# OPTIMAL SETTING OF WIRE-EDM PROCESS PARAMETERS BY ASSIGNMENTS OF WEIGHTS METHOD

*A Project report submitted in partial fulfilment of requirement*

*for the report of degree of*

**BACHELOR OF TECHNOLOGY**

**In**

**MECHANICAL ENGINEERING**

**BY**

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# ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY AND SCIENCES(A)

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## CERTIFICATE

This is to certify that the Project report entitled "**OPTIMAL SETTING OF WIRE-EDM PROCESS PARAMETERS BY ASSIGNMENTS OF WEIGHTS METHODS**" has been carried out by **B. NITISH BHARADWAJ (318126520067), HARSHA VARDHAN INAPAKURTHI(318126520082), GOGULA DILIP KUMAR(318126520080), KOVIRI HEMACHANDH(318126520090), SAI PRAMOD RAVADA(318126520109)** under the guidance of B.B. ASHOK KUMAR, in partial fulfilment of requirements for the award of Degree of Bachelor of Technology in Mechanical Engineering during the academic year of (2018-2022) in ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY AND SCIENCES(A), VISAKHAPATNAM.

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# ABSTRACT

Manufacturers are increasingly switching from mild steel to medium carbon steel, which has superior strength and wear resistance. Because of its outstanding machinability and high tensile strengths under heavy working loads, EN24 steel was chosen for the current project. Axles, shafts, gears, bolts, studs, spindles, and other automotive components are all often made of this material. Using the Assignments of weight approach, the impact of various Wire-EDM process parameters such as Flushing pressure (FP), Pulse-on-time ($T_{ON}$),Pulse-off-time ($T_{OFF}$), Wire Feed (WF), Wire tension (WT), and Servo voltage (SV) on several criteria was investigated. Taguchi's typical L18 orthogonal array was used to conduct the research. On the values of the multi-response performance index (MRPI), Taguchi's higher-is-better characteristic was used. The optimal setting of process parameters was obtained at a Flushing Pressure: level 2-8kg/cm2; Pulse-on-time: level 3-125µs; Pulse-off- time: level 1-55µs; Wire Feed: level 3-6mm/min; Wire Tension: level 3-4Kg-f and Servo Voltage: level 1-20 Volts, respectively. The MRPI, ANOVA results revealed that the most critical parameter in achieving larger multiple responses is Pulse-off-time.

**Keywords:**

EN24 Medium Carbon Steel, Orthogonal Array (OA), Taguchi Method, Assignments of Weight Method, Multi-Response Performance Index (MRPI).

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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 rises 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.<br>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.

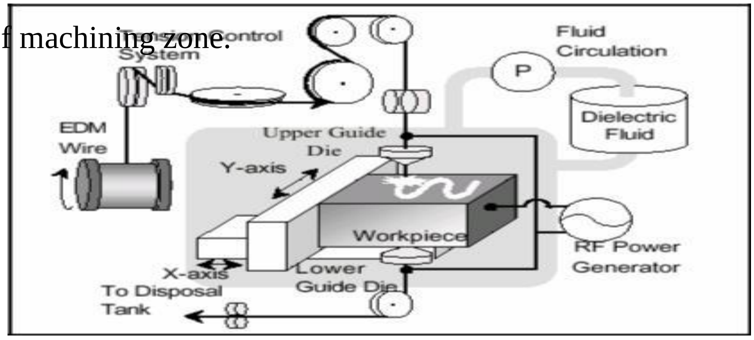


**Figure 1.1 Wire Electrical Discharge Machining System**

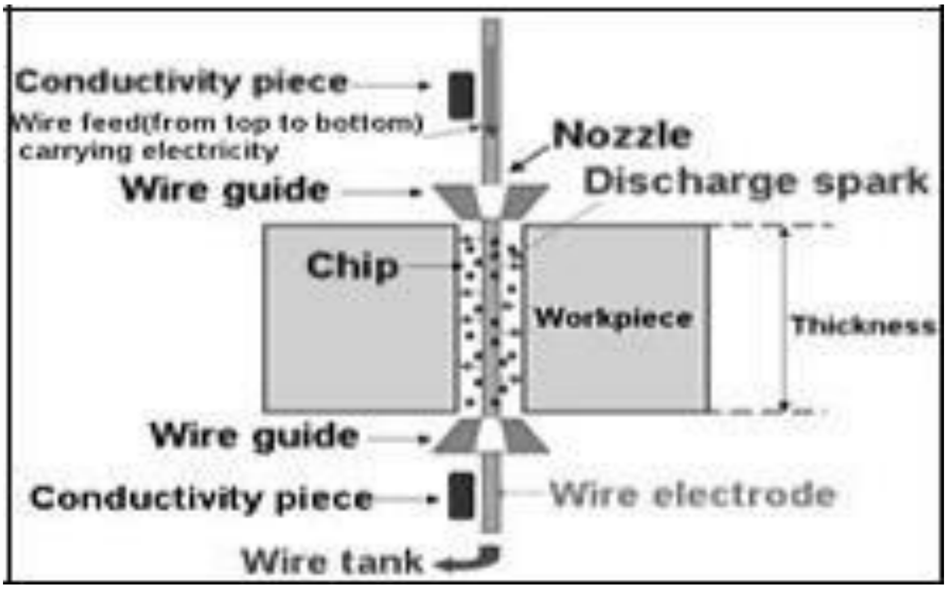


**Figure 1.2 Close View of Cutting Zone in WED**

### 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 affected 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.

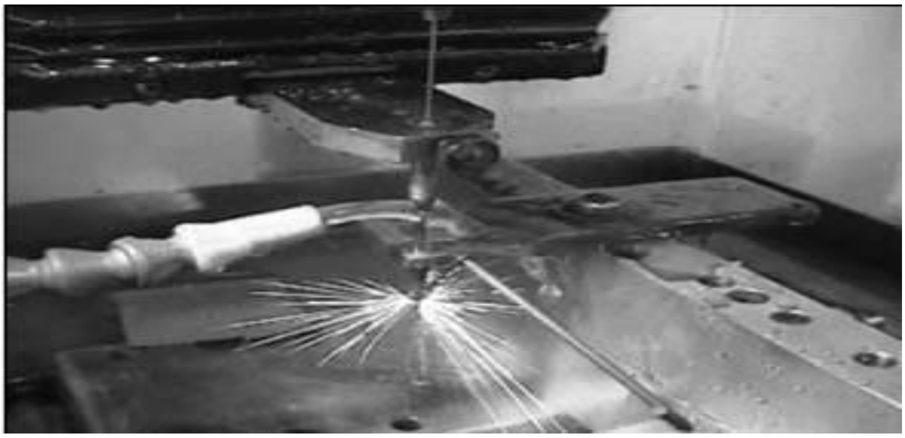


**Figure 1.3 Generation of Spark in WEDM**

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 brasscoated 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.

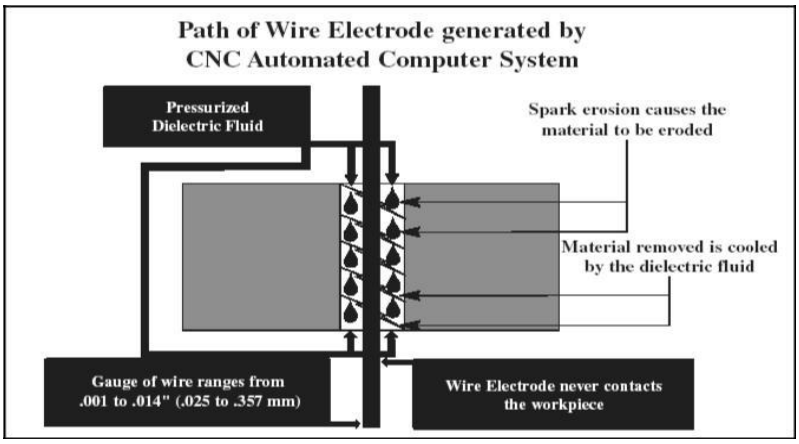


Figure 1.4 Path of Wire in WEDM

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

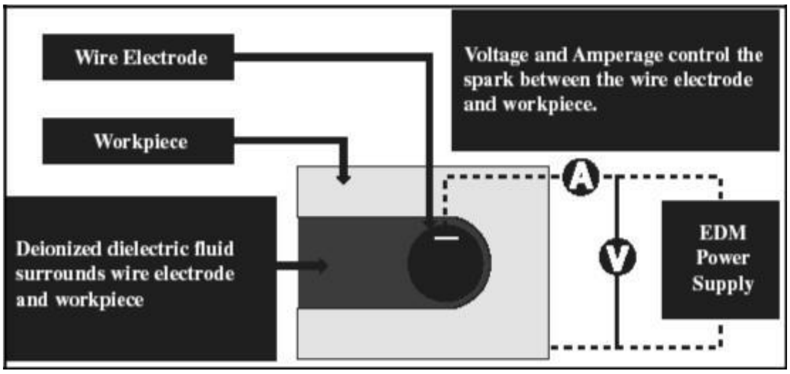


Figure 1.5 Power Generation in WEDM

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.

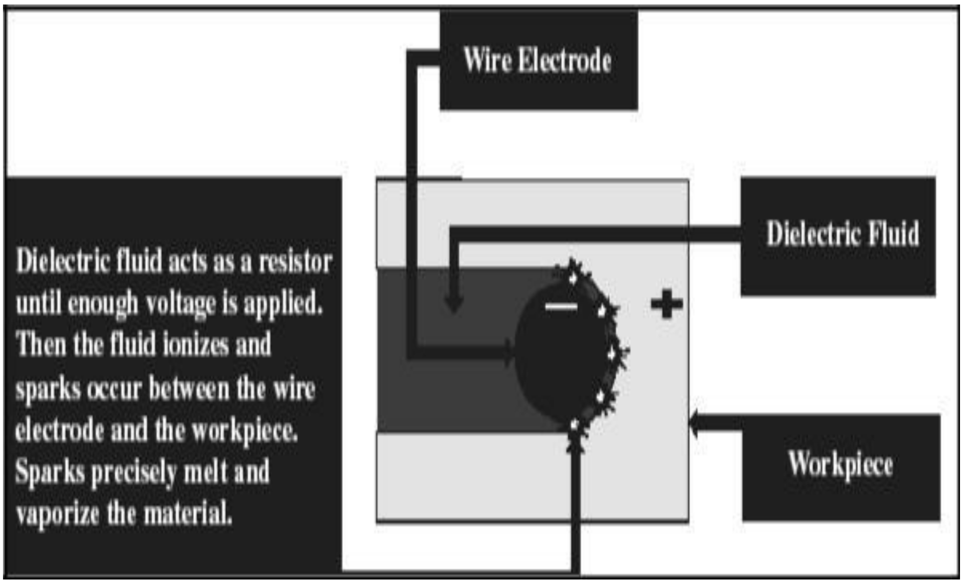


**Figure 1.6 Erosion of Material in WEDM**

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

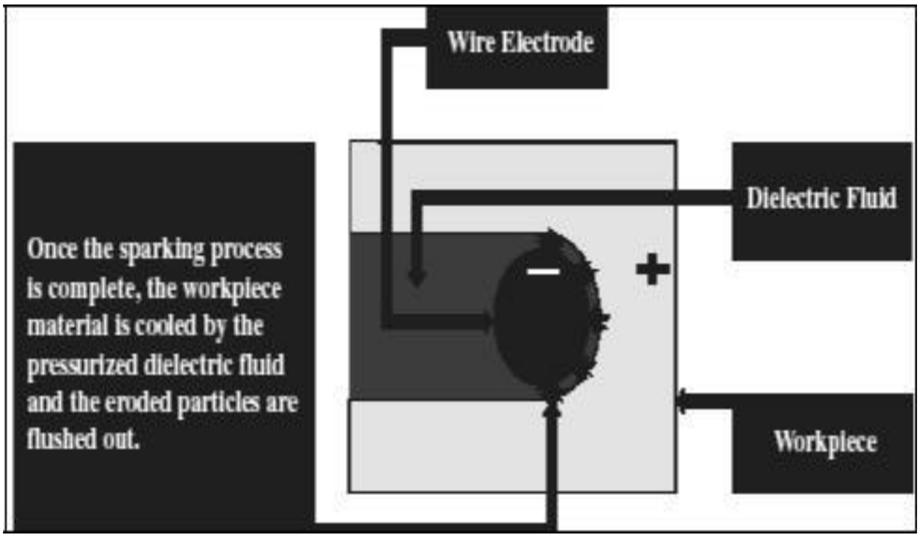


**Figure 1.7 Spark Erosion during ON Time**

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.

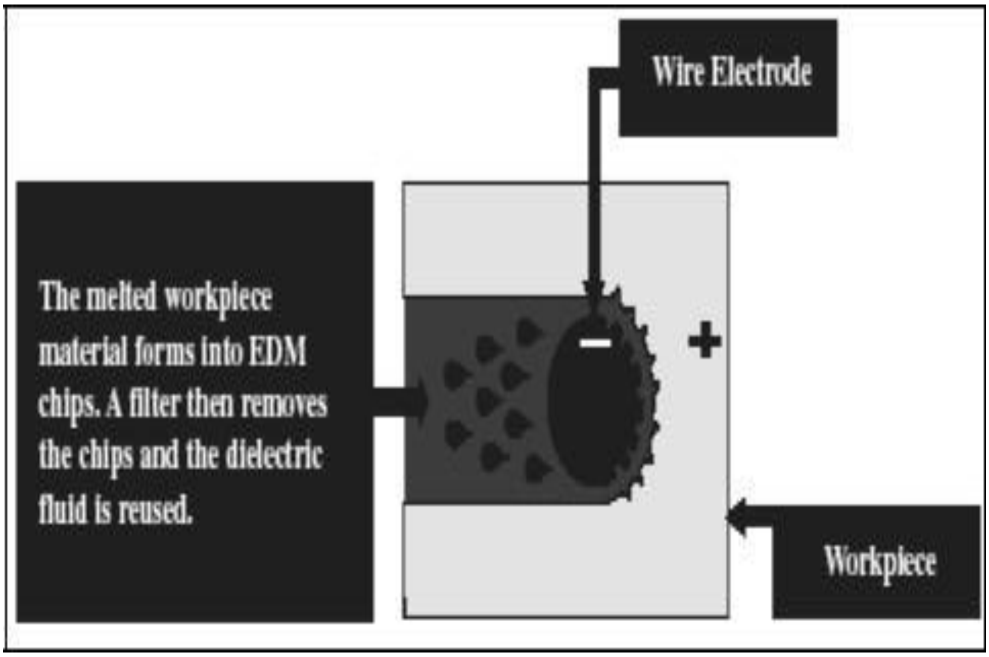


**Figure 1.8 Chip Removal by Filtration**

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:

#### 1.5.1 Influence of Wire Material Characteristics

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

### 1.5.2 Effect of Wire Tension

Within a considerable range, an increase in wire tension significantly increases the cutting speed.

A higher tension decreases the wire vibration amplitude and hence decreases the cut width, so that the speed is higher for the same discharge energy. However, if the applied tension exceeds the tensile strength of the wire, it leads to wire breakage.

### 1.5.3 Effect of Frequency

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

### 1.5.4 Heat Affected Zone

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

### 1.5.5Thickness of the Work Piece

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

### 1.5.6 Material of the Work Piece

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

### 1.5.7 Time ON

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

### 1.5.8 Time OFF

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

### 1.5.9 Current

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

### 1.5.10 Voltage

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

### 1.5.11 Gap Size

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

### 1.5.12 Surface Finish

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

### 1.5.13 Polarity

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

### 1.5.14 Material Removal Rate (MRR)

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

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

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

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

### 1.5.18 Duty Factor

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

### 1.5.19 Dielectric –Fluid Functions:

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

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

### 1.5.20 De-Ionized Water

De-ionised water absorbs materials that make the water electrically conductive during the sparking process. As water absorbs materials the dielectric characteristics of the water change**.** This also changes the water's ionization point and it affects the reliability and repeatability of the sparking process. Given these facts it would appear that deionised water is not an acceptable dielectric fluid. But wire-cut EDM uses dielectric fluid differently than 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.

### 1.5.21 De-Ionized water - Considerations

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

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

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

### 1.5.22 Filtration

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

### 1.5.23 Wire-Cut Chip Removal

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

### 1.5.24 High Velocity Fluid Flow

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

### 1.5.25 Positioning Fluid-Flow Nozzles

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

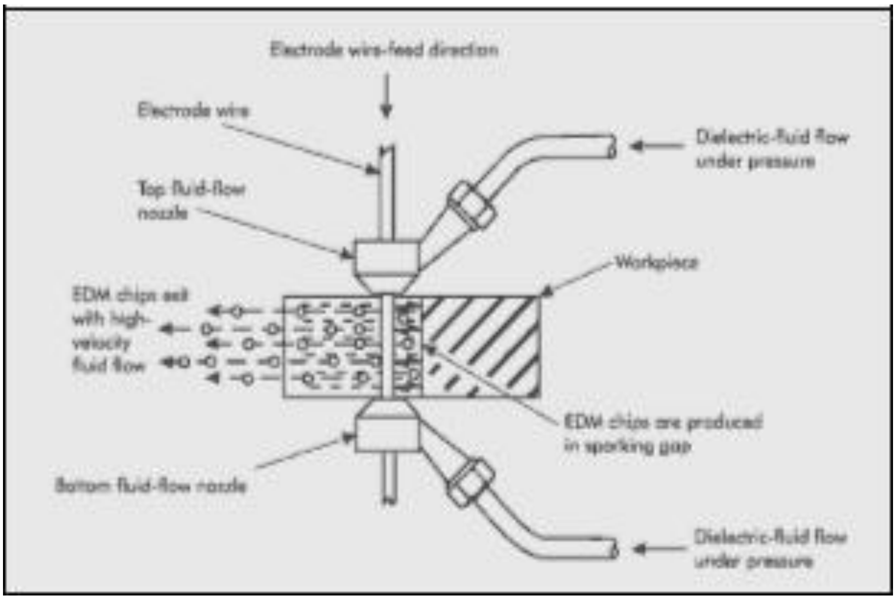


Figure 1.9 Wire Cut Fluid Flow Nozzles

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

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

Full-wire plunge machining creates a sparking area on the electrode wire, Figure 1.10 illustrates this type of machining. In full-wire plunge machining centre enough care needs to be taken in controlling the fluid flow as it surrounds the electrode tool wire. After establishing the machined kerf slot, fluid flow is fairly consistent. But at the start of the machining operation fluid flow may be difficult to establish. If the electrode tool wire enters from a surface outside of the work piece. Fluid flow may be controllable enough to allow efficient machining conditions. In this case, reduced sparking energy should be used until the tool wire machines a slot into the workpiece. Otherwise, wire breakage is likely. A preferred method for starting a wire-cut machining operation is to provide a pre-drilled start hole in the workpiece to create positive fluid control by surrounding the electrode tool wire with fluid. In Partial wire finish machining wire plunge creates less than $180^0$ sparking area as shown in Figure 1.11. In partial-wire machining, a curtain of fluid covers the workpiece in the sparking area and encloses the electrode wire. Chips are carried away with the fluid as it flows past the machined surface. Fluid flow for partial-wire machining is at a much lower velocity than 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.

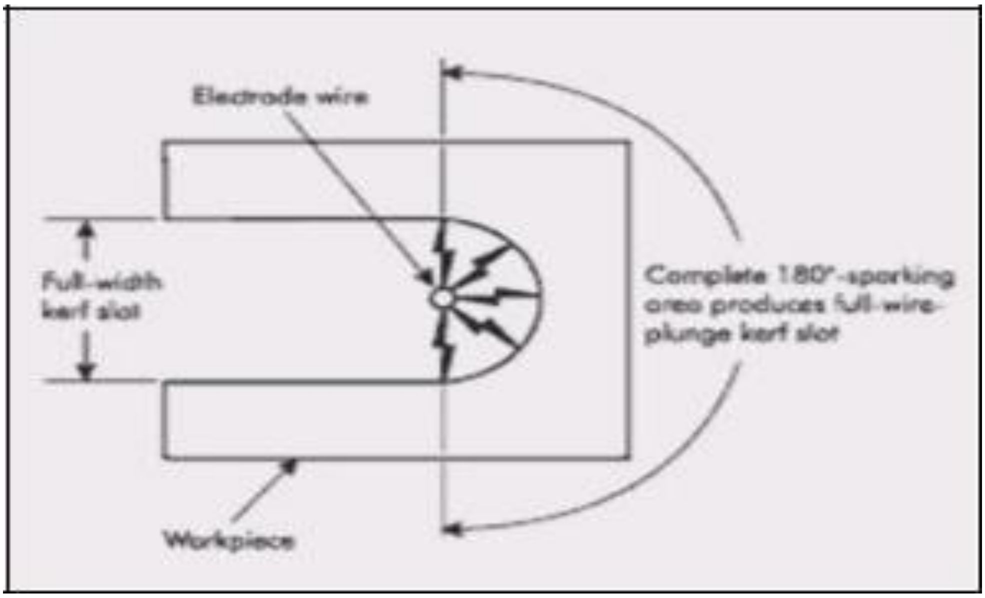


**Figure 1.10 Full-Wire Finish Machining**

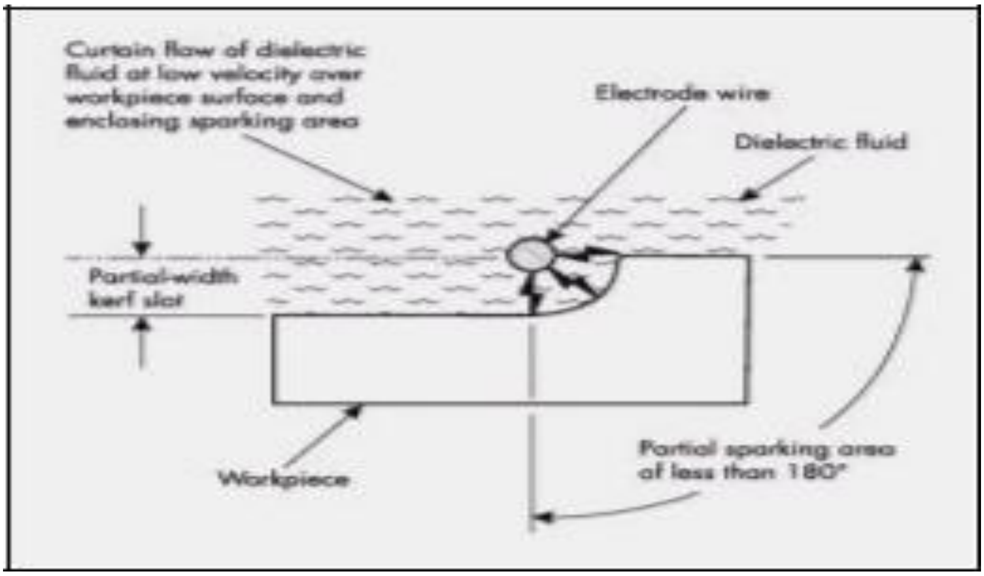


**Figure 1.11 Partial-Wire Finish Machining**

### 1.5.26 Minimum Wall Thickness for Fluid Control

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

### 1.5.27 Wire EDM Transport System

Wire EDM uses an electrically charged thin brass wire, which is moved by computer control, close to, but not touching, the part to be cut. The wire and the work piece are either fully submerged, or the part is vigorously flushed with a dielectric liquid. The small gap creates a spark, which vaporizes small particles of the work piece as the wire advances. The disintegrated particles are flushed away by dielectric fluid, and the wire is able to advance further. The wire itself is traveling – advancing from a large spool, and after use as an electrode, into a spent wire bin. The travel of the wire is determined by the machine’s computer program. The complexities of the wire transport system as shown in Figure 1.12 and automatic wire threader (AWT) both have a direct impact on performance. Since the wire used in the wire EDM is small and flexible, no more than two times larger than a human hair, threading reliably over long periods of time without extensive maintenance has been perceived as a problem.

However, the most important feature of a wire EDM machine, in terms of real profitability to the end user, is the AWT-a reliable AWT system can add many hours of Available foe every week, month and year. The AWT makes it possible to schedule work more efficiently on the wire EDM machine based upon the importance rather than the length-time-of cut.

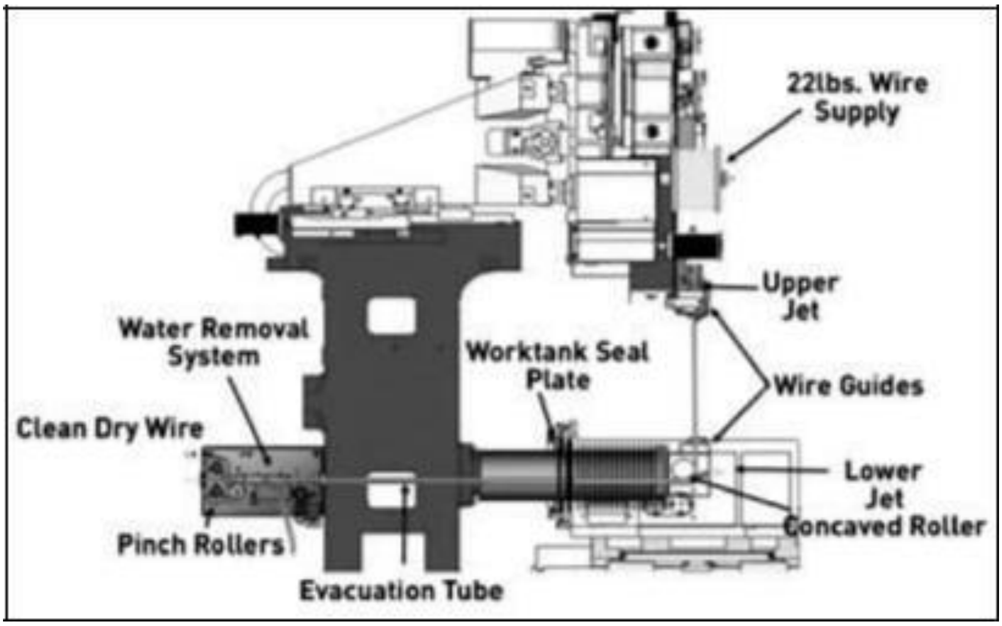


Figure 1.12 Wire EDM Transport System

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

## 1.6. Materials That WEDM Can Cut:

### 1.6.1 Carbide

Tungsten carbide, third in hardness to diamond and boron carbide, is an extremely difficult material to machine. Except for diamond cutting tools and diamond-impregnated grinding wheels, EDM presents the only practical method to machine this hardened material. To bind tungsten carbide when it is sintered, cobalt is added. The amount of cobalt, from 6% to 15%, determines the hardness and toughness of the carbide. The electrical conductivity of cobalt exceeds that of tungsten, so EDM erodes the cobalt binder in tungsten carbide. The carbide granules fall out of the compound during cutting, so the amount of cobalt binder determines the wire EDM speed, and the energy applied during the cutting determines the depth of binder that is removed. When cutting carbide on certain wire EDM machines, the initial first cut can cause surface micro-cracks. To eliminate them, skim cuts are used. However, at our company, we have repeatedly cut carbide parts with a single cut. When precision carbide parts are needed, skim cuts are used. Some older wire EDM machines used capacitors. Since these machines applied more energy into the cut, there was a greater danger for surface 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.

### 1.6.2 Polycrystalline Diamond

The introduction of polycrystalline diamond (PCD) on a tungsten carbide substrate has greatly increased cutting efficiency. PCD is a man-made diamond crystal that is sintered with cobalt at very high temperatures and under great pressure. The tungsten substrate provides support for the thin diamond layer. The cobalt in PCD does not act as a binder, but rather as a catalyst for the diamond crystals. In addition, the electrical conductivity of the cobalt allows PCD to be EDMed. When PCD is EDMed, only the cobalt between the diamonds crystals is being EDMed.

EDM machining PCD, like EDM machining carbide, is much slower than cutting steel. Cutting speed for PCD depends upon the amount of cobalt that has been sintered with the diamond crystals and the particle size of PCD. Large particles of PCD require very high open voltage for it to be cut. Also, some power supplies cut PCD better than others.

### 1.6.3 Ceramics

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

### 1.6.4 Cost Savings with WEDM

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

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

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

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

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

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

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

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

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

**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

# 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.

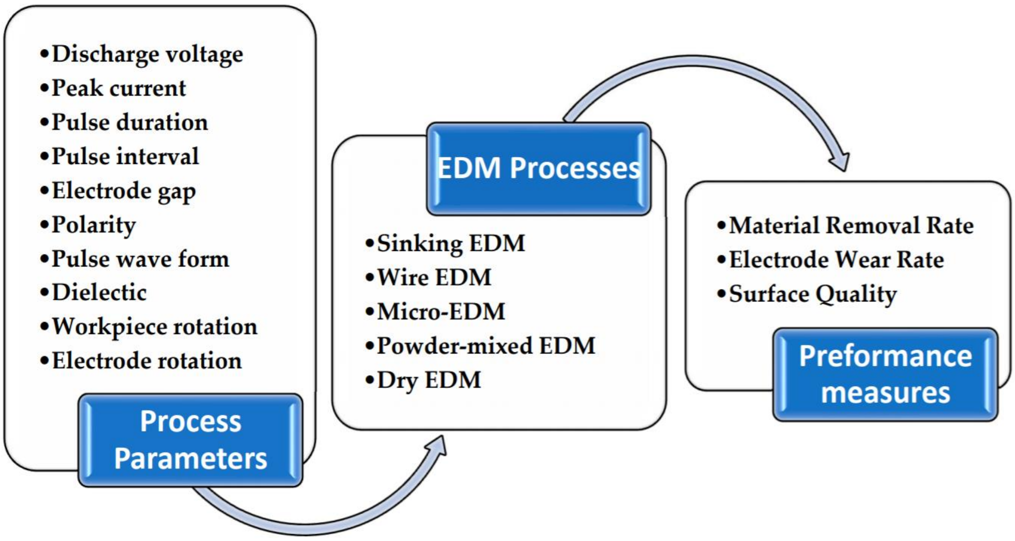


**Figure 2.1. The processes of electric discharge machining (EDM) and their process parameters and performance measures.**

## 2.1.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<br>Die sinking EDM [85,104–110].<br>Wire EDM [111–113]<br>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<br>Die sinking EDM [118].<br>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<br>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<br>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<br>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 due to air quenching from heat treatment [133]. |

|  |  |  |
|---|---|---|
| Powder-mixed EDM [116,128–131].<br>Micro-EDM [132]. |  |  |
| AISI O1<br>Die sinking EDM [76].<br>Wire EDM [134].<br>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<br>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<br>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<br>Die sinking EDM [144–147].<br>Wire EDM [148–151].<br>Dry EDM [103,152].<br>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, | 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]. |

| | | |
|---|---|---|
| | Mo 1.00–1.50, V 0.80–1.15 | |
| P20 Die sinking EDM [161–164].<br>Dry EDM [165].<br>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<br>Die sinking EDM [23].<br>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<br>Die sinking EDM [171].<br>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<br>Die sinking EDM [174].<br>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<br>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<br>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<br>Die sinking EDM [184]. | 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 |

| | | |
|---|---|---|
| Micro-EDM [185]. | | |
| DIN 1.2714<br>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<br>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<br>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<br>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<br>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<br>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.

**Table 2.2 Wire EDM Process Parameters**

| 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, | SR | The surface roughness of the workpiece in the EDM process was |

| | | | | | |
|---|---|---|---|---|---|
| | | | PCON, and SCON | | 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 |

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.

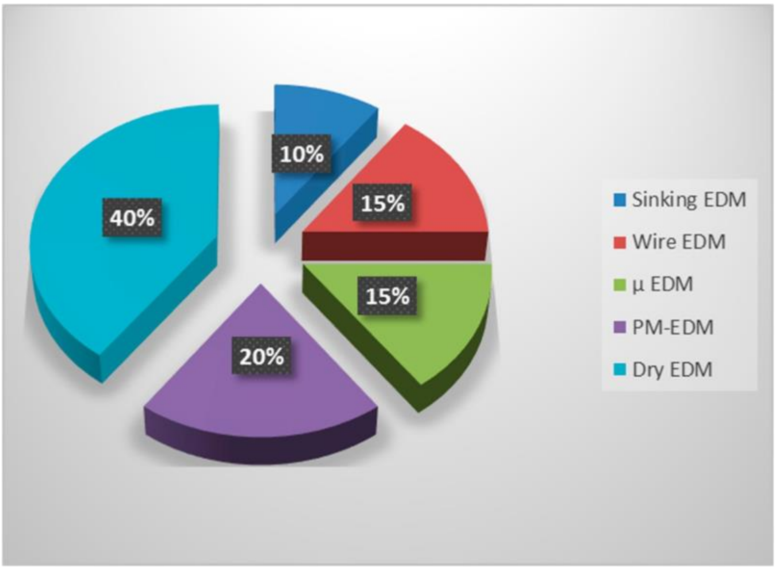


**Figure 2.2. Percentage of research related to EDM processes.**

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 e*ff*ect of major operating parameters on key performance measures.

**Table 2.3. General e*ff*ect of major operating parameters on key performance measures.**

↑ ↑ **Time** **Speed**

**Discharge Current**

**Pulse-O**ff

**Pulse-On Time**

**Electrode Rotation**

**Voltage**

| | | | | | | |
|---|---|---|---|---|---|---|
| **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 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.
- 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.

# CHAPTER 3

# METHODOLOGY

# METHODOLOGY

In assignments of weights method, a set of original responses are mapped into a ratio so that the optimal levels can be found based on this ratio. This value can be treated as MRPI value to find the optimal combinations of the process parameters. The following steps are involved in the method:

**Step1**: determine the weights (w) for each response for all experiments. Weight of response is the ratio between response at any trial to the summation of all responses.

**Step2**: transform the data of response into weighted data by multiplying the observed data with its own weight.

**Step3**: divide the data as larger the better with smaller the better.

**Step4**: treat this value as multi response performance index (MRPI).

The weights for all the response variables have been computed as the following equations

$$\mathbf{MRPI = W_{MRR} * Y_{MRR} + W_{SR} * Y_{SR}}$$

$$\mathbf{W_{MRR} = MRR / \sum MRR}$$

$$\mathbf{W_{SR} = (1/SR) / \sum (1/SR)}$$

## 3.1 INTRODUCTION TO TAGUCHI DESIGN OF EXPERIMENTS

### 3.1.1 DESIGN OF EXPERIMENTS

In general usage, design of experiments (DOE) or experimental design is the design of any information gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics these terms are usually used for controlled experiments. Former planned experimentation is often used in evaluating physical objects, chemical formulations, structures. components and materials. Other types of study and their design are discussed in the articles on opinion polls and statistics surveys (which are types of observational study), natural experimentation and quasi-experiments (for example, quasi experimental design), see experiment for the distinction between these types of experiments or studies.

In the design experiments, the experimenter is often inserted in the effect of some process or intervention (the treatment) on some objects (the experimental units) which may be people, parts of people, groups of people, plants, animals etc. Design of experiments is thus a discipline that has very broad application across all the natural and social sciences and engineering

Designed experiments are also powerful tools to achieve manufacturing cost savings by minimizing process variation and reducing network, scrap and the need for inspection. A strategically planned and executed experiment may provide a great deal of information about the effect on a response variable due to one or more factors. Many experiments involve holding certain factors constant and holding the altering levels of another variable. Thus One-Factor-at-a-Time (OFAT) approach to process knowledge is however inefficient when compared with changing factor levels simultaneously.

Taguchi Method:

One method presented in this study is an experimental design process called the Taguchi design method. Taguchi design, developed by Dr. Genichi Taguchi, is a set of methodologies by which the inherent variability of materials and manufacturing processes has been taken into account at the design stage.

Three steps procedure for experimental design:

1. Find the total degree of freedom (TOF)

Select a standard orthogonal array using the following two rules:

2. The number of runs in the orthogonal design Total DOF

The selected orthogonal array should be able to accommodate the factor level combinations in the experiment.

3. Assign factors to appropriate columns Therefore, not only controlled factors can be considered but also noise factors

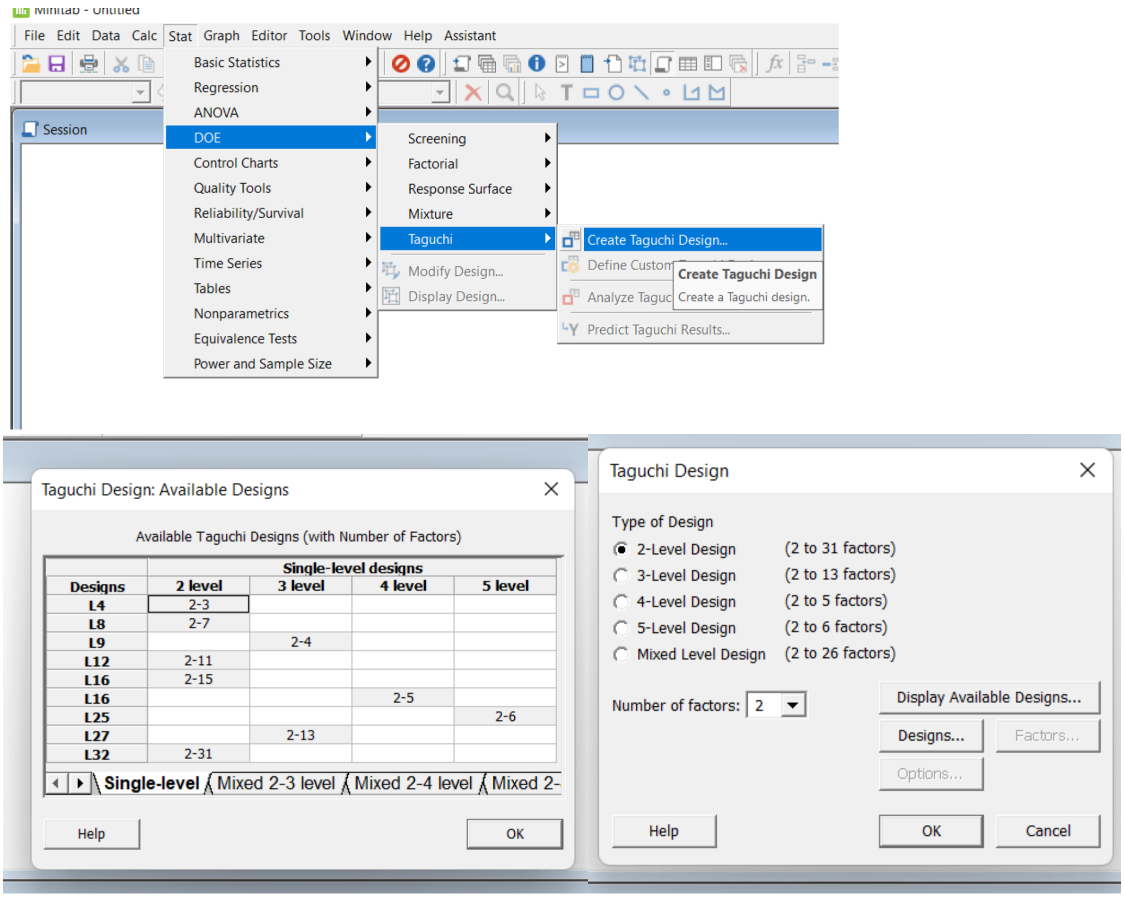
Although similar to design of experiments (DOE), the Taguchi design only conducts the balanced (orthogonal) experimental combinations, which makes the Taguchi design even more effective than a factorial design. By using the Taguchi techniques, industries are able to greatly reduce product development cycle time for both design and production, therefore reducing costs and increasing profit. The complete procedure in Taguchi design method can be divided into three stages; system design, parameter design and tolerance design. Of the three design stages, the second stage i.e. the paramater design is the most important stage.

Taguchi's Orthogonal Array (OA) provides a set of well-balanced experiments (with less number of experimental run), and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output; serve as objective function in the optimization process. Taguchi method uses a statistical measure of performance called signal-to-noise ratio. The S/N ratio take moth variability and the mean into the account. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The ratio depends upon the quality characteristics of product/process to be optimized. The standard S/N ratios generally used are as follows:

| | |
|---|---|
| Nominal-is-Best (NB) | S/N = −10*log(Σ(1/$Y^2$)/n) |
| Lower-the-Better (LB) | S/N = −10*log(Σ($Y^2$)/n) |
| Higher-the-Better (HB) | S/N = −10*log(Σ(1/$Y^2$)/n) |

The optimal setting is the parameter combination, which has the highest S/N ratio. Because, of the irrespective quality criteria may be (NB, LB, HB) S/N ratio should always be maximized.

Once experimental data is normalized using NB/LB/HB criteria; normalized value lies in between 0 & 1. Zero represents worst quality to be rejected and one represents most satisfactory quality. Since S/N ratio is expressed as mean to the noise; maximizing S/N ratio ensures minimum deviation and hence it its (S/N ratio) to be maximized.



Available Taguchi Designs (with Number of Factors)

| | Single-level designs | | | |
|---|---|---|---|---|
| **Designs** | **2 level** | **3 level** | **4 level** | **5 level** |
| **L4** | 2-3 | | | |
| **L8** | 2-7 | | | |
| **L9** | | 2-4 | | |
| **L12** | 2-11 | | | |
| **L16** | 2-15 | | | |
| **L16** | | | 2-5 | |
| **L25** | | | | 2-6 |
| **L27** | | 2-13 | | |
| **L32** | 2-31 | | | |

Type of Design

| | |
|---|---|
| ● 2-Level Design | (2 to 31 factors) |
| ○ 3-Level Design | (2 to 13 factors) |
| ○ 4-Level Design | (2 to 5 factors) |
| ○ 5-Level Design | (2 to 6 factors) |
| ○ Mixed Level Design | (2 to 26 factors) |

Number of factors: 2

**Fig 3.1: MINITAB for DOE using TAGUCHI DESIGN and Taguchi 3 level design**

## 3.2 REGRESSION ANALYSIS

In statistics, regression analysis is statistical technique for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables when the focus is on the relationship between a dependent variable and one or more independent variables. More specifically.

Regression analysis helps one understand how the typical value of the dependent variable changes when any one of the independent variables are varied, while the other independent variables are held fixed. Most commonly, regression analysis estimates the conditional expectation of the dependent variable given the independent variables- that is the average value of the dependent variable when the independent variables are fixed. Less commonly, the focus is on quantile or other location parameter of the conditional distribution of the dependent variables given the independent variables. In all cases, the estimation target is the function of the independent variables called the regression function. In regression analysis, it is also of interest to characterize the variation of dependent variable around the regression function, which can be described by a probability distribution.

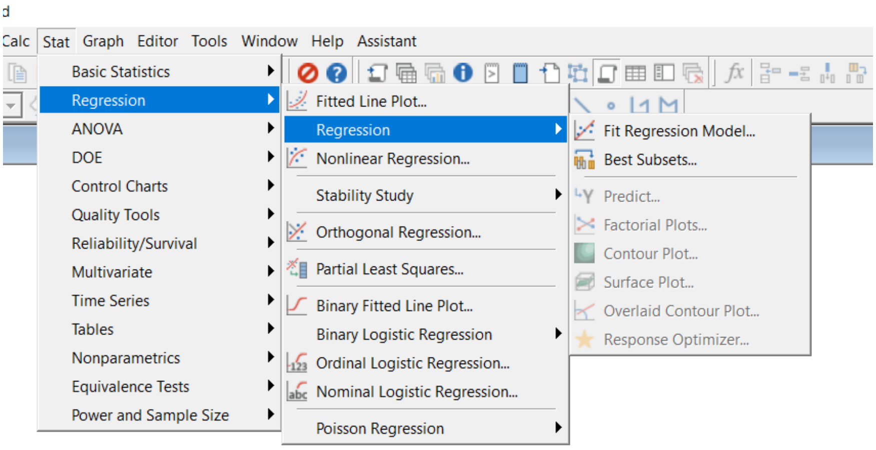


**fig 3.2: REGRESSION ANALYSIS using MINITAB**

## 3.3 ANOVA

Analysis of Variance (ANOVA) is a collection of statistical models used to analyze the differences between group means and their associated procedures (such as "variation" among and between groups), in which the observed variance in a particular variable is partitioned into components and attributable to different sources of variation. In its simplest for, ANOVA provides statistical test of whether or not the means of several groups are all equal, and therefore generalizes t-test to more than two groups. Doing multiple two sample t-tests would result in an increased chance of committing a type 1 error. For this reason, ANOVAs are useful in comparing (testing) three or more means (groups or variables) for statistical significances.

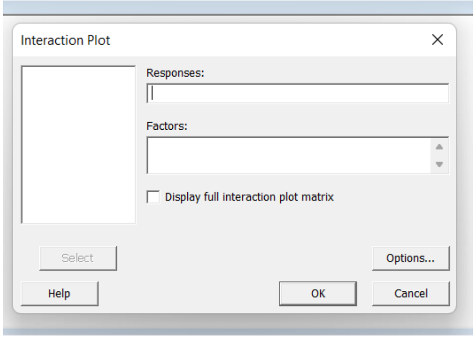


**fig 3.3: Interaction plot in ANOVA**

# CHAPTER 4

# EXPERIMENTS AND DETAILS

# EXPERIMENTS AND DETAILS

## 4.1 Experimentation & Design of Orthogonal Array

The work material selected for the present study was EN24 and it is a nickel-chromium-molybdenum combination and offers high tensile strength, good ductility and wear resistance characteristics. It is also suitable for a variety of elevated temperature applications. It is frequently used in metal cutting tools such as twist drills, milling cutters, shaping tools, thread chasers, reamers, countersinks and wood working tools etc. The commercial applications for this material include high strength shafts, punches & dies, drill bushings, retaining rings and gears. The chemical composition and mechanical properties of work material were given in tables 1 and 2 respectively. The process parameters of Wire EDM selected were given in table 3 and the machining was performed on work piece using taguchi's standard L18 orthogonal array design given in table 4.

**Table 4.1 Chemical Composition of EN24 Steel**

| Element | % Weight |
|---|---|
| Carbon | 0.36-0.44 |
| Silicon | 0.10-0.35 |
| Manganese | 0.45-0.70 |
| Sulphur | 0.040max |
| Phosphorous | 0.035max |
| Chromium | 1.00-1.40 |
| Molybdenum | 0.20-0.35 |
| Nickel | 1.30-1.70 |

**Table 4.2 Mechanical Properties of EN24 Steel**

| Property | Density (g/cm3) | Max Stress (N/mm2) | Yield Stress (N/mm2) | Elongation (%) | Hardness (BHN) |
|---|---|---|---|---|---|
| Value | 7.8 | 850-1000 | 650-680 | 13 | 248-302 |

**Fig. 4.1 EN24 WORK PIECE**

### Table 4.3 WEDM Parameters and their Levels

| Factor | Parameter | 1 | 2 | 3 |
|---|---|---|---|---|
| A | Flushing Pressure, kg/cm2 | 4 | 8 | - |
| B | Pulse-on-Time (TON), µs | 115 | 120 | 125 |
| C | Pulse-off-Time (TOFF), µs | 55 | 58 | 61 |
| D | Wire Feed (WF), m/min | 2 | 3 | 4 |
| E | Wire Tension (WT), Kg-f | 2 | 4 | 6 |
| F | Spark Gap voltage (SV), Volts | 20 | 25 | 30 |

### Table 4.4 L18 OA Design

| S.No. | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 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 |

# CHAPTER 5

# RESULTS AND DISCUSSIONS

## 5.1 Results& Discussions

The experimental results of material removal rate and surface roughness measured were given in table 5.1 The analysis was carried out using MINITAB-18 software. The effect of process parameters on responses were studied using Taguchi method.

**Table 5.1 Experimental Results of Responses**

| S.No. | MRR (mm$^3$/min) | Ra (µm) |
|---|---|---|
| 1 | 9.7 | 2.91 |
| 2 | 7.32 | 3.37 |
| 3 | 7.34 | 2.98 |
| 4 | 8.33 | 2.97 |
| 5 | 7.33 | 3.22 |
| 6 | 7.70 | 3.23 |
| 7 | 8.01 | 3.15 |
| 8 | 8.55 | 3.35 |
| 9 | 7.00 | 3.21 |
| 10 | 8.45 | 3.19 |
| 11 | 7.06 | 2.84 |
| 12 | 7.07 | 3.20 |
| 13 | 10.05 | 3.61 |
| 14 | 8.24 | 3.54 |
| 15 | 6.69 | 3.02 |
| 16 | 9.72 | 3.33 |
| 17 | 8.48 | 3.48 |
| 18 | 7.01 | 3.41 |

The table 5.2 shows the value of MRPI of all the experiments. MRPI is the ratio between the summation of larger the better data to the summation of smaller the better data. In the present study material removal rate has the larger the better-quality characteristic and surface roughness has smaller the better characteristics respectively.

**Table 5.2 Weights & MRPI Values of Responses**

| S.No. | Weights | | MRPI | S/N of MRPI |
|---|---|---|---|---|
| | MRR | Ra | | |
| 1 | 0.0673 | 0.0613 | 0.8314 | -1.6038 |
| 2 | 0.0508 | 0.0529 | 0.5502 | -5.1895 |
| 3 | 0.0510 | 0.0598 | 0.5523 | -5.1565 |
| 4 | 0.0578 | 0.0600 | 0.6600 | -3.6091 |
| 5 | 0.0509 | 0.0554 | 0.5512 | -5.1738 |
| 6 | 0.0535 | 0.0552 | 0.5898 | -4.5859 |
| 7 | 0.0556 | 0.0566 | 0.6237 | -4.1004 |
| 8 | 0.0594 | 0.0532 | 0.6857 | -3.2773 |
| 9 | 0.0486 | 0.0555 | 0.5184 | -5.7067 |
| 10 | 0.0587 | 0.0559 | 0.6739 | -3.4280 |
| 11 | 0.0490 | 0.0628 | 0.5243 | -5.6084 |
| 12 | 0.0491 | 0.0557 | 0.5253 | -5.5918 |
| 13 | 0.0698 | 0.0494 | 0.8794 | -1.1162 |
| 14 | 0.0572 | 0.0504 | 0.6496 | -3.7470 |
| 15 | 0.0464 | 0.0590 | 0.4890 | -6.2138 |
| 16 | 0.0675 | 0.0535 | 0.8341 | -1.5756 |
| 17 | 0.0589 | 0.0512 | 0.6775 | -3.3818 |
| 18 | 0.0487 | 0.0523 | 0.5194 | -5.6899 |

Table 5.3 shows the consolidated MRPI of all the input factors with all the levels. The values have been computed by adding the all MRPI values for corresponding level of each process parameters.

**Table 5.3 Taguchi Results for MRPI versus WEDM parameters**

| Level | FP | $T_{ON}$ | $T_{OFF}$ | WT | WF | SV |
|---|---|---|---|---|---|---|
| 1 | -4.267 | -4.430 | -2.572 | -4.354 | -4.223 | -3.259 |
| 2 | -4.039 | -4.074 | -4.396 | -4.477 | -4.243 | -4.562 |
| 3 | | -3.955 | -5.491 | -3.628 | -3.994 | -4.638 |
| Delta | 0.228 | 0.474 | 2.919 | 0.849 | 0.249 | 1.379 |
| Rank | 6 | 4 | 1 | 3 | 5 | 2 |

From the main effect plot analysis (shown in figure1) the optimal combination of process parameters for achieving maximum MRPI is found at

Flushing pressure (FP): level$_2$; 8kg/cm$^2$

Pulse-on-Time ($T_{ON}$): level $_3$;125µs

Pulse-off-Time ($T_{OFF}$): level$_1$; 55µs

Wire Tension (WT): level$_3$; 6Kg-f

Wire Feed (WF): level$_3$, 4mm/min

Servo Voltage (SV): level$_1$; 20 volts

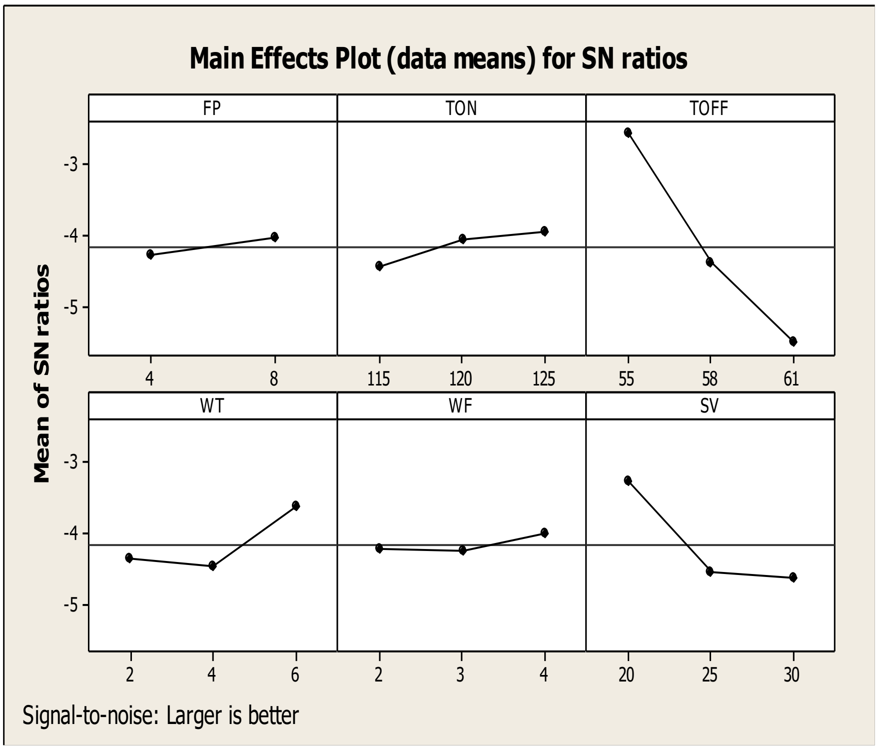


**Figure 5.1 Main Effect Plots for Means of MRPI**

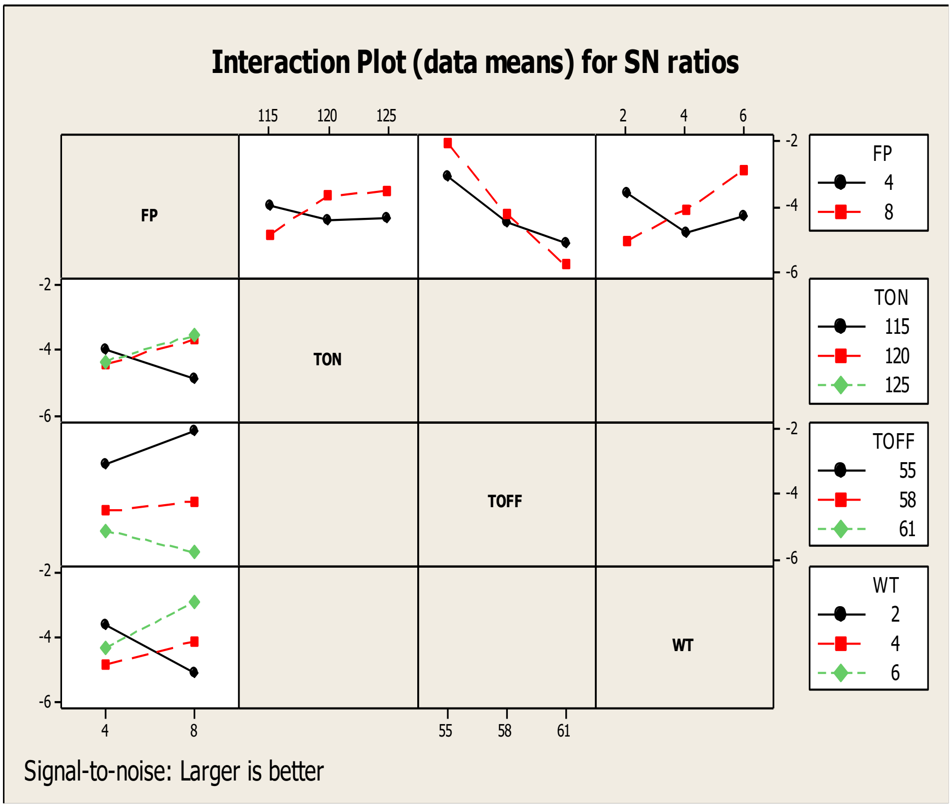


**Figure 5.2 Interaction Plots for S/N Ratios of MRPI**

## 5.2 Regression & ANOVA Results

Regression analysis has been employed to prepare first order models for the responses. ANOVA results of the responses were given in table 8. From the results it is observed that pulse-off-time has the highest influencing factor for the multi-responses. The residual plots were drawn and shown in figure 3. A very good agreement has been found between the predicted and experimental values hence the models prepared were best fit and accurate.

The regression equation is

**MRPI = 2.48 + 0.00583 FP + 0.00336 TON - 0.0363 TOFF + 0.0119 WT + 0.0095 WF - 0.0102 SV**

**Table 5.4 ANOVA Results for MRPI**

| Source | DF | AdjSS | AdjMS | F | P |
|---|---|---|---|---|---|
| FP | 1 | 0.002445 | 0.002445 | 0.46 | 0.522 |
| TON | 2 | 0.003792 | 0.001896 | 0.36 | 0.713 |
| TOFF | 2 | 0.147530 | 0.073765 | 13.96 | 0.006 |
| WT | 2 | 0.010932 | 0.005466 | 1.03 | 0.411 |
| WF | 2 | 0.001383 | 0.000692 | 0.13 | 0.880 |
| SV | 2 | 0.042169 | 0.021085 | 3.99 | 0.079 |
| Error | 6 | 0.031708 | 0.005285 | | |
| Total | 17 | | | | |

**S = 0.0726956, $R^2$=86.79%, $R^2$ (adj) = 62.56%**

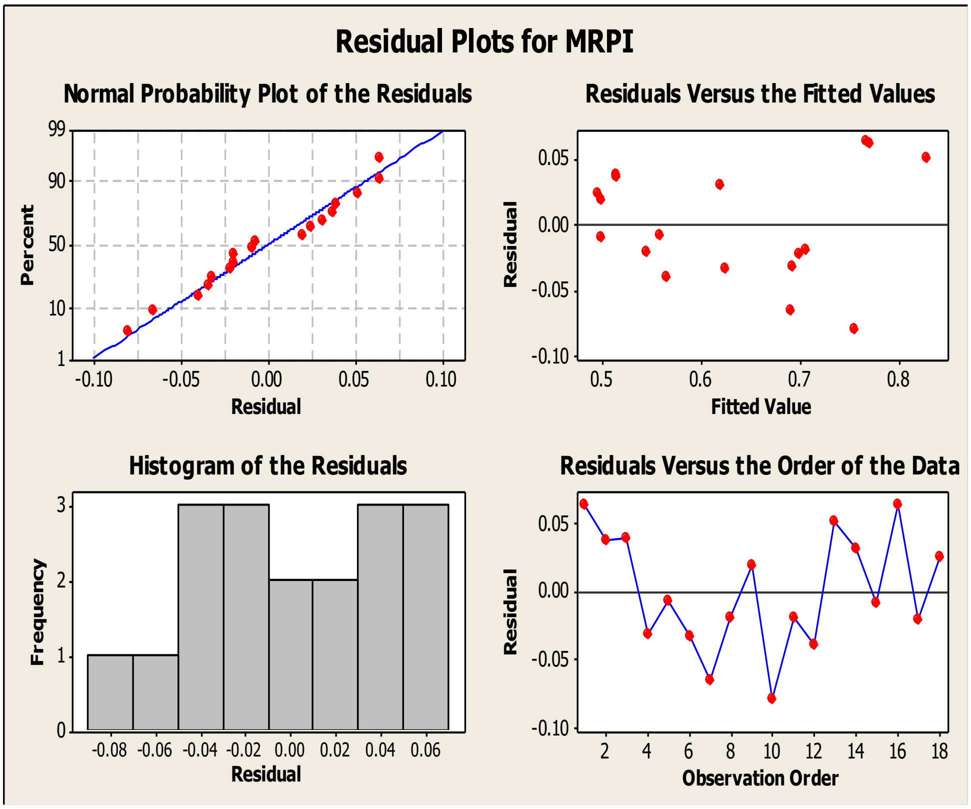


**Figure 5.3 Residual Plots for MRPI**

# CHAPTER 6

# CONCLUSIONS

# CONCLUSIONS

From the Assignments of weights, Taguchi and ANOVA analysis results the following conclusions can be drawn:

1. The optimal condition for achieving maximum MRPI is obtained at
   Flushing pressure (FP): level2; 8kg/cm2
   Pulse-on-Time ($T_{ON}$): level 3;125µs
   Pulse-off-Time ($T_{OFF}$): level1; 55µs
   Wire Tension (WT): level3; 6Kg-f
   Wire Feed (WF): level3, 4mm/min
   Servo Voltage (SV): level1; 20 volts
2. ANOVA results showed that Pulse-off-time ($T_{OFF}$) is the most predominant factor for the multi-responses.
3. The models prepared for MRPI is found to be in good agreement with the experimental results and it can be used for the prediction of responses.

# CHAPTER 7

# REFERENCES

# REFERENCES

[1] N. Tosun, C. Cogun and G.tosun, “A Study On Kerf And Material Removal Rate In Wire Electrical Discharge Machining Based On Taguchi Method,” Journal of Materials Processing Technology,Vol. 152, No. 3, PP. 316-322, October 2004.

[2] S.S.Mahapatra and Amar Patnaik, “Optimization Of Wire Electrical Discharge Machining (WEDM) Process Parameters Using Taguchi Method”, The International Journal of AdvancedManufacturing Technology Volume 34, Numbers 9-10 (2007), 911-925, DOI: .1007/s00170- 06-0672-6.

[3] A.Thillaivanan; Asoka, P.; Srinivasan, K.N. Saravanan, “Optimization of operating parameters for EDM process based on the taguchi method and artificial neural network”, International Journal of Engineering Science and Technology, Vol. 2, No. 12(2010), 6880-6888, ISSN:0975-5462.

[4] M.Sadeghi, H.Razavi, A.Esmaeilzadeh, F.Kolahan,Optimization of cutting conditions in WEDM process using regression modelling and Tabu-search algorithm, Proc. Inst. Mech. Eng.Part B J. Eng. Manufacture 225 (10) (2011) 1825–1834.

[5] C.P.S.Prakash, Dr.B.J.Ranganath, Influence of Machining Parameters in WEDM for Different Workpiece Thickness, International Journal of Applied Engineering Research (IJAER) Volume3, Number 8 (2008), pp 1087-1090.

[6] J. Yuan, K. Wang, T. Yu and M. Fang “ Reliable multi-objective optimization of high-speed WEDM process based on Gaussian process regression,” International Journal of MachineTools and Manufacture, vol. 160, no. 1, pp. 9-14, March 2005.

[7] Tsai, K.M. and Wang, P.J., (2001), “Predictions on surface finish in electrical discharge machining based upon neural network models”, International Journal of Machine Tools andManufacture, Vol. 41, pp.1385–1403.

[8] Rao, G. K. M.; Rangajanardhaa, G.; Rao, D. H.; Rao, M. S. (2009). Development of hybrid model and optimization of surface roughness in electric discharge machining using ArtificialNeural Networks and genetic algorithm, Journal of Materials Processing Technology, Vol. 209, No. 3, 1512–1520.

[9] Pragya Shandilya, P. K. Jain, N. K. Jain, “RSM and ANN Modeling Approaches For PredictingAverage Cutting Speed during WEDM of SiCp/6061 Al MMC”, International Conference On Design and Manufacturing, vol.64, pp. 767774, (2013).

[10] Jasvinder Pal., and Nishant. (2014).Parameters optimization of wire EDM for surface roughness Using Taguchi technique. International Journal of Technical Research, Vol. 3(1), pp. 23-28.

[11] G.Ugrasen, H.V.Ravindra, G.V.Naveen Prakash, R.Keshavamurthy. ”Estimation of machining Performances using MRA, GMDH and artificial neural network in Wire EDM of EN-31.” Procedia Materials Science 6 (2014)1788 – 1797’

[12] Rao, R. V.; Pawar, P. J. (2010). Process parameters modeling and optimization of wire electric discharge machining. Advances in Production Engineering and Management, Vol. 5, No. 3,139-150, ISSN-1854-6250.

[13] H. Singh, R. Garg “Effect of Process Parameters on Material removal rate in WEDM”, Journal of Achievement in Material and Manufacturing Engineering, Vol. 32, Issue No. 1, 2009, 71-74.

[14] F. Han, J. Jiang, D. Yu “Influence of Machining Parameters on Surface Roughness in finish cut of WEDM”, International Journal of Advanced Manufacturing Technology, Vol. 34, 2007, 538- 546.

[15] Patil, C.A. Waghmare, “Optimization of Process Parameters in Wire-Edm using Response Surface Methodology”, International Journal of Mechanical and Production Engineering, Volume- 2, Issue-8, ISSN: 2320-2092, 2014.

[16] Tilekar, S., Das, S. S., Patowari P. K. "Process Parameter Optimization of Wire EDM on Aluminum and Mild Steel by Using Taguchi Method." Procedia Materials Science.5,pp.2577-2584. 2014.

[17] P. Abinesh, Dr. K. Varatharajan, Dr. G. Satheesh Kumar,” Optimization of Process Parameter Influencing MRR, Surface Roughness and Electrode Wear During Machining of Titanium Alloys by WEDM” International Journal of Engineering Research and General Science VolumE 2, Issue 4, June-July, 2014 ISSN 2091-2730.

[18] D. Scott, S. Boyina and K.P. Rajurkar, “Analysis and Optimization of Parameter Combination in Wire Electrical Discharge”, International Journal of Production

Research, 29, pp. 2189-2207, 1991.

[19] Srinivas Athreya, Dr Y.D.Venkatesh, Application of Taguchi Method for Optimization Of Process Parameters in Improving the Surface Roughness of Lathe Facing Operation.

[20] Rao T.B., Krishna A.G., 2013, Simultaneous optimization of multiple performance characteristics in WEDM for machining ZC63/SiCp MMC, Advanced Manufacturing, Vol.1, pp. 265-275.

[21] H. Singh, R. Garg "Effect of Process Parameters on Material removal rate in WEDM", Journal of Achievement in Material and Manufacturing Engineering, Vol. 32, Issue No. 1, 2009, 71-74.

[22] F. Han, J. Jiang, D. Yu "Influence of Machining Parameters on Surface Roughness in finish cuT of WEDM", International Journal of Advanced Manufacturing Technology, Vol. 34, 2007, 538- 546.

[23] Patil, C.A. Waghmare, "Optimization of Process Parameters in Wire-Edm using ResponseSurface Methodology", International Journal of Mechanical and Production Engineering, Volume- 2, Issue-8, ISSN: 2320-2092, 2014.

[24] Tilekar, S., Das, S. S., Patowari P. K. "Process Parameter Optimization of Wire EDM on Aluminum and Mild Steel by Using Taguchi Method." Procedia Materials Science. 5, pp.2577-2584. 2014.

[25] Gokler, M. I., Ozanozgu, A. M.(2000), "Experimental investigation of effects of cutting parameters on surface roughness in the WEDM process", International Journal of Machine Tools & Manufacture, 40,1831–1848.

[26] Ramakrishna R and Karunamoorthy L (2008), "Modeling and Multi-Response Optimization of Inconel 718 on Machining of CNC WEDM Process", Journal of Materials Processing Technology, Vol. 207, pp. 343-349.

[27] Spedding T A and Wang Z Q (1997), "Parametric Optimization and Surface Characterizationof Wire Electrical Discharge Machining Process", Precis. Eng., Vol. 20, pp. 5-15.

[28] Ramkumar N, Subramanian P, Rajmohan M. A multi-criteria decision making model for outsourcing inbound logistics of an automotive industry using the AHP and TOPSIS. Int J Enterprise NetwManag., 2009, 3(3):223-245.

[29] Patel, V., Patel, J. D., Maniya, K. D. "Selection of the wire cut electrical discharge machining process parameters using AHP/TOPSIS method." International Journal of Advance Engineering and Research Development. 1, 2014.

[30] Zlatko Pavić, Vedran Novoselac (Mechanical Engineering Faculty in Slavonski Brod, University of Osijek, Croatia), Notes on TOPSIS Method, International Journal of Research in Engineering and Science (IJRES) ISSN (Online): 2320-9364, ISSN (Print): 2320-9356.

[31] Rao T.B., Krishna A.G., 2013, Simultaneous optimization of multiple performance characteristics in WEDM for machining ZC63/SiCp MMC, Advanced Manufacturing, Vol.1, pp. 265-275.

[32] H. Singh, R. Garg “Effect of Process Parameters on Material removal rate in WEDM”, Journal of Achievement in Material and Manufacturing Engineering, Vol. 32, Issue No. 1, 2009, 71-74.

[33] F. Han, J. Jiang, D. Yu “Influence of Machining Parameters on Surface Roughness in finish cuT of WEDM”, International Journal of Advanced Manufacturing Technology, Vol. 34, 2007, 538- 546.

[34] Patil, C.A. Waghmare, “Optimization of Process Parameters in Wire-Edm using ResponseSurface Methodology”, International Journal of Mechanical and Production Engineering, Volume- 2, Issue-8, ISSN: 2320-2092, 2014.

[35] Tilekar, S., Das, S. S., Patowari P. K. "Process Parameter Optimization of Wire EDM on Aluminum and Mild Steel by Using Taguchi Method." Procedia Materials Science. 5, pp.2577-2584. 2014.

[36] Gokler, M. I., Ozanozgu, A. M.(2000), “Experimental investigation of effects of cutting parameters on surface roughness in the WEDM process”, International Journal of Machine Tools & Manufacture, 40,1831–1848.

[37] Ramakrishna R and Karunamoorthy L (2008), “Modeling and Multi-Response Optimization of Inconel 718 on Machining of CNC WEDM Process”, Journal of Materials Processing Technology, Vol. 207, pp. 343-349.

[38] Spedding T A and Wang Z Q (1997), “Parametric Optimization and Surface Characterizationof Wire Electrical Discharge Machining Process”, Precis. Eng., Vol.

20, pp. 5-15.

[39] Ramkumar N, Subramanian P, Rajmohan M. A multi-criteria decision making model for outsourcing inbound logistics of an automotive industry using the AHP and TOPSIS. Int J Enterprise NetwManag., 2009, 3(3):223-245.

[40] Patel, V., Patel, J. D., Maniya, K. D. "Selection of the wire cut electrical discharge machining process parameters using AHP/TOPSIS method." International Journal of Advance Engineering and Research Development. 1, 2014.

[41] Zlatko Pavić, Vedran Novoselac (Mechanical Engineering Faculty in Slavonski Brod, University of Osijek, Croatia), Notes on TOPSIS Method, International Journal of Research in Engineering and Science (IJRES) ISSN (Online): 2320-9364, ISSN (Print): 2320-9356.

[42] V. S. Gadakh “Parametric optimization of Wire Electrical Discharge Machining using TOPSIS METHOD”, Advances in Production Engineering and Management, Vol. 7, Issue No. 3, 2012, 157-164.

[43] Tripathy S., Tripathy D.K.: Multi-attribute optimization of machining process parametersin powder mixed electro-discharge machining using TOPSIS and Grey relational analysis. Engineering Science and Technology, an International Journal, 2015.

[44] Dewangan S., Gangopadhyay S., Biswas C.K.: Study of surface integrity and dimensional accuracy in EDM using Fuzzy TOPSIS and sensitivity analysis”. Measurement, 2015, Vol.63, pp. 364-376. [

[45] Kuldip Singh Sangwan, Sachin Saxena, Girish Kant: Optimization of Machining Parameters to Minimize Surface Roughness using Integrated ANN-GA Approach. Procedia CIRP, 2015, Vol. 29, pp. 305-310.

[46] Shivakoti, I., Shivakoti, I., Pradhan, B. B., Diyaley, S., Ghadai, R. K., Kalita, K. "Fuzzy TOPSIS-Based Selection of Laser Beam Micro-marking Process Parameters." Arabian Journal for Science and Engineering. 1-7. 2017.

[47] Senthil P., Vinodh S., Singh A.K.: Parametric optimisation of EDM on Al-Cu/TiB2 in-situ metal matrix composites using TOPSIS method. International Journal of Machining and Machinability of Materials, 2014, Vol. 16, No. 1, pp. 80-94

[48] Rao, G. K. M.; Rangajanardhaa, G.; Rao, D. H.; Rao, M. S. (2009). Development of hybridmodel and optimization of surface roughness in electric discharge machining using artificial neural networks and genetic algorithm, Journal of Materials Processing Technology, Vol. 209, No. 3, 1512–1520, doi:10.1016/j.jmatprotec.2008.04.003.

[49] G.R. Jahanshahloo, F. Hosseinzadeh Lotfi, M.Lzadikhah, “An Algorithmic Method to Extend TOPSIS for Decision-Making Problems with Interval Data”, Applied Mathematics and Computations, (2005).

[50] M. Behzadian, S. Otaghsara, M. Yazdani and J. Ignatius, “A State-of-the-Art Survey of TOPSIS Applications”, Expert Systems with Applications, (2012), 39(17), pp. 13051-13069.

[51] R. Simanaviciene and L. Ustinovichius, “Sensitivity Analysis for Multiple Criteria Decision Making Methods: TOPSIS and SAW”, Procedia Social and Behavioral Sciences, (2010), 2, pp. 7743-7744.

[52] Pema Wangchen Bhutia, Ruben Phipon, Application of ahp and topsis method for supplier selection problem, IOSR Journal of Engineering (IOSRJEN) e-ISSN: 22503021, p-ISSN: 2278- 8719, Volume 2, Issue 10 (October 2012), PP 43-50.

[53] Roberts E., 2017, Neural networks. Course notes, Accessed 16th May 2017, Retrieved from networks/Architecture/feedforward.html

[54] Vasudevan D., Selladurai V., Nagaraj P., 2004, Determination of closed form solution for acceptance sampling using ANN, Quality Assurance, Vol. 11, No. 1, pp. 43-61.

[55] Reza Atefi, Ali Razmavar, Farhad Teimoori and Farshad Teimoori, “The influence of EDM parameters in finishing stage on MRR of hot worked steel using ANN”, Journal of Basic and Applied Scientific Research, Vol.2(3), pp.2307-2311, 2011

[56] Purushothaman S and Srinivasa Y G (1994), “A Back Propagation Algorithm Applied to Tool Wear Monitoring”, International Journal of Machine Tools Manufacture, Vol. 34, pp. 625-631.

[57] M. M. Rahman, MD. Ashikur Rahman Khan, K. Kadirgama, Rosli A.Bakar, “Prediction

of material removal rate for Ti-5Al-2.5Sn in EDM using multi-layered perceptron neural network technique", Recent Researches in Neural Networks, Fuzzy Systems, EvolutionaryComputing and Automation, pp.17-23,2011

[58] Azli Yahya, Trias Andromeda, Ameruddin Baharom, Arif Abd Rahim and Nazriah Mahmud,"Material removal rate prediction of electrical discharge machining process using artificial neural network", Journal of Mechanics Engineering and Automation, Vol.1, pp.298-302, 2011

[59] G.Ugrasen, H.V.Ravindra, G.V.Naveen Prakash, R.Keshavamurthy. "Estimation of machining Performances using MRA, GMDH and artificial neural network in Wire EDM of EN-31." Procedia Materials Science 6 (2014)1788 – 1797'

[60] Deepak Kumar Panda, Rajat Kumar Bhoi, Artificial Neural Network Prediction of Material Removal Rate in Electro Discharge Machining, Materials and Manufacturing Processes(2005), 20: 4, 645 — 672.

[61] Cascade and feed forward back propagation artificial neural network models for prediction of compressive strength of ready mix concrete, Second International Conference on Emerging Trends in Engineering (SICETE), Dr. J.J. Magdum College of Engineering, Jaysingpur, India, Vol. 3 pp 1-6.

[62] P.Rossini, Artificial Neural Networks versus Multiple Regression in the Valuation of Residential Property. Australian Land Economics Review, 1997, 3:1.

[63] Zain.AM, Haron.H, Qasem.SN, Sharif.S, "Regression And ANN Models For Estimating Minimum Value Of Machining Performance. Applied Mathematical Modelling,2012;36:1477-92.

[64] N.Nguyen and A. Cripps, "Predicting Housing Value: A Comparison of Multiple RegressioNAnalysis and Artificial Neural Networks", Journal of Real Estate Research, 2002, 22:3,313– 36.

[65] Linder.R, Konig. IR, Weimar .C, Diener .HC, Poppl .SJ, Ziegler. A, "Two Models For Outcome Prediction A Comparison Of Logistic Regression And Neural Networks", Methods Info Med. 2006; 45:536-540.

[66] Ch.Suresh, Dr.K.VenkataSubbaiah and Ch.Raju, “Effect of process parameters on surface roughness of HSS M35 in Wire EDM during taper cutting”, International Journal of Advanced Mechanical Engineering, Vol.8, pp.127-136, 2018.

[67] Mahapatra, S. and Patnaik, A., “Parametric optimization of wire electrical discharge machining (wedm) process using Taguchi method”, J. of the Braz. Soc. of Mech. Sci. & Eng., 28, 422-429, 2006.

[68] Miller, S. F., Chen, C.K., Shih, A. J., Qu, J., “Investigation of wire electrical discharge machining of thin cross-sections and compliant mechanisms”, International Journal of Machine Tools & Manufacture, 45, 1717–1725, 2005.

[69] Miller, S. F., Shih, A. J., Qu, J.. “Investigation of the spark cycle on material removal rate in wire electrical discharge machining of advanced materials”, International Journal of Machine Tools & Manufacture, 44, 391–400, 2004.

[70] M.K.Rodge, S.S.Sarpata, S.B.Sharma, “Investigation on process response and parameters in Wire EDM of Inconel 625”, International Journal of Mechanical Engineering and Technology, 4(1), 54-65, 2013.

[71] Ch. Maheswara Rao, K. Jagadeeswara Rao and K. Suresh Babu, “Optimization of Material Removal Rate and Surface Roughness Using Grey Analysis” International Journal of Engineering Research and Development, e-ISSN: 2278-067X, p-ISSN:2278-800X, Vol. 12, Issue 3, (Part-1), pp. 49-58, March 2016.

[72] Ch. Maheswara Rao and K. VenkataSubbaiah, “Effect and Optimization of EDM Process Parameters on Surface Roughness for EN41 Steel”, International Journal of Hybrid Information Technology, ISSN: 1738-9968, Vol-9, No.5, pp.343-358, 2016.

[73] Ch. Maheswara Rao, K. VenkataSubbaiah and K. Jagadeeswara Rao, “Experimental Investigation of Surface Roughness Characteristics Ra, Rq and Rz”, International Journal of Hybrid Information Technology, ISSN: 1738-9968, Vol-9, No.7, pp.373-388, 2016.

[74] Ch. Maheswara Rao and K. VenkataSubbaiah, “Application of WSM, WPM and TOPSIS Methods for the Optimization of Multiple Responses”, International Journal of Hybrid Information Technology, ISSN: 1738-9968, Vol-9, No.10, pp.59-72, 2016.

[75] Ch. Maheswara Rao, K. VenkataSubbaiah and K. Sowjanya, “Influence of Speed, Feed and Depth of cut on Multiple Responses in CNC Turning”, International Journal of Advanced Science and Technology, ISSN: 2005-4238, Vol-92, pp.59-76, 2016.

[76] K.Kumar, R.Ravi Kumar, “Modelling and optimization of Wire EDM Process”, International Journal of Modern Engineering Research (IJMER), Vol.3, PP-1645-1648, 2013.

[77] Kanlayasiri, K., Boonmung, S., “An investigation on effects of wire-EDM machining parameters on surface roughness of newly developed DC53 die steel”, Journal of Materials Processing Technology, 187–188, pp.26–29, 2007.

[78] Kuriakose, S., Shunmugam, M.S., “Multi-objective optimization of wire electro discharge machining process by non-dominated sorting genetic algorithm”, Journal of Materials Processing Technology, 170, pp.133-141, 2005.

[79] ArindamMukhuti, Amruta Rout, S.Tripathy, “Optimization of Inconel 600 using Wire EDM by MOORA and Taguchi’s method”, International Conference of Electrical, Electronics and Optimization Techniques, 2016.

[80] A.Muniappan, R.Sathiyaraj, C.Thiyagarajan, “Optimization of process parameters using multi objective optimization on the basis of ratio analysis”, International Journal of Mechanical and Production Engineering, Vol.3, PP-133-137, 2018.

[81] Ch. Maheswara Rao, K. VenkataSubbaiah and Ch. Suresh, “Prediction of Optimal Designs for Material Removal Rate and Surface Roughness Characteristics”, International Journal of Lean Thinking, Vol-7, Issue-2, pp.24-46, December-2016.

[82] Ch.Maheswara Rao, K.VenkataSubbaiah, “Investigation of the Impact of Nose Radius on the Multiple Performance Characteristics”, Journal of Advancements in Material Engineering, e-ISSN: 2582-0036, Vol.3, Issue.2, pp. 1-11, 2018.

[83] Ch.Maheswara Rao, K.VenkataSubbaiah, “Multi-Objective Optimization of Material Removal Rate and Surface Roughness in Dry Turning of Aluminium Alloy AA7075 Using Taguchi-Utility Method”, Journal of Recent Activities in Production, e-ISSN: 2581-9771, Vol.3, Issue.2, pp. 1-14, 2018.

[84] Ch.Maheswara Rao, K.VenkataSubbaiah, “Preference Number Based Taguchi-Utility Method for the Optimization of Multiple Responses”, Journal of Recent Activities in Production, e-ISSN: 2581-9771, Vol.3, Issue.2, pp. 1-7, 2018.

[85] T.VictorBabu, Ch.Maheswara Rao, “Application of AHP and Utility Methods in Optimization of Turning Process Parameters”, Journal of Mechanical and Mechanics Engineering, ISSN: 2581-3722, Vol.4, Issue.4, pp. 36-46, 2018