# EXPERIMENTAL INVESTIGATION ON VARIOUS PERFORMANCE CHARACTERISTICS OF HASTELLOY–C276 USING ENTROPY-TOPSIS

*A Project report submitted in partial fulfilment of the requirements for the Award of the Degree of*

**BACHELOR OF TECHNOLOGY**

**IN**

**MECHANICAL ENGINEERING**

*Submitted by*

| | |
|---|---|
| PATHIVADA PRAVEEN KUMAR | 319126520103 |
| VIJAYA VANAPALLI | 320126520L12 |
| VAKKALANKA VENKATA RAJGOPAL | 319126520118 |
| MEELA UDAY KUMAR | 319126520093 |

*Under the Esteemed Guidance of*

**CH. MAHESWARA RAO, (Ph. D), M. Tech, M.B.A,**

Assistant Professor

**DEPARTMENT OF MECHANICAL ENGINEERING**

ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY AND SCIENCES (A)
(Permanently Affiliated to Andhra University, Approved by AICTE, Accredited by NBA Tier-I, NAAC)
Sangivalasa - 531162, Bheemunipatnam (Mandal), Visakhapatnam (District)

Andhra Pradesh -India

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**DEPARTMENT OF MECHANICAL ENGINEERING**

**ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY AND SCIENCES**

**(UGC Autonomous & Permanently Affiliated to Andhra University)**

# CERTIFICATE

This is to certify that the project report entitled **"Experimental Investigation on Various Performance Characteristics of HASTELLOY–C276 using Entropy – TOPSIS"** being submitted by **PATHIVADA PRAVEEN KUMAR (319126520103), VIJAYAVANAPALLI (320126520L12), VAKKALANKA VENKAT RAJ GOPAL (319126520118), MEELA UDAY KUMAR (319126520093)** to the Department of Mechanical Engineering, ANITS is a record of the bonafide work carried out by them under the esteemed guidance of **Mr. CH. MAHESWARA RAO**. The results embodied in the report have not been submitted to any other University or Institute for the award of any degree or diploma.

**Project Guide**

**CH. MAHESWARA RAO**
**Assistance professor**
**Dept. of Mechanical**
**Engineering,**
**ANITS.**

PROFESSOR & HEAD
Department of Mechanical Engineering
ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY & SCIENCES
Sangivalasa-531 162, VISAKHAPATNAM Dist. A.P.

**Head of the Department**

18-4-23

**Dr. B. NAGARAJU**
**Professor**
**Dept. of Mechanical**
**Engineering,**
**ANITS.**

**THIS PROJECT IS APPROVED BY THE BOARD OF EXAMINERS**

**INTERNAL EXAMINER:** 18·4·23

**EXTERNAL EXAMINER:** S. Dey 18/4/23

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| | |
|---|---|
| **PATHIVADA PRAVEEN KUMAR** | **319126520103** |
| **VIJAYA VANAPALLI** | **320126520L12** |
| **VAKKALANKA VENKATA RAJ GOPAL** | **319126520118** |
| **MEELA UDAY KUMAR** | **319126520093** |

# ABSTRACT

The aim of the project work is to create an acceptable set of Wire EDM process parameters for cutting Hastelloy. The work material selected is good at heat resistance capabilities as well as resistance to chloride pitting and crevice corrosion cracking. As a result, it mostly fits in with marine engineering, nuclear power plants, boilers, pressure vessels, and gas turbines, etc. The controllable parameters during machining have been identified as Flushing Pressure (FP), Pulse-On-Time ($T_{ON}$), Pulse-Off-Time ($T_{OFF}$) Wire Feed (WF). $L_{16}$ Orthogonal Array ($2^{\wedge 1}*3^{\wedge 5}$) design was planning to be used for the experimentation. The responses to be obtained Material Removal Rate (M RR) and Surface Roughness Characteristics ($R_a$, $R_q$, $R_y$, $R_z$,) were planning to optimize using Topsis Method.

**Key Words:** Wire EDM, Flushing Pressure, Pulse-On-Time ($T_{ON}$), Pulse-Off-Time ($T_{OFF}$)Wire Feed (WF), Material Removal Rate (MRR), Surface Roughness Characteristics ($R_a$, $R_q$, $R_y$, $R_z$,), Topsis.

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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 kerfs' 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. Deionised 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.

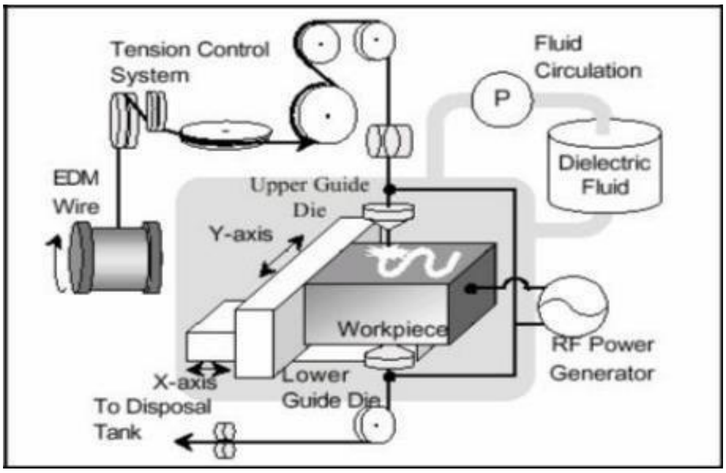

**Fig 1.1 Wire Electrical Discharge Machining System**

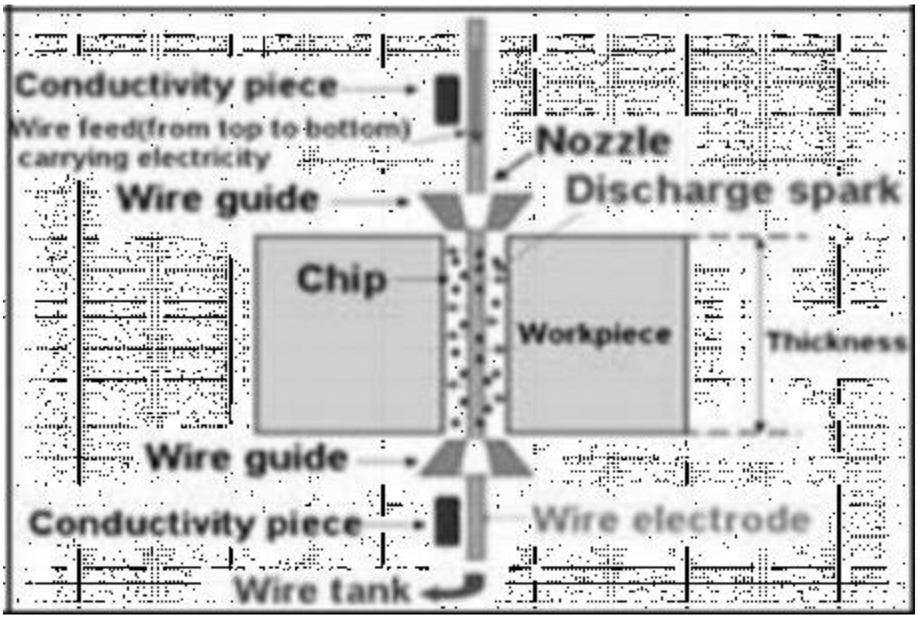

**Fig 1.2 Close View of Cutting Zone in WEDM**

## 1.3. How Wire EDM Works

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

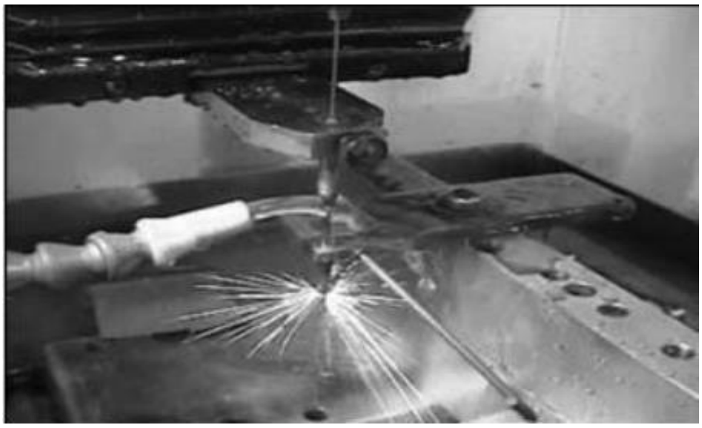

**Fig 1.3 Generation of Spark in WEDM**

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 deionised 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 chillers to keep the liquid at a constant temperature.

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

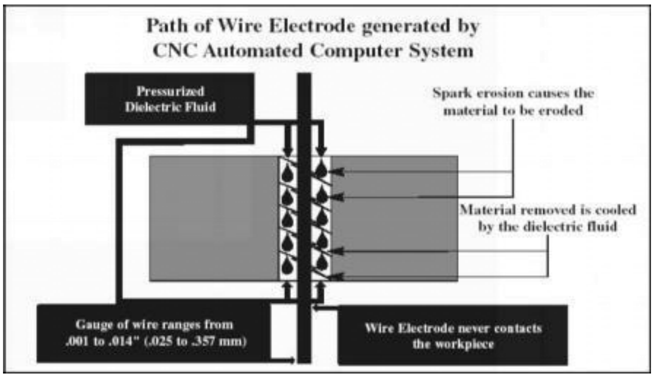

**Fig 1.4 Path of Wire in WEDM**

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

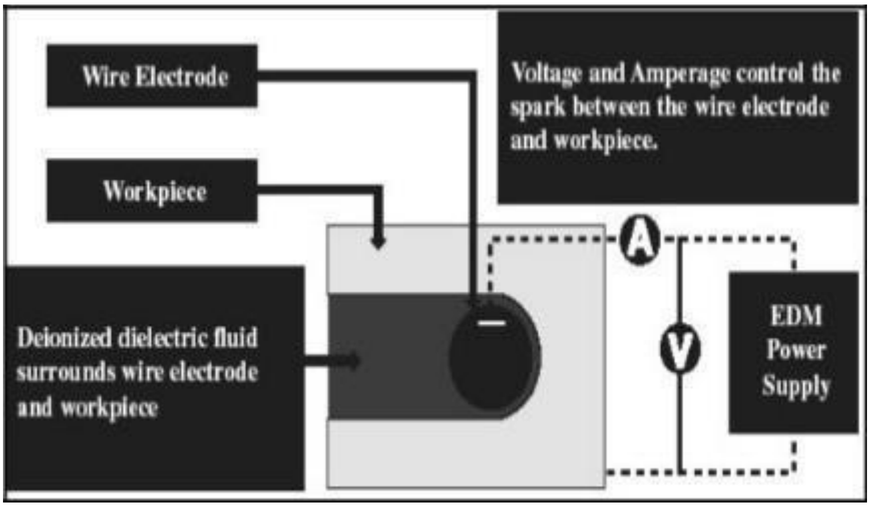

**Fig 1.5 Power Generations in WEDM**

Power Supply Generates Volts and Amps**:** Deionised 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.

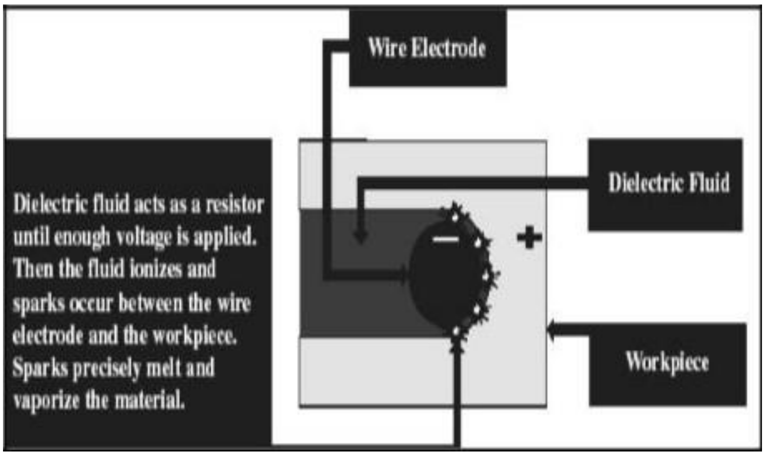

**Fig 1.6 Erosion of Material in WEDM**

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

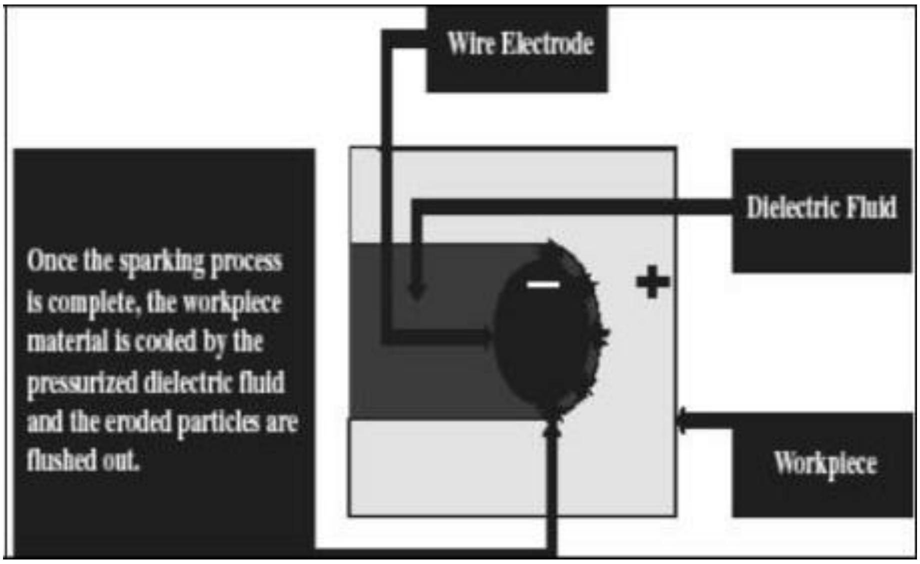

**Fig 1.7 Spark Erosion during ON Time**

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.

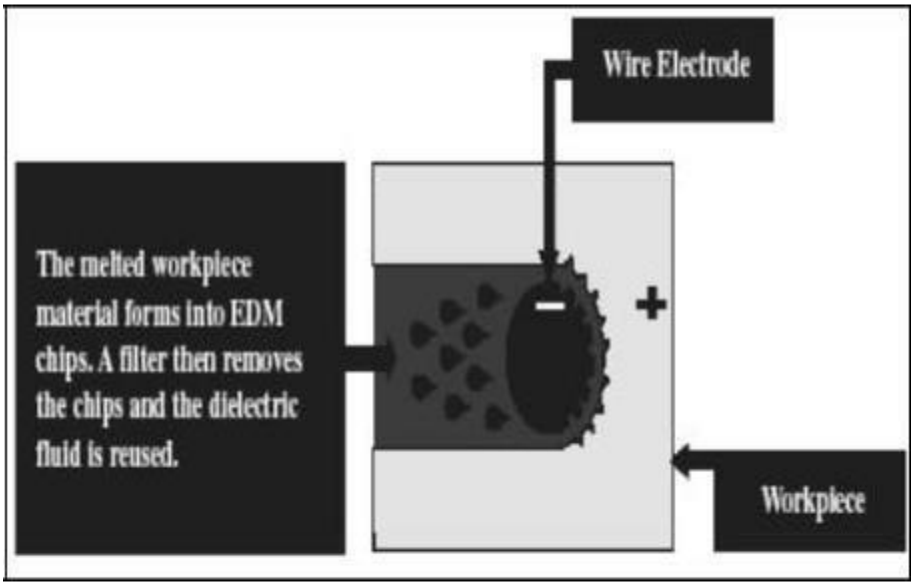

**Fig 1.8 Chip Removal by Filtration**

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

## 1.5. Process Parameters and Their Influence

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

## Influence of Wire Material Characteristics

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

## Effect of Wire Tension

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

## Effect of Frequency

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

## Heat Affected Zone

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

## Thickness of the Work Piece

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

## Material of the Work Piece

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

## Time ON

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

## Time OFF

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

## Current

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

## Voltage

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

## Gap Size

This is one of the most crucial parts of the EDM system. The size of the gap is governed by the servo control system whose motion is controlled by gap width sensors. They control the motion of the ram head or the quill, which in turn governs the gap size. Typical values of the gap size are between 0.010 to 0.050 mm, although gap sizes as small as of several hundred to several thousands of 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.

## Surface Finish

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

## Polarity

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

## Material Removal Rate (MRR)

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

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

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

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

## Duty Factor

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

## Dielectric –Fluid Functions:

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

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

## De-Ionized Water

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

## De-Ionized water - Considerations

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

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

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

## Filtration

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

## Wire-Cut Chip Removal

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

## High Velocity Fluid Flow

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

## Positioning Fluid-Flow Nozzles

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

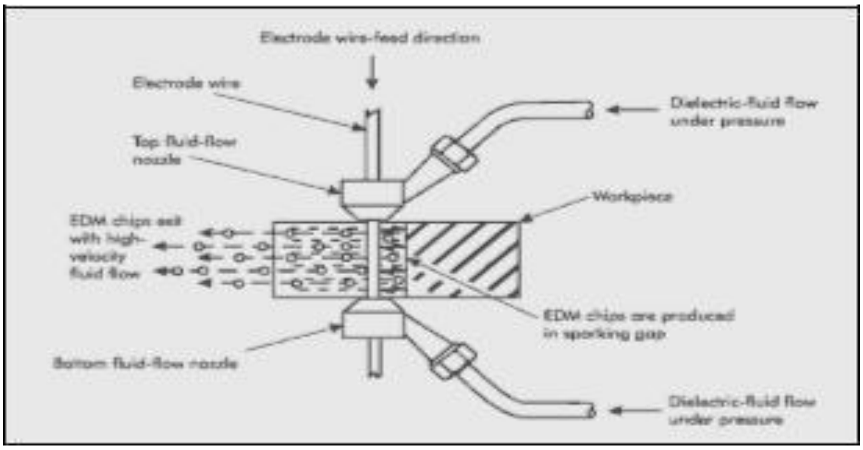

**Fig 1.9 Wire Cut Fluid Flow Nozzles**

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 work piece. 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 work piece 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.

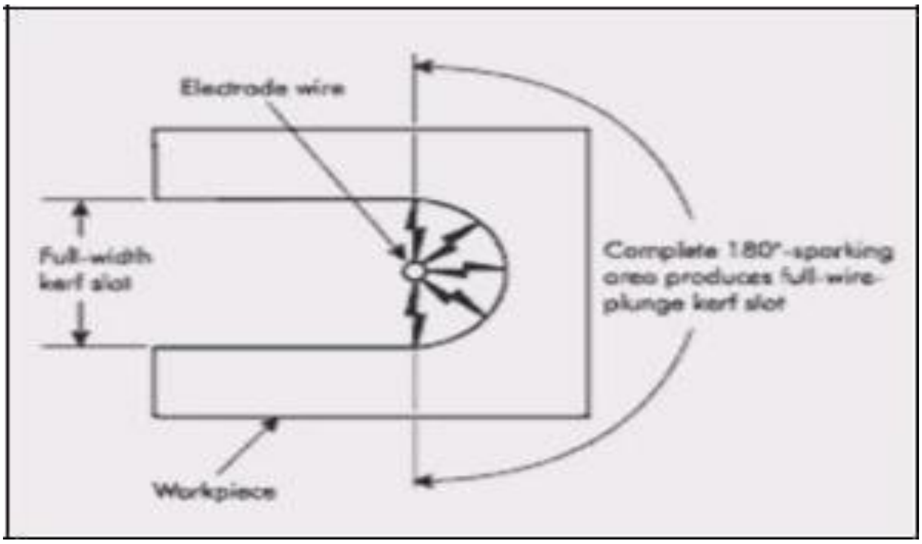

**Fig 1.10 Full-Wire Finish Machining**

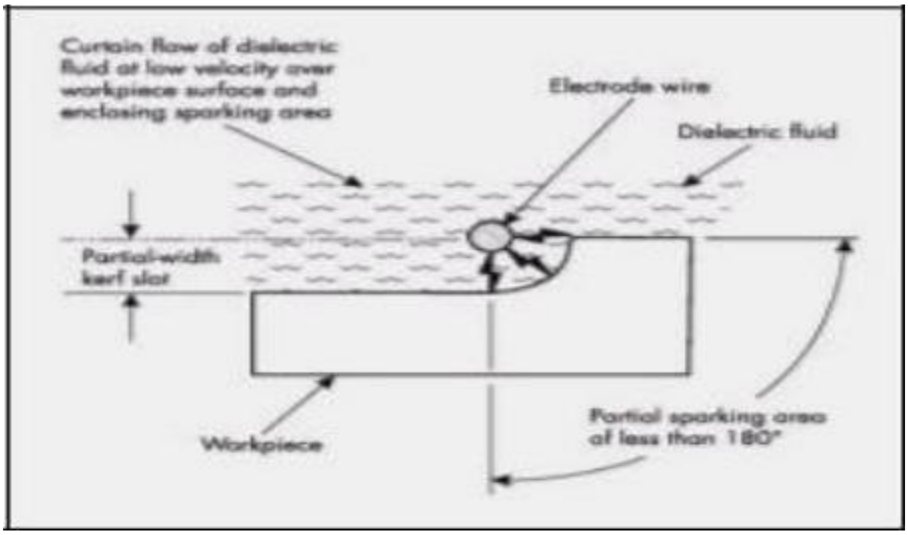

**Fig 1.11 Partial-Wire Finish Machining**

## Minimum Wall Thickness for Fluid Control

Loss of fluid in the sparking area also occurs due to insufficient material at the sides of the machining operation. In most machining operation it is desirable to remove as little of work piece 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 work piece surface from fluid coming through the nozzle. Therefore a wall thickness of less than 0.25 inch (6.35mm) should be used with full-plunge machining. Any thinner wall thickness can result in escaping fluid, increased machining time and possible wire breakage.

## Wire EDM Transport System

Wire EDM uses an electrically charged thin brass wire, which is moved by computer control, close to, but not touching, the part to be cut. The wire and the work piece are either fully submerged, or the part is vigorously flushed with a dielectric liquid. The small gap creates a spark, which vaporizes small particles of the work piece as the wire advances. The disintegrated particles are flushed away by dielectric fluid, and the wire is able to advance further. The wire itself is traveling – advancing from a large spool, and after use as an electrode, into a spent wire bin. The travel of the wire is determined bythe machine's computer program.

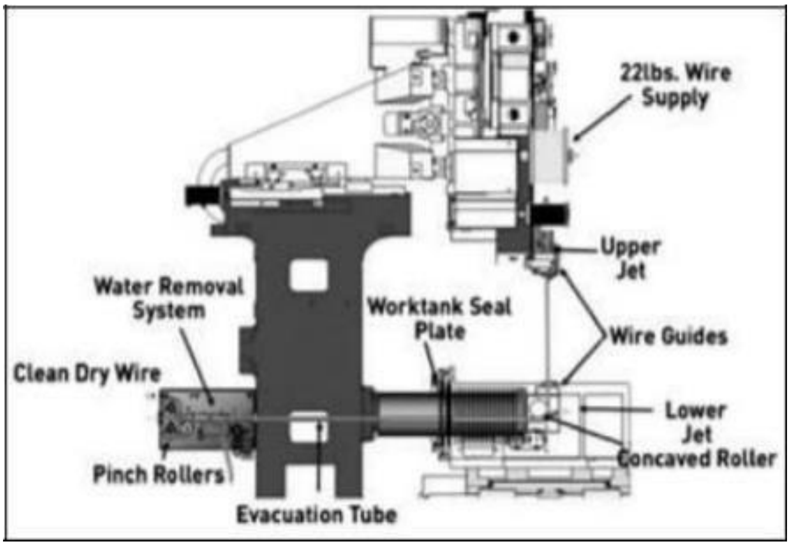

**Fig 1.12 Wire EDM Transport System**

The complexities of the wire transport system as shown in Figure 1.12 and automatic wire threaded (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. Most AWTs use a high-pressure water jet as the main wire transport system between the upper and lower guides. The entire transport system must be maintained according to the manufacturer's recommendations. Wire guide types, the complexity of the jet, the cutting system, drive pulleys and tensioning all have an impact on reliability and performance. When it becomes possible, depending upon type of application, to operate in an unattended environment overnights, weekends and holidays, it is realistic to gain hundreds of machining hours per year. In fact, a highly reliable machining system, operating on a continuing basis will outperform a less reliable system cutting at high speed. Failure to properly maintain this valuable machine feature will affect production.

## 1.6. Materials That WEDM Can Cut:

### Carbide

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

## Polycrystalline Diamond

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

## Ceramics

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

## Cost Savings with WEDM

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

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

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

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

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

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

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

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

**Internal Contours:** Pipes, gears, pultrusion moulds 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 REVIEW

WEDM is an essential operation among several manufacturing processes, which gives importance to variety, precision and accuracy. Several researchers have contributed their work towards an improvement in the performance characteristics namely the Surface

Roughness (SR), Cutting Speed (CS), Dimensional Accuracy (DA), Material Removal Rate (MRR), Kerf Width (KW) etc.

**Nihat Tosun and Can Cogon [1]** An investigation on wire wear in WEDM- In this study, the effect of cutting parameters on wire electrode wear was investigated experimentally in Wire Electrical Discharge Machining (WEDM). The experiments were conducted under different settings of pulse duration, open circuit voltage, wire speed and dielectric fluid pressure. Brass wire of 0.25 mm diameter and AISI 4140 steel of 10 mm thickness were used as tool and work piece material. It is found experimentally that the increasing pulse duration and open circuit voltage increase the Wire Wear Ratio (WWR) whereas the increasing wire speed decreases it. The variation of work piece material removal rate and average surface roughness were also investigated in relation to the WWR. The variation of the WWR with machining parameters was modelled statistically by using regression analysis technique. The level of importance of the machining parameters on the WWR was determined by using Analysis Of Variance (ANOVA) method

**S.S. Mahapatra and Amar Patnaik[2]** studied optimization of Wire Electrical Discharge Machining (WEDM) process parameters using Taguchi method. Wire electrical discharge machining (WEDM) is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in WEDM is treated as a challenging one because improvement of more than one machining performance measures viz. Metal Removal Rate (MRR), Surface Finish (SF) and cutting width (kerf) are sought to obtain a precision work. Using Taguchi’s parameter design, significant machining parameters affecting the performance measures are identified as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow. It has been observed that a combination of factors for optimization of each performance measure is different. In this study, the relationship between control factors and responses like MRR, SF and kerf was established by means of nonlinear regression analysis, resulting in a valid mathematical model. Finally, genetic algorithm, a popular evolutionary approach, was employed to optimize the wire electrical discharge machining process with multiple objectives. The study demonstrated that the WEDM process parameters can be adjusted to achieve better metal removal rate, surface finish and cutting width simultaneously.

**Goswami and Kumar [3]** investigated on surface integrity, material removal rate and wire wear ratio of Nimonic 80A using WEDM process. Taguchi's design of experiments methodology has been used for planning and designing the experiments. They concluded that Pulse on Time ($T_{ON}$) and Pulse off Time ($T_{OFF}$) have been found to be the most significant factors for MRR at 95% significance level. The higher discharge energy results in melting expulsion, leading to the formation of a deeper and larger crater on the surface of the work piece. The recast layer has been observed to increase with increase in pulse-on time and peak current.

**Dabade and Karidkar [4]** used Taguchi technique to analysis of response variables in WEDM of Inconel 718. Pulse on time was found to be the most significant factor for all the response variables such as MRR, SR, Kerf width and Dimensional deviation with percentage contributions as 54.32 %, 58.42 %, 83.21 % and 36.11 % respectively. Surface roughness improves with increase in pulse off time, wire tension and spark gap voltage. Wire feed and servo voltage was observed to be insignificant factors for kerf width. Dimensional deviation was affected by increase in pulse on time, peak current, wire feed and spark gap set voltage. But increasing pulse off time and wire tension found to be improving dimensional deviation.

**R.N. Ahmad et.al. [5]** Studied the mach inability of aluminium matrix composite reinforced 5% alumina Al2O3 on WEDM. The most optimum machining parameters that will increase the mach inability of AMC based on MRR were determined. The two-level full factorial design of experiment approach was used to determine the combination of machining parameters based on Pulse-off time (µs), Wire Tension (kgf/mm) and Servo Voltage (V). Result of calculated MRR was examined using Regression Analysis Method to determine the mathematical model between machining parameter and machining characteristics. It was found that the servo voltage has much influence on the Material Removal Rate (MRR). Low servo voltage value can increase MRR and machining production rate will increase simultaneously. For good quality of AMC reinforced with 5% alumina, the value of pulse off time and wire tension was set to 150 µs and 1750 gram/mm and servo voltage was set to 40 V. It was also concluded that adjusting the pulse-off time setting is an appropriate strategy to control the discharging frequency.

**R. Bagherian Azhiri et. al. [6]** Presented the experimental study while machining of Al/Sic aluminium matrix by dry WEDM process. Brass wire and oxygen gas were selected through a series of experiments due to their guaranteed superior cutting velocity. Taguchi’s orthogonal array was used to study the effect of Pulse On Time, Pulse Off Time, Gap

Voltage, Discharge Current, Wire Tension And Wire Feed On Cutting Velocity (CV) And Surface Roughness (SR). Adaptive neuron fuzzy inference system was used to correlate relationship between process inputs and responses. At the end, a grey relational analysis was used to maximize CV and minimize SR simultaneously. According to ANOVA, it was found that pulse on time and current have significant effect on CV and SR. It was concluded in exploratory experiments that oxygen gas and brass wire results in higher cutting velocity and oxygen gas can create a chemical reaction, also increases corrosion rate of work piece. The setting of 126 µs pulse on time, 40 µs pulse off time, 230 A discharge current, 12 mm/min wire feed, 20 V gap voltage, and 4 gr. wire tension resulted in higher cutting velocity regarding lower surface roughness.

**Sumit Raj and Kaushik Kumar[7]** have optimised material removing rate in die sinking electro discharge machining of EN45 steel tool. The main aim of this paper is to maximization of MRR in die sinking electro-discharge machining of EN45 material using Taguchi method. EN45 is a manganese spring steel with high carbon content. EN45 is used widely in the motor vehicle industry for leaf springs, truncated conical springs, helical springs and spring plates and many general engineering applications. The experiments conducted based on the L27 Orthogonal array and results were optimized. Experiment were carried out using four input parameters viz. Peak Current (Ip), Pulse on Time ($T_{on}$), Pulse Off Time ($T_{off}$) And Voltage (V) with three different levels. The effects of different input parameters and effect of their combination on MRR determined using Taguchi and ANOVA table. It was observed that peak current and pulse off time are more significant factor for MRR.

**Kaladhar et.al.[8]** Applied Taguchi method to determine the optimum process parameters for turning of AISI 304 austenitic steel on CNC lathe. They conducted tests at four levels of cutting speed, feed and depth of cut. The influence of these parameters are investigated on the surface roughness and Material Removal Rate (MRR). The results revealed that cutting speed significantly affects the surface roughness followed by noise radius while depth of cut affects the MRR most followed by cutting speed.

**Reddy and Valli [9]** show the effect of process parameters on the machining of EN-31 tool steel with copper as a tool in the rotary Electrical Discharge Machining Process (EDM) with help of linear regression analysis and Taguchi's method. Material removal rate, tool wear ratio and surface roughness was used as response variables. Results showed that

MRR, TWR and SR was greatly influenced by peak current. Experimental results also confirmed that simultaneous optimization of MRR, TWR an SR was not possible for a given set of control factors.

**Samruddhi Rao et. al. [10]** presented a detailed overview of Taguchi Method in terms of its evolution, concept, steps involved and its interdisciplinary applications. It could be concluded that this method with its perfect amalgamation of statistical and quality control techniques was one of the effective and efficient methods of its kind to highlight the benefits of designing quality into products upstream rather than inspecting out bad products downstream. It offers a quantitative solution to identify design factors to optimize quality and reduce cost. Also the application of this method is not confined to a particular domain but also to other fields like product and service sec-tors. It thus is a powerful method as compared to the other intuitive and more cumbersome methods encompassing a large number of fields in terms of application.

**M. Adinarayana et.al. [11]** Have presented in paper the multi response optimization of turning parameters for turning on AISI 4340 Alloy Steel. Experiments are designed and conducted based on Taguchi's L27 Orthogonal array design. This paper discusses an investigation into the use of Taguchi parameter Design and Regression analysis to predict and optimize the Surface Roughness, Metal Removal Rate and Power Consumption in turning operations using CVD Cutting Tool. The Analysis of Variance (ANOVA) is employed to analyse the influence of Process Parameters during Turning. This paper also remarks the advantages of multi-objective optimization approach over the single-objective one. The useful results have been obtained by this research for other similar type of studies and can be helpful for further research works on the Tool life and Vibration of tools etc.

**Singh and Kumar [12]** obtain an optimal setting of turning process parameters (cutting speed, feed rate and depth of cut) resulting in an optimal value of the cutting force and feed force when machining EN24 steel with Tic-coated Tungsten carbide inserts using Taguchi's parameter design approach. They uses Taguchi's L27 orthogonal array, signal to noise ratios (S/N) and analysis of variance (ANOVA) for the study.

**Arshad Noor Siddiqueea et.al. [13]** Has conducted experiment on CNC lathe machine using solid carbide cutting tool on material AISI 321 austenitic stainless steel, to optimize deep drilling parameters with the help of Taguchi method for minimizing surface roughness. The cutting parameters such as cutting fluid, speed, feed and hole-depth considered. Taguchi L18 orthogonal array used as design of experiment. To determine which machining parameter significantly affects the surface roughness the Signal-To-Noise (S/N) Ratio and Analysis of Variance (ANOVA) is used. Results revealed that the machining done using cutting fluid, at a speed of 500 p.m. with a feed of 0.04 mm/s and hole-depth of 25 mm is the optimum condition. The results of ANOVA indicated that all four cutting parameters significantly affected the surface roughness with maximum contribution from speed (27.02%), followed by cutting fluid (25.10%), feed (22.99%), and hole-depth (14.29%).

**Arun Kumar Parida and Bharat Chandra Routara [14]** developed Taguchi's design of experiment to optimize the process parameters in turning operation with dry environment. The machining was conducted with Taguchi L9 orthogonal array, and based on the S/N ratio analysis, the optimal process parameters for surface roughness and MRR were calculated separately. An attempt was made to optimize the multi responses using technique For Order Preference by Similarity to Ideal Solution (TOPSIS) with Taguchi approach.

**Yogendra Tyagi et.al. [15]** Has conducted experiment to study the optimization of drilling of mild steel with the help of CNC drilling machining operation with tool use high speed steel by using Taguchi method and signal-to-noise ratio applied to find optimum process parameter for CNC drilling machining. L9 orthogonal array and Analysis Of Variance (ANOVA) are used to study the performance characteristics of machining parameter (spindle speed, feed, and depth) to achieve good surface finish and high material removal rate (MRR). Results obtained by Taguchi method and signal-to-noise ratio match closely with (ANOVA) and the feed is most effective factor for MRR. And spindle speed is the most effective factor for surface roughness.

**Mandal et.al. [16]** Presented a study on modelling and optimization of machining nimonic C-263 super alloy using multi cut strategy in Wire Electrical Discharge Machining (WEDM). The mathematical modelling for cutting rate, surface roughness, spark gap and wire wear ration were developed by using regression analysis, which considered Pulse On Time ($T_{ON}$), Pulse Off Time ($T_{OFF}$), Servo Voltage (SV) And Dielectric Flow Rate (FR) as the machining parameters. It can be observed that all the mathematical models suggested are fairly fitted with the experimental result with a confidence level of 95%. Moreover, the minimum surface roughness value of 1.38 mm can be achieved by optimal setting of controlling parameters ($T_{ON}$: 0.95µs, $T_{OFF}$: 200µs, SV: 75V and FR: 8L/min). Thus, it can be concluded that the multi cut strategy improves the surface roughness of the work piece.

**Pradhan and Das [17]** have used an Elman network for producing a mapping between machining parameter such As Discharge Current, Pulse Duration, Duty Cycle and Voltage, and the response MRR in EDM process. Training and testing of ANN model were performed with extensive data sets from EDM experiments on AISI D2 tool steel from finishing, semi-finishing to roughening operations. The mean percentage error of the model was found to be 5.86 percent, which showed that the proposed model is in a satisfactory level to predict the MRR in EDM process.

**S. Tripathy and D.K. Tripathy [18]** employed Taguchi method combined with Technique Order Of Preference By Similarity to Ideal Solution (TOPSIS) and Grey Relational Analysis (GRA) have been adopted to evaluate the effectiveness of optimizing multiple performance characteristics for PMEDM of H-11 die steel using copper electrode. The effect of process variables such As Powder Concentration (CP), Peak Current (IP), Pulse On Time ($T_{on}$), Duty Cycle (DC) and Gap Voltage (GV) on response parameters such as Material Removal Rate (MRR), Tool Wear Rate (TWR), Electrode Wear Ratio (EWR) and Surface Roughness (SR) have been investigated using chromium powder mixed to the dielectric fluid. Analysis Of Variance (ANOVA) and F-test were performed to determine the significant parameters at a 95% confidence interval. Predicted results have been verified by confirmatory tests which show an improvement of 0.161689 and 0.2593 in the preference values using TOPSIS and GRA respectively. The recommended settings of process parameters is found to be CP = 6 g/l, IP =6Amp, $T_{on}$ = 100 µs, DC = 90% and GV = 50 V from TOPSIS and CP = 6 g/l, IP = 3Amp, $T_{on}$ = 150 µs, DC = 70% and VG = 30 V from GRA.

**Kosaraju et. al. [19]** investigate the effect of process parameters (Cutting Speed, Feed Rate and Depth Of Cut) on machinability performance characteristics and there by optimization of turning of Titanium Grade 5 based on Taguchi's L9 orthogonal array, Signal To Noise Ratios (S/N) And Analysis Of Variance (ANOVA). The cutting speed was identified as the most influential machining parameter on cutting force and temperature.

**Dewangan et.al. [20]** Investigated the influence of various EDM process parameters on various aspects of surface integrity like White Layer Thickness, Surface Crack Density and Surface Roughness. A response surface methodology-based design of experiment was considered for the purpose. The present study also recommends an optimal setting of EDM process parameters with an aim to improve surface integrity aspects after EDM of AISI P20 tool steel. This is achieved by simultaneous optimization of multiple attributes using Fuzzy-TOPSIS-based multi-criteria decision-making approach.

**Senthil et.al. [21]** Presented a study which focused on optimization of EDM process parameters of Al-CuTiB2 metal matrix composites. This composite was synthesized using in-situ casting and L18 orthogonal arrays were applied to optimize EDM process parameters. A multi-attribute decision making technique, namely TOPSIS was applied for solving multi-criteria optimization in the EDM process. The optimal EDM process parameters were found and the results obtained using TOPSIS were in agreement with the practitioners' parameters.

**Gadakh [22]** applied Techniques for Order Preference by Similarity to Ideal Solution (TOPSIS) method for solving multiple criteria optimization problem in WEDM process. A good amount of research has been done in this area for optimal process parameter selection and most of the works used experimental data for the optimization. In this paper, a new approach has been considered by representing the experimental results in terms of linguistic variables since experimental results involves some sort of uncertainties. Expressing the responses in linguistic terms enables the decision maker to account for uncertainty and fuzziness embedded in the experimental data.

**Nayak and Mahapatra [23]** used AHP and TOPSIS method for optimization of multi responses such as MRR, Surface Finish and Kerf concluded that the methodology is capable of optimizing any type of problem with any number of responses.

**Patel et.al. [24]** Applied AHP/TOPSIS technique for the selection of optimal process parameters in the WEDM process in which Pulse On Time, Pulse Off Time, Flushing Pressure, Wire Tension, Servo Voltage, Wire Feed are taken as input process parameters. Material Removal Rate, Kerf Width and Surface Roughness are considered as output responses.

S**harma et.al. [25]** Conducted experiments or multi quality characteristics of WEDM process parameters with RSM. They concluded that as pulse on time and peak current increases; MRR and SR also increases. The wire tension had insignificant effect on MRR and SR. Pulse off time, servo voltage, peak current and interaction of pulse off time and peak current, servo voltage and peak current, pulse on time and pulse off time, pulse on time and servo voltage were the significant factor for surface roughness.

**Shandilya et.al.[26]** presented the Response Surface Methodology (RSM) and ANN based mathematical modelling for average cutting speed of SiCp/6061 Al metal matrix composite (MMC) during WEDM. Experiments were performed with four machining parameters servo voltage, pulse on time, pulse off time and wire feed rate. They concluded that ANN model shows better accuracy than RSM model. The prediction accuracy of ANN model was about three times better than RSM. The maximum absolute percentage error in the ANN prediction of MRR was found to be around of 5.25%, while for the RSM model, it was 15.07%. On the basis of correlation coefficient, the prediction accuracy of ANN model is higher than RSM model. Servo voltage is more significant parameter on average cutting speed than pulse off time and wire feed rate for 10% SiCp/6061 Al MMC.

**Pragya Shandilya et.al. [27]** Optimized the process parameters during machining of SiCp/6061 Al by Wire Electrical Discharge Machining (WEDM) with the use Of Response Surface Methodology (RSM). Four input process parameters i.e. Servo Voltage (V), PulseOn Time ($T_{ON}$), Pulse-Off Time ($T_{OFF}$) And Wire Feed Rate (WF) were chosen as variables to study the process performance in terms of Cutting Width (kerf). In addition to this some mathematical models were also developed for response parameter. Properties of the machined surface were examined by using Scanning Electron Microscope (SEM).
Voltage was the most significant parameter on MRR and kerf whereas pulse-off time and wire feed rate were less significant. Input process parameters were found to play a significant role in the minimization of kerf. Pulse-on time had insignificant effect on MRR and kerf. Based on the optimization results, it was found that 71.01V voltage, 1.00 µs pulse-on time, 6.04 µs pulse off time and 5.17 m/min wire feed rate were optimum. Effect of input process parameters showed that maximum value of MRR and minimum value of kerf can be obtained at lower level of voltage, lower level of pulse-on time or the prevention of wire breakage.

**Kompan Chomsamutr et.al. [28**] Conducted of research is to compare the cutting parameters of turning operation the work pieces of medium carbon steel (AISI 1045) by finding the longest tool life by Taguchi methods and Response Surface Methodology (RSM). This research is to test the collecting data by Taguchi method. The analyses of the impact among the factors are the depth of cut, cutting speed and feed rate. This research found that the most suitable response value; and tool life methods give the same suitable values, i.e. feed rate at 0.10 mm/rev, cutting speed at 150 m/min, and depth of cut at 0.5 mm, which is the value of longest tool life at 670.170 min, while the average error is by RSM at the percentage of 0.07 as relative to the testing value.

**Gopalsamy B.M. et.al. [29]** Applied Taguchi method to find out the optimum machining parameters while hard machining of hard steel and uses L18 Orthogonal Array, S/N ratio and ANOVA to study the performance characteristics of machining parameters which are cutting speed, feed, depth of cut and width of cut while considering surface finish and tool life as response. Results of the study obtained by Taguchi method match closely with ANOVA and cutting speed is the most influencing parameter.

**V.M. Kumar et. al. [30]** demonstrated optimization of parameters of WEDM process with Incoloy800 super alloy regarding multiple performance characteristics such as Material Removal Rate (MRR), Surface Roughness and Kerf Width with reference to Grey– Taguchi Method based analysis. Gap Voltage, Pulse On time, Pulse Off-time and Wire Feed were considered as process parameters. Taguchi’s L9 Orthogonal Array is used for conducting experiments. Optimized values of process parameters were determined using Grey Relational Analysis and the other prominent parameters were determined by Analysis of Variance ANOVA. Mathematical model was constructed by using non-linear regression analysis with variation of output responses with process parameters method and thus checked for significance. It was concluded that mathematical models can predict the output responses with substantial accuracy.

**Ristanoski et.al. [31]** Have investigated the use of a grouping based quadratic mean loss function for improving the performance of linear regression. In particular, segmenting the input time series into groups has been proposed and simultaneously optimizing both the average loss of each group and the variance of the loss between groups, over the entire series. The aim is to produce a linear model that has low overall error and is less sensitive to distribution changes in the time series and is more robust to outliers. The performance of the proposed method has experimentally been investigated and found that it can build models which are different from those produced by standard linear regression, whilst achieving significant reductions in prediction errors.

**Devarasiddappa et.al. [32]** Studied the application of artificial intelligence approach in modelling surface quality of aerospace alloys in WEDM process. In this work, they developed Artificial Neural Network (ANN) model for prediction of SR in WEDM of

Inconel 825 aerospace alloy. By using Box Behnken experimental design four process parameters pulse on time, pulse off time, peak current and servo voltage were investigated. As pulse on time and servo voltage decrease, SR is improved. In this experiment Analysis of Variance (ANOVA) shows that pulse on time is the most significant factor affecting SR with 76.12% contribution; followed by SV and pulse off time respectively with 7.18% and 5.3% contributions.

**Ugrasen et.al. [33]** Presented process optimization and estimation of machining performances using ANN in WEDM. Four input process parameters of WEDM like servo voltage, pulse on time, pulse off time and wire feed rate were selected as variables to study the process performance in terms of kerf width. ANOVA was carried out to study the effect of process parameters on process performance. ANOVA results show that voltage and wire feed rate are highly significant parameters and pulse off time is less significant. Pulse on time has insignificant effect on kerf width.

**G. Ugrasen et.al. [34]** Estimation of machining performances using MRA, GMDH and artificial neural network in Wire EDM of EN-31. This study on the development of model and its application to estimation of machining performances using Multiple Regression Analysis (MRA), Group Method Data Handling Technique (GMDH) and Artificial Neural Network (ANN). Experimentation was performed as per Taguchi's L'16 orthogonal array. Each experiment has been performed under different cutting conditions of pulse-on, pulse-off, current and bed speed. Among different process parameters voltage and flush rate were kept constant. Molybdenum wire having diameter of 0.18 mm was used as an electrode. Three responses namely accuracy, surface roughness, volumetric material removal rate have been considered for each experiment.

**G. Ugrasen et.al. [35]** Wire Electrical Discharge Machining (WEDM) is a specialized thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the main stream machining processes. This study outlines the development of model and its application to estimation of machining performances using Multiple Regression Analysis (MRA), Group Method Data Handling Technique (GMDH) and Artificial Neural Network (ANN). Experimentation was performed as per Taguchi's L'16orthogonal array. Each experiment has been performed under different cutting conditions of pulse-on, pulse-off, current and bed speed. Among different process parameters voltage and flush rate were kept constant.

**Panda and Bhai [36]** has developed an ANN model (using feed forward neural architecture) using Levenberg-Marquardt learning algorithm and logistic sigmoid transfer function to predict the material removal rate. Here they have considered the process parameters gap voltage, pulse duration and pulse interval. To evaluate the performance of ANN model, sum square error and R square coefficients were used and the validity of the neural network model was checked with the experimental data. In conclusion they concluded that a 3-7-1 feed forward neural model for EDM provides faster and more accurate results.

**A. Thaliana et.al.[37]** have explored a practical method of optimizing machining parameters for EDM process under the minimum total machining time based on Taguchi method and Artificial neural network. Feed-forward back-propagation neural networks with two backpropagation training algorithms: gradient descent, and gradient descent with momentum were developed for establishing a relation between the target parameters current and feed with the process parameters required total machining time, oversize and taper of a hole.

**Md.AshikurRahmanKhanet.al. [38]** Proposed an ANN model with multi-layer perception neural architecture for the prediction of SR on first commenced Ti-15-3 alloy in electrical discharge machining (EDM) process. The proposed models used process parameters such as peak current, pulse on time, pulse off time and servo voltage to develop a mapping with the target SR. Training of the ANN models was performed with LM learning algorithm using extensive data sets from experiments utilizing copper electrode as positive polarity. An average of 6.15% error was found between desired and ANN predicted SR which found to be in good agreement with the experimental results.

**Angelos Markopoulos et.al. [39**] Implemented an ANN model for the prediction of SR in EDM. For this purpose, they used Mat lab as well as Net lab. The process parameter to the ANN model were work piece material, pulse current and pulse duration at 3, 4 and 4 levels respectively. They used back propagation algorithm for training with model assessment criteria as MSE and R. Finally, they conclude that both Mat lab as well as Net lab was found efficient for prediction of SR of EDM process.

**Assarzadeh and Ghoreishi[40]** presented a research work on Neural Network Modelling and Multi-Objective Optimization of responses MRR and SR of EDM process with Augmented Lagrange Multiplier (ALM) algorithm. A 3–6–4–2-size Back-Propagation Neural Network was developed to predict these two responses efficiently. The Current (I), Period Of Pulses (T), And Source Voltage (V) were selected at 6, 4 and 4 levels respectively as network process parameters. Out of 96 experimental data sets 82 data sets were used for training and remaining 14 data sets were used for testing the network. The training model was trained with back propagation training algorithm with momentum term. Relative percentage error and total average percentage error were used to evaluate the models. From the results in terms of mean errors of 5.31% and 4.89% in predicting the MRR and Ra they conclude that the neural model can predict process performance with reasonable accuracy. Having established the process model, the Augmented Lagrange Multiplier (ALM) algorithm was implemented to optimize MRR subjected to three machining regimes of prescribed Ra constraints (i.e., finishing, semi-finishing and roughing) at appropriate operating conditions.

**H. Juhr et.al. [41]** Have made a comparison between NRF (Nonlinear Regression Function) and ANN for the generation of continuous parameter technology, which is a continuous mapping or regression. They found ANN's to much easier than NRF's. For modelling with ANN's, feedforward networks with three to five layers were used, which were trained with back-propagation with momentum term. For developing the continuous parameter generation technology, they considered the input parameters as Pulse Current, Discharge Duration and Duty Cycle and response parameters as Removal Rate, Wear Ratio and Arithmetic Mean Roughness. They used two major performance evaluation criteria sum of squared deviation and sum of relative deviation to evaluate the performance of the two mapping functions. Finally, they conclude that ANN shows better prediction accuracy than Nonlinear Regression Functions.

**Pushpendra S. Bharti et.al. [42]** Made an attempt to select the best back propagation (BP) algorithm from the list of training algorithms that are present in the Mat lab Neural Network Toolbox, for the training of ANN model of EDM process. In this work, thirteen BP algorithms, which are available in MATLAB 7.1, Neural Network Toolbox, are compared on the basis of mean absolute percentage error and correlation coefficient. Some important specifications that have been used for implementing the ANN modelling were data normalization which was performed in the range between 0.1 and 0.9, weight initialization which was done by Nguyen Windrow weight initialization technique, transfer functions used at hidden layers and output layer were hyperbolic tangent function (tansig) and logistic function (logsig) respectively. Out of thirteen BP algorithms investigated, Bayesian

Regularization Algorithm found to facilitate the best results for efficient training of ANN model.

**Joshi and Pande[43]** developed two models for the Electric Discharge Machining (EDM) Process using The Finite - Element Method (FEM) and Artificial Neural Network (ANN). A Two-Dimensional Axisymmetric Thermal (FEM) model of single-spark EDM process was developed with the consideration of many thermo-physical characteristics to predict the shape of crater cavity, MRR, and TWR. A multi-layered feed-forward neural network with leaning algorithms such as Gradient Descent (GD), GD with momentum (GDA), Levenberg – Marquardt (LM), Conjugate Gradient (CG), Scaled Conjugate Gradient (SCG) were employed to establish relation between input process conditions (discharge power, spark on time, and duty factor) and the process responses (crater geometry, material removal rate, and tool wear rate) for various work—tool work materials. The input parameters and targets of the ANN model was generated from the numerical (FEM) simulations. To evaluate the model, they used prediction error(%) and mean error (ME) and to improve the efficiency of model two BPNN architectures were tried out, viz. singlelayered (4 –N – 4) and two-layered (4 – N1 – N2 – 4). They found optimal ANN model with network architecture 4 – 8 – 12 – 4 and SCG training algorithm to give very good prediction accuracies for MRR (1.53%), crater depth (1.78%), and crater radius (1.16%) and a reasonable one for TWR (17.34%).

**Pramod Kumar Patowari et.al. [44]** Have applied ANN to model Material Transfer Rate (MTR) And Layer Thickness (LT) by EDM with Tungsten–Copper (W–Cu) P/M sintered electrodes. They have used input parameters to the ANN model such as Compaction Pressure (CP), Sintering Temperature (ST), Peak Current (IP), Pulse On Time ($T_{on}$), Pulse Off Time ($T_{off}$) with target measures like MTR and LT. A multilayer feed-forward neural network with gradient-descent learning algorithm with 5nos. of neuron in hidden layer has been used train the ANN model. Two activation functions tansig and purlin has been used in hidden and output layers, respectively. Two evaluate the ANN model two performance measures average error percentage and MSE have implemented. The performance measure MSE during training and testing of MRR were found to be 0.0014 and 0.0038, respectively. Another performance measure average error percentage during training and testing of MRR were found to be 3.3321 and 8.4365, respectively. While modelling LT, MSE during training and testing were found to be 0.0016 and 0.0020 respectively and average error percentage during training and testing were calculated to be 6.5732 and 3.1824 respectively.

**M K Pradhan et.al. [45]** Compared the performance and efficiency of Back Propagation Neural Network (BPN) and Radial Basis Function Neural Network (RBFN) for the prediction of SR in EDM. Three process parameters i.e. Pulses Current (IP), The Pulse Duration ($T_{on}$) And Duty Cycle IJ) were supplied to these two networks and corresponding experimental SR values were considered as target. Out of the 44 experimental data sets, 35 nos. were considered for training and remaining 9 data sets were considered for testing. They compared the performance of two networks in terms of Mean Absolute Error (MAE). MAE for test data of BPN and RBFN were found to be 0.297188 and 0.574888 respectively, which indicates BPN to be more accurate. They conclude that BPN is reasonably more accurate but RBFN is faster than the BPNs.

From the above literature gaps are found in WEDM machining of AISI1040 steel. In the present work, an attempt has been made to optimize the performance characteristics of Material Removal Rate (MRR) and Surface Roughness Characteristics ($R_a$ and $R_z$) using a composite method of Entropy combined with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Experiments were conducted using Taguchi’s standard L18 Orthogonal array with the process parameters of Flushing Pressure (FP), Pulse-On-Time ($T_{on}$), Pulse-Off-Time ($T_{off}$), Wire Feed (WF), Wire Tension (WT) and Servo Voltage (SV) and each at three different levels.

# CHAPTER-3 METHODOLOGY

## Proposed methodology:

TOPSIS decision making method is a technique introduced by Yoon and Hwang. It is a worldwide accepted approach to finding the best alternative that is closest to the ideal solution. The basic principle in this method is that chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS). The procedural steps involved are as follows.

## Step-1: Construct a standard decision matrix (A)

In a decision matrix, the rows are assigned to available alternatives and the columns are assigned to characteristics. The general decision matrix can be shown as

$$A = \begin{array}{c} \\ x_1 \\ x_2 \\ \cdots \\ x_n \end{array} \begin{array}{c} \begin{array}{cccc} f_1 & f_2 & \cdots & f_m \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} \end{array}$$

## Step-2: Construct a Normalized decision-making matrix (R)

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}$$

Normalize the decision matrix of $r_{ij}$ can be determined by using.

$$rij = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^{2}}}; \; i= 1,2,\ldots,m.$$

## Step-3: Construct weighted normalized decision matrix (V)

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1m} \\ v_{21} & v_{22} & \cdots & v_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ v_{n1} & v_{n2} & \cdots & v_{nm} \end{bmatrix}$$

$V_{ij} = W_{ij}\ r_{ij}$; i=1, 2...n, j=1, 2…m.

Where, $W_j$ represents the relative weight of the Jth criteria. In the present work the weights are calculated by entropy method.

## Step-4: Determine the Positive ideal solution (PIS) and Negative ideal solutions (NIS)

$$\begin{aligned} x^+ &= \left\{\{max_i v_{ij} | j \in J), (min_i v_{ij} | j \in J') | i = 1,2,\dots,n\right\} \\ &= \{x_1^+, x_2^+, \dots \dots x_m^+\} \\ x^- &= \left\{\{min_i v_{ij} | j \in J), (max_i v_{ij} | j \in J') | i = 1,2,\dots,n\right\} \\ &= \{x_1^-, x_2^-, \dots \dots x_m^-\} \end{aligned}$$

## Step-5: Determine the separation values from the PIS and NIS

The separation of each alternative from PIS is given by

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - x_j^+\right)^2}$$

The separation of each alternative from NIS is given by

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - x_j^-\right)^2}$$

### Step-6: Determine the relative closeness to the ideal solutions and corresponding Signal to noise (S/N) ratios.

Relative closeness coefficient,

$$C_i^{+} = \frac{S_i^{-}}{S_i^{+} + S_i^{-}}$$

The larger the Ci $^{+}$ value, the better the performance of the alternatives. The corresponding S/N ratios of Ci $^{+}$ were calculated from Taguchi's Larger-the-better characteristic.

# CHAPTER-4 EXPERIMANTATION DETAILS

In the current experiment, a brass electrode of 0.25 mm was used to machine HASTELLOY, utilizing Wire EDM, as illustrated in Fig. 4.1. Work material can be used to make gears, axles, bolts, spindles, shafts, studs, and other automotive parts. It is also utilized in technical applications where higher tensile strength is needed. Table 4.1 shows the levels of the selected process parameters. Table 4.2 contains information of the L16 orthogonal array used for the experiments. Fig. 4.3 shows machined work pieces. SJ 301 tester as shown in Fig.4.3. is used to measure the roughness of the cutting faces at three distinct positions, with the mean value being used as the final result.

**Fig 4.1: WEDM Experimental Setup**

**Fig 4.2 Machined Work Piece**

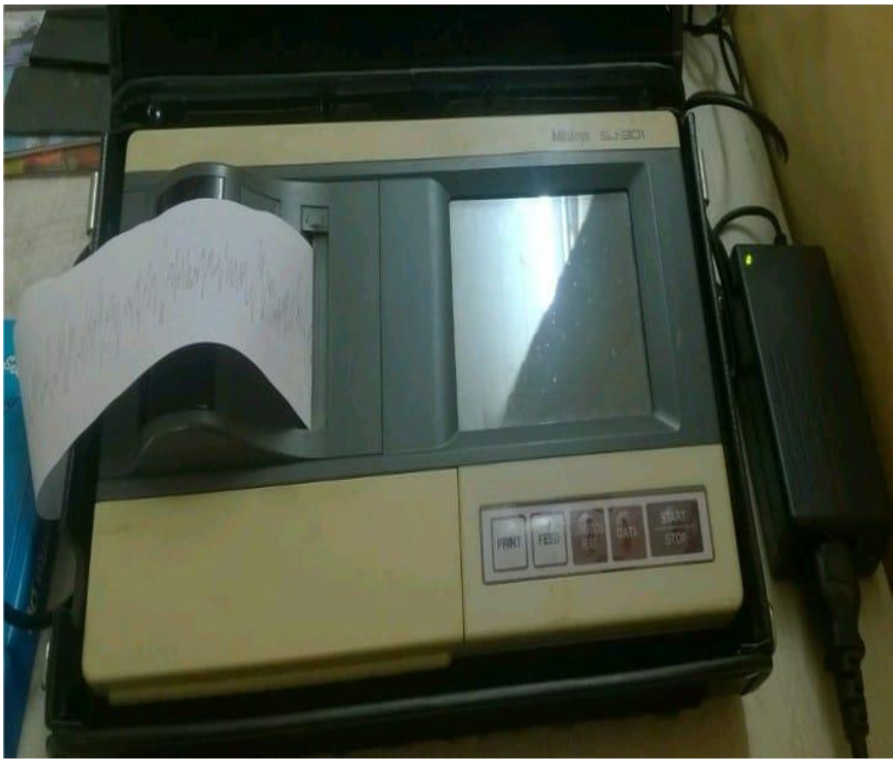

**Fig 4. 3: SJ301 Surface Roughness Tester**

The L16 orthogonal array design is a type of experimental design used in statistical analysis. It is a specific type of Taguchi design that consists of 16 runs or experiments with different combinations of factors. The $L_{16}$ design is an efficient way to study the effects of a relatively small number of factors on a particular response. It is named after the fact that it is based on an orthogonal array with 16 rows. An orthogonal array is a mathematical construct that ensures that each combination of factors appears the same number of times in the design, which helps to reduce the effects of confounding variables and improve the efficiency of the analysis. To use the $L_{16}$ orthogonal array design, the experimenter selects the factors that are believed to influence the response and assigns each factor to a specific level. The design is then used to run 16 experiments, each with a different combination of factor levels. The results of these experiments are analysed using statistical methods to determine the effects of each factor on the response. The $L_{16}$ orthogonal array design is particularly useful in industries such as manufacturing, where it can be used to optimize production processes and reduce the variability of output. It is also commonly used in quality control, product design, and other fields where statistical analysis is important for understanding and improving complex systems.

### Table 4.1: Fixed Parameters and Corresponding Levels

| S.NO | PROCESS PARAMETERS | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| **1** | **PULSE-ON-TIME** | 112 | 114 | 116 | 118 |
| **2** | **PULSE-OFF-TIME** | 51 | 53 | 55 | 57 |
| **3** | **FLUSHING PRESSURE** | 7 | 8 | 9 | 10 |
| **4** | **WIRE FEED** | 5 | 6 | 7 | 8 |

### Table 4.2: L16 ORTHOGONAL ARRAY

| S.NO | TON | TOFF | FP | WF |
|---|---|---|---|---|
| 1 | 112 | 51 | 7 | 5 |
| 2 | 112 | 53 | 8 | 6 |

| | | | | |
|---|---|---|---|---|
| 3 | 112 | 55 | 9 | 7 |
| 4 | 112 | 57 | 10 | 8 |
| 5 | 114 | 51 | 8 | 7 |
| 6 | 114 | 53 | 7 | 8 |
| 7 | 114 | 55 | 10 | 5 |
| 8 | 114 | 57 | 9 | 6 |
| 9 | 116 | 51 | 9 | 8 |
| 10 | 116 | 53 | 10 | 7 |
| 11 | 116 | 55 | 7 | 6 |
| 12 | 116 | 57 | 8 | 5 |
| 13 | 118 | 51 | 10 | 6 |
| 14 | 118 | 53 | 9 | 5 |
| 15 | 118 | 55 | 8 | 8 |
| 16 | 118 | 57 | 7 | 7 |

# CHAPTER-5

# RESULTS AND DISCUSSIONS

The measured experimental results of Material Removal Rate (MRR) and Surface Roughness characteristics ($R_a$, $R_q$, $R_y$, $R_z$,) are optimized using Entropy-TOPSIS approach. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a popular MCDM/MADM method involving simple mathematical model calculations.

## Table 5.1 OUTPUT RESPONSES

| S.NO | $T_{ON}$ (μs) | $T_{OFF}$ (μs) | $F_P$ (Kg/cm$^3$) | $W_F$ (mm/min) |
|---|---|---|---|---|
| 1 | 112 | 51 | 7 | 5 |

| | | | | |
|---|---|---|---|---|
| 2 | 112 | 53 | 8 | 6 |
| 3 | 112 | 55 | 9 | 7 |
| 4 | 112 | 57 | 10 | 8 |
| 5 | 114 | 51 | 8 | 7 |
| 6 | 114 | 53 | 7 | 8 |
| 7 | 114 | 55 | 10 | 5 |
| 8 | 114 | 57 | 9 | 6 |
| 9 | 116 | 51 | 9 | 8 |
| 10 | 116 | 53 | 10 | 7 |
| 11 | 116 | 55 | 7 | 6 |
| 12 | 116 | 57 | 8 | 5 |
| 13 | 118 | 51 | 10 | 6 |
| 14 | 118 | 53 | 9 | 5 |
| 15 | 118 | 55 | 8 | 8 |
| 16 | 118 | 57 | 7 | 7 |

**Table 5.2 EXPERIMENTAL RESPONSES($Y_{ij}$)**

| **S.NO** | **MRR ($mm^3/mm$)** | **$R_a$ (μm)** | **$R_q$ (μm)** | **$R_y$ (μm)** | **$R_z$ (μm)** |
|---|---|---|---|---|---|
| 1 | 3.725 | 2.76 | 3.4 | 16.28 | 13.12 |
| 2 | 4.175 | 2.84 | 3.61 | 19.21 | 13.34 |
| 3 | 5.1 | 3.01 | 3.72 | 18.34 | 13.82 |
| 4 | 5.3 | 2.9 | 3.61 | 17.94 | 13.12 |
| 5 | 4.725 | 3.13 | 3.92 | 19.47 | 14.15 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 6 | 5 | 3.26 | 4.08 | 18.87 | 15.12 |
| 7 | 4.95 | 3.18 | 3.96 | 21.29 | 14.67 |
| 8 | 2.9375 | 2.98 | 3.74 | 18.38 | 12.98 |
| 9 | 3.5 | 3.19 | 3.89 | 17.13 | 13.53 |
| 10 | 4.025 | 2.85 | 3.58 | 18.8 | 13.84 |
| 11 | 4.6875 | 3.14 | 3.81 | 17.54 | 13.62 |
| 12 | 3.3575 | 3.3 | 4.06 | 18.76 | 14.34 |
| 13 | 4.1425 | 2.84 | 3.57 | 17.75 | 13.56 |
| 14 | 4.85 | 3.21 | 4.03 | 20.21 | 13.88 |
| 15 | 5.4675 | 3.13 | 3.87 | 19.52 | 14.17 |
| 16 | 6.6125 | 3.21 | 4.01 | 19.73 | 14.26 |

**Table 5.3 NORMALIZED VALUES ($r_{ij}$)**

| **S.NO** | **MRR ($mm^3/mm$)** | **$R_a$ (μm)** | **$R_q$ (μm)** | **$R_y$ (μm)** | **$R_q$ (μm)** |
|---|---|---|---|---|---|
| 1 | 0.2015 | 0.2253 | 0.2232 | 0.2181 | 0.2367 |
| 2 | 0.2258 | 0.2318 | 0.2369 | 0.2574 | 0.2407 |
| 3 | 0.2758 | 0.2457 | 0.2442 | 0.2457 | 0.2493 |
| 4 | 0.2866 | 0.2367 | 0.2369 | 0.2404 | 0.2367 |
| 5 | 0.2556 | 0.2555 | 0.2573 | 0.2609 | 0.2553 |
| 6 | 0.2704 | 0.2661 | 0.2678 | 0.2528 | 0.2728 |
| 7 | 0.2677 | 0.2596 | 0.2599 | 0.2719 | 0.2647 |
| 8 | 0.1589 | 0.2432 | 0.2455 | 0.2463 | 0.2342 |
| 9 | 0.1893 | 0.2604 | 0.2553 | 0.2295 | 0.2441 |
| 10 | 0.2177 | 0.2326 | 0.235 | 0.2519 | 0.2497 |
| 11 | 0.2535 | 0.2563 | 0.2501 | 0.235 | 0.2457 |
| 12 | 0.1816 | 0.2694 | 0.2665 | 0.2514 | 0.2587 |
| 13 | 0.224 | 0.2318 | 0.2343 | 0.2351 | 0.2446 |
| 14 | 0.2623 | 0.262 | 0.2645 | 0.2708 | 0.2504 |

| | | | | | |
|---|---|---|---|---|---|
| 15 | 0.2957 | 0.2555 | 0.255 | 0.2615 | 0.2557 |
| 16 | 0.3576 | 0.262 | 0.2632 | 0.2644 | 0.2573 |

### Table 5.4 ENTROPY VALUES

| | | | | | | |
|---|---|---|---|---|---|---|
| **$\xi j$ =** | 0.993 | 0.993 | 0.9994 | 0.9995 | 0.9994 | 0.9997 |
| | X | | | | | |
| **1-$\xi j$ =** | | 0.007 | 0.0006 | 0.0005 | 0.0006 | 0.0003 |
| **∑1-$\xi j$ =** | | 0.009 | | | | |
| **Wj** | | 0.7801 | 0.0612 | 0.0555 | 0.0695 | 0.0337 |

### Table 5.4 WEIGHT NORMILIZED VALUES

| **S.NO** | **MRR (mm$^3$/mm)** | **$R_a$ (mm)** | **$R_q$ (mm)** | **$R_y$ (mm)** | **$R_q$ (mm)** |
|---|---|---|---|---|---|
| 1 | 0.1572 | 0.0138 | 0.0124 | 0.0152 | 0.008 |
| 2 | 0.1761 | 0.0142 | 0.0132 | 0.0179 | 0.0081 |
| 3 | 0.2152 | 0.015 | 0.0136 | 0.0171 | 0.0084 |
| 4 | 0.2236 | 0.0145 | 0.0132 | 0.0167 | 0.008 |
| 5 | 0.1994 | 0.0156 | 0.0143 | 0.0181 | 0.0086 |
| 6 | 0.211 | 0.0163 | 0.0149 | 0.0176 | 0.0092 |
| 7 | 0.2088 | 0.0159 | 0.0144 | 0.0189 | 0.0089 |
| 8 | 0.1239 | 0.0149 | 0.0136 | 0.0176 | 0.0079 |
| 9 | 0.1477 | 0.0159 | 0.0142 | 0.016 | 0.0082 |
| 10 | 0.1698 | 0.0142 | 0.013 | 0.0175 | 0.0084 |
| 11 | 0.1978 | 0.0157 | 0.0139 | 0.0163 | 0.0083 |
| 12 | 0.1417 | 0.0165 | 0.0148 | 0.0175 | 0.0087 |
| 13 | 0.1748 | 0.0142 | 0.013 | 0.0163 | 0.0082 |
| 14 | 0.2046 | 0.016 | 0.0147 | 0.0188 | 0.0084 |
| 15 | 0.2307 | 0.0156 | 0.0141 | 0.0182 | 0.0086 |
| 16 | 0.279 | 0.016 | 0.0146 | 0.0184 | 0.0087 |

## Table 5.5 PIS and NIS VALUES

| | MRR(mm*3/min) | $R_a$ | $R_q$ | $R_y$ | $R_z$ |
|---|---|---|---|---|---|
| **PIS** | 0.279 | 0.0138 | 0.0124 | 0.0152 | 0.0079 |
| **NIS** | 0.1239 | 0.0165 | 0.0149 | 0.0189 | 0.0092 |

## Table 5.6 $Si^+$ AND $Si^-$, $Ci^+$ VALUES

| S.NO | $Si^+$ | $SI^-$ | $Ci^+$ | SNRA1 |
|---|---|---|---|---|
| 1 | 0.1218 | 0.0337 | 0.2167 | -13.2843 |
| 2 | 0.1029 | 0.0524 | 0.3372 | -9.4416 |
| 3 | 0.0639 | 0.0913 | 0.5884 | -4.6062 |
| 4 | 0.0554 | 0.0998 | 0.6429 | -3.8366 |
| 5 | 0.0797 | 0.0755 | 0.4862 | -6.2633 |
| 6 | 0.0682 | 0.0871 | 0.5608 | -5.0237 |
| 7 | 0.0703 | 0.085 | 0.5471 | -5.2382 |
| 8 | 0.1551 | 0.003 | 0.0191 | -34.375 |
| 9 | 0.1314 | 0.024 | 0.1544 | -16.2257 |
| 10 | 0.1092 | 0.046 | 0.2966 | -10.5575 |
| 11 | 0.0813 | 0.0739 | 0.4764 | -6.4412 |
| 12 | 0.1374 | 0.0178 | 0.1148 | -18.8003 |
| 13 | 0.1042 | 0.051 | 0.3287 | -9.6637 |
| 14 | 0.0745 | 0.0807 | 0.52 | -5.6803 |
| 15 | 0.0485 | 0.1068 | 0.6878 | -3.251 |
| 16 | 0.0045 | 0.1551 | 0.9716 | -0.2501 |

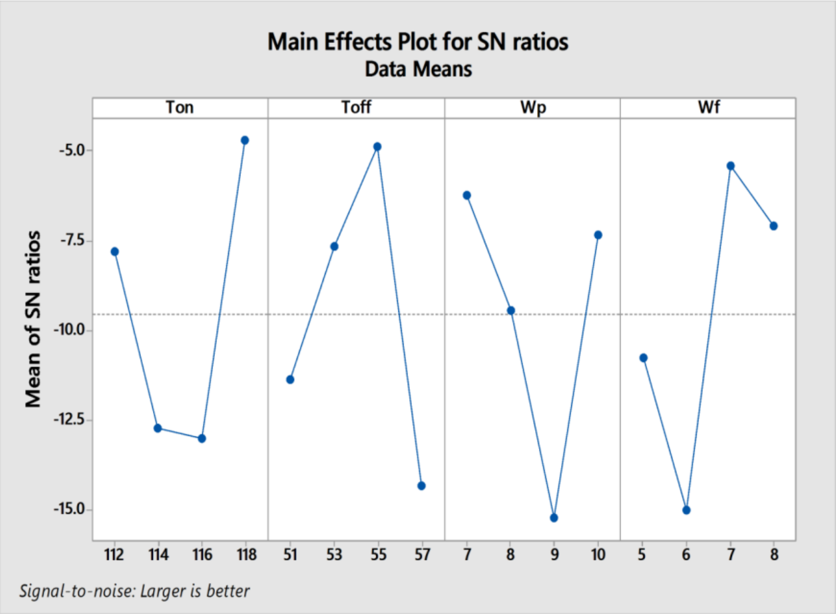

Fig 5.1 Main Effect Plot for SN ratio

## Table 5.7 ANALYSIS OF VARIANCE

| **Source** | **DF** | **Adjss** | **AdjMS** | **F-Value** | **P-Value** |
|---|---|---|---|---|---|
| **Model** | 13 | 0.883403 | 0.067954 | 7.96 | 0.117 |
| **Linear** | 4 | 0.204401 | 0.0511 | 5.99 | 0.148 |
| **Ton** | 1 | 0.090797 | 0.90797 | 10.63 | 0.083 |
| **Toff** | 1 | 0.051709 | 0.51709 | 6.06 | 0.133 |
| **Fp** | 1 | 0.000216 | 0.000216 | 0.03 | 0.88 |
| **Wf** | 1 | 0.006576 | 0.006576 | 0.77 | 0.473 |
| **Square** | 4 | 0.187414 | 0.046853 | 5.49 | 0.16 |
| **Ton*Ton** | 1 | 0.099274 | 0.99274 | 11.63 | 0.076 |
| **Toff*Toff** | 1 | 0.07287 | 0.07287 | 8.54 | 0.1 |
| **Fp*Fp** | 1 | 0.106282 | 0.106282 | 12.45 | 0.072 |
| **Wf*Wf** | 1 | 0.076509 | 0.076509 | 8.96 | 0.096 |
| **2-way Interaction** | 5 | 0.313048 | 0.6261 | 7.33 | 0.124 |
| **Ton*Toff** | 1 | 0.20801 | 0.020801 | 2.44 | 0.259 |
| **Ton*W** | 1 | 0.134343 | 0.134343 | 15.74 | 0.058 |

| | | | | | |
|---|---|---|---|---|---|
| **$T_{on}$*W** | 1 | 0.028966 | 0.028966 | 3.39 | 0.207 |
| **$T_{off}$*W** | 1 | 0.078319 | 0.078319 | 9.17 | 0.094 |
| **$T_{off}$*W** | 1 | 0.075582 | 0.075582 | 8.85 | 0.097 |
| **Error** | 2 | 0.017075 | 0.008538 | | |
| **Total** | 15 | 0.900479 | | | |

## Table 5.9 Model Summary

| **S** | **$R_2$** | **$R^2$(adj)** | **$R^2$(pred)** |
|---|---|---|---|
| 0.0923994 | 98.10% | 85.78% | 0.00% |

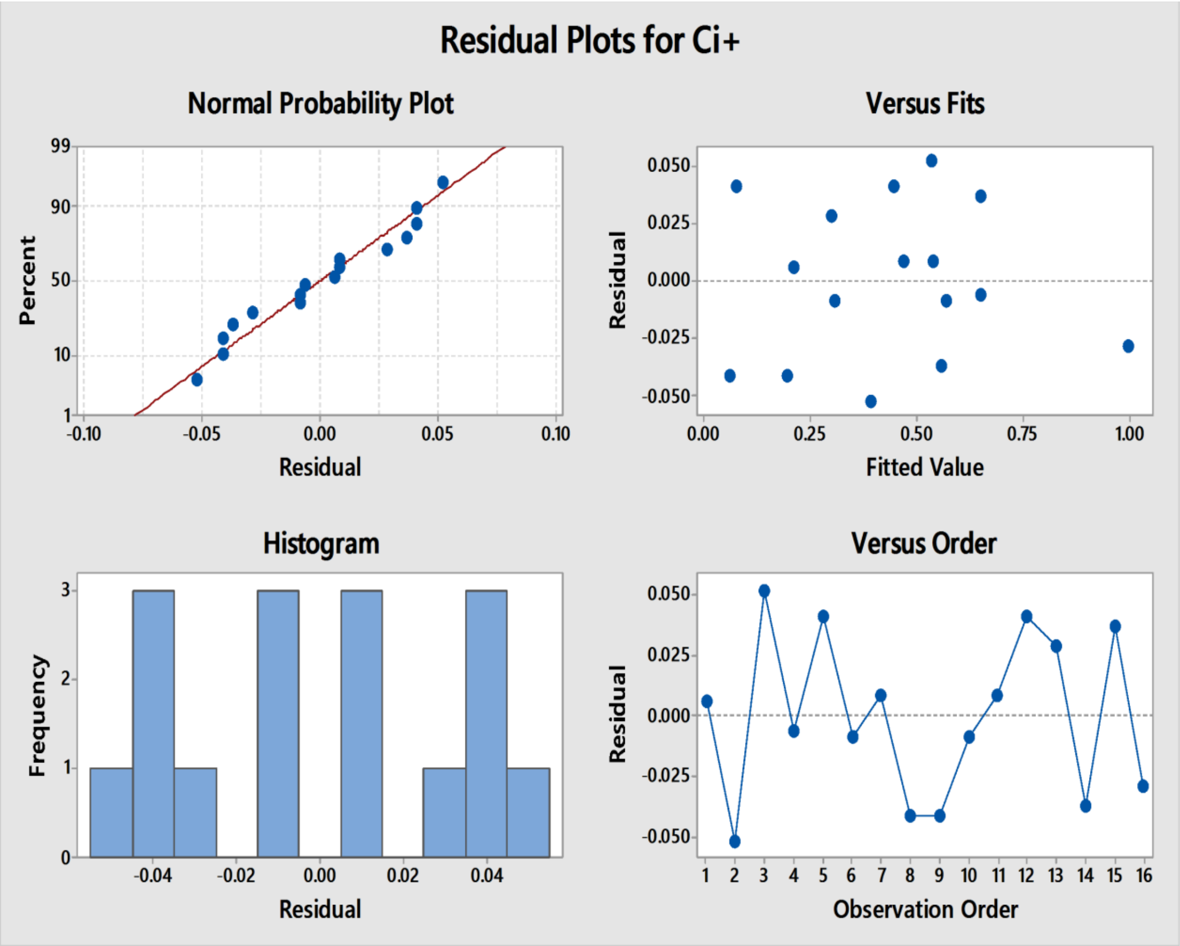

**Fig 5.2 Residual plots for $Ci^+$**

# CHAPTER-6

## CONCLUSIONS AND SCOPE OF FUTURE WORK

- From the Utility analysis, the optimal combination of WEDM process parameters is obtained at 115 µs of pulse-on-time (T), 57 us of pulse-off-time (To), 20 volts of spark gap voltage (SV), 2m/min of wire feed (WF) and 5Kg-f of wire tension (WT) respectively.
- ANOVA results showed that the Pulse-on-time(T) is the most influencing factor for the multiple response and followed by Pulse-off-time (Top), Spark Gap(SV),Wire Feed (WF) and Wire Tension (WT) respectively.
- The errors are distributed normally and they are not following any regular patterns in the residual plots hence the model prepared for the overall utility is best fit and it can be accurately used for the prediction of multiple responses.

## SCOPE OF FUTURE WORK

- For further extension of the work, we can conduct the experiments by changing the electrode wire type (copper, silver, molybdenum and tungsten), shape (rectangular, spherical) and coatings (Zinc, cadmium, tin, lead, antimony, bismuth or alloys) and etc.
- We can extend further by considering the parameters were fixed in this work like dielectric type, flushing pressure, Peak current (I), work piece material, duty cycle, frequency, work piece thickness, electrode wire diameter and etc.
- We can also determine the effect of WEDM process parameters machining.

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