EVALUATION OF SUITABLE WIRE EDM PROCESS PARAMETERS USING AHP & TQLFA

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

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IN

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Submitted by

NAMALA SAI	:	**319126520031**
THOTA CHAITHANYA	:	**319126520054**
MUGADA RAJESH	:	**319126520029**
KOVVURU SRIHARSHA	:	**319126520022**
YAMALA SURENDRA KUMAR	:	**319126520060**

Under the Esteemed guidance of

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

PRAGNANAM BRAHMA
ANITS

DEPARTMENT OF MECHANICAL ENGINEERING

ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY & SCIENCES (A)
(Permanently Affiliated to Andhra University, Approved by AICTE, Accredited by NBA Tier-I, NAAC)
Sangivalasa, Visakhapatnam (District) Andhra Pradesh -India– 531162.

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DEPARTMENT OF MECHANICAL ENGINEERING
ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY & SCIENCES
(UGC Autonomous & Permanently Affiliated to Andhra University)

PRAGNANAM BRAHMA
ANITS

CERTIFICATE

This is to certify that the Project Report entitled **"Evaluation of Suitable Wire EDM Process Parameters Using AHP & TQLFA"** being submitted by **NAMALA SAI (319126520031), THOTA CHAITHANYA (319126520054), MUGADA RAJESH (319126520029), KOVVURU SRIHARSHA (319126520022), YAMALA SURENDRA KUMAR (319126520060)** 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
Assistant Professor
Dept. of Mechanical Engg.
ANITS, Visakhapatnam.

Head of the Department

17.4.23

DR . B. NAGARAJU
Professor
Dept. of Mechanical Engg.
ANITS, Visakhapatnam.

THIS PROJECT WORK IS APPROVED BY THE FOLLOWING

BOARD OF EXAMINERS

INTERNAL EXAMINER 17/4/23

EXTERNAL EXAMINER 17/4/2023

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N. SAI (319126520031)

T. CHAITHANYA (319126520054)

M. RAJESH (319126520029)

K. SRIHARSHA (319126520022)

Y. SURENDRA KUMAR (319126520060)

ABSTRACT

The aim of the current work is to create an acceptable set of Wire EDM process parameters for cutting AISI1040 steel. The work material offers good 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 tension (WT), wire feed (WF), and servo voltage (SV). The responses obtained from Material Removal Rate (MRR) and Surface Roughness Characteristics (R_a & R_z) were optimized using Analytical Hierarchy Process (AHP) combined with Taguchi's Quality Loss Function Analysis (TQLFA) methods. L18 OA (2^1*3^5) was used. Here, the criterion weights are determined using AHP, and the results are produced as consistency ratio (CR) = $0.04<0.1$, λ_{max} = 3.039, W_{MRR} = 0.637, W_{Ra} = 0.258, and W_{Rz} = 0.105 respectively. Pulse-Off-Time (T_{OFF}) is discovered to be the highest influencing factor and Wire Feed (WF) to be the lowest influencing factor for providing the best values of the quality loss function from the Analysis of Means (ANOM) and Signal-to-Noise (S/N) ratio analysis. The ideal process parameter setting was achieved at the following values: Flushing Pressure: 8 kg/cm^2 (level 2), Pulse-On-Time: 125 µs (level 3), Pulse-Off-Time: 55 µs (level 1), Wire Tension: 6 kg-f (level 3), Wire Feed: 4 mm/min (level 3) and Servo Voltage: 20 volts (level 1), respectively.

Key Words: Analytical Hierarchy Process (AHP), Taguchi's Quality Loss Function Analysis (TQLFA), Material Removal Rate (MRR), Surface Roughness Characteristics (R_a & R_z), Analysis of Means (ANOM), Signal-to-Noise (S/N) ratio.

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NOMENCLATURE

AHP	Analytical Hierarchy Process
TQLFA	Taguchi's Quality Loss Function Analysis
MRR	Material Removal Rate
R_a & R_z	Surface Roughness Characteristics
ANOM	Analysis Of Means
S/N	Signal-to-Noise Ratio
AISI	American Iron and Steel Institute
FP	Flushing Pressure
T_{ON}	Pulse-on-Time
T_{OFF}	Pulse-off-Time
WT	Wire Tension
WF	Wire Feed
SV	Servo Voltage
WEDM	Wire Electrical Discharge Machining

CHAPTER 1

INTRODUCTION

The industrial industries have improved in the last few decades regard to automation, integrating artificial intelligence without dependency. The current demand is for fully automated production systems that strive for "zero defect manufacturing," which is made feasible by cutting-edge AI integration in conjunction with a multisensory approach. The implementation of condition monitoring and control systems for industrial processes significantly minimizes machining downtime. Condition monitoring techniques are intended to cut consumption of supplies and sources of energy, examination costs, and equipment downtime.

1.1 Smart Manufacturing and Industry 4.0

A new manufacturing paradigm known as "Industry 4.0" combines physical production with digital technology. It is a collaborative, data-determined method that makes use of data analytics to advance productivity of the process. It enables the production process to be monitored and optimised by enabling the industrial systems to gather, process, and analyse data. Using sophisticated data-driven systems, Industry 4.0 envisions fully automated production facilities. It consists of cloud computing, artificial intelligence, and the internet of things (IoT). Fig. 1.1 presents the essential components of Industry 4.0. The term "Smart manufacturing" is another name for the fourth industrial revolution. These systems use machine learning to develop real-time decision-making capabilities, which increases the processes' adaptability, flexibility, and failure-free nature.

The idea behind the "internet of things" is that digital or physical objects may communicate with one another over the internet without the need for human involvement. Such shared data in a smart industry can be used to monitor, predict, and regulate occurrences like machine failure or breakdown as well as to understand trends before specific events. The study of intelligence displayed by machines that is comparable to the natural intelligence held by humans is known as artificial intelligence. Machines now have the ability to learn from their prior experiences thanks to AI. Based on prior knowledge, intelligent robots are capable of making predictions and applying adaptive control. Soft computing, often known as computational intelligence, in artificial intelligence refers to those computational methods that are of estimating answers to extraordinarily difficult issues. A branch of soft computing called machine learning (ML) focuses on creating algorithms that mimic human learning. These algorithms are able to decide and anticipate things based on what they have learned from training data. Machine learning can be categorized into two main types: supervised and unsupervised learning, depending on whether the training data includes the desired output. The incorporation of AI has made process control, condition monitoring, and equipment well-being forecasts possible in modern industrial enterprises.

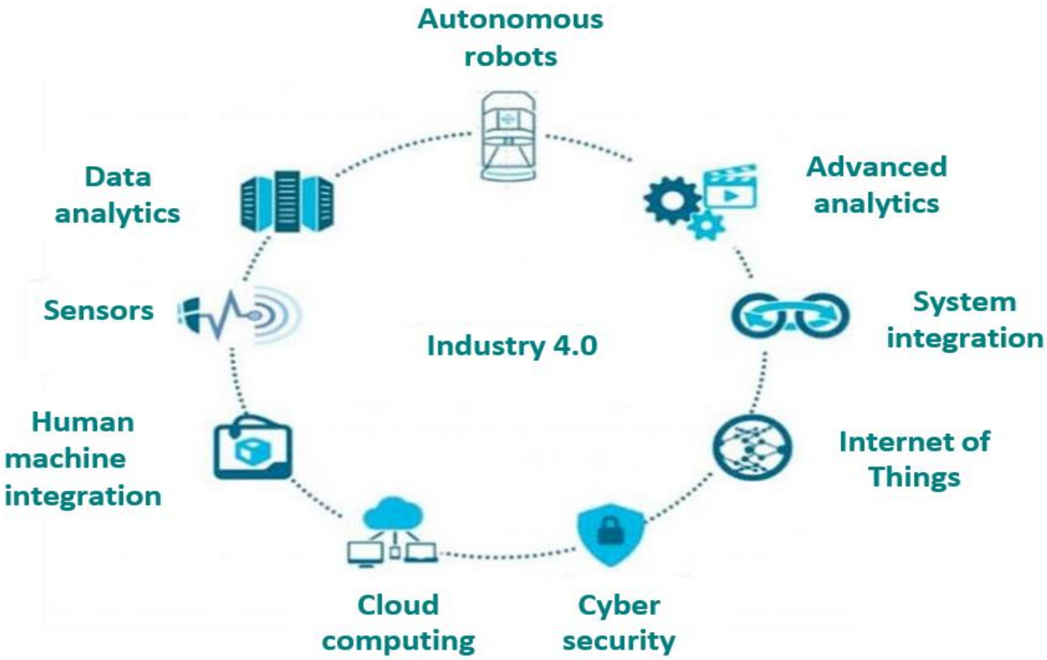

Figure 1. 1 : Aspects of Industry 4.0

1.2 Condition Monitoring Of Manufacturing Processes

Condition monitoring (CM) has been a significant area of research in industry over the past few decades, with a focus on enhancing productivity, reducing production costs, and improving part quality. To monitor the condition of a manufacturing process, it is necessary to monitor several variables that indicate its health. Raw sensor signals of physical variables such as temperature, force, vibration, sound, voltage, and current are the most effective means of extracting features for this purpose.The procedure and application determine which physical quantities to perceive and which feature to extract. Before the tool or machined parts suffer substantial harm, the condition monitoring system quickly identifies process faults. Early prediction allows for the implementation of corrective measures to mitigate potential damage. Tool changes, parameter tuning, and other process control measures are examples of corrective actions.

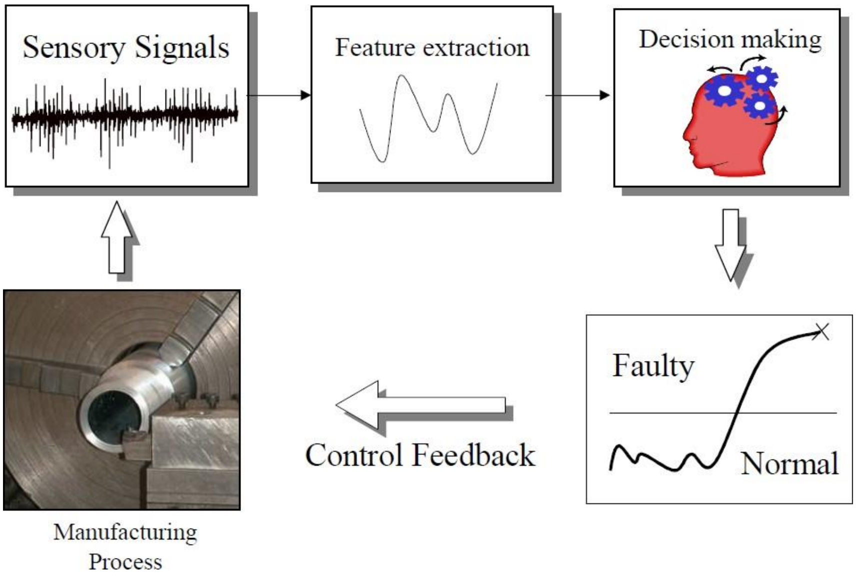

Figure 1. 2 : Structure of Condition Monitoring system

1.3 Wire Electric Discharge Machining

To produce high-performance materials like superalloys that have enhanced mechanical properties even at high temperatures, advanced manufacturing techniques are required. However, conventional machining of superalloys is challenging due to issues such as build-up edge, cold working of the work material, and fast tool wear. Electric discharge machining (EDM), a non-traditional machining method, offers several advantages over traditional techniques for processing challenging materials like superalloys and Ti alloys because the material removal process is non-contact process. The method was created in the 1940s utilising an RC circuit to manufacture tungsten and other hard materials. A particular type of EDM known as wire EDM, which was invented in the 1960s, uses controlled, repeated sparks to allow a travelling wire electrode to cut the desired profile. This method is a very alluring choice for shaping superalloys into delicate and complex structures. No matter how hard the material is, the method can machine it with minimal cutting forces and residual stresses, good surface polish, and electrical conductivity. A novel non-contact machining technique is WEDM. Regardless of how hard the material is, the method uses a thin metallic electrode to cut through it. This electro-thermal method melts and vaporises the workpiece material by utilising the heat energy from electric sparks. In the wire EDM process, both the workpiece and wire electrode undergo material removal, with new wire fed from a spool into the machining zone. A small gap, known as the inter-electrode gap or spark gap, separates the wire and workpiece, with dielectric fluid submerging the latter. Deionized water is the preferred dielectric for wire EDM, with the machining zone accessed through top and lower nozzles that flush the dielectric.Moreover, the dielectric fluid assists in cooling the workpiece, clearing the cutting area of debris, and reducing gas bubbles. In a CNC coded profile, the wire is translated in relation to the workpiece to machine the desired shape. Wire EDM enables the production of highly intricate and complex profiles on hard materials due to its non-contact process and CNC programmed profile. The process is known for its accuracy, flexibility, and precision with respect to geometry and dimensions. A schematic diagram of the wire EDM process is depicted in Figure 1.3.

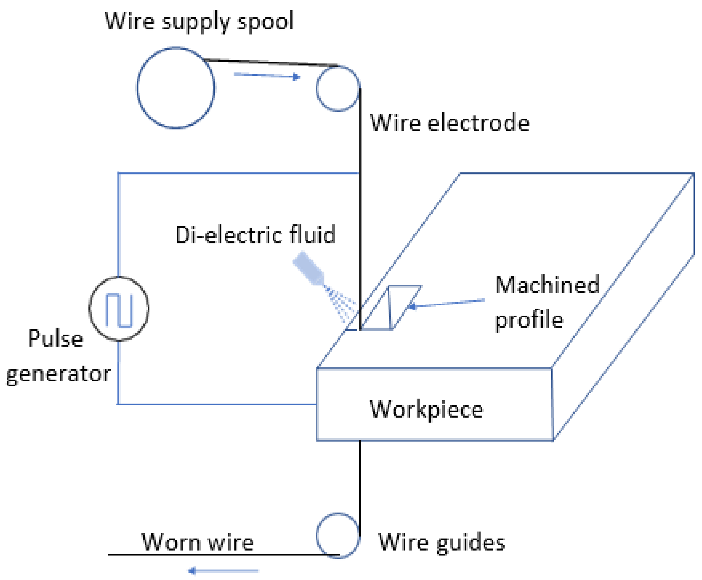

Figure 1. 3 : Wire EDM process

1.3.1 Working principle of Wire EDM

In wire EDM, the process is driven by repetitive electric discharges, with the workpiece and wire electrode connected to the positive and negative terminals, respectively. The tiny interelectrode gap between the two is filled with a dielectric fluid. A transistor-controlled pulse generator is used to deliver pulsed DC voltage with alternating on and off cycles.

Material removal and discharge occur during the pulse-on time, while restoration of the dielectric characteristics and removal of debris occur during the pulse-off time. Once the DC voltage is applied across the wire and workpiece electrodes, ionization of the dielectric fluid starts in the channel with the shortest interelectrode distance. The process of ionization occurs when the electrons from the wire electrode accelerate and collide with the dielectric molecules in their path towards the workpiece. Meanwhile, the free electrons produced in the inter-electrode gap approach the workpiece, and the positive ions approach the wire electrode. This ionization process results in the formation of a small channel composed of free electrons and ions called a discharge channel. As ionization intensifies, the resistance of the discharge channel decreases until it breaks through the dielectric barrier, causing it to become conductive. At this point, the dielectric is vaporized, and a rapid discharge takes place through a plasma channel from the wire electrode towards the workpiece, causing the electrodes to melt. The kinetic energy of the rapidly moving electrons is greater than that of ions, which results in more material being removed from the workpiece side than the electrode side. The plasma channel's temperature can reach as high as 10,000°C, which can melt any electrically conductive material. When voltage is applied to create a plasma channel, it collapses as soon as the voltage is removed. This collapse generates high-pressure waves that expel the molten material from the spark zone and create a crater on the workpiece's surface. The material that is expelled is called debris and is solidified almost instantly. During the pulse off period, the dielectric fluid removes any debris, dust, and vapor bubbles from the machining zone. However, some of the molten materials may resolidify back onto the machined surface, creating unwanted recast layers. To optimize the process, the dielectric characteristics are frequently disrupted and then repaired throughout the pulse on and off cycles.

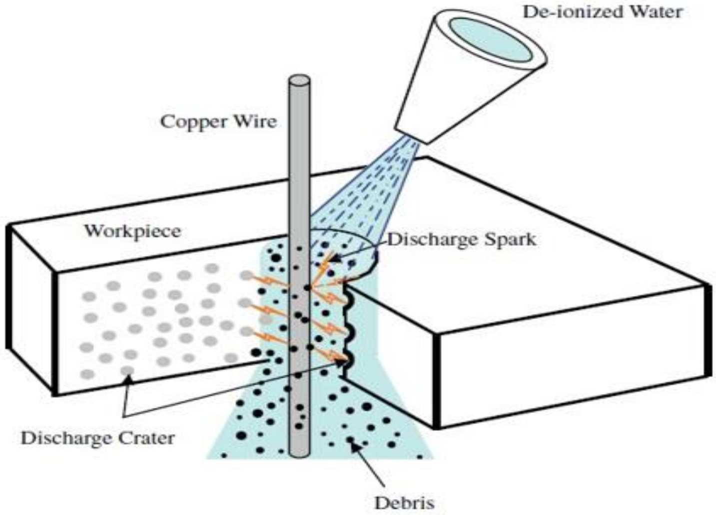

Figure 1. 4 : Material removal in Wire EDM process

1.3.2 Wire material

The performance of the process is greatly influenced by the wire material. The types, strengths, and sizes of the wire electrodes vary. This section discusses various wire electrode types that are frequently used in wire EDM.

Uncoated brass electrode: Since that brass is an excellent electrical conductor, using brass for wire electrodes is seen to be a suitable choice. When compared to pure copper wire, which was previously used before brass wires gained popularity, it can take tension better. These wire electrodes provide accuracy and a superior surface polish. These wires are very reasonably priced.

Zinc coated brass electrode: To enhance the precision and cutting rate of wire EDM processes, zinc-coated brass electrodes are utilized, which have a zinc covering of 20-30 μm thickness on a brass core. During sparking, the coating vaporizes at a faster rate than the core material due to its higher volatility. This protects the inner core from thermal shock, while the cooling effect from the heat sink effect minimizes the core material's exposure to heat. This allows coated wires to withstand more discharge energy, resulting in faster cutting. Furthermore, as the coating evaporates, the spark gap widens, resulting in better flushability.

Apart from the different types mentioned earlier, coated wires can also be transformed into diffused wire through heating. Wire electrodes are available in various types based on their tensile strengths, including hard (high tensile), half-hard, and soft (low tensile) wires. While half-hard or soft wires have a tensile strength of 400 N/mm^2, hard wires have a tensile strength of 900 N/mm^2. Soft wires are typically used for taper cutting, whereas hard wires are preferred for precise, straight cuts.

1.3.3 Control parameters

Any manufacturing operation must choose the right process parameters since poor process parameter sets might affect surface integrity or productivity. Understanding parameter settings is crucial when using wire EDM since poor parameter selection can result in wire breakage during the operation. The following process parameters can be changed on the current wire EDM equipment.

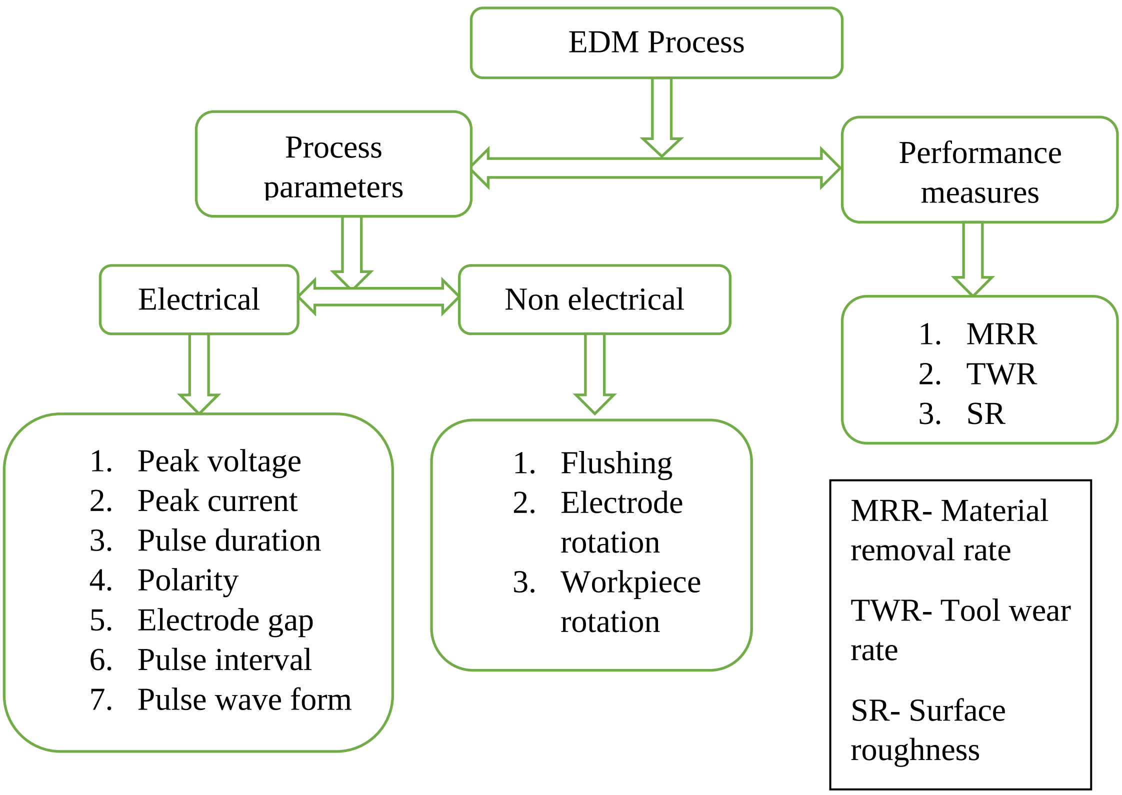

Figure 1. 5 : Control parameters and Performance measure of WEDM

Pulse on time: The duration for which voltage is applied between the electrodes is referred to as the pulse on time. During this period, a part of the pulse's duration is utilized to ionize the dielectric, leading up to the discharge during the ignition delay time. The remaining duration of the pulse on time is the discharge duration, in which the workpiece melts and vaporizes to remove material. In theory, higher pulse on time should result in greater material removal, and vice versa.

Pulse off time: Once the pulse on time is complete, the pulse off time begins, which is when the DC voltage between the electrodes is switched off by the pulse generator. During this time, the wire EDM machine takes the opportunity to clean up any debris and restore the dielectric characteristics of the spark gap. If the pulse off time is insufficient, debris may not be fully removed, leading to instability in the machining process.

Servo voltage: The wire EDM machine is equipped with an integrated gap control system that utilizes servo voltage to regulate the distance between the electrodes. The servo voltage, set by the operator, serves as the reference value for the average interelectrode voltage, and the internal servo feedback mechanism maintains the spark gap distance. When material is being removed from the workpiece during the spark erosion, the spark gap temporarily widens, causing the average voltage between the electrodes to increase above the servo voltage.

Wire feed rate: During spark erosion, both the workpiece and wire electrode experience material removal. To avoid rapid wear and breakage of the wire, fresh wire is constantly supplied to the machining zone from a spool. The rate at which new wire is supplied from the spool is determined by the wire feed rate. If the wire feed rate is too low, there may be simultaneous sparks from the same wire point, causing wire breakage. Conversely, if the wire feed rate is too high, the wire electrode will be wasted unnecessarily.

Pulse current: The amount of electrical current that flows through the electrodes during each pulse cycle is referred to as the pulse current. Two modes are typically available on wire EDM machines for adjusting the pulse current: power mode for rough cuts and fine mode for trimming. Power mode is used for regular profile cutting, while fine mode is used for removing the recast layer and enhancing the component's quality. During the finishing process, the peak pulse current is 10 A, while during rough-cutting, it can reach up to 40A.

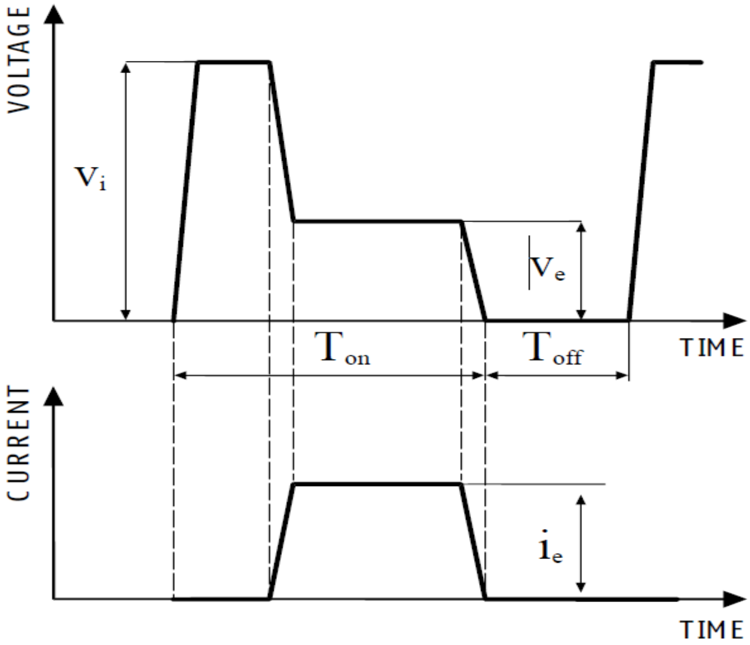

Figure 1. 6 : Discharge features showing T_{on} and T_{off} cycles

Flushing pressure: The control of dielectric flushing pressure from the top and bottom nozzles is achieved through flushing pressure adjustments. In wire EDM, the dielectric fluid flushing pressure can be modified to suit the machining needs. A higher pressure is typically used during roughing to effectively remove debris from the spark gap, while lower pressure suffices during trim cuts due to the lesser amount of debris. Using high pressure during trim cuts can introduce geometric errors, which is why it is best to use lower pressure in such cases.

Several more factors, including wire tension, can be manually adjusted depending on the EDM machine. Figure 1.6 provides the discharge characteristics, including the discharge current, discharge voltage, pulse on and pulse off time.

1.3.4 Applications of Wire EDM

Cutting elaborate and sophisticated features in challenging conductive materials requires the use of wire EDM. Because to the non-contact cutting action, the technique can machine both brittle and fragile parts as well as hard, brittle materials with essentially no cutting forces. The machining of fixtures, cams, gauges, gears, punches, and dies are examples of typical uses. Micro electrodes for micro USM, micro EDM, and other applications are also produced using this method. In the past decade, there has been significant improvement in the surface integrity of components machined by wire EDM, which has allowed them to replace conventionally machined parts in aircraft applications. Wire EDM has emerged as an alternative to broaching, which is a laborious process for milling fir tree slots and roots in turbine blades and discs. The capabilities of this process are highlighted in Figure 1.7, which displays some of the components cut using wire EDM.

1.3.5 Process stability of Wire EDM

The stability of the wire EDM process is significantly affected by the spark gap condition. Typically, the wire EDM process assumes that the debris and gas vapours produced during the discharge cycle will be flushed out of the inter-electrode compartment during the pulse off cycle. In this case, the dielectric breakdown that occurs during the discharge is followed by the restoration of the dielectric fluid's electric characteristics. The current discharges after an ignition delay time, which is the time required for the fluid to ionize and become conductive. To achieve the desired workpiece profile efficiently, these discharges go through a cycle, with each spark resulting in material removal in the form of a crater.

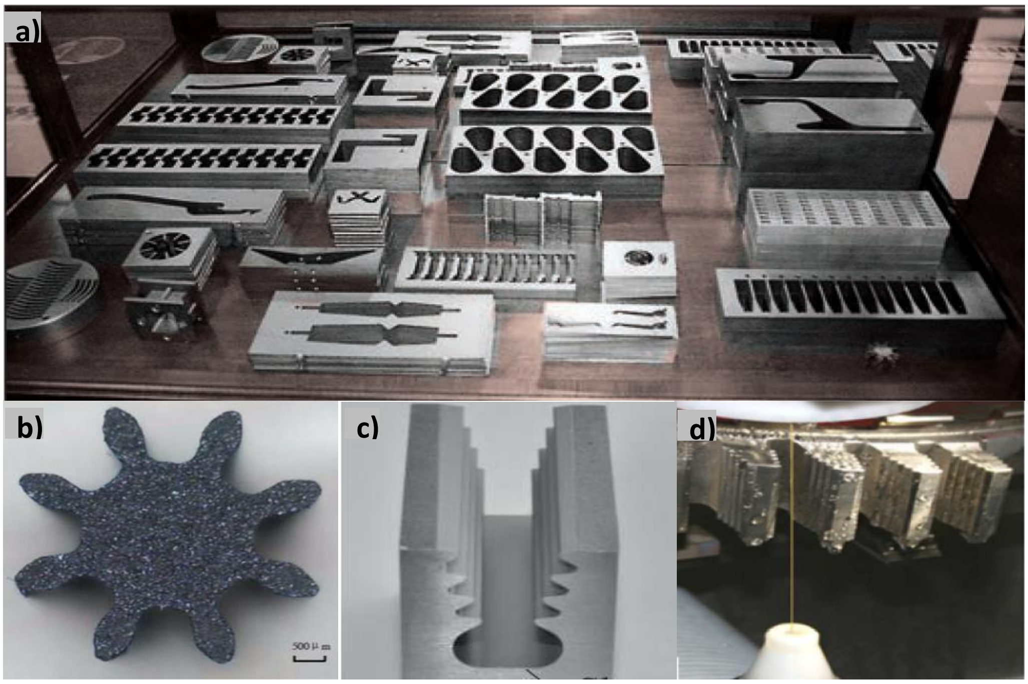

Figure 1. 7 : Wire electric discharge machined components

(a)Various profiles cut by wire EDM

(b) Miniature gear machined by WEDM

(c) WEDM cut firtree slot

(d) WEDM of firtree root slot

The discharge cycle behaviour described above is an idealistic concept that is frequently used to describe the wire EDM process mechanism. The flushing action of the dielectric, however, only completely removes the particles in the majority of real-world situations. The accumulation of debris in the spark gap under some extreme conditions might result in spark gap bridging and irreversible standstill. Machining circumstances that encourage debris stagnation are regarded as unstable circumstances. Depending on how quickly the debris is accumulating, the instability's degree and its effects will vary. Coarser surfaces, poor surface integrity, component damage, and process disruption due to wire breaks can all result from unstable process conditions. Fig. 1.8 compares the spark gap conditions for a stable and an unstable machining process.

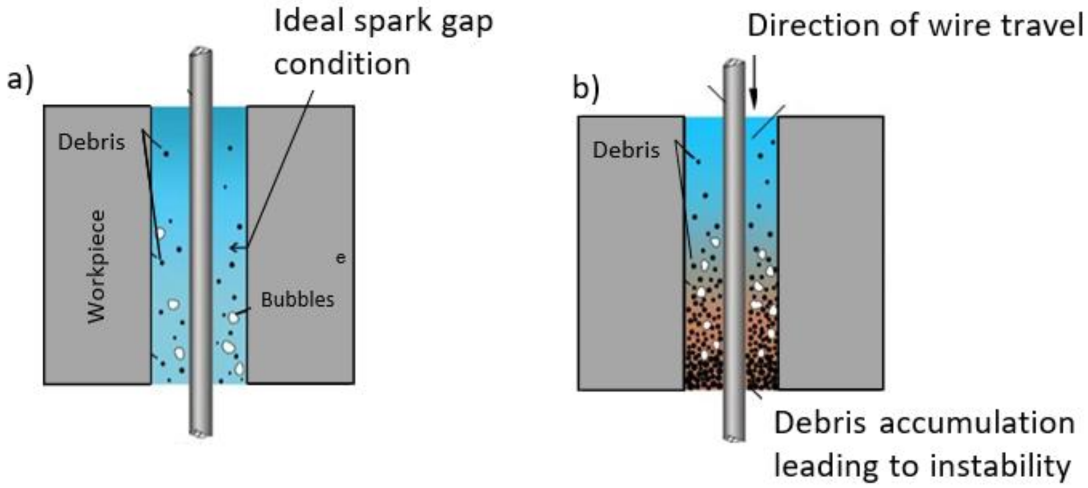

Figure 1. 8 : Comparison of spark gap condition during stable and unstable machining

The ratio of the pulse on time to the overall cycle duration is known as the duty cycle. The choice of duty cycle is crucial in determining the stability of the machining process.The likelihood of spark gap debris collection increases with duty cycle. This is due to the fact that at higher duty cycles, there is more debris but it takes less time to flush it out. The spacing between the spark gaps is another deciding element. A smaller spark gap has a higher likelihood of stagnation than a larger one. Process instability can also occur if the dielectric fluid pressure is insufficient to clear spark gap debris, particularly while performing a rough-cut operation. A number of additional elements, in addition to the control parameters already mentioned, also contribute to the instability of the process. The process may become unstable due to higher order interactions between the factors. Stochastic conditions in the spark gap are also brought on by external factors such wire vibration, the surrounding temperature, wire EDM sensations, etc. The machining letdowns brought on by process uncertainties is, in other words, a complicated and unpredictably occurring event. So, it is challenging to create a model that accurately links control parameters and process problems.

1.3.5.1 Types of discharge pulses

Between the wire electrode and the workpiece, four different discharges are possible. The ability to distinguish between the discharge pulses requires both voltage and current pulse cycles. The various discharge pulses are depicted in Fig. 1.9.

Normal discharge: The spark discharge that happens after an ignition delay is the usual spark discharge. This discharge meets the standards for a typical wire EDM pulse cycle. As the conductive plasma channel forms at the final stage of the ignition delay period, discharge current increases and voltage decreases. The proper restoration of the dielectric characteristics following each discharge is implied by an ideal ignition delay duration.

Arc discharge: A short ignition delay period distinguishes arc discharge. This suggests that there is debris present in the spark gap. Arc discharges are viewed as unappealing for better surface integrity since they might lead to surface degradation and rougher surfaces. Arc discharges, however, are frequently just as frequent as regular discharges at higher cutting rates.

Short circuit discharge: When the wire electrode comes into touch with the workpiece physically, a short circuit discharge occurs. So, in this instance, the plasma channel creation phenomenon is not present. Here, the spark gap is physically closed by the stationary debris, completing the circuit. As there is no delay in ignition, discharge takes place between the electrodes as soon as the voltage is delivered. Short circuit discharges do not exhibit voltage rise since the discharge occurs through physical contact. To maintain stable and continuous machining, short circuit pulses which are considered to be the main causes of wire ruptures and exterior damages must be evaded.

Open discharge: Open discharges are misdischarges in which there is no discharge current for the entirety of the pulse on time. Open discharges can occur for a variety of reasons. The current discharge will not occur if the applied voltage is insufficient to cause the dielectric interruption, the pulse on time is insufficient to finish the ionisation, or spark gap is excessive. Open discharges are not considered dangerous discharges because they don't result in component damage. Yet, as a higher percentage of open circuit discharges might reduce productivity, such discharges must also be managed in order to increase process efficiency.

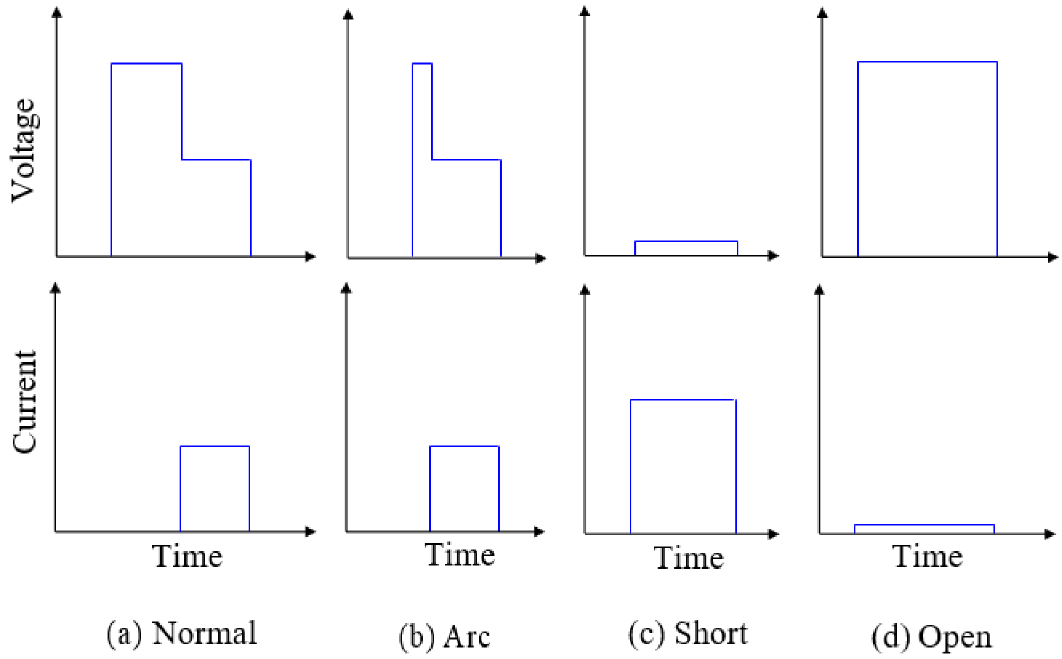

Figure 1. 9 : Various types of discharge pulses

1.3.5.2 Process failures

Events that occur during a manufacturing process and cause material loss, part damage, process disruption, or energy loss are referred to as process failures. In this regard, the failure of the wire EDM process is due to wire breaks and a lack of spark. The most common reasons for wire breaking are believed to be arc and short circuit sparks. Wire breaks can cause process interruptions, which can lead to component damage and resource waste. Wire breakage is frequently associated with permanent surface damage to the workpiece. Even if the damage is slight, restarting the machining operation after rethreading may leave burrs and surface marks. Because rethreading requires time that could be spent on other tasks, wire breakage also lowers overall productivity and uses energy inefficiently. Process automation is impacted by frequent wire breaks, which require manual work. Another process stoppage occurs when the spark frequency falls to zero immediately after the commencement of the machining. This circumstance reduces productivity and wastes energy and wiring resources. The open circuit discharges discussed in the preceding subsection are believed to be the primary cause of this failure.

1.4 Condition Monitoring of Wire EDM

Wire EDM condition monitoring seeks to avoid process failures such wire breakages and spark absence in order to maintain the desired component quality. The monitoring system has the right sensors for gathering specific process data that might provide insight into the health of the machine. Machine health indicators are the components that can be extracted from the raw data to reveal details about probable process issues. Condition monitoring systems can be greatly tailored because there are so many different sensors available to measure various physical values. Current, voltage, audio, vision-based, infrared, and accelerometer sensors are some of the ones utilised to build wire EDM condition monitoring systems. An analogue to digital converter (ADC) transmits real-time data from the sensors to a workstation or computer system. The signals are typically filtered to reduce noise and make it easier to extract crucial information. The extracted features will be applied as indications of the wire EDM process's health. Most of these systems provide for process pauses brought on by cable breaks. Advanced adaptive control systems can take preventive action when issues are foreseen. Process control is used to restore the stability of the machining by modifying one or more control parameters.

1.5 Workpiece Materials and Their Specific Applications

The American Iron & Steel Institute (AISI) and the Society of Automotive Engineers (SAE), which have independently developed their own naming systems for steel alloys based on alloying elements, usage, and other considerations, are where stainless steels acquire their names. Understanding that the chemical makeup of the majority of alloy blends remains the same across categorization systems can help you understand why steel designations might be perplexing since the same alloy can have multiple IDs depending on which system is chosen.

AISI 1040 is a carbon steel that contains 0.40% carbon along with other alloying elements, such as manganese, chromium, nickel, and molybdenum. It is a popular grade of steel for many industrial applications due to its excellent strength, toughness, and wear resistance. AISI 1040 steel is often used in machinery parts, automotive components, and other structural applications. It can be heat treated to increase its hardness and strength, and it can be machined easily in its annealed or normalized condition. The mechanical properties of AISI 1040 steel depend on its heat treatment and the composition of its alloying elements. In its annealed condition, it has a tensile strength of 550 MPa (80 ksi) and a yield strength of 355 MPa (51 ksi). When heat treated, its strength can increase significantly, reaching tensile strengths of up to 1000 MPa (145 ksi).Overall, AISI 1040 steel is a versatile and widely used carbon steel that offers a good balance of strength, toughness, and machinability.

The composition of AISI 1040 steel is as follows:

Carbon (C): 0.37-0.44 %

Manganese (Mn): 0.60-0.90 %

Phosphorus (P): 0.040 % max

Sulfur (S): 0.050 % max

Silicon (Si): 0.15-0.35 %

In addition to these elements, AISI 1040 steel may also contain small amounts of other alloying elements, such as chromium, nickel, and molybdenum, depending on the specific manufacturing process and intended application.

The carbon content in AISI 1040 steel is relatively high, making it medium carbon composition gives the steel good strength and toughness while maintaining good machinability and weldability. The manganese content provides additional strength and wear resistance, while the silicon content helps improve the steel's resistance to oxidation and corrosion.

1.5.1 Corrosion and Heat resistance

The AISI 1040 steel alloy offers many benefits with its corrosion resistance properties. It provides maximum resistance in atmospheres with high humidity, preventing rust and pitting of the material surface. Additionally, it is resistant to most corrosive agents, such as acidic solutions, alkaline solutions and salt sprays. With its superior ability to resist chemicals and humid environments, this alloy makes an excellent choice for a variety of applications, including high-temperature and cryogenic storage tanks, farm equipment, ships, bridges and naval applications. The heat resistance of AISI 1040 steel is remarkable, making it a favourite choice for use in extreme temperatures. It is well-suited to applications demanding excellent mechanical strength and toughness at both room temperature and in high-temperature environments. With a capacity to resist scaling and oxidation at temperatures up to 800°C, this versatile steel has been seen used in a variety of engineering scenarios where heat retention might be an issue. Furthermore, its tenacity remains satisfactory even when the steel is subjected to temperatures exceeding 1,000°C, making it a reliable option for durable results through countless heating cycles.

1.5.2 Applications of 1040 steel

AISI 1040 steel is used in a wide range of applications across various industries due to its excellent strength, toughness, and wear resistance. Here are some common applications of AISI 1040 steel:

1. Machinery parts: AISI 1040 steel is often used to manufacture various machinery parts, such as gears, shafts, axles, and couplings. Its high strength and toughness make it ideal for heavy-duty applications.

2. Automotive components: Many automotive components, such as crankshafts, connecting rods, and suspension components, are made of AISI 1040 steel due to its excellent fatigue fatigue resistance and wear resistance.

3. Structural applications: AISI 1040 steel is also used in various structural applications, such as bridges, buildings, and pipelines. Its high strength and durability make it suitable for these applications.

4.Tools and dies: AISI 1040 steel can be heat treated to increase its hardness, making it suitable for manufacturing various tools and dies used in metalworking and other manufacturing processes.

5. Fasteners: Many fasteners, such as bolts, nuts, and screws; are made of AISI 1040 steel due to its high strength and corrosion resistance.

1.6 Introduction to Minitab

Minitab is a statistical software tool. Researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner created it at Pennsylvania State University in 1972. Minitab started off as a simplified version of NIST's OMNITAB statistical analysis tool. It can be applied to statistical research as well as statistics education. Computer programmes for statistical analysis offer the advantage of being more precise, dependable, and generally quicker than manual methods for generating statistics and creating graphs. After you are familiar with certain basic concepts, using Minitab is not too difficult. Minitab Inc., a privately held business with headquarters in State College, Pennsylvania, and subsidiaries in Coventry, England (Minitab Ltd.), Paris, France (Minitab SARL), and Sydney, Australia (Minitab SARL), distributes Minitab (Minitab Pty.).

To implement six sigma, CMMI, and other statistics-based process improvement techniques today, Minitab is frequently utilised. English, French, German, Japanese, Korean, Simplified Chinese, and Spanish are just a few of the 7 languages that Minitab 16, the most recent version of the programme, is available in. Two additional items from Minitab Inc. that go along with Minitab 16 are: By combining Minitab data with management and governance tools and documents, Quality Companion 3 is an integrated tool for managing Six Sigma and Lean Manufacturing initiatives. The Quality Trainer eLearning product interacts with Minitab 16 to help users grow their statistical knowledge and proficiency with the programme at the same time. It teaches statistical techniques and concepts in the context of quality improvement.

1.6.1 Minitab project and worksheets

Projects and worksheets are the two major types of files in Minitab. Consider a spread sheet with data variables as the equivalent of a worksheet. Worksheets, graphs, and commands make up projects. Graphs, worksheets, and commands will all be saved each time you save a Minitab project. Yet, each component can be saved separately and used in different documents or Minitab projects. Projects and their components can also be printed.

The Menu bar: You can navigate through menu and select commands. The built-in routines are located here.

The Toolbar: Certain Minitab commands have shortcuts.

1.6.2 Two windows in MINITAB

1. Session Window: This screen allows you to enter instructions and presents the statistical findings of your data analysis.

2. Worksheet Window: A row-and-column grid used for data entry and manipulation.

Although it resembles a spreadsheet, this area does not update its columns when entries are modified.

Additional windows include:

• Graph Window: Each graph that is generated has its own window opened.

• Report Window: The report manager in Version 13 helps you arrange your findings in a report.

• Other Windows: Project Manager and History are additional windows.

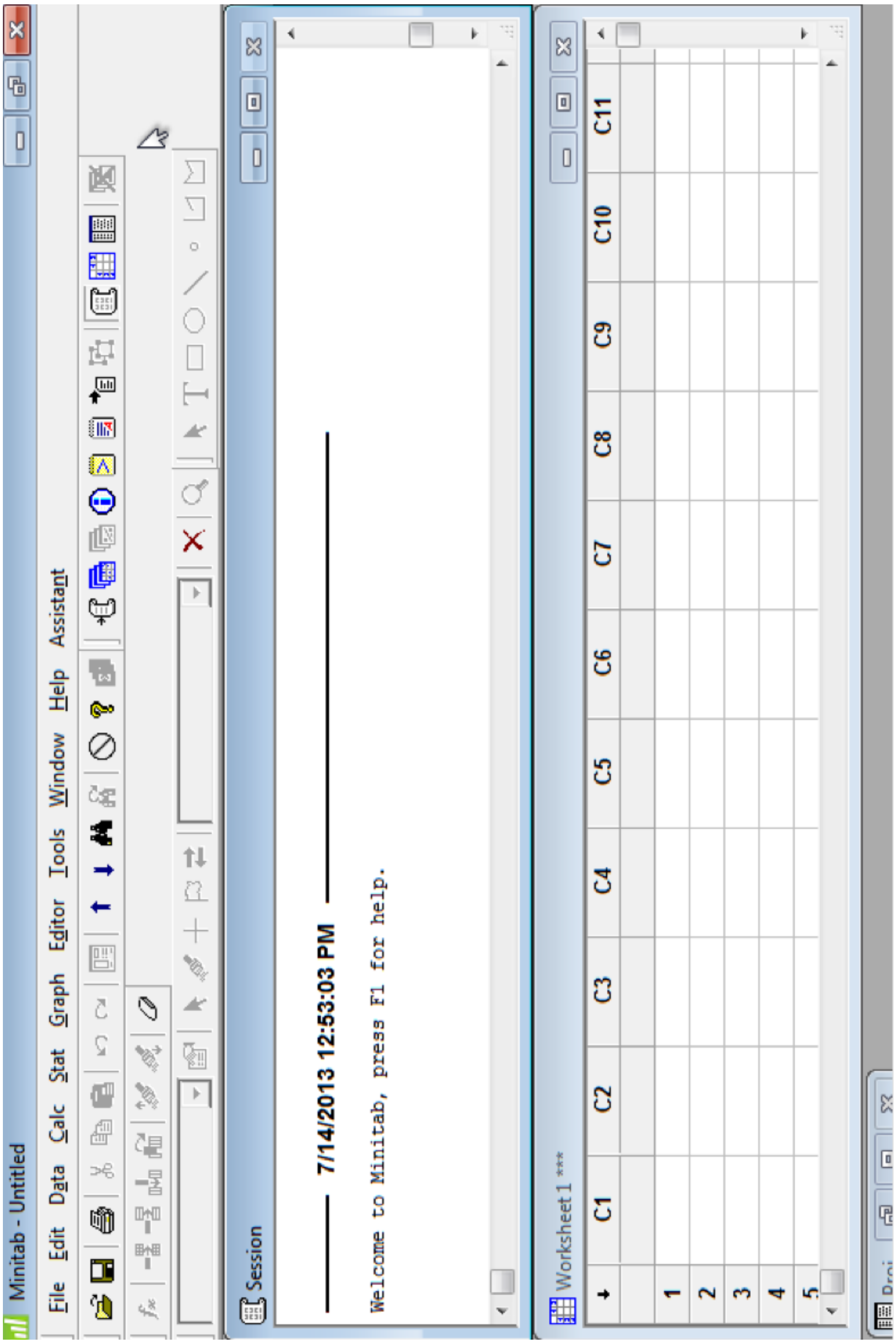

Figure 1. 10 : Minitab Interface

CHAPTER 2

LITERATURE SURVEY

This chapter discuss about the literature review of WEDM previous papers. Engineers must solve a problem to get the best parameters for the desired outcome using the available sources. Choosing the machining parameters to achieve the desired outcome is often somewhat difficult. This is actually determined by the table the machine-tool designer provides and the engineers' experience. Hence, optimization becomes crucial in order to satisfy both economy and quality of the machined object.

Ashish Goyal [1] examined the effect of various WEDM process parameters on two performance metrics: material removal rate (MRR) and surface roughness (Ra). In a series of 18 trials, various tool electrodes were utilized, including both zinc-coated and cryogenically treated zinc-coated ones. The ANOVA analysis revealed that the pulse on time, current intensity, and type of tool electrode used all had a significant effect on both the material removal rate and surface roughness.

Carmita Camposeco-Negrete [2] studied AISI O1 tool steel with WEDM. He evaluated surface roughness, material removal rate, electric power, servo voltage, and voltage over machining time. The pulse-on time was discovered to be the most important element determining responses.

Pramanik et al. [3] investigated the geometrical errors caused by Ti6Al4V alloy wire electrical discharge machining, with a particular focus on cylindricity, circularity, and diametric errors.

R.Prasanna et al. [4] optimised WCEDM process parameters for titanium alloy machining. (Ti–6Al–2Sn–4Zr–2Mo). The effects of the pulse on time, pulse off time, voltage, and wire feed rate on material removal rate and surface roughness were examined. They concluded that voltage is the most important feature of all.

Raymond Magabe et al. [5] used WEDM to machine Ni55.8Ti shape memory alloy. The impact of input parameters such as spark gap voltage, pulse on-time, pulse off-time, and wire feed on productivity (measured by MRR) and surface quality (measured by Rz) have been explored. The NSGA-II was used to optimise the various replies. The empirical models created successfully predict the MRR and Rz values. Ni55.8Ti wire-EDM with NSGA-II-optimized settings produced superior surface quality (Rz - 6.20 m) and process productivity (MRR-0.021 g/min). Depending on the requirements, the NSGA solutions developed in this work could be used to improve process performance.

S. Suresh et al. [6] investigated the effects of WEDM parameters on surface roughness (Ra) and MRR (material removal rate) in Al7075 and nano-silicon carbide-based metal matrix nanocomposites (SiC). They discovered that gap voltage and reinforcement weight percentage are key criteria for material removal rate and surface roughness, respectively. The surface quality performance attributes are most affected by changing the input control parameters in WEDM. Because WEDM method is unsystematic, improving the input process variables is a time-consuming task for the researchers.

Amit Kumar et al. [7] optimized the WEDM process parameters while cutting M2-grade high-speed steel. (HSS). To optimise the response variables material removal rate (MRR), surface roughness, and Kerf width, a regression model of significant factors such as pulse-on time, pulse-off time, peak current, and wire feed is utilised.

Ramy Abdallah et al. [8] studied the effects of operation conditions and cut orientation on composites. For each cut direction, a Taguchi L18 fractional factorial orthogonal array with four variable parameters-open voltage, ignition current, pulse-on and pulse-off time-was run.

Titus Thankachan et al. [9] performed an experiment on a friction stir processed (FSPed) copper-BN surface composite and examined the effects of pulse discharge on time (Pulse on), pulse discharge off time (Pulse off), wire feed rate (Wire FR), and material characteristics of various Boron Nitride (BN) volume fractions. ANOVA and grey analysis were used to improve the responses.

Yan et al. [10] analysis of the SiCp/Al composite's machining characteristics led to the identification of the ideal wire electrical discharge machining process parameters. It has been found that as pulse-on time, servo voltage, wire feed rate, and wire tension rise, the material removal rate decreases and increases. Surface roughness is increased by longer pulse-on and pulse-off times, though induced current and wire-feed have less of an impact.

Amit Kumar et al. [11] used an Al2O3 nanopowder mixed dielectric medium to mill Inconel 825. Experimental data revealed that NPM EDM produced a maximum MRR of 47 mg/min and a minimum SR of 1.487 m. These values were found to be 44% and 51% higher than those achieved by standard EDM techniques, respectively. Furthermore, NPMEDM significantly improved the surface texture of the machined surface.

Rakesh Chaudhari et al. [12] increased the machining performance of Nitinol alloy mixed with dielectric fluid in WEDM. The impact of various WEDM machining parameters, such as current, pulse-on time (T_{on}), pulse-off time (T_{off}), and alterations in MWCNT powder concentration, on material removal rate (MRR) and surface roughness (SR) was studied. A complex parameter-free TLBO algorithm was employed to determine the optimal combination of multiple responses.

Himanshu Payal et al. [13] optimised the die-sinking EDM process parameters when milling Inconel 825 with three different electrode types: graphite, copper, and copper-tungsten using the GRA and PCA approaches. With a graphite electrode, they achieved good MRR, TWR, and SR values.As a result, while working with tough materials like composites, the EDM technique is critical. Many scholars investigated the impact of WEDM process settings on various multi-responses using various optimisation methodologies.

K. Anand Babu et al. [14] aimed to optimize the electrical discharge wire-cutting process parameters for the AA6082/fly ash/Al2O3 hybrid composite using the Taguchi approach and the Entropy-VIKOR method. Based on their findings, the most critical parameter for process performance, including cutting speed, wire wear ratio, kerf width, and over-cut, was pulse OFF time. Pulse ON time, servo feed, and wire type were identified as the following essential parameters in order of importance.

Gopal P.M. et al. [15] enhanced the surface polish (R_a) and material removal rate (MRR) of a novel Mg/BN/CRT hybrid MMC by focusing on critical process factors, such as reinforcement weight percentage and size, pulse on time, pulse off time, and wire feed. The Taguchi-based orthogonal array technique was employed to conduct WEDM trials. Mathematical models for MRR and R_a were developed, and they were found to have better predictive power and were consistent with the experimental results obtained.

Meinam Annebushan Singha et al. [16] focused to manufacture silicon carbide through a rapid hot press sintering method and identify the critical parameters that would yield optimal machining conditions in wire electric discharge machining.

Amresh Kumar et al. [17] used the WEDM method to machine an aluminium-based hybrid composite. The ideal machining conditions for hybrid composites were discovered using an analytical hierarchy method and a genetic algorithm.

V. Kavimani et al. [18] explored the result of the WEDM parameter on the material removal rate (MRR) and surface roughness (R_a) of a newly settled metal matrix composite. To explore the influence of two material parameters and three machining parameters on the desired output responses, two material parameters and three machining parameters were chosen. After that, the Taguchi coupled Grey relation approach is employed to investigate the output response variables MRR and $R_{a.}$

Malik Shadab et al. [19] used Metaheuristic Techniques to improve the WEDM parameters. The research needed the Taguchi L25 orthogonal array. For optimization, a TLBO method based on RSM was applied.

R. Karthikeyan et al. [20] used a feed-forward ANN model and a genetic algorithm to advance material removal rate and surface roughness in neural power software.

P. Vaidyaa et al. [21] used a hybrid artificial neural network (ANN) connected genetic algorithm technique to optimise the multi-objective features of wire electrical discharge machining (WEDM) in SLM-fabricated AlSi10Mg.The Taguchi experimental design is used to calculate microhardness and surface roughness while accounting for the three major contributing elements.

Ahmed A et al. [22] used the WEDM technique to mill AISI 1045 steel. The goal of this study is to develop an ANN model that can forecast surface roughness (Ra) and metal removal rate (MRR) values. In this study, the Taguchi technique (Design of Experiments), artificial neural network (ANN), and analysis of variances (ANOVA) were employed as research methods.

C. Balasubramaniyan et al. [23] focus on Ni44Ti50Cu4Zr2 SMA coated wire electric discharge machining at high temperatures. (W-EDM). Surface undulation and material removal were evaluated utilising machining quality metrics such as current (I), servo voltage (SV), pulse on time (Ton), angle of cut (AC), and pulse off time. (Toff). In trials, the response surface technique was utilised to study the parametric analysis of machining features. (RSM-CCD).

Soutrik Bose et al. [24] utilized a unique optimization technique named desirable grey relational analysis (DGRA) for multi-objective optimization. This technique combines the desirability function with grey relational analysis. The experimental results were compared with predicted outcomes using a multi-criteria decision-making strategy called the fuzzy methodology for order preference by similarity to ideal solution (FTOPSIS) along with a fuzzy analytical hierarchy procedure for criteria weights.

Daniel Das et al. [25] investigate the effect of wire-cut electrical discharge machining on the input properties of Ti alloys. The TOPSIS approach was used to predict the optimisation component.

Kozak et al. [26] studied WEDM machining of a material with low electrical conductivity (Si3N4). The cutting velocity was discovered to vary greatly depending on the clamp location. MRR rises as the incision approaches the clamp. The MRR lowers as the wire moves away from the clamp. As a result, the true MRR was revealed to be dependent on the exact machining geometry and the relative location of the wire electrode in relation to the clamping. Si3N4 was machined with silver paint added to the work piece to prevent energy loss due to drop voltage in the work piece. MRR increased significantly after silver plating.

Karunamoorthy et al. [27] applied Taguchi's robust design approach to WEDM, together with a multi response optimisation method. Each experiment was run with different cutting parameters such as pulse on time, wire tension, delay time, wire feed speed, and ignition current intensity. Three answers were assessed for each technique: material removal rate, surface roughness, and wire wear ratio. Taguchi's parameter design was discovered to be a straightforward, systematic, dependable, and more efficient way to machining parameter optimisation. The pulse on time and ignition current were discovered to have a bigger influence than the other parameters.

Liao et al. [28] conducted an evaluation of various parameters in wire electrical discharge machining of SKD11 alloy steel, including material removal rate (MRR), surface roughness, gap width, sparking frequency, average gap voltage, and normal ratio, using the Taguchi method. The results showed that both table feed and pulse-on time significantly affected the metal removal rate, gap voltage, and total discharge frequency, with pulse-on time being the primary factor influencing gap width and surface roughness.

Hascalyk and Caydas [29] studied the relationship between surface roughness and open circuit voltage and dielectric fluid pressure. An increase in the pulse on time and open circuit voltage results in higher surface roughness. This can be attributed to the increased discharge energy, which affects surface roughness. Additionally, the work material type also plays a role in determining the surface roughness, as annealed samples exhibit higher roughness ratings compared to quenched/tempered ones due to their superior heat conductivity. In the latter case, heat dissipates more quickly throughout the sample instead of accumulating on the surface. Increasing dielectric fluid pressure results in a reduction in surface roughness, possibly due to its cooling effect, as well as better removal of debris. The cutting performance is also improved by increasing the dielectric fluid pressure since it facilitates more efficient removal of particles from the machining gap.

Konda et al. [30] divided the multiple potential factors influencing WEDM performance measures into five major categories: workpiece material and dielectric fluid parameters, machine characteristics, configurable machining settings, and component shape. In order to optimize the effects of variables, the DOE technique was employed and the resulting experimental data was verified through the use of (S/N) ratio analysis.

Tarng et al. [31] to tackle the issue of optimizing multiple responses, employed a combination of neural network methodology and simulated annealing algorithm.The calculation of CS and SR was found to be influenced by several crucial machining parameters such as pulse on/off time, peak current, open circuit voltage, servo reference voltage, electrical capacitance, and table speed. These parameters were demonstrated to have a significant impact on the CS and SR values.

Hewidy et al. [32] modelled the machining characteristics of Inconel-601 wire electrical discharge machining using RSM. The Response Surface Method (RSM) approach in parameter analysis provides the benefit of illustrating the impact of individual working parameters on the ultimate response parameter value. In the context of volumetric metal removal rate, an increase in peak current value and water pressure usually results in a corresponding rise in the said rate.

Lack of studies looking at the influence of controllable parameters may be one potential gap in the literature about AISI 1040 workpieces in terms of material removal rate and surface roughness. The need for additional research on the effects of tool wear on material removal rate and surface roughness in the context of milling AISI 1040 workpieces is another potential gap in the literature.While there are some studies that have explored the relationship between tool wear and these parameters, there is still a need for more comprehensive research that takes into account different levels of tool wear and their effects on material removal rate and surface roughness.

Last but not least, study is required to examine how machining variables like Flushing pressuure, Pulse on and off time, ffeed rate, wire tension, servo voltage affect the rate of material removal and the surface roughness of an AISI 1040 workpiece. To completely comprehend how machining parameters affect the material removal rate and surface roughness of an AISI 1040 workpiece, more research is required.

CHAPTER 3

METHODOLOGY

3.1 Design Of Experiments (DOE) Overview

Customized experiments can be used in the business world to explore characteristics of a process or a product that affect product quality. Direct improvement operations increase a product's ability to be manufactured, dependability, quality, and field performance after identifying the process variables and product elements that affect product quality. The most information possible must be extracted from each experiment because resources are scarce. In comparison to random or unplanned tests, well-designed experiments frequently require fewer runs and generate noticeably more information. An effective experiment pinpoints the key impacts. if two input variables interact with one another.

Instead of a "one factor at a time" experiment, they should be incorporated into the design. There is an interaction when the magnitude of one input variable is modified by the level of another input variable.

Planning, screening, optimization, and verification are the common four stages of designed experiments.

3.1.1 Planning

You might be able to avoid problems by properly planning ahead and carrying out your trial plan. The capacity to finish the experiment, for instance, may depend on the availability of staff, equipment, financing, and system mechanics. The preparation needed prior to starting an experiment varies on the issue. The following steps must be followed:

• Specify the issue. Making a strong problem statement aids in choosing the appropriate variables to investigate.

• Specify the goal. A clearly stated purpose will guarantee that the experiment provides the correct answers and produces useful, applicable data. Define the experiment's goals at this stage.

• Create an experimentation strategy that will yield useful data. Review pertinent background knowledge, such as theoretical concepts and understanding from past observational or experimental research.

Verify the control of the measurement and process systems. An ideal statistical process control (SPC) system would measure that the process and measures are both under statistical control. Numerous tools are available in Minitab to study your measuring system and assess process control.

3.1.2 Screening

Numerous potentially significant variables are present in the design and implementation of many processes. Screening assists in lowering the number of variables by highlighting the important factors that affect product excellence. This limitation enables process improvement efforts to be concentrated on the essential elements. The "best" ideal settings for these elements are suggested through screening. The following techniques for screening are frequently employed:

- Industry frequently employs two-level complete and fractional factorial designs.
- Despite their limited resolution, Plackett-Burman designs are useful for various screening experiments and robustness testing.
- For modest screening trials, general full factorial designs may also be helpful.

3.1.3 Optimization

It is necessary to determine the "best" or ideal values for these experimental components after the critical variables have been identified through screening. The process aim determines the best factor values.

Among the optimisation techniques provided by Minitab are general full factorial designs (designs with more than two levels), response surface designs, mixture designs, and Taguchi designs.

• The Factorial Designs overview provides instructions for generating and assessing general complete factorial designs.

• The Reaction Surfaces overview describes the procedures for developing and analysing central composite and Box-Behnken designs.

• The Mixture Designs Overview discusses the creation and analysis of simplex centroid, simplex lattice, and extreme vertices designs. The ratios of the components (factors) are more significant than their absolute values in the class of response surface designs known as mixture designs.

• Response optimisation describes strategies for optimising a variety of replies. Minitab provides numerical optimisation, an interactive graph, and an overlaying contour plot to assist in selecting the "best" settings to concurrently optimise several replies.

• Taguchi's artwork overview provides information on how to examine Taguchi designs. Other names for Taguchi designs are robust designs, inner-outer array designs, and orthogonal array designs. These designs are used to create products that are robust to circumstances in the environment where they will be used.

3.1.4 Verification

Verification includes conducting a subsequent experiment under the predicted "best" processing conditions in order to validate the outputs of the optimization.

3.2 Advantages & Disadvantages of DOE

One-factor-at-a-time (OFAT) technique was replaced by DOE, which is now a more popular modelling technique. The link between parameters and answers is one of DOE's primary advantages. To put it another way, DOE demonstrates how factors interact, allowing us to concentrate on adjusting crucial parameters to get the greatest results. In order to find the best possible output characteristics, DOE can also provide us the most ideal collection of parametric parameters. Additionally, based on the input values, the created mathematical model can be utilised as a prediction model to forecast potential output responses. DOE's ability to reduce experimentation time and expense is another key factor in its adoption. The way DOE works, the number of runs or experiments is decided before any real experimentation is carried out. We can save time and money by doing away with the need to repeat pointless trial runs. Most often, a mistake will occur during an experiment. While some of these may be avoidable, others are simply uncontrollable. We may continue the analysis while handling these problems thanks to DOE. When it comes to anticipating linear behavior, DOE is really good. DOE, however, does not necessarily produce the optimal outcomes when dealing with nonlinear behaviour.

3.3 Factorial Designs

3.3(a) Factorial designs overview

The simultaneous investigation of the impacts that various factors could have on a process is made possible by factororial designs. It is more time and cost effective to alter the variables simultaneously throughout an experiment than to do it one at a time.Additionally, this enables the analysis of the interactions between the variables. Interactions are the driving force behind many processes. It may be required to conduct factorial experiments to find important interactions that would otherwise go unnoticed.

3.3(b) Screening designs

A vast number of potential input variables (factors) are present in many process development and manufacturing applications. The total number of input variables can be reduced via screening, which concentrates on the most important input variables or process conditions that affect product quality. This lowering allows the process improvement efforts to concentrate on only a few key components.Screening may also make recommendations for the "best" or "optimal" settings for various components. Afterward, optimisation tests might be used to identify the ideal values. In the business world, it is common practise to "screen" for critical parameters that influence process output measures or product quality using Plackett-Burman designs, two-level full factorial designs, and fractional factorial designs. The use of general complete factorial designs (designs with more than two levels) is appropriate for small screening inquiries.

3.3.1 Full factorial designs

Responses to each combination of the experimental factor values are assessed in a full factorial experiment. The combinations of factor levels serve as the contexts for the evaluation of replies. Each of the experimental conditions is referred to as a "run," and the measurement of the reaction is referred to as a "observation." The entire set of runs makes up the "design."

3.3.1(a) Two-level full factorial designs

There are just two levels for each experimental component in a two-level full factorial design. Every combination of these factor values is covered by the experimental runs. Even though two-level factorial designs are only able to study a small area of the factor space in depth, they still provide insightful information for only a few number of runs per component. due to the fact that two-level factorials can highlight significant themes that act as a roadmap for further investigation.

3.3.1(b) General full factorial designs

A broad complete factorial design allows for any number of levels for the experimental components. For instance, Factor A might have two levels, Factor B might have three levels, and Factor C might have five levels. The experimental runs encompass all possible combinations of these factor values. Employing generic complete factorial designs may be appropriate for small screening tests or optimisation inquiries.

3.3.2 Fractional factorial designs

An excessively high number of runs may result from measuring responses in a full factorial experiment at every possible combination of the factor values. For example, a two-level full factorial design with six factors requires 64 runs, while a design with nine factors requires 512 trials.

Save time and money by using designs that don't include all of the factor-level combinations. Factorial designs that omit one or more level alternatives are called fractional factorial designs. Minitab creates fractional factorial designs with two levels for up to 15 elements.

Fractional factorial designs are advantageous for factor screening since they reduce the number of runs to a reasonable level. A fraction of the whole factorial design is used in the runs that are conducted.

3.3.3 Plackett-Burman designs

The Plackett-Burman design is a common resolution III, two-level fractional factorial design for investigating the main effects. In a resolution III design, the principal effects are aliased utilizing two-way interactions. Minitab can create designs for up to 47 variables. The number of runs, which can range from 12 to 48 and are always multiples of 4, determines each design. There must be fewer factors than runs for this to be true.

3.4 Choosing a Factorial Design

The specifications for each trial run are laid forth in the layout or design. It covers the blocking system, randomization, replication, and factor level combinations. These specifics outline the experimental settings for each test run. It's important to note the response (observation) when carrying out an experiment under predetermined circumstances. Any experimental setup used to gauge a reaction is referred to as a run. Minitab supports Plackett-Burman designs, full and fractional two-level factorials, and complete factorials for more than two levels.

3.5 Taguchi Method

Taguchi's experimental design method is straightforward and easy to utilize in solving numerous technical challenges. It can be used to quickly uncover flaws in a manufacturing process using existing data or to narrow the area of a research endeavor. The Taguchi method also allows for the analysis of a wide variety of factors without requiring an excessive amount of experimentation. Furthermore, it allows for the identification of the critical parameters that have the largest impact on the performance characteristic value in order to run additional trials on these parameters while disregarding those with little influence.

Dr. Genichi Taguchi developed a meticulous statistical approach to improving products and processes. The strategy emphasizes moving the quality issue upstream, to the design stage, and preventing defects through process improvement. Taguchi has underlined the need of reducing variance as the primary technique for improving quality. Taguchi defines a product's quality level as the total loss sustained by society as a result of a product's inability to perform as intended and as a result of adverse side effects, including operating costs. Some loss is unavoidable from the moment a product is delivered to the buyer, and fewer losses result in more desired items. This loss must be measured in order to compare alternative product designs and manufacturing procedures. This is accomplished by employing a quadratic loss function. When undertaking manufacturing quality control, the producer frequently establishes a target value for the performance characteristic and a tolerance range around it. A desirable product has a performance characteristic value that falls within a tolerance range of roughly 3. When utilising the loss function as a quality metric, the focus is on the desired value of the performance characteristic, and departures from that value are punished. A larger deviation from the target number results in a greater loss of quality.

3.5.1 Signal-to-Noise (S/N) ratio

The desired value (mean) for the output characteristic and the undesirable value, respectively, are referred to as "signal" and "noise" in the Taguchi technique. the standard deviation. The S/N ratio measures the sensitivity of the controlled quality characteristic under inquiry to noise elements, which are uncontrolled external influencing factors. As a result, Taguchi uses the S/N ratio to calculate the quality feature that deviates from the ideal value. There are essentially two S/N ratios accessible, depending on the type of characteristic: Lower-the-Better and Higher-the-Better.

Smaller-the-Better

The smaller is better quality characteristic can be given as

$$\frac{S}{N} = -10\ log_{10}[y^2]$$

Higher-the-Better

The smaller is better quality characteristic can be given as

$$\frac{S}{N} = -10\ log_{10}\left[\frac{1}{y^2}\right]$$

Where y is the response value.

3.6 Analytical Hirerachy Process

Thomas L. Saaty, an American mathematician, created the Analytic Hierarchy Process (AHP) as a method for making decisions in the 1970s. AHP is a multi-criteria decision-making method that simplifies difficult choices into smaller, more manageable components to assist both individuals and organisations in reaching conclusions.

In the AHP method, a decision is divided into a hierarchy of criteria, sub-criteria, and alternatives. The hierarchy's various components are then compared pairwise. The relative importance of each piece in the hierarchy is represented using a scale of numerical values to achieve this. Although the procedure includes subjective comparisons and judgments, quantitative computations are also used to assure consistency and objectivity.

Many different industries, including business, engineering, healthcare, and public policy, frequently employ the AHP approach. It is especially helpful when there are several factors to take into account and the decision-makers have different tastes and viewpoints. In general, AHP offers a structured and systematic approach to decision-making that can assist both people and organisations in making more informed and efficient choices.

3.6.1 Steps involved in AHP

1. Identify the issue.
2. Expand the problem's goals or take into account all the players, goals, and results.
3. Determine the factors that affect the behaviour.
4. Organize the problem into a hierarchy of distinct levels, including the purpose, the primary criteria, the secondary criteria, and possible solutions.
5. Evaluate each component in the respective level by comparison, then calibrate it using a numerical scale. This calls for (n-1)/2 comparisons, where n is the number of elements and is taken into account along with the fact that all diagonal elements are equal or equal to "1," and the other elements are just the reciprocals of the preceding comparisons.
6. Calculate each criterion's or alternative's maximum Eigen value, consistency index CI, consistency ratio CR, and normalised values.
7. Decisions are made based on the normalised values if the highest Eigen value, CI, and CR are satisfactory; otherwise, the process is repeated until these values fall within the desired range.

3.7 Experimental Procedure

Nowadays, producers are more concerned with obtaining multiple performance qualities than just one. Although there are numerous multi objective optimisation methods available, the Taguchi quality loss $\left(L_{ij}\right)$ method approach has been employed in this work because, compared to other methods, it needs relatively little computing labour and yields findings that are incredibly accurate. The following are the steps in the process:

Step 1: Taguchi quality loss (L_{ij}) for the responses.

$L_{ij} = Y_{ij}^2$ For lower the better characteristics (LB)

$L_{ij} = \frac{1}{Y_{ij}^2}$ For higher the better characteristics (HB)

For maximazation, we use higher the better, For minimization, we use lower the better

Step 2: Normalization of the responses.

$N_{ij} = \frac{L_{ij}}{L^*}$, Where, L^* = max L_{ij}

Step 3: Construct a pairwise comparision matrix and assign individual weights fot the criteria.

Step 4: Consistency Inspection (0<CR<0.1)

The value of CR should lie between 0 and 0.1 then only the ratio will be valid.

Step 5: Calculation of Weight Normalized Values of Responses ($W_i N_{ij}$)

Step 6: Calculation of Taguchi quality loss function.

$T_{ij} = \frac{1}{n}\sum_{i=1}^{n} W_i N_{ij}$ Where, W is weights of the responses such that $\sum W_i$ = 1

Step 7: Using Taguchi and ANOVA, determine the ideal parametric levels and their significances.

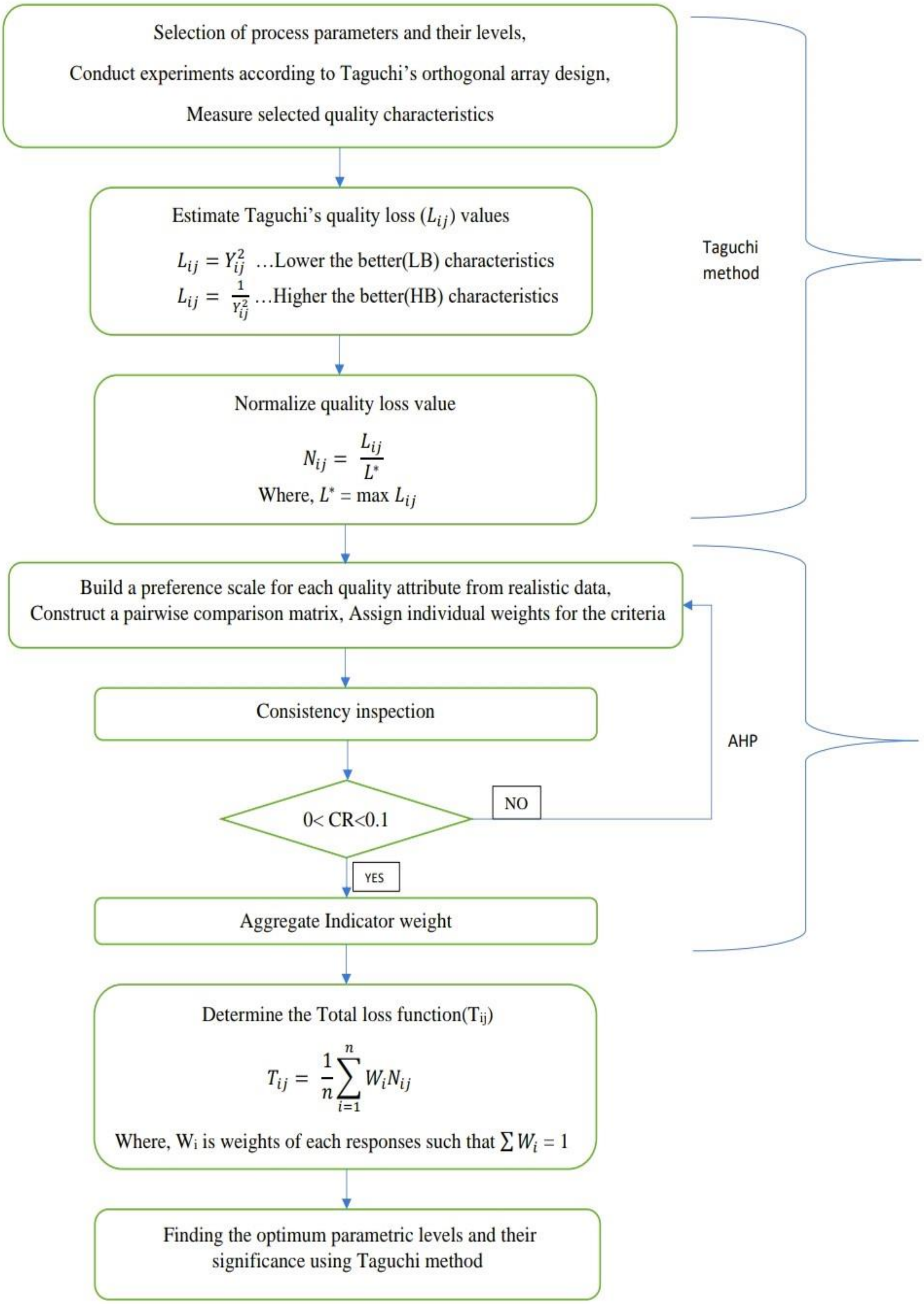

Figure 3. 1 : Methodology

CHAPTER 4

EXPERIMENTAL DETAILS

The experimental phases involved in the current work are clearly explained in this chapter. This includes selection of work material, selection of process parameters with their levels and selection of appropriate orthogonal array etc.

4.1 Selection of Work Material

In the current experiment, a brass electrode of 0.25 mm was used to machine medium carbon steel, AISI1040, 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. Tables 4.1 and 4.2 lists the chemical and mechanical characteristics of AISI1040 steel.

Table 4. 1 : Chemical Composition of AISI 1040

Element	Carbon	Silicon	Manganese	Sulphur	Phosphorus
%	0.36 - 0.44	0.10 - 0.40	0.60 - 1.00	0.05	0.05

Table 4. 2 : Mechanical Properties of AISI 1040

UTS (MPa)	YS (MPa)	Elongation (%)	Hardness
550	280	16	201-255

4.2.Selection of the Process Parameters and Their Levels

In an unusual process, choosing the proper combination of process parameters and defining the parameter range are crucial steps. Slight variations in the process parameters will have a negative impact on the accuracy and surface roughness of the machined components. In general, there are two categories of process parameters:

- Fixed parameters
- Controlled parameters

The tool geometry, work piece hardness, its mechanical characteristics, and the environmental conditions are taken into account in this study as fixed parameters that won't change throughout the investigation, whereas FP, T_{on}, T_{off}, WT, WF, and SV are thought of as controlled parameters that will change for each experiment. Table 4.3 lists the chosen process parameters for the experiment along with their upper and lower bounds, notations, and units.

Table 4. 3 : Fixed Parameters and Corresponding Levels

Process Parameter	**L - 1**	**L - 2**	**L - 3**
FP (kg/cm$^{2)}$	04	08	-
T_{off} (μs)	115	120	125
T_{on} (μs)	55	58	61
WT (kg-f)	02	04	06
WF (mm/min)	02	03	04
SV (volts)	20	25	30

4.3. Selection of Orthogonal Array (OA)

Taguchi has developed a design called orthogonal array it is used to study the entire design space with a smaller number of experiments. For the three parameters with mixed levels Taguchi standard L18 has been chosen and it is given in the Table 4.4

The L18 orthogonal array design is a type of experimental design used in statistical analysis. It is a specific type of Taguchi design that consists of 18 runs or experiments with different combinations of factors. The L18 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 18 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 L18 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 18 experiments, each with a different combination of factor levels.The results of these experiments are analyzed using statistical methods to determine the effects of each factor on the response. The L18 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. 4 : L18 OA Design

S.NO	FP (kg/cm^{2})	T_{on} (μs)	T_{off} (μs)	WT (kg-f)	WF (mm/min)	SV (volts)
1	4	115	55	2	2	20
2	4	115	58	4	3	25
3	4	115	61	6	4	30
4	4	120	55	2	3	25
5	4	120	58	4	4	30
6	4	120	61	6	2	20
7	4	125	55	4	2	30
8	4	125	58	6	3	20
9	4	125	61	2	4	25
10	8	115	55	6	4	25
11	8	115	58	2	2	30
12	8	115	61	4	3	20
13	8	120	55	4	4	20
14	8	120	58	6	2	25

15	8	120	61	2	3	30
16	8	125	55	6	3	30
17	8	125	58	2	4	20
18	8	125	61	4	2	25

WEDM's experimental setup is shown in Fig. 4.1. The necessary cut form is programmed into the CNC controller, and the control system makes sure the cutting operation is perfectly managed. Tester for surface roughness is shown in Fig. 4.2. The stylus measures any height changes or surface irregularities as it moves across the surface. In the following step, the instrument computes and displays the roughness parameters R_a, R_z, and R_q. Fig. 4.3 depicts machined workpieces with one experiment to be performed on each side. As a result, 18 experiments were performed using a total of 5 workpieces.

Figure 4. 1 : WEDM Experimental Setup

Figure 4. 2 : SJ301 Surface Roughness Tester

Figure 4. 3 : Machined Workpieces

CHAPTER 5

RESULTS AND DISSCUSSION

In this chapter the experimental results of Material Removal Rate (MRR) and Surface Roughness (R_a and R_z) are analyzed using Taguchi and Anova methods. The focus of the work is to identify the optimal combination of process parameters that concurrently maximizes the material removal rate and minimizes the surface roughness.

5.1. Experimental Results

To determine how the WEDM process settings affect the various performance characteristics, a total of 18 tests were conducted. Table 5.1 lists features of material removal rate and surface roughness that were measured. The values for Taguchi's quality loss were tabulated in Table 5.2 and the replies were later normalized, the results are shown in Table 5.3.

Table 5. 1 : Output Responses

S.NO	MRR (mm^3/min)	R_a (μm)	R_z (μm)
1	8.4204	2.5032	13.9056
2	7.2597	2.6216	15.2776
3	6.9008	2.4008	15.3151
4	7.8915	2.4237	14.1967
5	7.1902	2.4955	15.9591
6	7.3215	2.5658	16.3575
7	7.7430	2.4728	15.8616
8	8.8791	2.6294	16.6926
9	6.9232	2.6065	16.0197
10	8.3181	2.5323	15.3131
11	6.9764	2.5105	15.0291
12	7.7513	2.6403	16.0149
13	9.8805	2.7400	16.9233

14	8.4247	2.9679	16.9644
15	6.6119	2.6071	15.5482
16	9.1397	2.5923	16.6620
17	9.0195	2.7440	16.8876
18	7.4033	2.6909	16.698

Table 5. 2 : Quality Loss Function values (L_{ij})

S.NO	MRR (mm^3/min)	R_a (μm)	R_z (μm)
1	0.0141	6.2660	193.3657
2	0.0190	6.8728	233.4051
3	0.0210	5.7638	234.5523
4	0.0161	5.8743	201.5463
5	0.0193	6.2275	254.6929
6	0.0187	6.5833	267.5678
7	0.0167	6.1147	251.5904
8	0.0127	6.9137	278.6429
9	0.0209	6.7938	256.6308
10	0.0145	6.4125	234.4910
11	0.0205	6.3026	225.8738
12	0.0166	6.9712	256.4770
13	0.0102	7.5076	286.3981
14	0.0141	7.2787	287.7909
15	0.0229	6.7970	241.7465
16	0.0120	6.7200	277.6222
17	0.0123	705295	285.1910
18	0.0182	7.2409	278.8232

Table 5. 3 : Normalized Values (N_{ij})

S.NO	MRR (mm^3/min)	R_a (μm)	R_z (μm)
1	0.6159	0.8322	0.6719
2	0.8286	0.9128	0.8110
3	0.9170	0.7655	0.8150
4	0.7012	0.7802	0.7003
5	0.8447	0.8271	0.8850
6	0.8146	0.8743	0.9297
7	0.7284	0.8121	0.8742
8	0.5539	0.9182	0.9682
9	0.9111	0.9023	0.8917
10	0.6311	0.8517	0.8148
11	0.8972	0.8371	0.7849
12	0.7268	0.9258	0.8912
13	0.4473	0.9971	0.9952
14	0.6153	0.9667	1.0000
15	0.9989	0.9027	0.8400
16	0.5228	0.8925	0.9647
17	0.5368	1.0000	0.9910
18	0.7967	0.9617	0.9688

5.2 AHP Results

The weights of the individual criteria were discovered using AHP. The weights are calculated and discovered to be, W_{MRR} = 0.632, W_{Ra} = 0.258, and W_{Rz} = 0.105 respectively and CR = 0.04 < 0.1, λmax = 3.039. After determining the individual weights for the responses, the weighted normalized values of the responses are determined. The outcomes are listed in Table 5.5.

Table 5. 4 : AHP Results

	MRR (mm^3/min)	**R_a (μm)**	**R_z (μm)**
MRR	1	3	5
R_a	0.3333	1	3
R_z	0.2	0.3333	1

CR = 0.04 < 0.1 , λmax = 3.039

Table 5. 5 : Weighted Values

W_{MRR}	0.637
W_{R_a}	0.258
W_{R_z}	0.105

Table 5. 6 : Weight Normalized Values of Responses

S.NO	**MRR (mm^3/min)**	**R_a (μm)**	**R_z (μm)**	**Total Quality Loss(T_{ij})**	**SN of T_{ij}**
1	0.3923	0.2147	0.0705	0.2259	12.9233
2	0.5278	0.2355	0.0852	0.2828	10.9699
3	0.5841	0.1975	0.0856	0.2891	10.7800
4	0.4467	0.2013	0.0735	0.2405	12.3779
5	0.5380	0.2134	0.0929	0.2815	11.0119
6	0.5189	0.2256	0.0976	0.2807	11.0349
7	0.4640	0.2095	0.0918	0.2551	11.8660
8	0.3528	0.2369	0.1017	0.2305	12.7479
9	0.5804	0.2328	0.0936	0.3023	10.3924
10	0.4020	0.2197	0.0856	0.2358	12.5503
11	0.5715	0.2160	0.0824	0.2900	10.7530

12	0.4630	0.2389	0.0936	0.2651	11.5305
13	0.2849	0.2572	0.1045	0.2156	13.3287
14	0.3919	0.2494	0.1050	0.2488	12.0839
15	0.6363	0.2329	0.0882	0.3191	9.9207
16	0.3330	0.2303	0.1013	0.2215	13.0919
17	0.3419	0.2580	0.1041	0.2347	12.5912
18	0.5075	0.2481	0.1017	0.2858	10.8792

5.3 Taguchi Analysis

Using MINITAB-17 Software, the Taguchi method has been used for the analysis. Taguchi analysis was performed on the responses using the Lower-the-Better characteristic. The findings of the Taguchi analysis are shown in Table 5.6. The main effect plots are shown in Fig. 5.5 and were produced using the mean values of the process parameters. From the plot we can deduce that for the process parameters FP, T_{on}, T_{off}, WT, WF, SV the optimum levels found at Level 2, Level 3, Level 1, Level 3, Level 3, Level 1 respectively.

Table 5. 7 : Taguchi Analysis: T_{ij} versus FP, T_{ON}, T_{OFF}, WT, WF, SV

Level	**FP** (kg/cm$^{2)}$	**T_{on}** (µs)	**T_{off}** (µs)	**WT** (kg-f)	**WF** (mm/min)	**SV** (volts)
1	0.2654	0.2648	0.2324	0.2687	0.2644	0.2421
2	0.2574	0.2644	0.2614	0.2643	0.2599	0.2660
3	-	0.2550	0.2903	0.2510	0.2598	0.2760
Δ	0.0080	0.0098	0.0580	0.0177	0.0046	0.0340
Rank	5	4	1	3	6	2

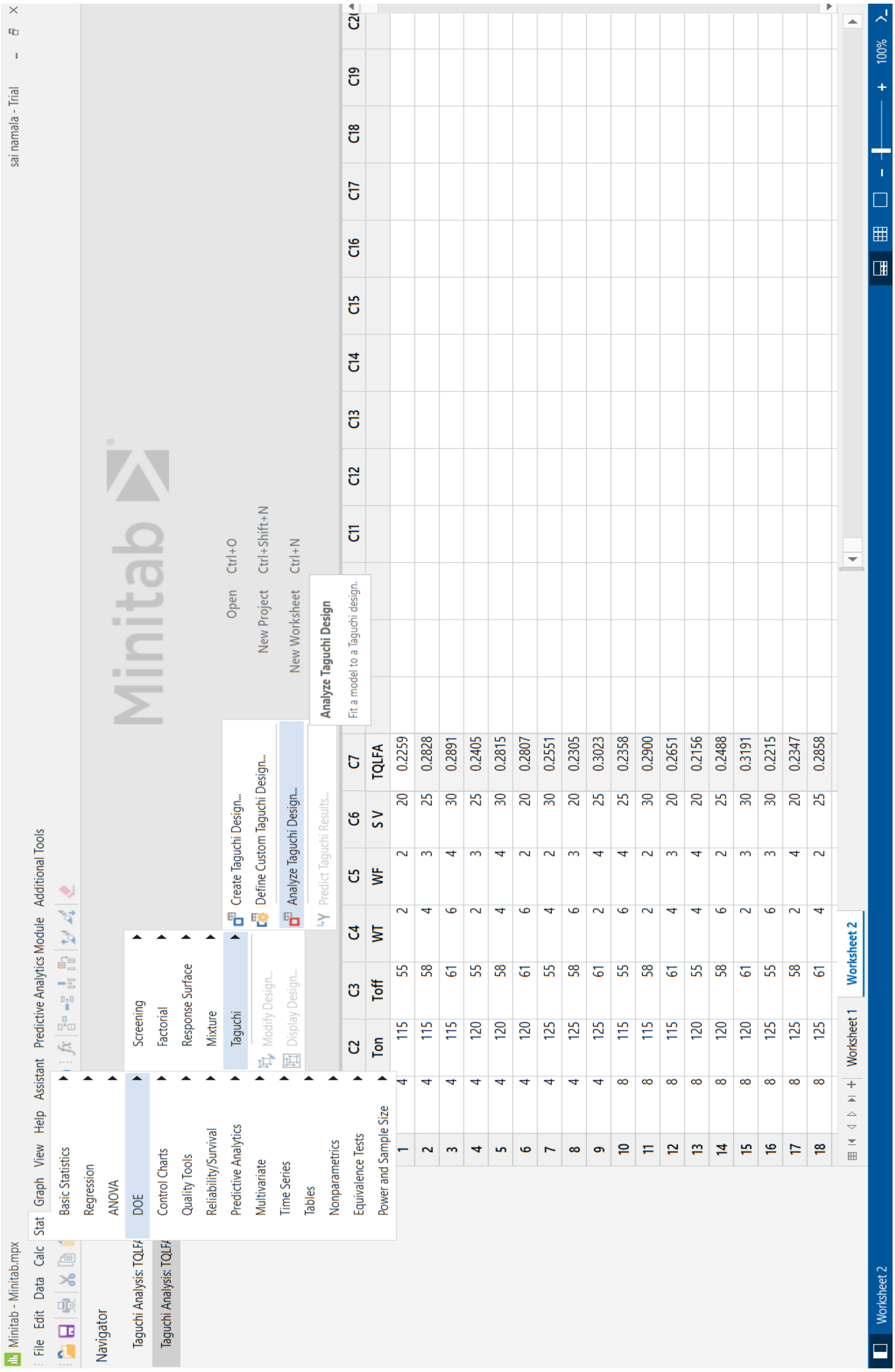

Figure 5. 1 : Taguchi analysis

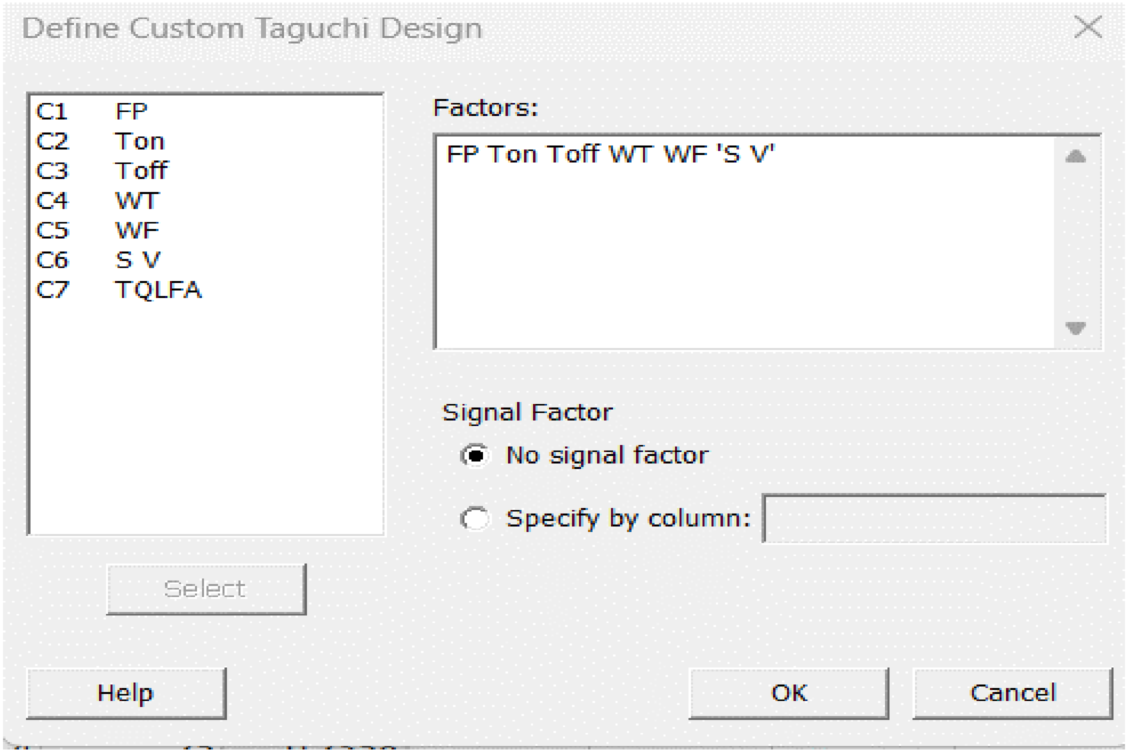

Figure 5. 2 : Input Factors

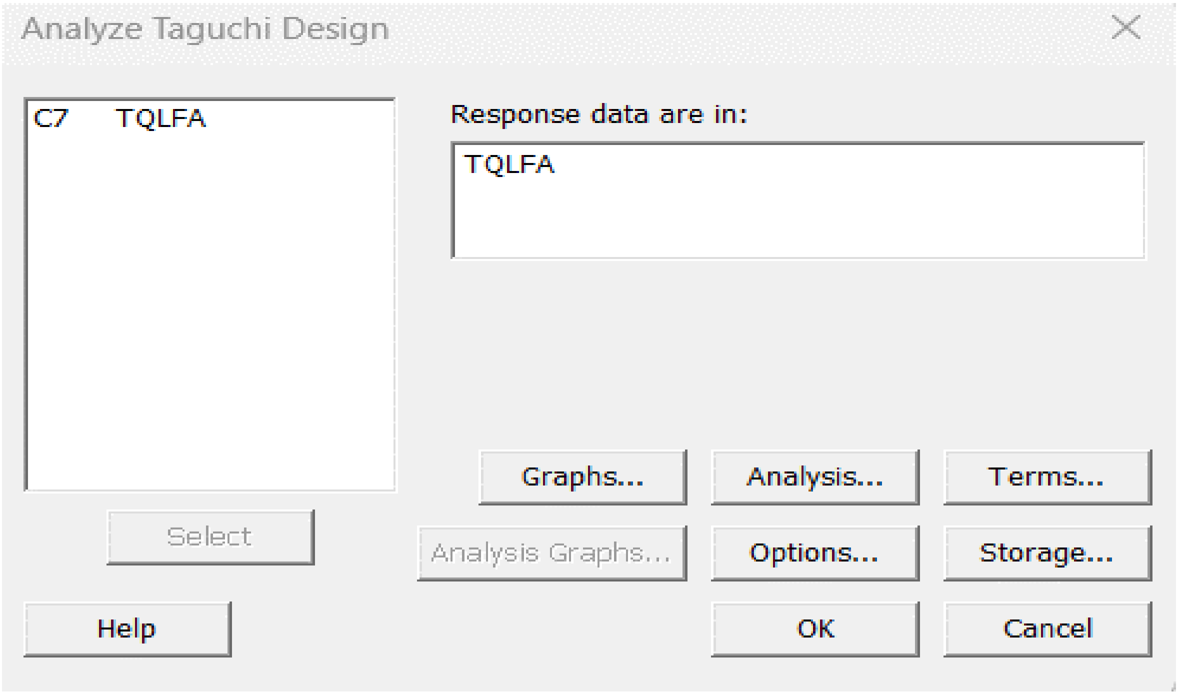

Figure 5. 3 : Output Responses

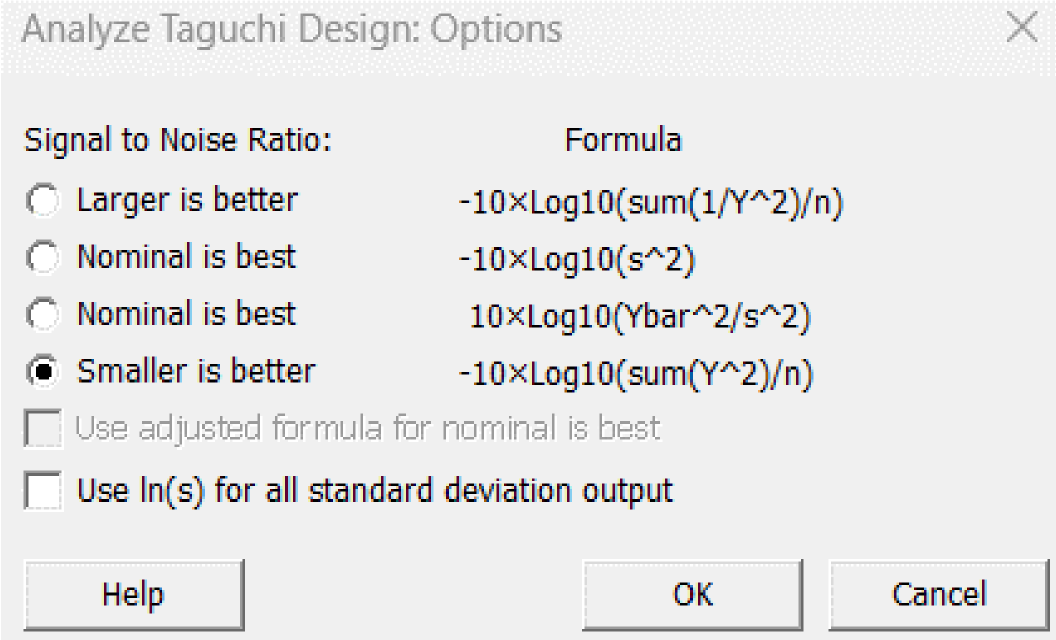

Figure 5. 4 : Selection of SN Ratio

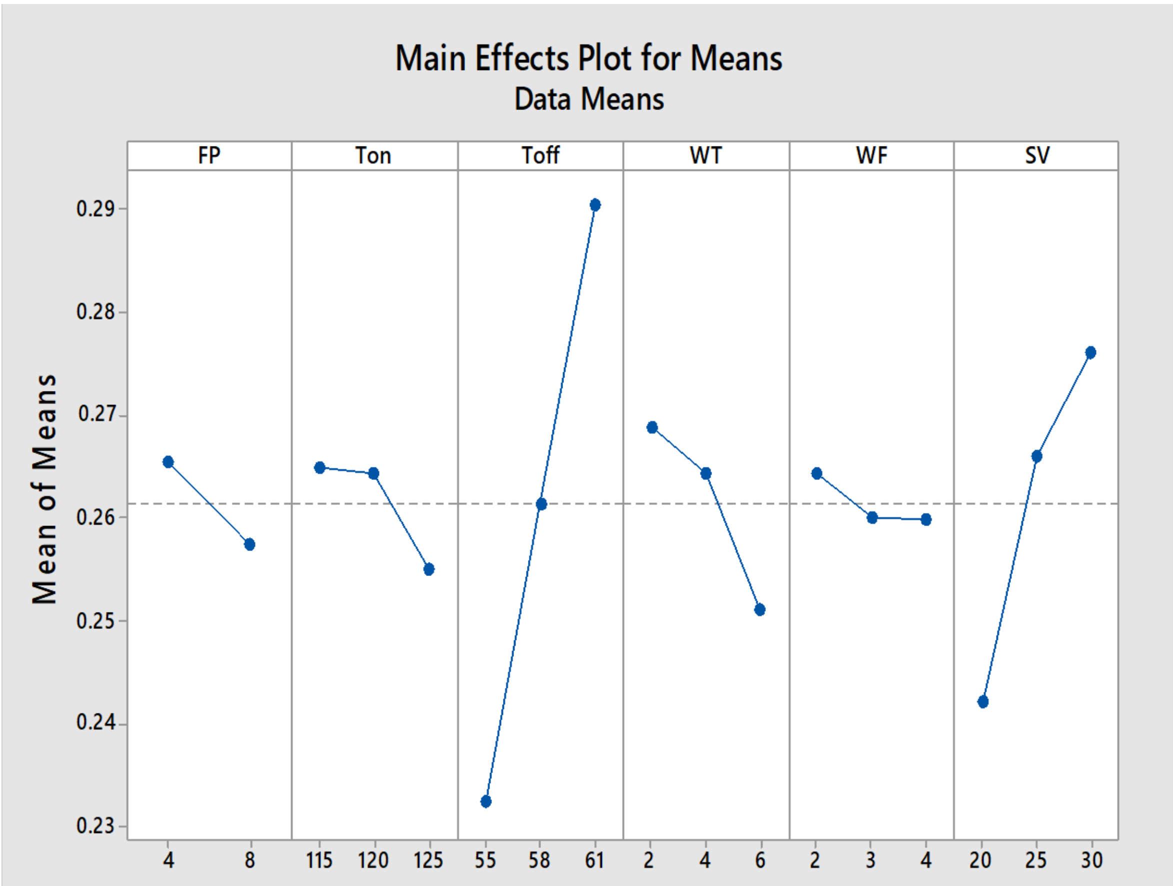

Figure 5. 5 : Main Effect Plots for Means of T_{ij}

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 Conclusions

The workpiece AISI 1040 Steel has been machined using Wire EDM process with help of brass electrode. For this, ANOM and S/N ratio analysis have been used for providing the best values of the quality loss function. Taguchi method and AHP method has been adopted for the design of experiments.

In this study, the suitable cutting process parameters for material removal rate and surface roughness for the workpiece AISI 1040 have been measured.

From the experimental results on WEDM machining, the following conclusions can be drawn:

- Pulse-off-time is found to be the most influencing control parameter in affecting the multi-responses.
- Wire Feed is found to be the least influencing control parameter in affecting the multi-responses.
- The optimal setting of process parameters was obtained at FP: Level-2, 8 kg/cm^2; T_{ON}: Level-3, 125μs; T_{OFF}: Level-1, 55μs; WT: Level-3, 6 kg-f; WF: Level-3, 4 mm/min; SV: Level-1, 20 volts respectively.
- The proposed methodology can be effective for employing/solving multi-objective optimization problems efficiently.

6.2 Future Scope of Work

The current work focuses on the optimization of wire EDM process parameters in the machining of AISI 1040 with a brass electrode wire (0.25 mm) has been done by using Taguchi based utility method and AHP.

For further extension of the work we can conduct the experiments by the following methods.

1. We can conduct the experiment by changing the electrode wire type i.e.; copper, graphite, silver, molybdenum and tungsten.

2. We can conduct the experiment by changing the shape of wire i.e.; rectangular,spherical.

3. We can conduct the experiment by using different coated wires i.e.; zinc, cadmium, tin, lead, antimony, bismuth or alloys.

4. We can conduct the experiment by considering the parameters which were fixed in this work like dielectric type, flushing pressure, Peak current.

5. We can also conduct the experiment by changing the work piece material, Duty cycle, frequency, work piece thickness, electrode wire diameter etc.

6. We can also determine the effect of WEDM process parameters on the residual stresses developed during machining.

CHAPTER 7

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