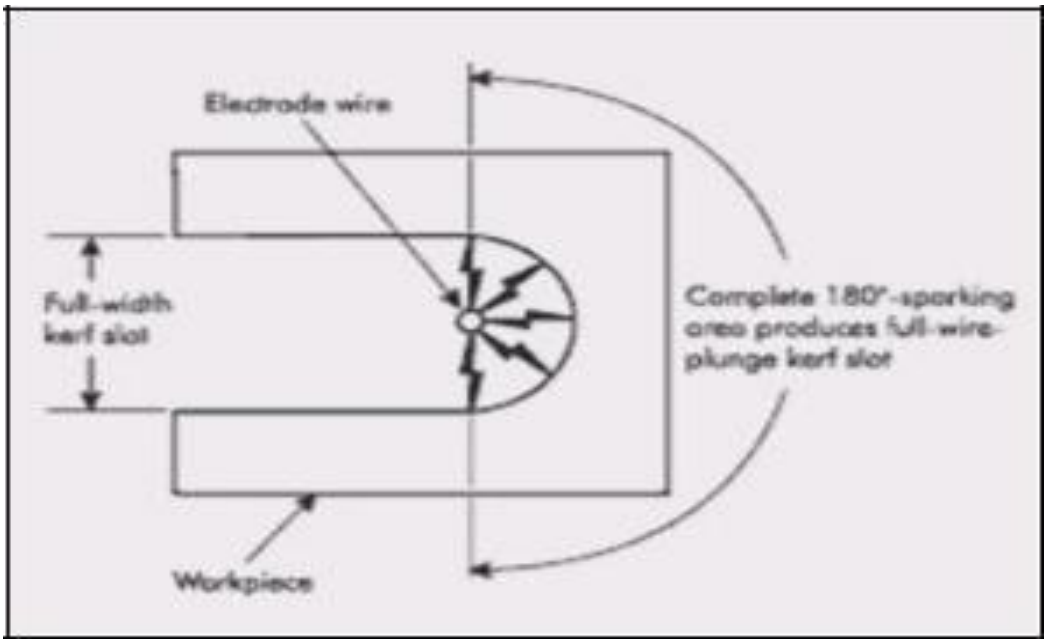

Figure 1.10 Full-Wire Finish Machining

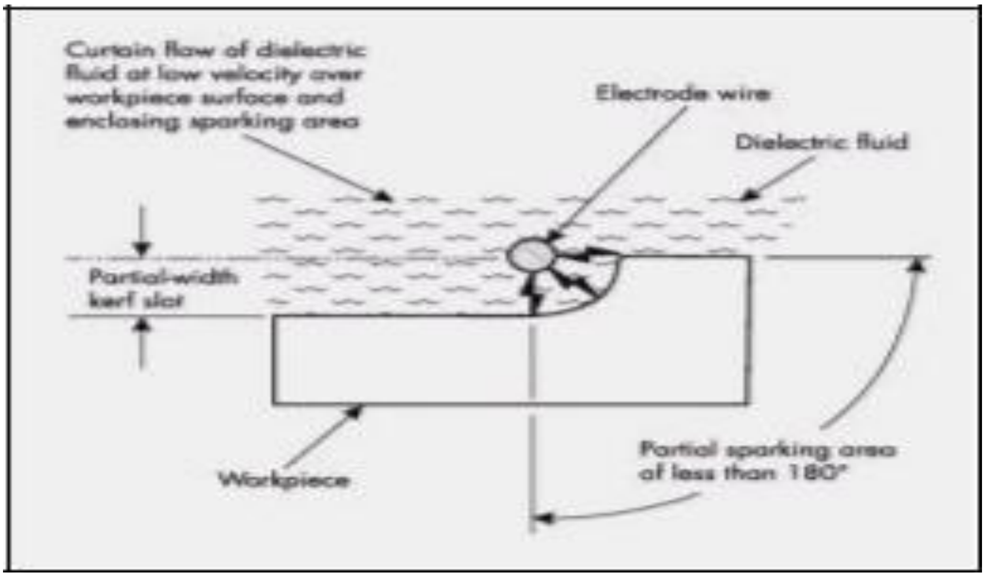

Figure 1.11 Partial-Wire Finish Machining

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.

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.

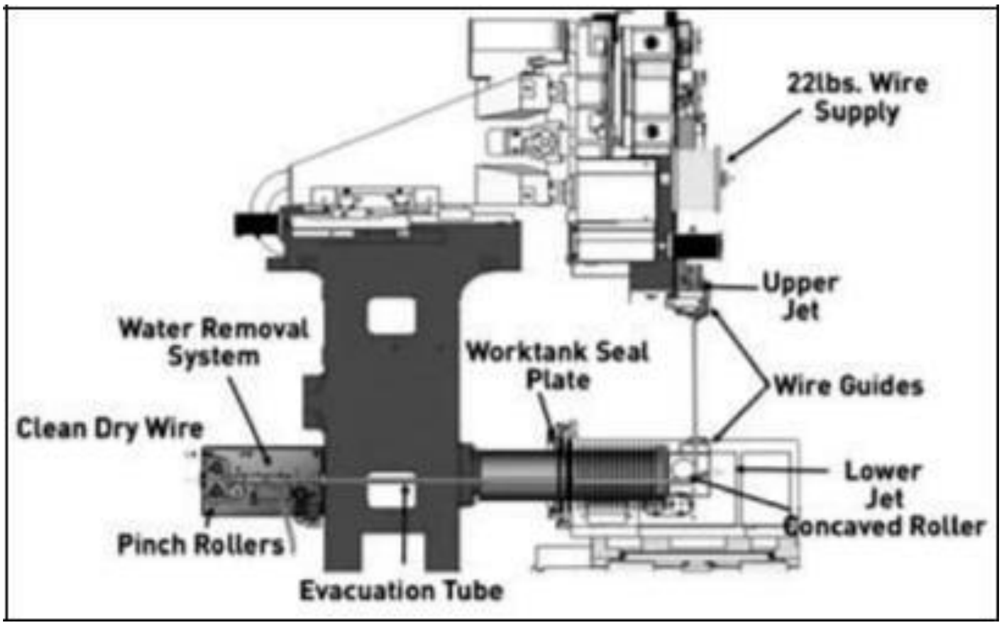

Figure 1.12 Wire EDM Transport System

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:

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 micro-cracking. 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 power-supplied 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 high-precision 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.

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.

Ceramics

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

Cost Savings with WEDM

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

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.

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.

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.

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.

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.

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.

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.

Internal Contours: Pipes, gears, pultrusion molds all benefit from wire EDM.

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.

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.

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.

Applications: machine tools with disposable blades also cut with a wire EDM.

1.7. Benefits of Wire EDM

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.

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.

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.

Reduced Costs

To be competitive in today's market it is important to take advantage of every cost-saving 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.

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.

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.

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 molds, 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. The review of this kind with an emphasis on tool and die materials is extremely useful to relevant professions, practitioners, and researchers. 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 tool steel 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 favorable characteristics. In addition to unique characteristics, most modern materials need special manufacturing processes to enable them to be machined with ease [1,2]. Most of these materials are usually difficult to cut by conventional manufacturing processes [3–7]. 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 [8,9].

Tool steels and other tool materials (e.g., carbides) are such widely used hard-to-cut materials because of their high hardness and abrasion wear resistance, in addition to their ability to withstand high load and to operate in rapidly changing temperatures [6]. Tool steels have a wide range of applications, including stamping and metal-working dies, cutting tools, hammers, and machine parts [10]. Applications of these tools in the manufacturing sector is very large; thus, there exists huge machining requirements of tools, tooling, dies, and molds [11]. Before being put to use, these steels are subjected to heat treatment to meet the required properties for specific application [12,13]. In addition to iron and carbon, tool steels have in them other elements (e.g., Cr, W, V, Mo, etc.) to increase their strength, hardness, hot strength and hot hardness, and wear resistance. Although these steels can be machined by conventional methods, they come with serious concerns with regard to very poor tool life and part accuracy [14].

Electric discharge machining (EDM) is one of the most advanced manufacturing methods used to successfully machine conductive hard-to-cut materials [8,15–19]. EDM is the process of choice to machine hard-to-cut materials widely used in modern industries to facilitate accurate machining [20–25], 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 [23,26–28]. 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 [29–35], among others. Furthermore, some other articles presented a discussion of specific objectives; for example, Barenji et al. [36] developed a model for prediction of material removal rate (MRR) and tool wear rate (TWR) for the EDM of AISI D6 tool steel. They reported that higher values of pulse-on time resulted in higher MRR and lesser TWR. Long et al. [37] used powder-mixed EDM for machining die steels. Titanium powder was used for mixing, and surface quality was analyzed. It was revealed that the quality of surface layer was improved at optimal parameters. Shabgard et al. [38] studied the effects of the key input variables of wire EDM of ASP30 tool steel. The output responses under consideration were MRR and surface roughness. The results revealed that an increase in spraying pressure of dielectric fluid led to a higher MRR and surface roughness. EDM of AISI M42 high-speed tool steel alloy was conducted to study the effect of major input parameters on MRR. It was revealed that tool polarity was the most influential factor and, at negative polarity, maximum MRR was achieved. P20 tool steel was machined using wire EDM, and pulse-on time, pulse-off time, peak current, and spark gap voltage were varied. The output responses under study were kerf width and MRR. The best combination of parameters was reported to achieve maximum MRR [39]. Sharma and Sinha [40] applied rotary-EDM to machine AISI D2 tool steel using a copper electrode. MRR, TWR, and machining rate were studied by varying input parameters (peak current, voltage, duty cycle, and electrode rotation speed). Bahgat et al. [41] conducted experiments to study the effect of major input variables on MRR, electrode wear ratio, and surface roughness while machining H13 die steel. It was reported that higher MRR and lower electrode wear rate were achieved using a copper electrode, whereas lower surface roughness was attained with a brass electrode. Gopal et al. [42] compared the performance of unprocessed and equal channel angular pressing (ECAP)-processed copper electrode while machining AISI H13 tool steel using EDM. It was reported that the triple-ECAP-passed electrode gave better machining quality. Despite many existing review papers, to the best of authors' knowledge, there is no study that reviewed the EDM process specifically for tool and die steels. Since tool and die steels have usage in a wide range of applications and they are difficult to cut with the conventional manufacturing processes, non-conventional processes such as EDM are becoming prevalent for their machining. Generally, one of the largest uses of the EDM process is in tool-, die-, and mold-making. All these industries mostly use various kinds of tool steels. 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.

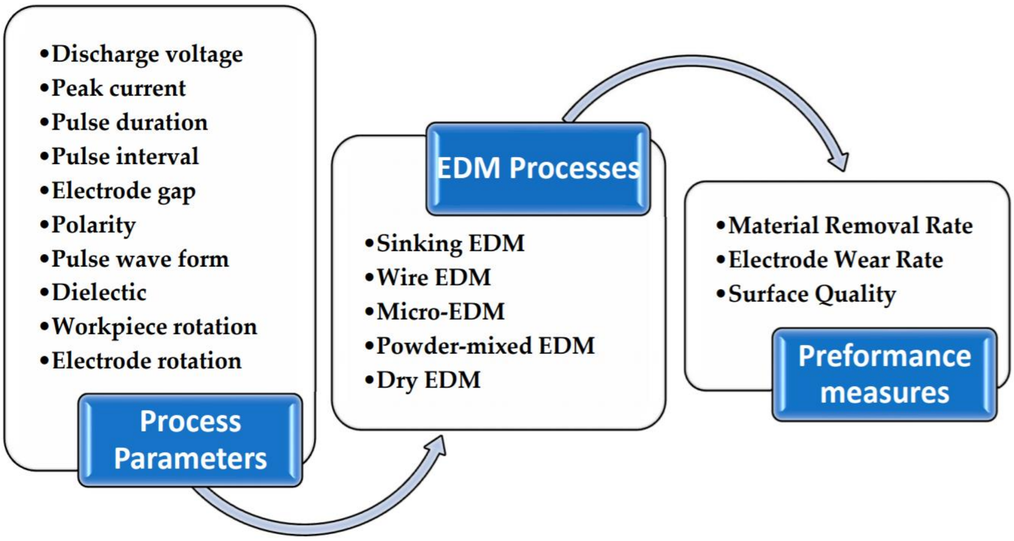

Figure 2.1. The processes of electric discharge machining (EDM) and their process parameters and performance measures.

Various Grades of Tool Steels

Steels can be categorized into four groups, namely, stainless steel, tool steel, carbon steel, and alloy steel. Each of these groups has its own characteristics which make it suitable for specific applications. Tool steels are mainly employed for making cutting and metal-working tools [12]. In order to meet the required conditions these tools encounter under service conditions, tool steels must have many properties such as the ability to withstand high load, the ability to operate in rapidly changing temperatures, high abrasive resistance, etc. Normally, the tool steels are used in hardened conditions by heat treatment, and they are subsequently tempered to meet the required properties for specific application [12]. Tool steels are high-hardness and abrasion-resistant alloy steels. In addition to iron and carbon, tool steels include many other elements to increase hardness and wear resistance and hot strength and hot hardness. Furthermore, they also possess adequate toughness which can be achieved by tempering, which is performed subsequent to hardening. Applications of tool steels include stamping and extrusion dies, cutting tools, hammers, and machine parts [10]. Properties of widely and recently used different grades of tool steels, as well as the EDM processes considered for each grade, are summarized in Table2.1.

Table 2.1. Details of various EDM processes used by researchers for different grades of tool steels

Different Grades and Corresponding Machining Operations	Composition (Weight %)	Properties
AISI D2 Die sinking EDM [85,104–110]. Wire EDM [111–113] Powder-mixed EDM [114–116].	C 1.5, Si 0.3, Mn 0.3, Mo 1.0, Cr 12.0, Ni 0.3, V 0.8, Co 1.0.	High-carbon and high-chromium tool steel. It has high resistance to wear and abrasion. D2 grade is heat-treatable steel with hardness in the range 55–62 HRC. Its corrosion resistance depends on the percentage of chromium [117].
AISI D3 Die sinking EDM [118]. Wire EDM [119].	C 2.00, Si 0.30, Mn 0.30, Cr 12.00	High-carbon, high-chromium tool steel. It has excellent resistance to wear and abrasion and has good dimensional stability and high compressive strength. Its hardness is in the range of 58–64 HRC [120].
AISI D5 Wire EDM [121,122].	C 1.53, Si 0.89, Mn 0.46, Cr 12.00, Mo 1.00, Ni 0.384	Similar to other grades in group D, D5 has high carbon and high chromium content; it is the most commonly used steel among the group D steels [123].
AISI D6 Die sinking EDM [124].	Cr 12.5, C 2.05, W 1.3, Mn 0.8, Si 0.3	In addition to high carbon and high chromium contents, D6 tool steel is alloyed with tungsten. D6 steel has high compressive strength, high wear resistance, high surface hardness, and good hardening stability [125].
AISI H11 Die sinking EDM [109,126]. Dry EDM [78,127].	Cr 4.75–5.50, Mo 1.10–1.75, Si 0.80–1.20, V 0.80–1.20, C 0.32–0.45, Ni 0.3, Cu 0.25, Mn 0.20–0.50, P 0.03, S 0.03	H11 grade is one of the most commonly used chromium hot-work steels. It has low carbon content and has good toughness and deep hardness

Powder-mixed EDM [116,128–131]. Micro-EDM [132].		due to air quenching from heat treatment [133].
AISI O1 Die sinking EDM [76]. Wire EDM [134]. Powder-mixed EDM [135,136].	C 0.85–1.00, Mn 1.00–1.40, Si 0.50, Cr 0.40–0.60, Ni 0.30, W 0.40–0.60, V 0.30, Cu 0.25, P 0.0, S 0.03	O1 is oil-hardening tool steel. It has good machinability and dimensional stability in hardening. It also has a good combination of high surface hardness and toughness after hardening and tempering. O1 grade has good resistance to wear and abrasion due to its content of tungsten and chromium [137].
AISI O2 Powder-mixed EDM [116].	OHNS: C 0.82, Si 0.18, Mn 0.52, Cr 0.49, V 0.19, Mo 0.13, Ni 0.05;	O2 grade is oil-hardening tool steel. It has good durability, excellent wear resistance, and an ability to hold a good cutting edge [138].
AISI M2 Die sinking EDM [139–141]. Wire EDM [142].	C 0.78–1.05, Cr 3.75–4.50, W 5.50–6.75, Mo 4.50–5.50, V 1.75–2.20.	M2 grade is molybdenum-based high speed steel (HSS). It is a medium alloyed HSS. It has good machinability, well-balanced toughness, wear resistance, and red hardiness properties [143].
SKD11 Die sinking EDM [144–147]. Wire EDM [148–151]. Dry EDM [103,152]. Powder-mixed EDM [54,136,153–155].	C 1.40–1.60, Si Max 0.40, Mn Max 0.60, P Max 0.030, S Max 0.030, Cr 11.0–13.0, Mo 0.80–1.20, V 0.20–0.50.	SKD 11 is high-carbon and high-chromium alloy steel. It has high hardness and a tempering hardening effect. It also has good resistance to wear, quenching, and less deformation. Currently, it has the best wear resistance of alloy tool steel [156].
SKD61 Die sinking EDM [157]. Powder-mixed EDM [136,158,159].	C 0.35–0.42, Si 0.80–1.20, Mn 0.25–0.50, P Max 0.030, S Max 0.020, Cr 4.80–5.50, Mo 1.00–1.50, V 0.80–1.15	KSD61 is hot-work steel; it has high creep, temperature fatigue resistance, and high toughness. It also has a good ability to be polished and

		good thermal conductivity [160].
P20 Die sinking EDM [161–164]. Dry EDM [165]. Powder-mixed EDM [166].	C 0.28–0.40, Si 0.20–0.80, Mn 0.60–1.00, P Max. 0.030, S Max. 0.030, Cr 1.40–2.00, Mo 0.30–0.55.	P20 tool steel is a chrome-moly alloy steel with a carbon content of approximately 0.35 to 0.40. P20 has good mirror-polish ability and less texture, making finishing easier. It distributes a uniform hardness level even across large blocks [167].
BÖHLER W300 Die sinking EDM [168–170].	C 0.36, Si 1.1, Cr 5.0, Mo 1.3, V 0.4	BÖHLER W300 is hot-work tool steel and it has high impact strength and excellent hot tensile properties.
EN 31 Die sinking EDM [23]. Powder-mixed EDM [61].	C 0.9–1.2, Si 0.1–0.3, Mn 0.3–0.7, Cr 1–1.6, S Max 0.025 and P Max 0.025.	EN 31 is a high-carbon alloy steel. It has high hardness with compressive strength. Moreover, it has high resistance against wear and abrasion.
ASP 2023 Die sinking EDM [171]. Wire EDM [172].	C 1.28, Cr 4.1, Mo 5.0, W 6.4, V 3.1	ASP 2023 is a high-alloy high-speed steel. It has dimension and shape stability during heat treatment. It has good toughness even for large dimensions. ASP 2023 has high hardness and good wear resistance [173].
C45 Die sinking EDM [174]. Wire EDM [175].	C 0.43–0.50, Si 0.17–0.4, Mn 0.50–0.8	C45 is a medium carbon steel. It has high strength and hardness. It features extreme size accuracy, straightness, and concentricity combined with minimal wear in high-speed applications [176].
DC 53 Wire EDM [177,178].	C 0.95, Si 1.0, Mn 0.4, Cr 8.0, Mo 2.0, V 0.3	DC53 has exceptional toughness, wear resistance, compressive strength, and temper resistance. It also has excellent machining characteristics [179].

DIN 1.2379 Die sinking EDM [180–182].	C 1.50, Si 0.30, Cr 12.0, Mo 0.80, V 0.80	This grade has high abrasive resistance, adhesive wear resistance, and compressive strength. It also has good toughness and good dimensional stability [183].
DIN 1.2738 Die sinking EDM [184]. Micro-EDM [185].	C 0.4, Mn 1.5, Cr 1.9, Ni 1.0, Mo 0.22	This grade has good toughness, wear resistance, stability in hardness, and high hardenability
DIN 1.2714 Die sinking EDM [186].	C 0.50–0.60, Si 0.10–0.40, Mn 0.65–0.95, Cr 1.0–1.2, P max. 0.03, S max. 0.03, V 0.07–0.12, Ni 1.50–1.80, Mo 0.45–0.55	DIN 1.2714 has good hardenability and uniform hardness over sections with big dimensions. Furthermore, it has good strength and toughness in addition to its tempering resistance and dimensional stability [187].
DIN 1.2080 Die sinking EDM [182].	C 2.00–2.35, Mn 0.60, Si 0.60, Cr 11.00–13.50, Ni 0.30, W 1.00, V 1.00, Cu 0.25, P 0.03, S 0.03	DIN 1.2080 is high-carbon/chromium tool steel. It has very high wear resistance and compressive strength. It can be hardened with a very slight change in size.
AISI 4340 Die sinking EDM [188].	C 0.38–0.43, Si 0.15–0.35, Mn 0.6–0.8, P 0.035, S 0.04, Cr 0.7–0.9, Ni 1.65–2.0, Mo 0.2–0.3	AISI 4340 is a heat-treatable and low-alloy steel containing chromium, nickel, and molybdenum. It has high toughness and strength in the heat-treated conditions [189].
S390 Wire EDM [148].	C 1.64, Cr 4.80, W 10.40, Co 8.00, V 4.80, Mo 2.00, Si 0.60, Mn 0.30	This material has the ability to maintain its strength and hardness level under extremely high cutting temperatures.
M238 HH Die sinking EDM [74].	C 0.36 0, Si 0.28, Mn 1.52, P 0.008, S 0.001, Cr 1.88, Mo 0.22, Ni 0.95, Al 0.021	It is hardened and tempered plastic mold steel. There is reduction of hardness in the center of large sizes due to the Ni-addition.
Vanadis-4E Wire EDM [190].	C 1.4, Si 0.4, Mn 0.4, Cr 4.7, Mo 3.5, Va 3.5	This grade has very good ductility, high abrasive/adhesive wear resistance, and high

		compressive strength. Moreover, it has good dimensional stability during heat treatment, good through-hardening properties, and temper back resistance [191].

Earlier studies were also conducted to investigate the relationship between processes and performance parameters [54,142]. The main researches in optimizing process parameters of EDM machining are summarized in Table 2.2.

No.	Authors	Process	Process parameters	Machining performance	Remarks
1	(Younis et al., 2015) [182]	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) [74]	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) [197]	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) [190]	W EDM	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 2014) [139]	EDM	I, Ton, and Toff	MRR and SR	The optimal parameters (I, Ton, and Toff) to 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) [118]	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) [107]	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) [170]	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) [126]	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) [198]	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 and Pandey, 2012) [141]	EDM	Is, Ton, τ, and Vg	MRR, EWR, and SR	EWR and surface 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) [196]	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) [116]	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) [194]	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) [121]	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. 2009) [157]	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) [159]	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) [193]	EDM	IN, Ton, Toff, V, S, and W	MRR	The factors most influencing the cost-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) [192]	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) [119]	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) [114]	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) [177,178]	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 pulse-peak current. The SR increases as the pulse-on time and pulse-peak current increase.

23	(Kansal et al. 2007) [115]	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) [164]	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 Chen 2007) [154]	EDM	V, Pd, τ, Ip, PCON, regular distance for electrode lift, time interval for electrode lift, and powder size	Precision and accuracy of the high-speed EDM	81.5% of the high-speed 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) [186	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) [188]	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) [158]	EDM	P, PD, V, Vg, PCON, and SCON	SR	The surface roughness of the workpiece in the EDM 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) [61]	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) [161]	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) [122]	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) [103]	Dry EDM	G and Gain	MRR	The monotonous oscillation using a piezoelectric actuator was not useful in dry EDM.
33	(Singh et al. 2004) [23]	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) [142]	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) [105]	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) [135]	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) [152]	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 related to tool steel machining 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 tool steel properties and 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 near-optimal operating parameters, which may be attributed to the popularity of these two processes. Figure 2.2 shows the percentages of the EDM processes utilized for studying tool steel machining.

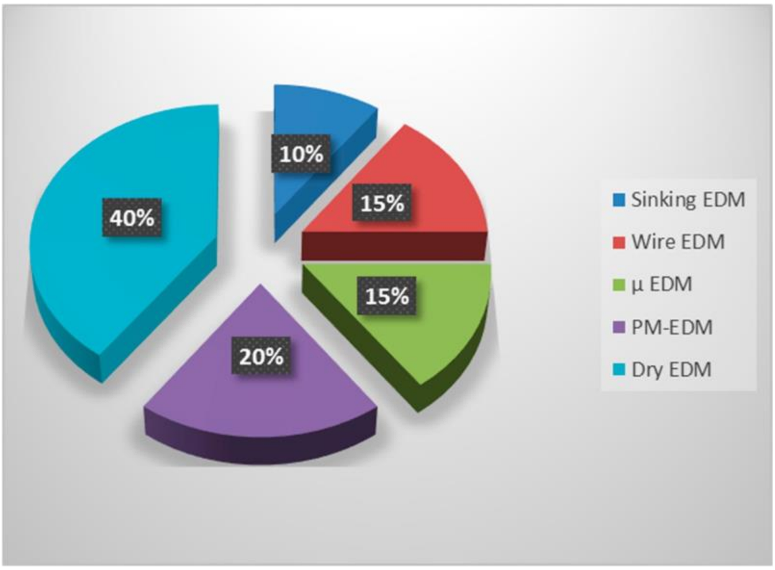

Figure 2.2. Percentage of research related to EDM processes.

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

- According to the general agreement of the results, the main factors influencing the MRR of different tool steel grades 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.
- Table 2.3 shows the general effect of major operating parameters on key performance measures.

Table 2.3. General effect of major operating parameters on key performance measures

	Discharge Current	Pulse-On Time	Pulse-Off Time	Voltage	Electrode Rotation Speed
MRR ↑	↑	↑	↓	↗↘	↑
EWR ↓	↓	↓	↓	↓	↓
SR ↓	↓	↓	↑	↓	↑

- 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 multi objective optimization method taguchi based utility and AHP is employed for optimizing the control 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

2 Full factorial technique
3 Fractional factorial technique
4 Taguchi orthogonal array
5 Response surface method (central composite design).

3.2. Taguchi Optimization Method

Taguchi techniques are statistical methods developed by Genichi Taguchi to improve the Quality of manufacturing goods. 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.

Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach i.e., System design, parameter design and tolerance 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. Following on from system design is 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. Finally, 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. To obtain high cutting performance, the parameter design proposed by Taguchi method is adopted in this project work.

3.3. Analytic Hierarchy process(AHP)

However, in the proposed work, the associate weight for each response required for calculation of overall utility index can be obtained with the help of Analytic Hierarchy Process (AHP). The analytic hierarchy process (AHP) is a structured technique for dealing with complex decisions that was developed by Thomas L. Saaty in the 1980 year. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. The base of this model is comparing variables by pair wise by Matrix relationship. In this way, pair wise of the effective variables on the concrete Pavement were considered and based on relative weights the output was extent. AHP helps decision makers to find a solution that best suits their goal and their understanding of the problem. It is a process of organizing decisions that people are already dealing with, but trying to do in their heads. The AHP was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem tangible or intangible, carefully measured or roughly estimated, well or poorly-understood anything at all that applies to the decision at hand. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy. In making the comparisons, the decision makers can use concrete data about the elements, or they can use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations. The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. This capability distinguishes the AHP from other decision-making techniques. In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal. Thus, they allow a straightforward consideration of the various courses of action. Steps of AHP method are as follows:

a) Define the objective and identify the Criteria/ Alternatives.

b) A pairwise comparison matrix (A) using the fundamental scale of the Analytic Hierarchy process Saaty has been constructed.

c) The relative normalized weight (W_j) of each criterion has been calculated by the geometric mean method of AHP. The Geometric mean of rows in the comparison matrix can be calculated by

$$GM_j = \left[\prod_{j=1}^{M} b_{ij}\right]^{\frac{1}{M}} \qquad ------Eq.3.1$$

$$W_j = \frac{GM_j}{\sum_{j=1}^{M} GM_j} \qquad ------Eq.3.2$$

d) The maximum eigen value, λ_{max} can be calculated by the matrix product of the pairwise comparison matrix and weight vectors and adding all elements of the resulting vector.

e) The consistency index (CI) can be determined by

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \qquad ----- Eq. 3.3$$

The smaller the value of CI, the smaller is the deviation from Consistency.

f) Consistency ratio (CR) has been calculated by

$$CR = \frac{CI}{RI} \qquad ----- Eq. 3.4$$

where RI is the random index value obtained by different orders of the pairwise comparison matrices. Usually, a CR of 0.1 or less is considered as acceptable indicating unbiased judgments made by the decision makers.

3.4. Taguchi-Utility Method

Utility can be defined as the usefulness of a product or a process in reference to the levels of expectations to the consumers. The performance evaluation of any machining process depends on number of output characteristic. Therefore, a combined measure is necessary to gauge its overall performance, which must take into account the relative contribution of all the quality characteristics. Such a composite index represents the overall utility of a product/process. It provides a methodological framework for the evaluation of alternative attributes made by individuals, firms and organizations. Utility refers to the satisfaction that each attribute provides to the decision maker. Thus, utility theory assumes that any decision is made on the basis of the utility maximization principle, according to which the best choice is the one that provides the highest satisfaction to the decision maker.

According to the utility theory, if X_i is the measure of effectiveness of an attribute (or quality characteristics) i and there are n attributes evaluating the outcome space, then the joint utility function can be expressed as

$$U(X_1, X_2, \ldots \ldots . X_n) = f\big(U_1(X_1), U_2(X_2) \ldots \ldots U_n(X_n)\big) \qquad ----- Eq. 3.5$$

Here, $U_i(X_i)$ is the utility of the i^{th} attribute.

The overall utility function is the sum of individual utilities if the attributes are independent, and is given as follows:

$$U(X_1, X_2 \ldots \ldots X_n) = \sum_{i=1}^{n} U_i(X_i) \qquad ----- Eq. 3.6$$

The overall utility function after assigning weights to the attributes can be expressed as:

$$U(X_1, X_2 \ldots \ldots X_n) = \sum_{i=1}^{n} W_i U_i(X_i) \qquad ----- Eq. 3.7$$

The preference number can be expressed on a logarithmic scale as follows:

$$p_i = A\ X\ log\left(\frac{X_i}{X_i'}\right) \qquad ----- Eq. 3.8$$

Here, X_i is the value of any quality characteristic or attribute i, X_i' is just acceptable value of quality characteristic or attribute i and A is a constant. The value A can be found by the condition that if $X_i = X^*$ (where X* is the optimal or best value), then $P_i = 9$ Therefore,

$$A = \frac{9}{log\frac{X^*}{X_i'}} \qquad ------Eq. 3.9$$

The overall utility can be expressed as follows:

$$U = \sum_{i=1}^{n} W_i P_i \qquad ------Eq. 3.10$$

Subject to the condition: $\sum_{i=1}^{n} W_i = 1$ $\qquad ------Eq. 3.11$

Overall utility index that has been computed treated as a single objective function for optimization. Among various quality characteristics types, viz. Lower-the-Better (LB), Higher-the-Better (HB), and Nominal-the-Best (NB) suggested by Taguchi, the utility function would be higher. In the proposed approach utility values of individual responses are determined to calculate overall utility index. Overall utility index is treated as the single objective function for optimization.

3.5 Proposed

The following steps followed in AHP-UTILITY are given below

- Selection of process parameters and their levels.
- Conduct the experiments as per the Taguchi Design of Experiments.
- Measure the selected quality characteristics.
- Construct preference scale for each quality characteristic from realistic data.
- Assign weights to the characteristics based on Analytical Hierarchy Process (AHP).
- Determine the individual utility values and use these values as a response of selected experimental plan.
- Find the overall utility index (U) values for the alternatives.
- Analyze the results with taguchi method.
- Determine the optimal setting of process parameters for optimum utility.
- Conduct ANOVA for finding the significance of the factors.
- Run the confirmation experiment and compare the predicted optimal values with the actual ones.

CHAPTER 4

EXPERIMENTAL SETUP

In the present work a medium carbon and medium tensile steel called AISI 1040 as shown in figure 4.1 was taken as the work piece. AISI 1040 steel is suitable for the engineering applications where higher tensile strengths are required. It is used for shafts, gears, spindles, axles, bolts & studs, automobile parts and etc. The chemical composition and mechanical properties of AISI 1040 steel are given in tables 4.1 and 4.2 respectively. For machining CNC WEDM (ELECTRONICA Hitech, JOB MASTER D-ZIRE) was used. Brass wire of 0.25 mm and distilled water are used as electrode and dielectric fluid.

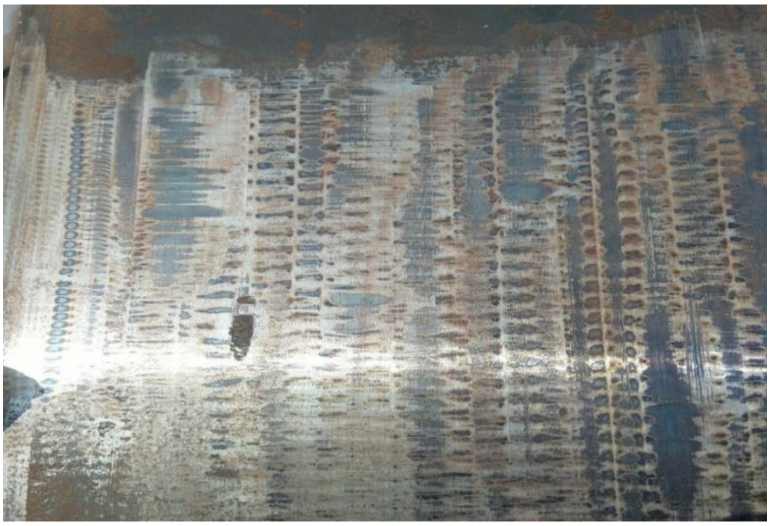

Figure 4.1. AISI 1040 Steel

Table 4.1. Chemical Composition of AISI 1040

Element	Composition (%)	Reference Range (%)
C	0.40	0.36-0.44
Si	0.25	0.10-0.40
Mn	0.80	0.60-1.00
S	0.05	0.05
P	0.05	0.05

Table 4.2. Mechanical Properties of AISI 1040

Property	Value
Yield Strength	280 MPa
Ultimate Tensile Strength	550MPa
Elongation	1 %
Rockwell Hardness	201-255

4.1. WEDM Machine Details

The experiments were carried out on a CNC WEDM (ELECTRONICA Hitech, JOB MASTER D-ZIRE) shown in the figure 4.2. The WEDM machine has the following specifications:

Table size	: 630 mm x 470 mm
Work- tank Internal Dimensions	: 800 mm x 650 mm
Main Table Travel X, Y	: 400 mm x 300 mm
Auxiliary Table Travel U, V	: 80 mm x 80 mm
Z-Axis Travel	: 250 mm
Maximum Taper Angle	: ± 30/50 Deg/mm
Job Admit	: 245 mm
Max. Work Piece Weight	: 300 Kg
Machining Type	: Flush
Jog Speed, X, Y	: 1000 mm/min
Jog Speed U, V	: 500 mm/m in
Jog Speed Z	: 600 mm/min
Wire Threading	: SAWT
Machine Foot Print	: 2350 mm x 2100 mm

Wire Diameter : 0.15 -0.3 mm

Wire Spool Size : DIN 125, DIN 160, P3R, P5R

Cutting Speed : 160 mm^2/min

Best Surface Finish : 0.6 µ R_a

Figure 4.2. WEDM Setup

4.2. Range of Process Parameters

The pilot experiments were carried by varying the process parameters Flushing Pressure (F.P) Pulse-On-Time (T_{ON}), Pulse-Off-Time (T_{OFF}), Servo Voltage (SV), Wire Feed (WF) and Wire Tension (WT) to study their effect on output parameters Surface Roughness (R_a) and Material Removal Rate (MRR). The ranges of these process parameters are given in Table 4.3. From these ranges of the process parameters, different levels of process parameters (Table 4.4) would be selected for the Taguchi experimental design and the experimental design using MINITAB i.e. L18 OA is given in the table 4.5.

Table 4.3. Process Parameters and Their Ranges

S.No.	Parameter	Range	Units
1	Pulse-On-Time (T_{ON})	115-131	µsec
2	Pulse-Off-Time (T_{OFF})	40-63	µsec
3	Peak Current (IP)	180-230	Ampere
4	Spark Gap Voltage	10-20	Volts
5	Wire Feed (WF)	0-10	m/min
6	Wire Tension (WT)	0-5	Kg-f
7	Flushing Pressure (F.P)	3-15	Kg/cm2

Table 4.4. Process Parameters and Their Levels

Parameter	Units	Level-1	Level-2	Level-3
Flushing Pressure (F P)	Kg/cm^2	4	8	_
Pulse-On-Time (T_{ON})	µsec	115	120	125
Pulse-Off-Time (T_{OFF})	µsec	55	58	61
Wire Feed (WF)	mm/min	2	3	4
Wire Tension (WT)	Kg-f	2	4	6
Servo Voltage (S V)	Volts	20	25	30

Table 4.5. L18 Orthogonal Array (OA)

S.No	F P (Kg/cm^2)	T_{ON} (µsec)	T_{OFF} (µsec)	WT (Kg-f)	WF (mm/min)	SV (Volts)
1	4	115	55	2	2	20
2	4	115	58	4	3	25
3	4	115	61	6	4	30
4	4	120	55	2	3	25
5	4	120	58	4	4	30
6	4	120	61	6	2	20
7	4	125	55	4	2	30
8	4	125	58	6	3	20
9	4	125	61	2	4	25
10	8	115	55	6	4	25
11	8	115	58	2	2	30
12	8	115	61	4	3	20
13	8	120	55	4	4	20
14	8	120	58	6	2	25
15	8	120	61	2	3	30
16	8	125	55	6	3	30
17	8	125	58	2	4	20

18	8	125	61	4	2	25

4.3. Experimentation Procedure

A plate of 150mm x 150 mm x 25 mm size of AISI 1040 STEEL is mounted on the WEDM machine (Figure 4.2) and specimens of 20 mm x 20 mm size are cut. The following steps were followed in the cutting operation:

- The brass wire of diameter 0.25 (figure 4.3) was made vertical with the help of verticality block.
- The work piece of AISI 1040 was mounted and clamped on the work table.
- A reference point on the work piece was set for setting work co-ordinate system (WCS). The programming was done with the reference to the WCS. The reference point was defined by the ground edges of the work piece.
- Water is used as the dielectric fluid.
- The program was made for cutting operation of the work piece and a profile of 20 mm x 20 mm square was cut.
- While performing various experiments, the following precautionary measures were taken:
- Each set of experiments was performed at room temperature in a narrow temperature range (range 27ºC).
- Before taking measurements of surface roughness, the work piece was cleaned with acetone.

After machining the work pieces were tested for the roughness (R_a) using surface tester SJ-301 as shown in figure 4.4.

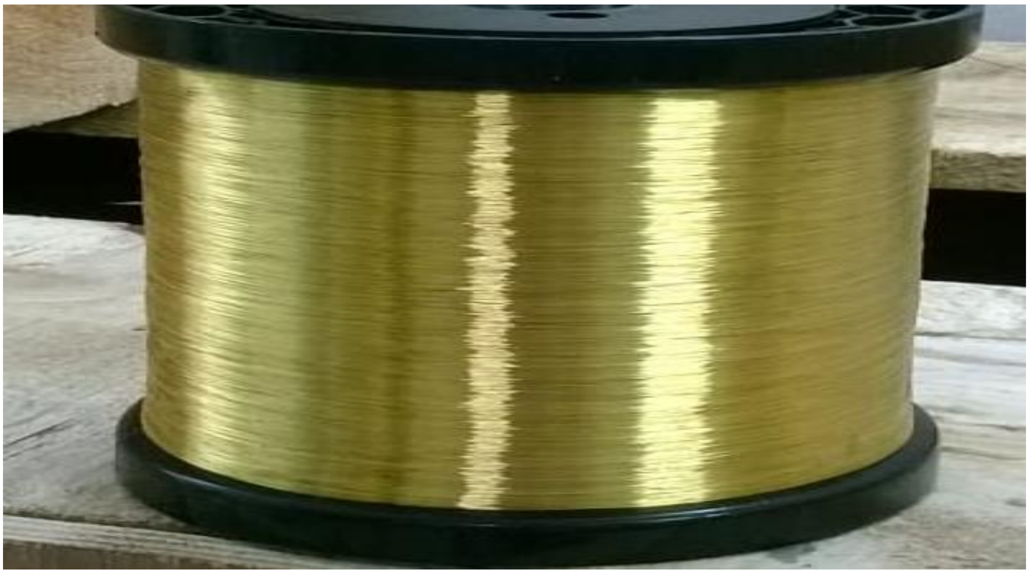

Figure 4.3. WEDM Brass Wire

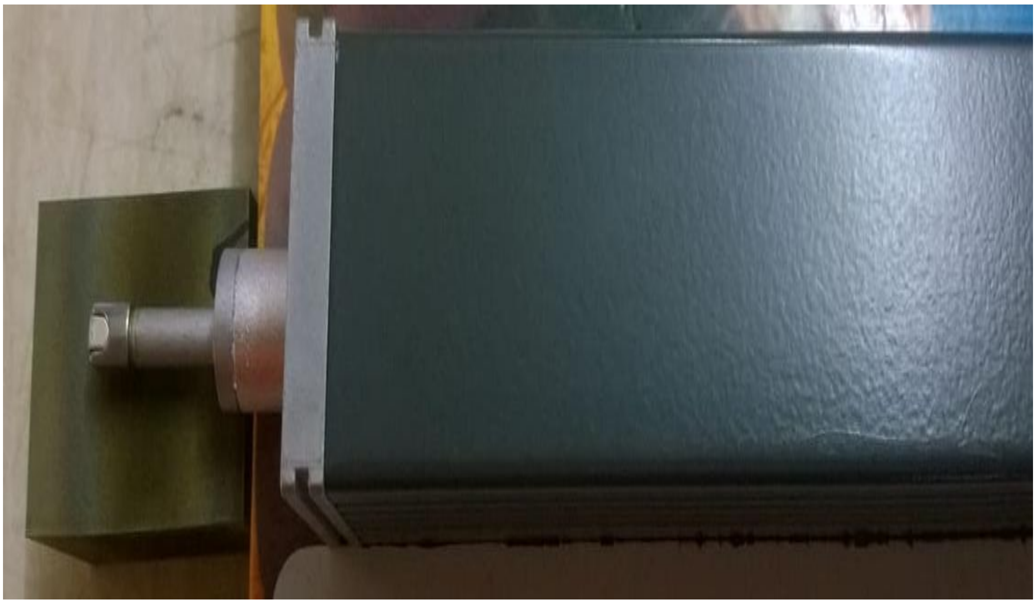

Figure 4.4. Measurement of Surface Roughness

CHAPTER 5
RESULTS & DISCUSSIONS

In this chapter the experimental results of material removal rate (MRR) and surface roughness (R_a) are analyzed using Taguchi based utility and AHP method. The focus of the work is to identify the optimal combination of process parameters that concurrently maximizes the material removal rate and minimizes the surface roughness concurrently.

5.1. Experimental Results

The measured results of both material removal rate and surface roughness characteristics were tabulated in table 5.1. In the present work, in order to determine the weights of each criterion, a pair wise comparison matrix as shown in the table 5.2 is developed using Analytical hierarchy process (AHP). The criterion weights are obtained as W_{MRR} = 0.25 and W_{Ra} = 0.75 respectively. The value of CR is calculated as 0.0% which is less than the allowed value of CR (=0.1), indicating the fact that there is a good consistency in the judgments made by the decision maker while assigning values in the pair – wise comparison matrix.

Table 5.1 Experimental Results

S.No.	MRR (cm^3/min)	R_a (µm)
1	9.7	2.43
2	7.32	2.755
3	7.34	2.355
4	8.33	2.351
5	7.33	2.524
6	7.7	2.491
7	8.01	2.526
8	8.55	2.726
9	7	2.59
10	8.45	2.492
11	7.06	2.251
12	7.07	2.645
13	10.05	2.964
14	8.24	2.752

15	6.69	2.433
16	9.72	2.679
17	8.48	2.768
18	7.01	2.704

Table 5.2. Pair Wise Comparison Matrix

Criteria	MRR	R_a
MRR	1	1/3
R_a	3	1

The experimental results of responses were explored to calculate the utility values of individual quality attributes (also called preference number) by using the following equations 1 and 2 respectively.

$P_{MRR} = 50.9337 * \log(X_i/6.69)$ ………Eq.5.1

$P_{Ra} = -75.3138 * \log(X_i/2.964)$ ……….Eq.5.2

The calculated individual utility values are given in the table 5.3. Now, the overall utility index values along with the weights of the attributes can be calculated using the equation 5.3 and the values obtained and the corresponding S/N ratios (Higher-the-Better) are given in the table 5.4.

$U = P_{MRR} * W_{MRR} + P_{Ra} * W_{Ra}$ ………Eq.5.3

Table 5.3. Individual Utility Values of Responses

S.No.	P_{MRR}	P_{Ra}
1	8.2179	6.4920
2	1.9907	2.3874
3	2.0511	7.5238
4	4.8489	7.5766
5	2.0170	5.2494
6	3.1070	5.6862
7	3.9830	5.2268

8	5.4244	2.7339
9	0.9983	4.4059
10	5.1647	5.6711
11	1.1868	9.0000
12	1.2173	3.7205
13	9.0000	0
14	4.6095	2.4251
15	0	6.4544
16	8.2614	3.3063
17	5.2411	2.2293
18	1.0289	2.9975

Table 5.4. Overall Utility (U) and S/N Ratios of U

S.No.	Overall Utility (U)	S/N of U
1	6.9234	16.8064
2	2.2882	7.1899
3	6.1556	15.7854
4	6.8946	16.7702
5	4.4413	12.9502
6	5.0414	14.0510
7	4.9158	13.8319
8	3.4065	10.6462
9	3.554	11.0143
10	5.5445	14.8772
11	7.0467	16.9597
12	3.0947	9.8124

13	2.25	7.0437
14	2.9712	9.4586
15	4.8408	13.6983
16	4.5450	13.1507
17	2.9822	9.4907
18	2.5053	7.9772

The values of the overall utility are analyzed using taguchi's Higher-the-Better characteristic and the signal to noise (S/N) ratios were calculated. From the mean values of process parameters given in the table 5.5, the main effect plot has been plotted to identify the optimal combination of process parameters on the multi response. From the main effect plot for mean values of overall utility are shown in figure 5.1. The optimal combination of cutting parameters is obtained at FP:4kg/cm^2; T_{ON}:115 μs; T_{OFF}: 55 μs; WF: 2 mm/min; WT : 2 kg–f and SV: 30 V respectively.

Table 5.5. Mean Values of Overall Utility Values

Level	FP	T_{ON}	T_{OFF}	WT	WF	SV
1	4.847	5.176	5.179	5.374	4.901	3.950
2	3.976	4.407	3.856	3.249	4.178	3.960
3		3.651	4.199	4.611	4.155	5.324
Delta	0.871	1.524	1.323	2.124	0.746	1.375
Rank	5	2	4	1	6	3

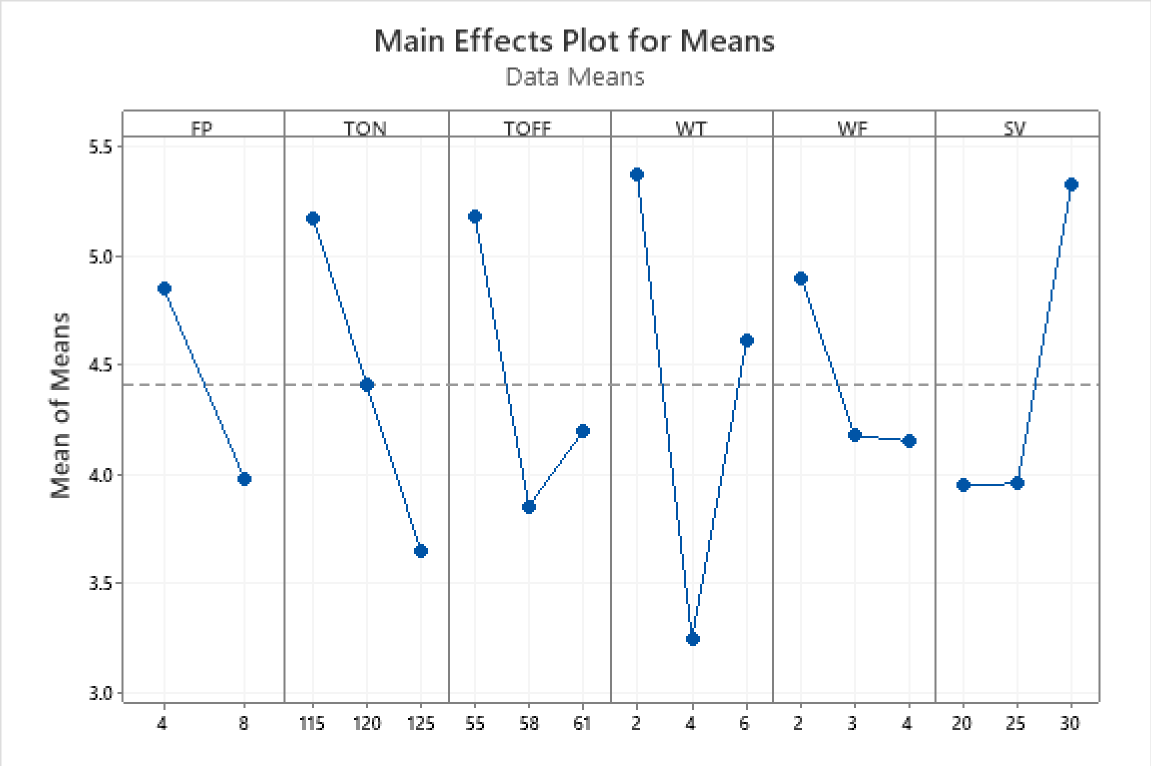

Figure 5.1. Main Effect Plot for Means of Overall Utility (U)

5.2. ANOVA Results

The Analysis of variance is used to investigate the significance of cutting parameters on the performance characteristic. This is accomplished by separating the total variability of the overall utility, which is measured by the sum of squared deviations from the total mean of the overall utility, into contributions by each parameter and the error. The percentage contribution by each factor to the total sum of the squared deviations SST can be used to evaluate the importance of the cutting parameter change on the performance characteristic. In addition, the F-test can also be used to determine which factor has a significant effect on the performance characteristic. Usually, the change of a determined factor has a significant effect on the performance characteristic when the F value is large. From the results of table 5.6, it is clear that the Wire Tension is the most influencing parameter for the overall utility value.

Table 5.6. ANOVA Results

Source	DF	Adj SS	Adj MS	F-value	P
FP	1	3.415	3.4151	3.79	0.100
TON	2	6.968	3.4842	3.86	0.084
TOFF	2	5.657	2.8283	3.14	0.117
WT	2	13.898	6.9488	7.70	0.022
WF	2	2.158	1.0789	1.20	0.365

SV	2	7.503	3.7514	4.16	0.074
Error	6	5.412	0.9020		
Total	17	45.010			

S = 0.949742, R^2 = 87.98%, R^2 (adj) = 65.93%

From the residual plots of figure 5.2, it is observed that all the errors are following the normal distribution as all the residuals are laying near to the straight line in the normal probability plot. Versus fits and order plots are implying that the errors are distributed on both the sides of mean line i.e. they are not following any regular pattern hence maintaining the constant variance.

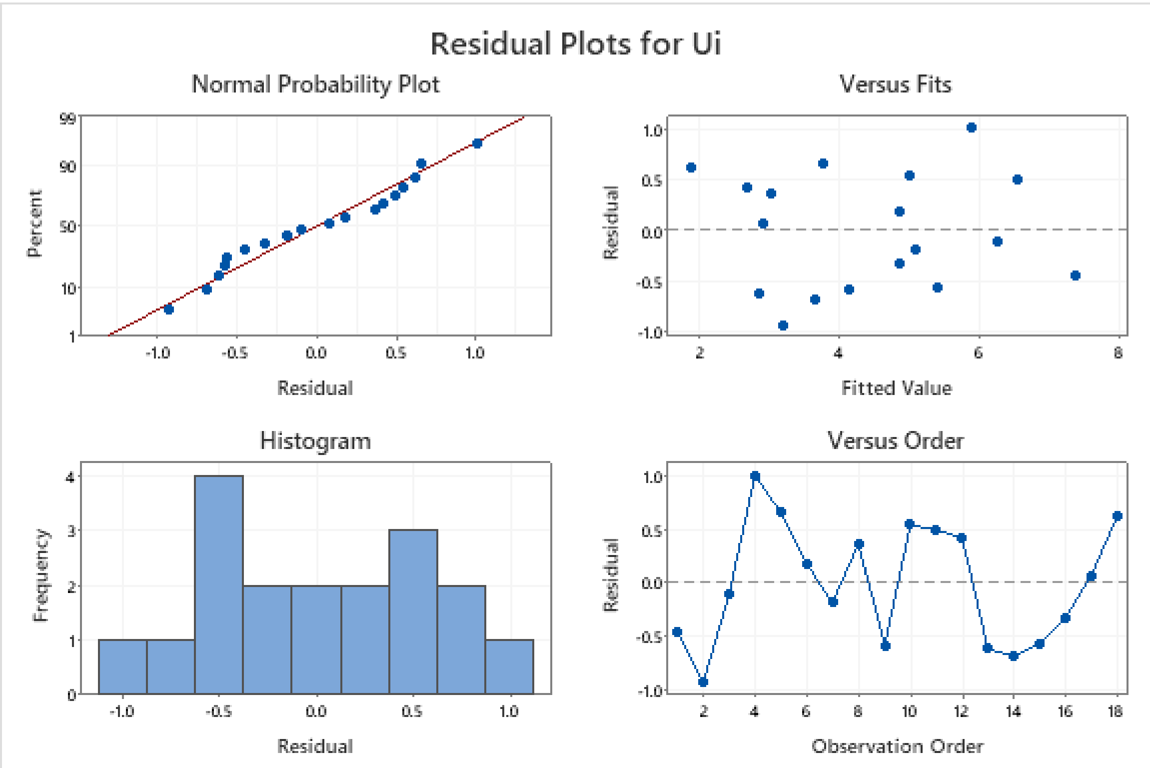

Figure 5.2 Residual Plots for Overall Utility

CHAPTER 6

CONCLUSIONS

The present work discussed an application of taguchi based Utility method and AHP for investigating the effects of Wire EDM parameters on material removal rate and surface roughness in Machining of AISI 1040 steel. From the results of Utility analysis and ANOVA the following conclusions can be drawn:

- From the Utility analysis, the optimal combination of machining parameters is obtained at

Flushing Pressure (FP)	: Level 1 :	4 kg/cm^2
Pulse -On-Time (T_{ON})	: Level 1 :	115 µs
Pulse-Off-Time(T_{OFF})	: Level 1 :	55 µs
Wire Tension (WT)	: Level 1 :	2 kg-f
Wire Feed (WF)	: Level 1 :	2 mm/min
Servo Voltage (SV)	: Level 3 :	30Volts

- ANOVA results concluded that the Wire Tension is the most influencing parameter on the multi-responses.
- The errors are distributed normally and they are not following any regular patterns hence following the assumptions normality and constant variance of ANOVA.
- The model prepared for the overall utility(U_i) is the best fit and it can be accurately used for the prediction of multiple 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 tool steel grades in different EDM types under dielectric fluids with different material powders. There is a lack of studies covering this point.
- Use of Different 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 micro-EDM. 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.

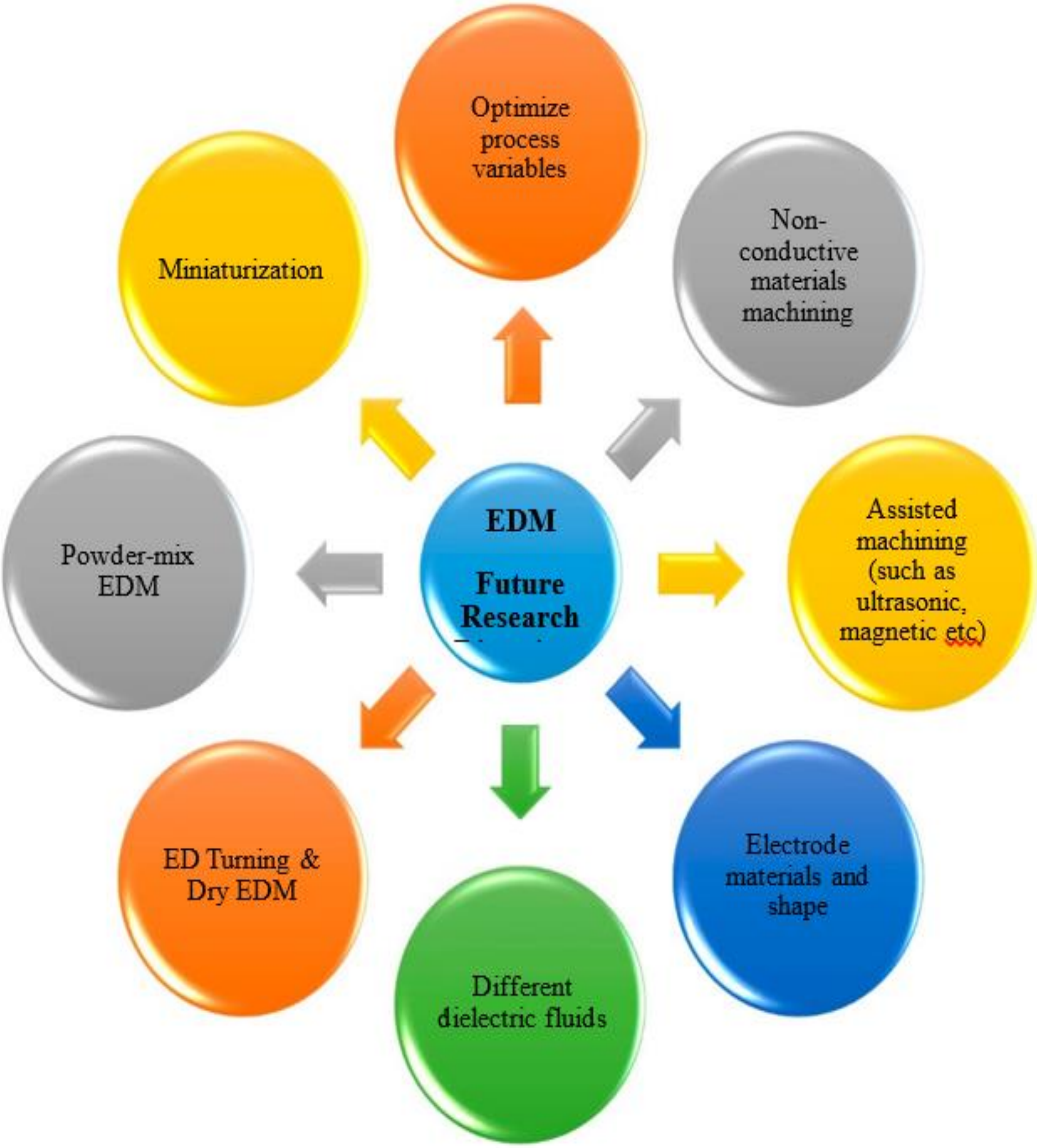

Figure 7.1. Future research areas in the EDM field

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

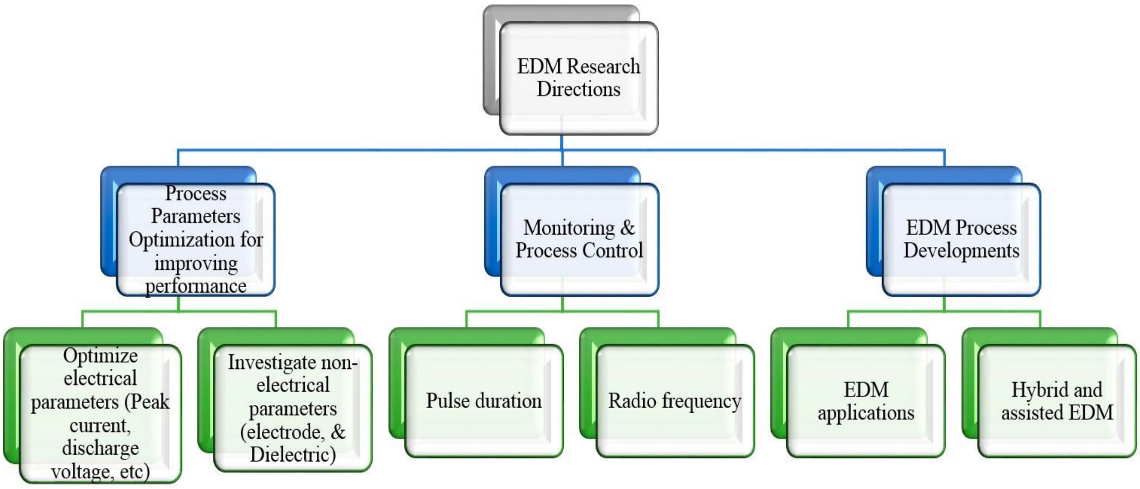

Figure 7.2. Classification of research directions.

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