STUDY OF POWDER MIXED WIRE ELECTRO-DISCHARGE MACHINING OF Ti6Al4V ALLOY

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“STATEMENT OF ORIGINALITY”

I Shri Sadananda Chakraborty registered on 31st May 2018 do hereby declare that this thesis entitled “**Study of powder mixed wire electro-discharge machining of Ti6Al4V alloy**” contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

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PREFACE

Due to broad application in manufacturing sectors, wire electric discharge machining (WEDM) has become a widespread non-traditional method for machining of technically advanced materials. The process is also extensively used for versatile capability in making irregular through cutting geometry of hard and tough material like Ti6Al4V. In the thermal-assisted WEDM process, the surface of the machined area is greatly affected by transforming the surface morphology, i.e. crater, recast layer, and HAZ zone. But the critical importance based upon precision manufacturing; negative feedback is always reduced by implementing advanced techniques in the WEDM process. In terms of mixing powder particles in the dielectric, the performance efficiencies not only improve, but the WEDM process can also reduce the overall cost of production. Very few attempts were explored the machinability criteria of alloy by adding multiple powders with a dielectric in the WEDM process. Some reports are focused on the effect of different dielectrics in EDM as well as the WEDM process. In this study, the powder mixed wire EDM (PMWEDM) process is employed to enhance the machining ability, such as metal removal rate, surface topography, and dimensional accuracy (corner accuracy) of the tough alloys.

The contents of the thesis work have been presented through chapter 1 to 6 in a well designed manner. Chapter 1 outlines an overview of wire electric discharge machining processes, material removal mechanism, applications and technological parameters involve in this machining process. The new approach of powder mixed in dielectric along with working principle has been introduced. The role of dielectric and wire electrode along with their applications, are discussed in this chapter. Comprehensive evaluations of prior research are integrated and examined to identify the current gaps in knowledge, which are then emphasized in this chapter to define the research objectives.Chapter 2 explains the operational features of WEDM machine and experimental setup and measurement instruments used in the present set of research.

The impact of powders and dielectric has been discussed elaborately, and the problem statement has been highlighted in chapter 3. This chapter contains an overview for considering different powders and their properties used in the WEDM process. The influence of different dielectrics has been analyzed on the response measures such as material removal rate, surface roughness and dielectric consumption. Apart from this, the hazard and operability (HAZOP) study is established for improving production quality, lower cost, safety process and pollution towards the environment during WEDM operation.

The parametric study and optimization of machining outputs in PMWEDM process have been explained in chapter 4. The influence of the control factors on the WEDM process performance has been studied through response surface methodology. After process modelling, multi-objective optimization, particle swarm optimization (PSO) coupled with the GRA approach, is also carried out to find out the optimized combinations of process parameters for achieving desired dimensional accuracy of PMWEDM. 3D and 2D topography of machining surfaces have been analyzed in the present investigation. The machined surface is examined through the scanning electron microscope.

Chapter 5 includes a comparative analysis of PMWEDM process parameters on the considered responses on Ti6Al4V material by PMWEDM process. The sensitivity analysis has been conducted to find out the most hazardous inputs which affect on WEDM outputs. The most influence of powder in dielectric during corner operation has been reported. SEM figures are also analyzed and highlighted an enhancement in machined surface geometry in the presence of powder in dielectric fluid. The corner accuracy in the WEDM process is compared with powder mixed WEDM in this chapter. In chapter 6, the general conclusions from the the present research work have been drawn in detail.

It is believed that the present research outcomes will provide a lot of knowledge to the elementary, practical researchers and production engineers for proper understanding of the numerous input variable influences along with new approach of powder mixed wire electrical discharge machining. The study also provides an appropriate direction and guideline to the manufacturing engineers for satisfying their present needs and precision manufacturing of intricate profiles for advanced manufacturing industries.

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For my parents and beloved wife

STUDY OF POWDER MIXED WIRE ELECTRO-DISCHARGE MACHINING OF TI6AL4V ALLOY

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CHAPTER: 1

INTRODUCTION

1.1. General Statement of Wire Electric Discharge Machining (WEDM)

Introducing cutting-edge manufacturing process technology aimed at precision machining of highly durable and resilient metals and alloys, with the goal of producing macro and micro parts to enhance performance quality, necessitates a profound understanding of the distinctive attributes and failure analysis of unconventional machining processes. Among all the non-conventional processes, electric discharge machining is mostly recognized and is considered an ideal method for its applicability in the most advanced manufacturing industry for machining different electrical and thermally conductive materials and superalloys. Even quite low conductive material and highly exquisite portions are also machined through the EDM process.

Since 1940s, many inventions of electric discharge machining have been done to improve the machining performance and stability of the EDM process. Process stability is the key factor for turning a natural material removal process into a controllable machining process. Due to continuous process improvement, many EDM machines have become so stable that they can be operated around the clock if monitored by an adaptive control system. The demand for high machining precision with low surface roughness characteristics has become significant.

The wire electric discharge machining process has provided a wide range of flexibility and consistency to machining complex shapes in contours through cutting circular, blind complex cavities, non-circular holes and generating tapered parts [1]. WEDM has extreme potential to meet the requirement of successfully solving the manufacturing problem where other machining processes are failed. Despite its extensive capability, some fault existences are always present during machining in WEDM operations.

1.1.1. Necessity of WEDM

With the recent development of precision technology, the WEDM process has been established for fulfilling industrial requirements with high machining accuracy and relatively small restricted circumstances. WEDM process is one the most cost-effective techniques for processing hard, tough and conductive metal and alloy. It becomes more popular machining process for its wide range of industrial applications.

Some advantages of the WEDM process are given below:

1. No impact of cutting force: WEDM is a non-traditional machining process where a sufficient amount of gap should be maintained during operation. Due to this, no shearing action is found in the machining channel.
2. Enhancement of product efficiency: A typical range of 0.03 to 0.35 mm metal wire produced high tolerance parts without deformation of the job piece very smoothly; as a result, better product efficiency can be achieved.
3. Higher processing range: Any type of conductive material can be machined by the WEDM process where the machining responses are not affected by the harness properties. Now a day very low conductive materials are also machined by WEDM process.
4. High security and environment friendly: The dielectric fluid of the WEDM process is a non-flammable liquid which keeps the machining zone safe. Built-in induction and the intelligent control system improve the easiness of use.
5. Machining of complex parts: Wire EDM can easily machine precise and complex curve shapes with lower surface roughness.
6. Save the cost of the product: Processing high hard material using conventional methods is challenging and requires higher cost cutting tool material. But wire EDM process takes less time and money to shape the job. In addition, the wastage of material from the job piece is less, and no heat treatment is required; as a result cleanup process can be reduced.

1.1.2. Basic Material Removal Mechanism

The process of electrical discharge machining consists of two electrodes maintaining a gap where a channel of dielectric fluid flow bridges the electrodes. A schematic view of wire cut EDM machine is illustrated in Figure 1.1. A series of discrete electrical sparks are generated when a voltage is employed to the electrodes. Electrical energy is converted into spark energy, which is then used for the evaporation of the metal. The electrical sparks can rapidly heat the metal, leading to its evaporation. The spark generation only happens when the gap between the electrodes is less than at which the energy of the free electrons moving towards the positive terminal can break the work function or ionization energy of the dielectric molecule.

Consequently, the dielectric channel between the two electrodes acts as ionized plasma due to the extremely high concentration of electrons. A voltage near around 30 to 250 volts is applied between the electrodes with a density in the range of $10^{5\sim7}$ volts per meter. The sparking frequency is normally up to 50 kHz, and the spark gap between tool and electrode is in the range 25 µm -50 µm. The plasma holds a very high temperature between 8000 °C to 12,000 °C and may be too high as 20,000 °C, which in turn starts extreme heating and melting and even evaporation of the surfaces of the electrodes.

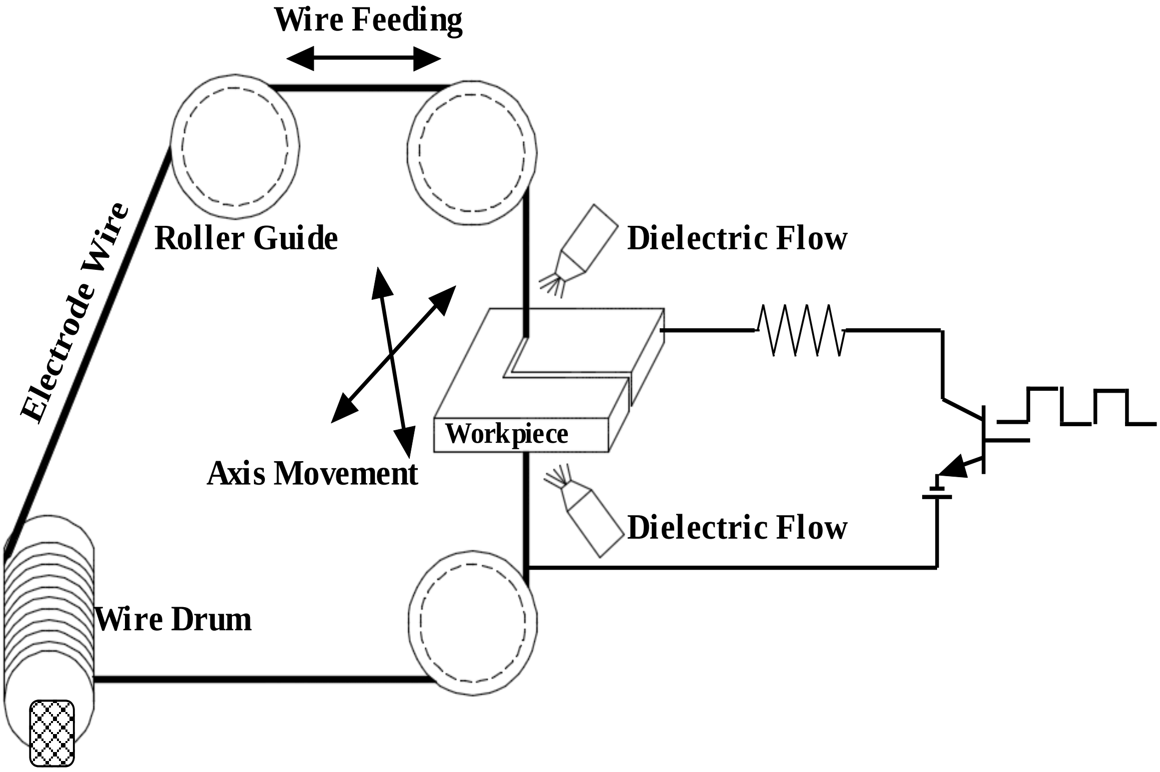


Figure 1.1. The kinematics of WEDM process.

As soon as the discharge through the electrodes gets stopped in the charging stage, a sudden reduction in temperature occurs in both electrode surfaces. This is due to unavailability of the potential difference between the poles. Consequently, the molten metal solidifies on the surfaces, making a white recast layer on the machined surface and the metal droplets become solidified micro-size craters. The recast layer exhibits more hardness than the parent material. At the same time, the sudden collapsing of the plasma channel creates a shock wave which imparts the molten metal forming a crater. The dielectric also plays a major function in purging the melt material from the inter-electrode gap. The material removal mechanism of WEDM process is presented in Figure 1.2.

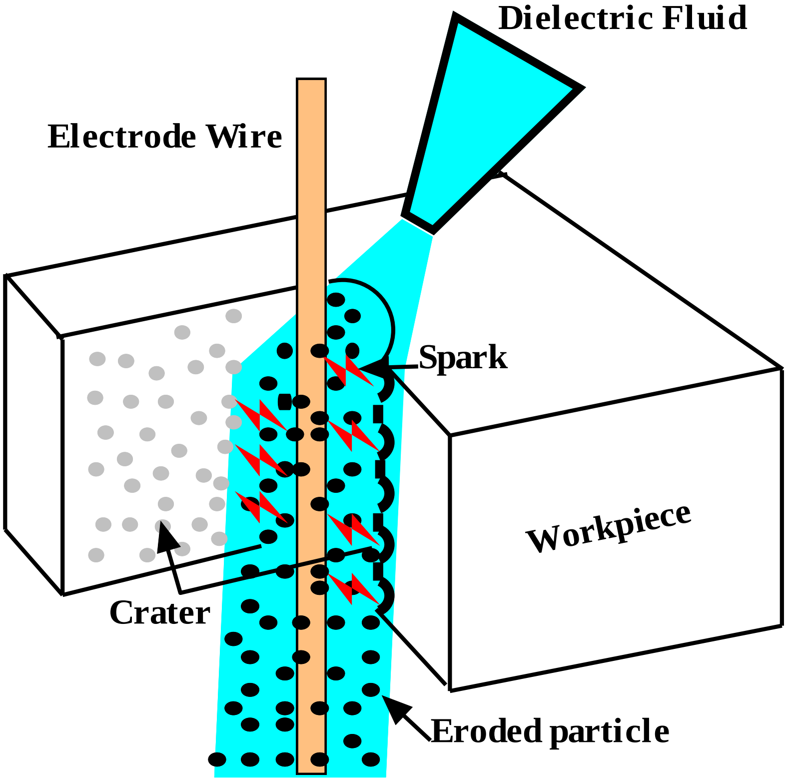


Figure 1.2. Material removal mechanism of WEDM process

1.1.3. Statement of the Technological Parameters

The new engineering materials have greater thermal, chemical, and mechanical properties, making it impossible to machine by traditional machining processes. This is because conventional machining is often based on removing material using tools harder than the workpiece. The higher machining cost of ceramics and composites and the damage accumulated during machining are significant obstacles to implementing these materials. In addition to the advanced materials, more complex shapes, low-rigidity structures, and micro-machined components with tight tolerances and fine surface quality are often needed. Traditional machining methods are often ineffective in machining these parts. To meet these demands, new processes are developed. These processes are called 'Modern Manufacturing Process' or 'Non-Traditional Process. EDM and WEDM are the most important machining process which meets the greatest requirement in industrial application.

Complications have been envisaged in the form of the technical factors that lead to the electric discharge machining process. Two broad classes of generators, commonly known as power supply units, are employed on electric discharge machines: the RC circuits and the transistor-controlled pulses.

In the RC circuit's category, the main restrictions to select from setup time are the resistance and capacitance of the resistor and capacitor. In an ultimate condition, both delivered maximum current in a single discharge. The RC circuit generator provides shorter time durations of the discharges more easily than the pulse-controlled generator. Moreover, the open-circuit voltage can be recognized as the steady state voltage of the RC circuit [2].

A train of voltage pulses is delivered to the electrodes in generators based on transistor control. Each pulse can be measured in shape, for occurrence, quasi-rectangular. In specific conditions, the time can be set between two successive pulses and the duration of each pulse. The amplitude of each pulse establishes the open circuit voltage. Thus, a pulse voltage pulse duration is similar to the maximum discharge duration. Ferriet et al. [3] proposed a framework to describe and measure the electrical input parameters during an electric discharge machining directly on inter-electrode volume with an oscilloscope external to the machine. Authors conducted their investigation in the field of micro-EDM, but it can be applied to any EDM process.

During the WEDM process, performance measures such as cutting speed, material removal rate and surface topography on machined face are greatly influenced by the pulse discharges. A narrowest gap of 25µm-50µm [4] is maintained between electrode and workpiece where a high frequency discharge pulse is established to erode the material from the workpiece in the dielectric medium. The control part of this mechanism is delivered by controlled pulse generator. Figure 1.3 has been illustrated that pulse generator can contribute short peak current and idle time, and desired length of pulse. It can allow one to select either rough machining condition i.e. higher energy or lower spark frequency, or finish machining condition i.e. higher frequency and lower energy.

The discharge pulses are categorised into five major forms: spark, arc, off, short and open pulses [5]. All forms are based on the time evaluation of the gap voltage and current. A spark pulse is an active and the most desirable discharge with an ignition delay time (t_d). Arc pulses are recognized by ignition delay discharges. Voltage or current (in narrowest gap) is not detected in 'off' pulses. Although arc pulses have a better material removal rate (MRR) compared to spark discharges, spark discharges achieve a better surface quality than arc pulses. Also, arc pulses promote wire breakage due to higher thermal load. Only this reason, arc pulses are not desirable. A short pulse signifies a current, which passes through by establishing direct contact or metal particle bridge between wire electrode and workpiece. The discharge between the wire electrode and workpiece does not occur in open circuit pulses. Hence, the energy is continuously collected in the electrodes for a discharge to take place. Therefore, concerning the effect on the MRR, normal is the best pulse than arc, which is the next best, whereas short and open are the worst pulses.

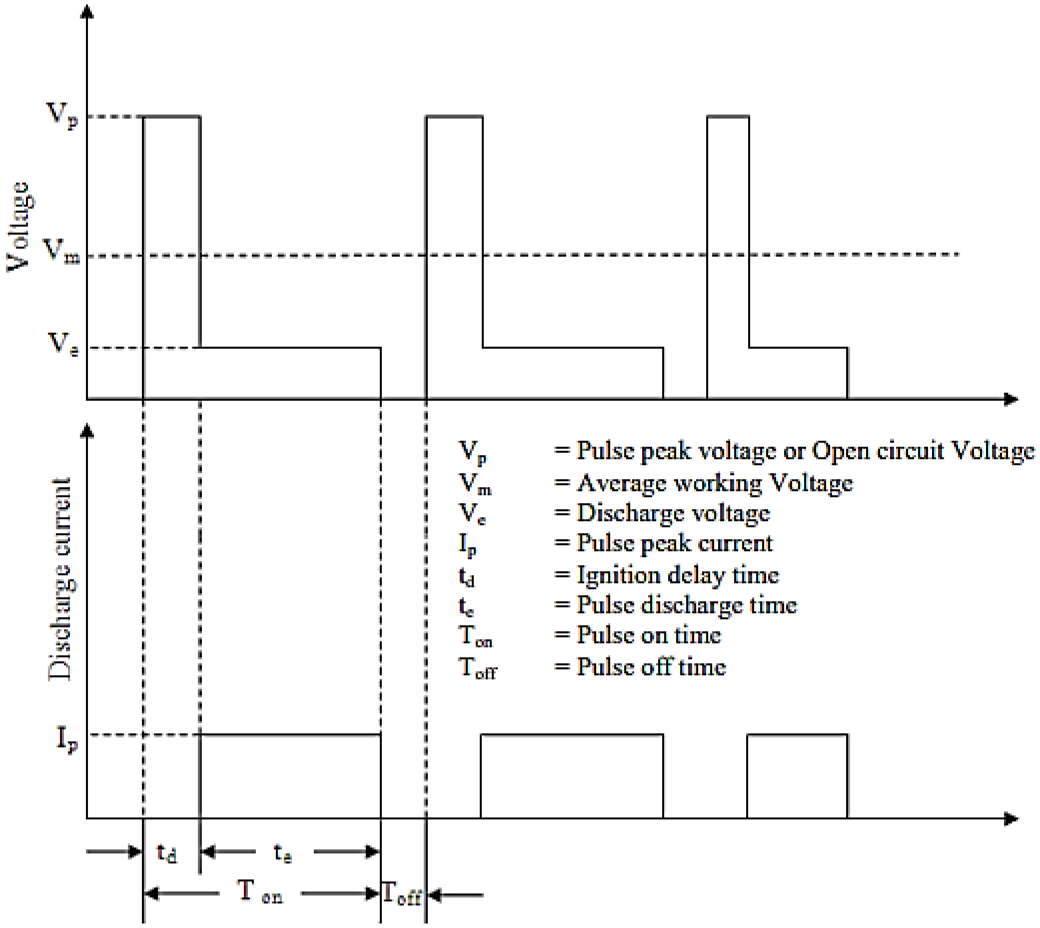


Figure. 1.3. Pulse parameters in an Iso-Energetic WEDM system [6]

The time between the applied voltage between electrode and workpiece, and the start of ignition is known as Ignition delay time (t_d). This is a WEDM process parameter inversely proportional to the electrical field strength at the spot of spark discharge and relates to physical circumstances in the gap. Due to this, it is considered as an online process evaluation parameter for the adaptive control system in WEDM [7-8]. The breakdown strength of the dielectric also influences the delay time. The delay time decreases with a set of lower dielectric breakdown strength values. Also, a lower value of delay time is achieved with an increase in the contamination level of the dielectric with the same gap width. A large variation of delay time for every pulse may be found at conditions even in stable conditions. Several researchers [9-11] have shown that average delay time decreases with an increase in tool wear rate and a decrease in MRR. Experimentally confirmed that pulses exclusion with very short ignition delay does not produce any enhancement in machining outputs. The surface topography made by wire electrical discharge machining is relative to material removal per discharge. It is determined by pulse energy per discharge.

The pulse energy per discharge can be determined by using the following equation [11]:

$$E = \int_{0}^{t_0} u(t)\, i(t) dt \tag{1.1}$$

Where $t_{0,}$ u(t), i(t) and E are termed as discharge duration, discharge voltage, discharge current and pulse energy per discharge, respectively. Since the discharge voltage u(t) stays almost constant during the discharge, the pulse energy per discharge is obtained by the pulse duration and discharge current.

1.1.4. Role of Dielectric Fluid

Dielectrics are electrically non-conductive in nature. When a particular potential difference is applied, it acts as a conducting medium. In the WEDM process, the dielectric fluid act as a spark conductor, amalgamating the spark energy to an extremely short gap [12]. Rapidly a spark discharge takes place. The dielectric becomes a non-conductive medium upto breakdown voltage. The concentrated potential difference of a dielectric (without breakdown) is defined as the dielectric strength.

The critical importance of the dielectric in WEDM operation is as follows:

(i) One crucial function of the dielectric is to insulate the workpiece from the electrode. The disruptive discharge ought occur across a spark gap that is as narrow as possible.

(ii) It flushes the debris particles from the machining gap to avoid short circuits and provides an environment for the next spark generation.

(iii) It compresses the bubble formation in the plasma channel.

(iv) It acts as a medium in which kinetic energy is converted into thermal energy, resulting in the evaporation of workpiece material.

(v) The dielectric ought to constrict the spark path as much as possible so that high energy density is achieved, increasing discharge efficiency simultaneously.

(vi) The dielectric must cool both the electrode and the workpiece. To avoid wire rupture, overheating the electrode must be avoided in the WEDM process.

The following essential requirements for selecting a suitable dielectric in many applications:

(i) It should have a particular stable dielectric strength to meet the process requirement.

(ii) It should deionize rapidly as soon as the spark discharge take place.

(iii) It should have tow velocity and a good wetting capacity.

(iv) It should be chemically neutral so as not to attack the wire-electrode, the work piece, the worktable or the dielectric container.

(v) The flashpoint of the dielectric must be sufficiently high to avoid any fire hazards.

(vi) It should not emit any toxic vapour to provide eco-friendly machining outputs.

1.2. **Powder Mixed Wire EDM (PMWEDM)**

The most augmentation of EDM process capability is termed as Powder mixed wire Electric discharge machining (PMEDM), which provides both mechanical and thermal interactions while machining to increase the efficiency of the process. It is also a revolutionary technique for achieving high accuracy. The electrically conductive powder is mixed in dielectric fluid, which works as an insulator that causes high MRR. At the same time, powder mixed dielectric modified the plasma channel and increased the spark gap between tool and electrode, causing easy removal of the debris particles; as a result, a superior surface finish is produced. Also, this process improves the surface characteristics of the machined surface.

Cause and effect diagram of process and performance measures of PMWEDM is highlighted in Figure 1.4. Plenty of metal powders and abrasives are used for developing the desired output of PMWEDM i.e. MRR and SR. It is essential to achieve better dimensional accuracy in the modern industrial application point of view. Moreover, the effect of significant process parameters such as pulse on time (T_{on}), pulse off time (T_{off}), peak current (I_p) and gap voltage (Vg), wire feed (WF) etc. along with the powder characteristics such as powder particle size and its concentration in dielectric plays a vital important role for efficient machining in wire electric discharge machining [13]. Analysis of surface topography, surface roughness, recast layer, and elements of the machined surface are also essential to fulfilling the requirement of desired surface quality.

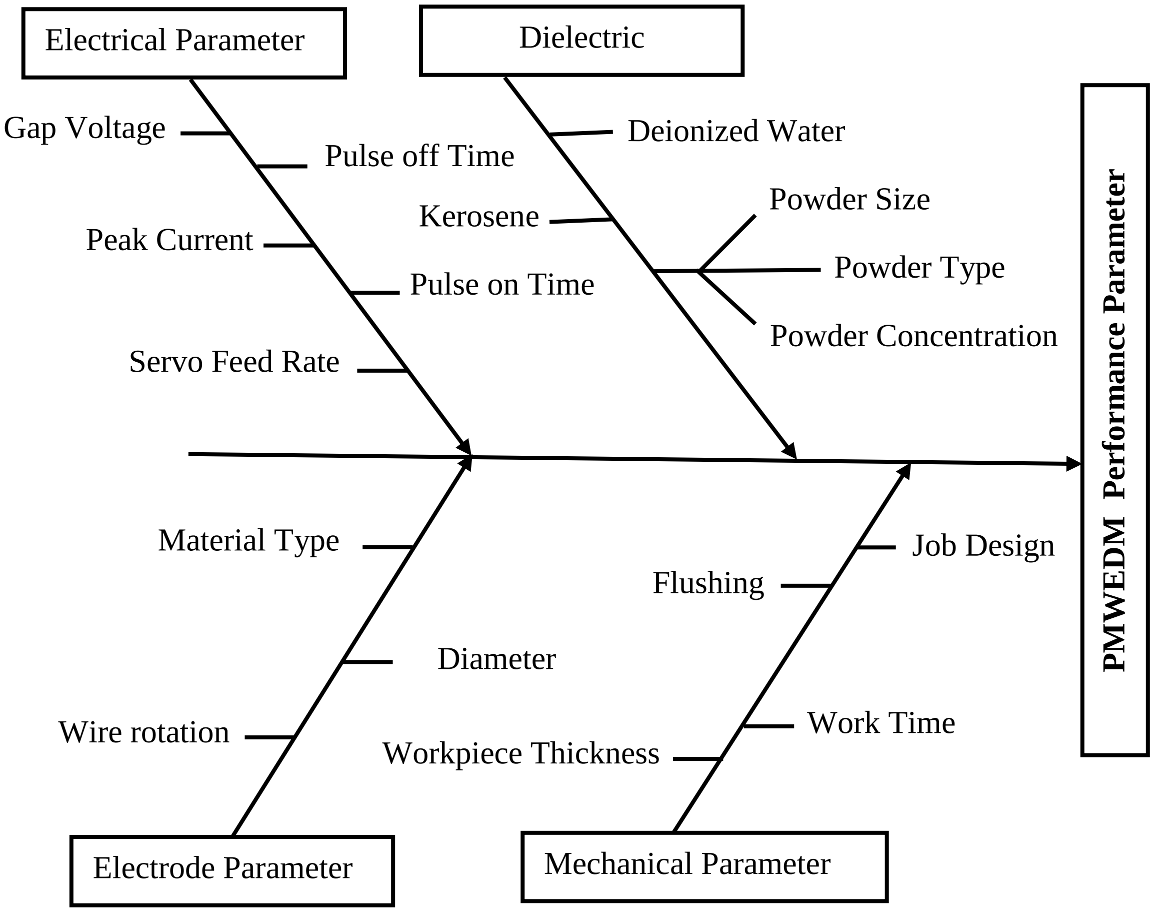


Figure 1.4. Effect of various input variables enhancing the WEDM performance

On the machined surface, the white recast layer has micro cracks which reduces microhardness, fatigue, corrosion and wear resistance of the parent metal. As referred in, those machined components are desirable to go further under some surface modifications or treatment processes, such as ion implantation, laser surface treatment for improving surface roughness, hardness, corrosion resistance etc. These costly secondary processes can be avoided if the surface alloying or modification could be done in EDM. Mixing powder in the dielectric is one of the means of alloying the machined surface. In the potential field, the hydrocarbons and present metal molecules are ionized. The metal ions may be found in the free form or carbide form as the hydrocarbons breakdowns under the potential field.

1.2.1. *Working Principle of PMWEDM*

Powder mixed wire EDM is a hybrid machining process with a different mechanism than conventional EDM. Due to the thermal and mechanical interaction, the process becomes more efficient. In this process, appropriate metals or abrasives are added with dielectric. A stirring system is used in the dielectric tank for better circulation of the powder. This system helps to reuse the powder simultaneously. The separation of debris particles is done by magnetic force.

PMEDM is a quite complex process than the conventional process. A better discharge distribution by the powder particles causes low surface roughness and high MRR. When sufficient voltage is applied between tool and workpiece, maintaining the gap 05 μm -25 μm, an electric field (10^5–10^7 V/m) is generated. The powder particles are energized by the supply voltage and act as conductors. These conductive particles rapidly break down and widen the gap between the electrode and workpiece. During that period, the particles organized themselves in a chain-like structure, resulting in a bridging effect depicted in Figure 1.5. This bridging effect caused a reduction in the dielectric's insulating ability. Consequently, a sequence of discharges led to an initial explosion. The faster erosion of the work material contributed to achieving a high Material Removal Rate (MRR). The large gap in the plasma channel helps to distribute uniform sparking; as a result, thin craters and a shallow recast layer on the machine surface are generated, showing the smooth surface finish.

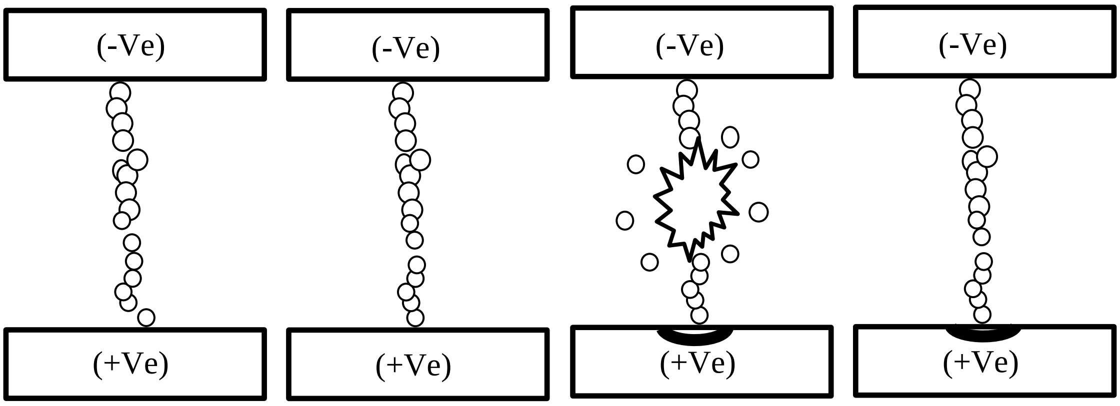


Figure 1.5. Bridging effect in powder mixed EDM [13]

1.2.2. *Powders Used in PMWEDM Process*

The character of the additive, in the form of powders, is typical and complex, as many researchers reported. A model of plasma channel with input parameters of PMWEDM has been illustrated in Figure 1.6. The process efficiency of Additive-mixed electro discharge machining (AEDM) depends upon the type of additive powder, its thermo-physical properties, i.e. conductivity (both electrical and thermal), density, specific heat, the size of the grains, and its mixing ratio with dielectric. The process of material removal is also multi-directional as many researchers reported. The state of discharge of the additive powders is the main criteria whether the particles show worthy abrasion action or not. The machining efficiency for the particles' abrasion action is found to be very little. The additive may be any metal powder (such as Copper, Nickel, Titanium, Manganese etc.), organic powder (such as Urea, epoxy). This hybrid application of EDM is called Powder Mixed EDM (PMEDM).

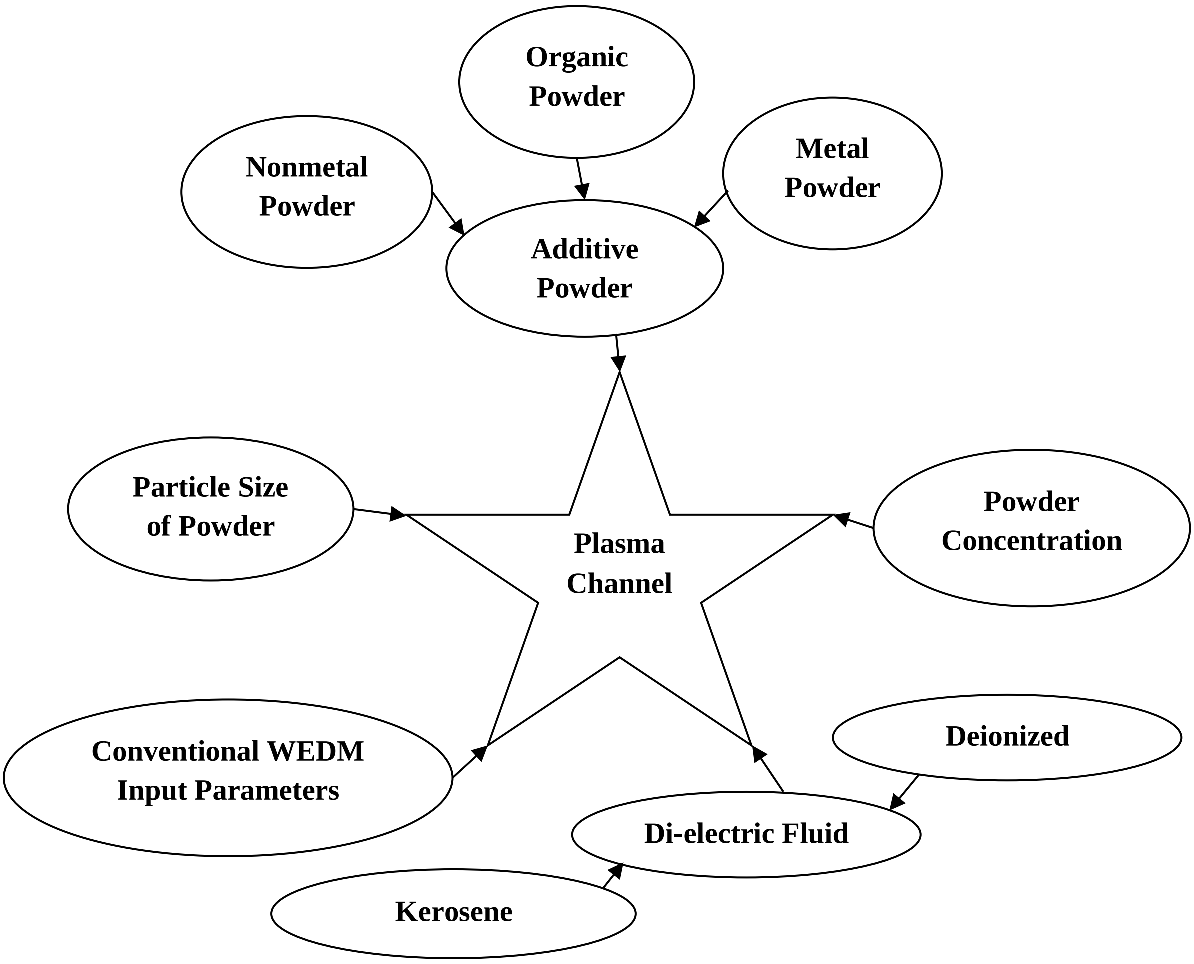


Figure 1.6. Model of plasma channel with input parameters of PMWEDM

1.2.3. *Applications of PMWEDM*

Nowadays, efficient machining with exact dimensional accuracy is highly demanding for the precision industry. Productivity, as well as quality, is the major factor for these industries. Powder mixed electric discharge machining has a large capability for doing this. From the application point of view, it has become more popular in the industry.

Various applications of PMEDM are:

1. **Micromachining:** WEDM is called a micro WEDM when the dimension is considered in microns. In the present manufacturing scenario, MWEDM is a versatile machining process. Thin wire diameter up to 100 µm, pulse energy of 10^{-5}- 10^{-7} J and gap 5-25µm are required during machining. Powder mixed wire EDM fulfils all the demands in micromachining of advanced material and composite used in the tool and die-making industry.
2. **Superior surface finish:** Every machining process has its own limitation; beyond that, how much recovery is obtained that is very much essential. Wire electric discharge machining is a spark thermal erosion process, so a recast layer is always present on the machined surface. Due to the enlarging gap and the early explosion of spark in PMWEDM, eroded material is removed quickly from the gap between tool and workpiece, creating uniform craters and lower recast thickness; as a result superior surface finish is produced on the workpiece.
3. **Surface treatment:** PMWEDM is also used for enhancing the surface properties such as wear resistance, corrosion résistance, and the hardness of the workpiece. A wide range of metal or abrasive powder is added with dielectric in PMWEDM. So a thin layer of the powder particle is observed on the workpiece surface after machining, which plays a significant role in surface treatment.
4. **Higher removal rate:** The metal removal rate of powder mixed wire EDM is higher than the normal WEDM process. As the higher MRR is obtained from the PMWEDM process, the machining time is also decreased. Some abrasive powders (SiC, Al_2O_3, B_4C) are most effective for enhancing metal removal rate in the PMWEDM process.

Machining of advanced material and composite: The development of new advanced material is highly demanding material in the advanced manufacturing industry such as marine, aerospace, cryogenic, nuclear engineering, military, and surgical instrument. The composite material has also high demand in automobile, tool, and die industries. Machining these materials into micro and macro parts with complex profiles is challenging. PMWEDM is the better choice for machining these materials with better dimensional accuracy when other machining processes are failed.

1.3. Literature Survey

1.3.1. Literature on Parametric Study of WEDM Process

First Joseph Priestly [14] discovered the concept of machining effects by the electrical discharges produced by DC power source causes melting and erosion of the work material. In 1969, Agei first introduced WEDM technology to manufacturing technology. Since then, this process has experienced significant growth in both theoretical and practical aspects. Starting from 1975, it gained popularity rapidly due to its excellent industrial applicability. It became the preferred choice for machining conductive, hard, and tough electrically conductive materials. Moreover, attempts have been made to machine low-conductive materials as well. However, the major drawbacks of this machining technique are poor cutting speed and low MRR, which present challenges for further improvement. Consequently, several researchers have been dedicated to developing process modifications to enhance both the quality and economic feasibility of the method.

The thermal-assisted WEDM process is not without its complexities, as it significantly affects the surface morphology of the machined area, including the formation of a crater, recast layer, and HAZ zone. However, the precision manufacturing aspect requires careful consideration, and advanced techniques are continuously being implemented to minimize negative feedback in the WEDM process. One such technique involves mixing powder particles in the dielectric, which not only improves performance efficiencies but also reduces the overall production cost.While numerous research efforts have been dedicated to optimizing the WEDM process and its advancements, only a few researchers are currently focusing on the hybrid WEDM process for machining materials with low machinability. Additionally, there is a lack of research on the dimensional accuracy concerning the uncut area in the corner section during the suspended powder mixed WEDM process. Extensive research is crucial in the field of powder mixed WEDM to enhance performance efficiency and cater to the current industrial requirements. Nevertheless, a comprehensive review of fundamental concepts and the progress made in WEDM research is elaborated in the following paragraph.

Bergs et al. [15] analysed the process parameter characteristics of WEDM during machining of X40Cr14 and TiAl6V4 and SiC alloy to find out the unstable process conditions which were caused by increasing discharge energy and pulse frequency. Experiments were conducted in two different series where both discharge energy and pulse frequency were gradually increased until the wire breakage by keeping the other parameter constant. It was reported that abnormal discharge ratio increased with the increase of discharge. The main reason behind the unstable process conditions was excessive discharge energy and actual exaggerated pulse frequency. The time dependent distribution of discharge was shown the characteristics of SiC material during machining. A higher value of abnormal discharge was seen during machining of titanium and ceramic material.

Chalisgaonkar and Kumar [16] developed a mechanistic model to predict the MRR, SR and wire consumption by selecting a wide range of machining parameters during titanium processing. The results revealed that higher wire consumption happened due to lower pulse discharge energy resulting in lower wire surface degradation. Pulse on time and servo voltage are the most significant parameters for all three responses. A higher amount of surface degradation properties was shown on the machining surface at high discharge energy conditions.

To explore the summarized impact of machining inputs on surface roughness in the WEDM process along with a set of influence parameters such as pulse duration, pulse interval time, material, dielectrics, pulse time, discharge current and dielectric, Han et al. [17] conducted experiments by designing a pulse generator. The authors also analysed the machining outcomes of short and long pulse under the condition of equivalent pulse energy and obtained the polarity effect. The results showed that surface roughness was improved by decreasing the discharge current and pulse duration. The reverse polarity with proper pulse energy could be improved surface roughness.

Payla et al. [18] established a fundamental relationship between machining inputs on energy efficiency at an industrial manufacturing scale. An investigation on processing EN31 steel through the WEDM was made to reflect the economic and environmental aspects. Power consumption were analysed with respect to every second time. Material removal rate and power consumption was tremendously increased with an increase of pulse on time and the reverse effect was seen with an increase of servo voltage due to low discharge energy in the machining gap. The wire tension did not play a significant role in power consumption but improved MRR.

Sen et al. [19] carried out a comparative study with three wire electrode of Plain brass wire, zinc-coated brass wire (ZCB), and silver-coated brass (SCB) wire for high precision machining. The surface characteristics were systematically discussed with different operating variables. As per experimental observations and analysis, the results showed that silver-coated brass wire provided better dimensional accuracy. Due to the high conductivity of silver, SCB wire provided sufficient uniform spark that leads to less chance of bubble formation and enhanced surface finish. Under high discharge conditions, the machining rate of the brass wire was inferior compared to the other two wires. However, under low discharge conditions, the brass wire yielded better results than the SCB wire.

Based on the L_9 orthogonal array, Sharma et al. [20] experimented on wire electric machining of Inconel 706 material by selecting pulse off time, pulse duration, wire feed and servo voltage as machining parameters. The hybrid concept was integrated to optimize the process variables and assess the response characteristics of surface roughness and material removal rate. The 3D surface of the machining surface was observed through SEM. The results proved that the hybrid approach was more accurate than the conventional method. The most influential inputs, such as pulse on time of 105 µs and pulse off time of 27µs, delivered the best outcome. The average thickness of recast layer formation on the machined surface was 39.6µm.

Sivaprakasam et al. [21] presented a theoretical and experimental study on micro WEDM of B_4C-reinforced aluminium metal matrix composite. Based on the response surface methodology, experimental work was carried out and they analyzed the effect of the inputs on MRR, SR and kerf width (KW). It was revealed that the combined effect of voltage-capacitance and capacitance-feed rate significantly influenced on MRR and KW. The interaction effect of voltage, capacitance, voltage-capacitance, and capacitance-feed rate influenced more on SR. The minimum obtained surface roughness was achieved 0.97 µm for the micro machined surface.

Wang et al. [22] introduced a novel concept of a combination of electric discharge and anodic etching for slicing the low-resistance silicon material. Some enhancements were adopted in the investigation, like a new wire winding system, hybrid electrolyte and high-efficiency pulse generator to prevent wastage during processing ultra-thin silicon wafers. Based on the wire electrolytic-spark slicing strategy experiments, the responses such as surface quality, wafer thickness and cutting speed were evaluated. A maximum machining rate was obtained as 600mm^2/min with a lesser wafer thickness of 120mm when the wire consumption was low.

For high-speed wire electrical discharge machining, Zhang et al. [23] reported on discharge channel motion characteristics and clarified the material removal mechanism. Based on the single pulse discharge experiments, the characteristic effects were analyzed on cutting efficiency. The result showed that discharge channel motion speeds were maximum at the beginning time of discharge, then dropped suddenly and finally came to a stable state due to a change in current density. The discharge motion laws were balanced with cutting efficiency laws. Experimentally it was seen that pulse width for high speed WEDM should not outstrip 75 μs.

Ming et al. [24] optimized the process variables using integrated GPR and NSGA-II and obtained a combination set input setting for better efficiency on WEDM of tungsten steel YG15. The impact of influencing parameters was analysed at the micron scale surface topography. From the experimental data and the analysis, it was concluded that pulse on time, pulse off time feed rate showed a greater impact on MRR. Meanwhile, the interaction effect of cutting feed rate and pulse on time showed a large variation in surface topography in terms of Sz and Sq.

1.3.2. Literature on Hybrid Machining Processes

The limitations of the electro thermal process are overcome by applying several hybrid techniques. EDSG and high-speed EDM drilling are examples of hybrid machining processes involving one conventional and one spark erosion process. An article reported an experimental study to overview the metal removal mechanism through the electrical discharge surface grinding (EDSG) process. The effect of electrical and grinding parameters was analyzed along with abrasive size and concentration. From the scanning electron microscope image analysis, it was observed that effective removal of particulates for the job without interrupting the base matrix. The other surface properties like depth of recast layer and HAZ formation were found to be large quantity for the positive tool polarity compared to negative polarity. The obtained optimal setting of machining parameters are as follows: negative polarity, Peak current of 3A, pulse on time of 60µs, pulse off time of 15µs, Speed- of 1400 RPM), the abrasive particle size of 220 Mesh and concentration of 5% [25].

Guo et al. [26] conducted an elaborate study on WEDM assisted by ultrasonic vibration and proved that it has better efficiency than conventional WEDM. Through a series of experiments, the machining mechanism was studied, revealing that high-frequency vibration of the tool wire has a significant ability to induce multiple channel discharges. Consequently, this leads to the instantaneous attainment of optimal Material Removal Rate (MRR) and Surface Roughness (SR) performances. The study revealed that the combination technology of WEDM assisted by ultrasonic vibration enhanced cutting efficiency and prevented the rupture of wire.

Near Dry ambience wire electric discharge machining was carried out by Kumar et al. [27] to experimentally investigate the feasibility of near dry WEDM of Monel superalloy using air and deionized water in mist form. The influence of mist form along with machining parameters on response measures in WEDM like surface finish and environmental hazard issues were discussed. A separate attachment of near dry operation was made for practical experimentation. The outcome of the study reflected that T_{on} and T_{off} were highly effective inputs on MRR and SR where T_{on} was involved with discharge energy and T_{off} provided sufficient time for flushing. In the comparative study between near dry and wet WEDM, it was observed that near dry WEDM consistently outperformed wet WEDM in terms of surface accuracy. However, it was noted that wet WEDM exhibited a higher MRR compared to the near dry operation.

The machining characteristics of thick-shaped memory alloy TiNi01 processing by a complex method of ultrasonic vibration (USV) and magnetic field (MF) assisted low-speed wire electrical discharging machining was investigated by wang et al. [28]. Under both conditions of USV and MF, the vibration simulation were analysed. The application of USV-MF complex assistance in WEDM-LS resulted in more stable and uniform discharges contributed to a reduction in wire breakage. A confirmation test was carried out to verify the predicted model for responses. The result established that the novel hybrid technique significantly improved the pulse discharge, machining efficiency and machined surface topography of machining exceeding the thickness of 50 mm of titanium- nickle-based alloy material.

An investigation was performed on the combined process of wire electric discharge machining (WEDM) and wire electrochemical machining(WECM) for removing the recast layer on the machining surface generated due to the metal removal mechanism of melting and evaporation during the WEDM process. All experiments were conducted with the same tool and electrolyte. An analytical model was developed based on the double layer model, and the Faraday's law of electrolysis and the effects of the influence parameters on SR were discussed. The experiment results proved that the recast layer made using WEDM process can be dissolved with wire electric discharge chemical machining; resulted in reduction of surface roughness [29].

Zhang et al. [30] investigated the machinability of the Ti6Al4V material by using a hybrid technique of wire electric discharge machining with ultrasonic vibration and magnetic field-assisted. The effect of pulse on time on response measures, including the material removal rate, surface roughness and surface crack density, was explored. The considered typical inputs ranges of pulse-on time of 16-22(μs), current of 2-3(A), ultrasonic vibration power of 50-100(W), magnetic flux density 0.2-0.3(T) demonstrated as the optimum result. The stability of the hybrid process was determined by analyzing the discharge waveform and the characteristics of machining.

1.3.3. Past Research Work on Machining Accuracy in Powder Mixed Wire EDM

Many efforts have been made to improve machining performance since the innovation of the EDM process when it demands high precision with a superior surface finish, is the major key point for perfect machining of the tool and die industry. The new advancement of EDM, in addition to powder with dielectric, has fulfilled the requirement for solving such kinds of problems. The mechanism of machining and technological development of powder mixed electric discharge machining has been discussed by H.K. Kansal et al. [31]. This paper has presented a detailed research report on PMEDM and concluded that the past research fulfilled all industrial needs in terms of productivity and surface quality of the job.

Vijaykumar S. Jatti and Shivraj Bagane [32] focused on developing FEM of powder mixed EDM. The material is used as Beryllium copper alloy, which has high fatigue strength, corrosion resistance, wire resistance, and non-sparking quality. In a single discharge of the machining process, the temperature distribution on the work surface during machining has been discussed through the axis-symmetric 3D model using ANSIS 15.0 software. The experiments were conducted by varying the abrasive powder (Al_2O_3 mesh size 150μm) concentration and gap current when all other process parameters are kept constant like pulse on time pulse off time, gap voltage and flushing pressure. The result concluded that the FE model gives a better prediction of real-time results of MRR.

Gangadharudu Talla et al. [33] made an attempt to fabricate and machined through the EDM process by adding aluminium and alumina powder (weight ratio 80:20) with kerosene dielectric. A semi-empirical model was proposed for MRR and Ra based on the thermo mechanical properties of workpiece material along with the process parameters of EDM. Therefore, multi-objective optimization is used to determine the optimal solution of the process parameter with the help of PCA-based grey relation analysis. Better improvement in surface quality, as well as MRR, can be achieved by mixing suspended conductive powder in the dielectric. From the empirical model, it is understood that density, thermal conductivity, the coefficient of thermal expansion of the material has the most significant effect on Ra and MRR.

S. Tripathy and D.K. Tripathy [34] investigated the performance characteristics and surface quality for H-1 die steel to explore the effect input parameters and adopted Taguchi methodology with the technique of TOPSIS and GRA to evaluate the effectiveness of the multi-objective optimization of the process parameter for PMEDM. Several input parameters were chosen as process variables like peak current, duty cycle gap voltage, and pulse on time and powder concentration. To determine the significant parameter ANOVA and F test was performed at 95 % confidence level. An improvement was shown after verifying the predicted result value using two optimization techniques. It was observed from the experimental investigation that surface roughness values were reduced on increasing the chromium powder concentration up to 6gm/l during machining. Also, surface topography was greatly enhanced with less defects and microcracks by well distribution of recast layer and crater formation.

Ahmed Al-Khazraji et al. [35] carried out an experimental study to investigate the effect of powder (SiC) mixed Electric discharge machining parameter on performance using both copper and graphite electrodes in order to get desired fatigue life, total heat flux and white layer thickness of AISI D2 die steel material. A good agreement was obtained when copper electrode with a high pulse on time and low current was applied during machining of PMEDM. Fatigue life was increased with increasing in pulse on time and decreasing in pulse off time for the graphite electrode compared to the copper electrode.

A state of review in recent development in hybrid machining based on EDM phenomena was reported by Shabgard et al. [36]. The authors classified a wide range of previous work, which contains powder mixed EDM, magnetic field-assisted EDM, dry and near dry EDM and ultrasonic vibration-assisted EDM processes. These processes were essentially required to develop to overcome the limitation of the EDM process in order to increase the ability to machine a hard material with a complex shape which greatly functioned in the precision industry. Finally, this paper revealed the possible research area of the hybrid EDM machining process.

Kolli and Kumar [37] proposed an approach of graphite powder mixed with surfactant-assisted EDM and experimentally investigated the changes in surface properties on titanium alloy. It was reported that MRR and surface roughness increased by adding surfactant with a dielectric consisting of a mixture of EDM oil and graphite powder. The authors showed the influence of surfactant concentration on performance characteristics by keeping other machining parameters constant. The optimal solutions for MRR Ra and RLT were obtained by Taguchi methodology as discharge current, surfactant concentration and graphite powder concentration were considered for process parameters. Therefore, the outcome of the work revealed that (i) MRR increased with an increase in discharge current and powder concentration; (ii) surface roughness was directly proportional to the discharge current, surfactant concentration and graphite powder concentration; (iii) RLT initially increased with surfactant concentration (4-6 g/L) then decreased with surfactant (6-8 g/L) and directly proportional to discharge current.

Beri et al. [38] reported state of the art on PMEDM for getting the desired surface profile. PMEDM is one of the revolutionary techniques where there w no need to apply supplementary coating after EDM, reducing the overall cost of the product. The authors had discussed this process with the help of past research. Therefore, the paper highlighted the future perspective of PMEDM processed electrodes.

Prakash et al. [39] focused on the application of biocompatibility surface produced by powder mixed EDM of Ti-35Nb-7Ta-5Zr β- titanium alloy. The effect of Si powder mixed with dielectric including the pulse current and duration as an input on the several responses such surface topography, surface crack density, elemental composition, RLT, SR, MRR, and TWR were investigated. The pure silicon (Si) powder with an average particle size of 35 µm and a concentration range of 2g/l -8g/l was considered to carry out the experiment. The authors concluded that. (1) A significant improvement was seen in surface quality during machining with 4 g/l concentration of Si powder. Maximum crack-free surface and lower thickness of recast last were formed at that condition. On the other hand, 8g/l concentration increased the recast layer to 15 µm (2). At a higher concentration of 8g/l, the surface of Ti-35Nb-7Ta-5Zr β- titanium alloy was estimated to compose of several oxide phases like Ti oxide, Nb oxide and Si oxide and several carbide phases of Ti carbide and Si carbide. (3) A concentration of 4g/l potentially improved MRR and reduced TWR during the PMEDM process.

Based on the L_{27} orthogonal array, Kumar et al. [40] conducted experiments on powder mixed WEDM of WC-Co alloy by considering the Peak current, pulse on-time, pulse off-time and servo voltage as a controlling factor along with two powder (Al and Si) in the dielectric. A separate chamber with a stirring system was for the experimentation. SEM and EDX were applied to examine the material transfer during machining. The results revealed that crack density was highly influenced by peak current and pulse on time. The comparative study between Al and Si mixed WEDM process established that a lower recast layer thickness was obtained during using Si powder as it has low thermal conductivity. In the case of Al powder, the thickness of the white layer was reduced from 14 µm to 6 µm, whereas Si powder showed 4µm of thickness on the machine surface.

Shard et al. [41] investigated the influence of B_4C powder of average grain size 100 µm into kerosene oil in the EDM process. The statistical method ANOVA showed that MRR was greatly influenced by powder concentration and pulse on time. The interaction effect of abrasives concentration, pulse off time and peak current were directly effected on surface roughness (R_a). At a concentration level of 10g/l, the lower tool were rate and higher MRR were obtained from this study.

Abrasive mixed electric discharge machining of AISI 304 was carried out by Bhaumik and Maity [42] to investigate the MRR TWR and SR experimentally. A hybrid optimization technique, namely RSM and desirability coupled with fuzzy logic, was performed to determine the optimum level of process parameters such as peak current, pulse on time, gap voltage, duty cycle and powder concentration. From the experimental observation, it was seen that higher MRR and lower TWR and SR can be achieved while the peak current, pulse on time, gap voltage, duty cycle and powder concentration were considered as 4A, 150µs, 65V, 65% and 10g/l, respectively. ANOVA methods analysed that peak current was the most significant parameter for all the response measures.

Mohanty et al. [43] explored an optimization technique. Authors studied the impact of machining variables on the surface finish, electrode wear rate and the MRR in PMEDM operations. A pure copper with 12 mm diameter was used to machine the AlSiCp12% metal matrix composite. The significance of the process parameters was predicted using the desirability approach, and PSO was incorporated to determine the optimal input parameters setting. Finally, a validation test was performed to show the close difference between the predicted and experimental results. It was revealed that powder in dielectric enhanced machining efficiency by increasing the spark gap and improving the breakdown characteristics of the dielectric.

Han et al. [44] described the influence of process parameters such as pulse duration, pulse interval time, wire feed speed and single pulse energy on the finishing cut of WEDM. It was revealed that good surface finish could be achieved by decreasing discharge current and pulse duration. The machined surface produced by WEDM could be improved by reverse polarity with correct pulse energy.

S. Sarkar [45] studied the impact of wire deflection on corner profile during WEDM process. The author suggested an analytical model to attain enhanced precision and accuracy in gap force and wire lag under various machining conditions. This analytical model was developed to analyze the wire lag phenomenon while cutting the curve profile. The authors concluded that wire lag compensation was inversely proportion to the programmed path radius. The experimental data proved that the gap force intensity was inversely proportional to the job height.

1.4. Identification of Research Gap

Precision machining characteristics with high dimensional accuracy makes the material more adaptable towards the applications. The necessity of the non-conventional process becomes an appropriate alternate solution for the machining of this low conductive material. Wire electric discharge machining is the best choice for through cutting operation of complex shapes profile with high accuracy. Machining of Ti6Al4V is an immensely challenging task as it attributes high temperatures during the conventional method. However, the enhancement in machining efficiency of Ti6Al4V alloy is still a complicated job for the research community. In recent times, the WEDM process has shown significant progress as a potential method for machining materials with very low conductivity. However, after conducting a literature survey, it becomes evident that past researchers primarily concentrated on a hybrid technique of the EDM process, known as powder-mixed EDM. Only a limited number of attempts were focused on powder-mixed WEDM.

In the present investigation, the powder mixed wire EDM (PMWEDM) process has been employed to improve the performance efficiency of Ti6Al4V alloy. Due to the direct contamination of dielectric in the environment, the consideration of environmental issues in WEDM operation make the process more unique. Therefore, many past investigations are carried out on the WEDM process to enhance the MRR, kerf width, surface finish, and dimensional shift. No such investigation is carried out in the surfactant added PMWEDM process, considering the machining outputs such as surface roughness and corner inaccuracy. Moreover, the present study has focused on the effect of different powders with dielectrics and their impact on responses for better dimensional accuracy, which is essential for the advance manufacturing industry. Finally, the machining inputs are optimized using different optimization methods to obtain the best outputs.

1.5. Objectives and Scope of the Present Research

Based on the past survey, the following objectives of the present research are set as under:

i). To study the mechanism of material removal in powder mixed wire EDM
ii). To design and develop an experimental setup for the study of the effect of powder mixed dielectric on performance criteria
iii). To study the machining characterization of tough alloy material.
iv). To study the effect of machine controllable and uncontrollable parameters on responses like metal removal rate, cutting speed, surface finish, corner inaccuracy, etc.
v). To study the surface topography, surface roughness and heat-affected zone on the machined surface of powder mixed wire EDM, and
vi). To analyze and optimize the process parameters

The scope of the present investigation includes the systematic study on machining efficiency in a wide range of controlled parametric settings, including powder with a dielectric to establish a convenient technological guideline for processing intricate shapes on tough alloy material. Unlike selecting proper powder properties proposed by past researchers, the proposed methods in the present study are not only limited to the specific condition. Still, it will also be very helpful for the precision manufacturing industry and eschew form contamination in the environment. The proposed modelling, analysis and optimization methods can be applied to other machining areas with proper modification. The research results in the Wire EDM field show great potential for achieving higher dimensional accuracy and increased production rates. Additionally, the proposed hybrid technique utilized in this study has a significant impact on corner accuracy.

CHAPTER: 2

OPERATIONAL FEATURES OF WEDM MACHINE, EXPERIMENTATION AND MATERIAL DETAILS

2.1. Operational Features of WEDM Machine (Ezee Cut Plus)

All total experiments were performed on the Ezee Cut Plus wire electrical discharge machine. It consists of (a) one machine tool (b) one power supply unit (c) a dielectric unit. The machine tool includes of a main worktable and wire drive mechanism.

The primary table with a precision of 1 micrometer is under constant monitoring, controlled by stepper motors. The U and V axes are aligned parallel to the X and Y axes, respectively, and are also operated by stepper motors. The wire used in the process is fed from a wire drum and moves through the workpiece, supported under tension by a pair of wire rollers positioned on opposite sides of the workpiece. The lower wire roller remains fixed, while the upper wire roller is mounted on the U-V table, allowing it to be transversely displaced along the U and V axes concerning the lower wire roller.

The upper wire roller has the capability to move vertically along the Z-axis by adjusting the quill position. Electro-erosion of the workpiece material is achieved by applying a series of electrical pulses to move the wire along the X-axis and Y-axis. The material is removed as per the programmed path provided to the controller, and the X-Y controller displaces the workpiece transversely. The programmed path can be specified in the controller through a program. During the movement of the X-Y table along the predetermined path, a straight cut with a predetermined pattern is formed while the U-V table remains stationary.

The detailed view of the experimental set up for present work is shown in Figure 2.1. The technical specification of three different unit such as control panel, machine tool and voltage stabilizer of Ezeecut Plus wire EDM machine has been given in Table 2.1.

Figure 2.3 shows the details view of all component of wire cut EDM. The machining view in WEDM operation has been illustrated in Figure 2.2.

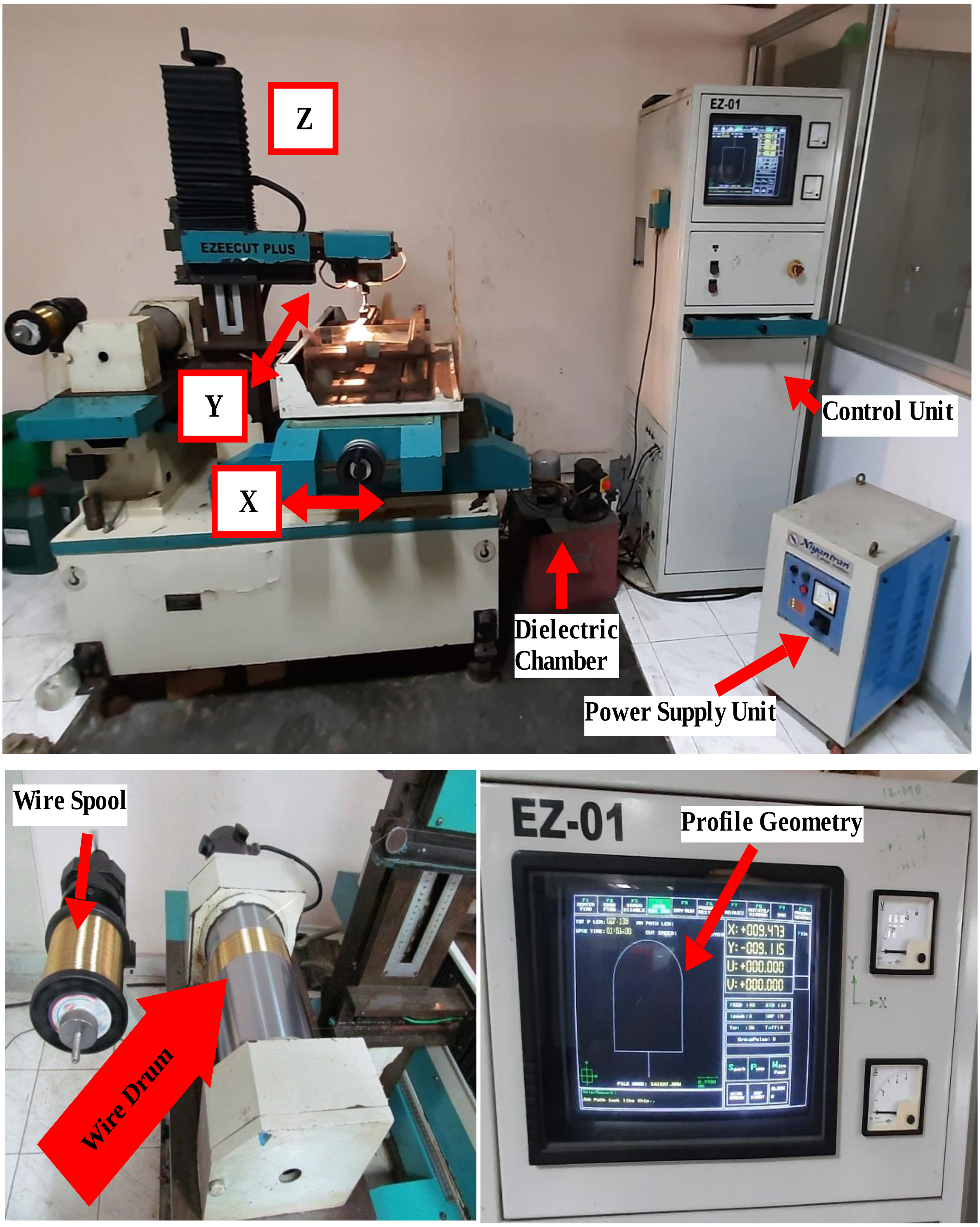


Figure 2.1 Photographic view of experimental set up (EZEECUT PLUS wire cut EDM)

Table 2.1 Technical specifications for wire-cut EDM machine

Table 2.1 (a) Control panel specifications

1	Control mode	CNC close loop.
2	Simultaneously controlled axis	X, Y, U, V.
3	Control panel size (L x W x H)	1150 x 650 x 1830 mm.
4	Control panel weight	175 kg.
5	Input program format	G code
6	Display	15” colour CRT
7	Minimum input command	0.001 mm.
8	Minimum increment	0.001 mm.
9	Interpolation function	Linear, circular.
10	Power requirement	415 V / 50Hz / 3 ph / 1.5 KVA max

Table 2.1 (b) Machine tool specifications

1	X ,Y axis travel	320 x 400 mm.
2	Maximum workpiece size	360 x 600 mm.
3	Max Z height	360 / 480 mm.
4	Max workpiece weight	300 kg.
5	Max taper cutting angle	3 degrees at 100 mm job height.
6	Machine tool size (L x W x H)	1500 x 1250 x 1700 mm.
7	Machine tool weight	1400 kg.
8	Wire diameter	: 0.2 to 0.25 mm. (Brass)
9	Achievable surface finish (R_a)	1 – 1.5 µm.
10	Max cutting speed	60 mm/min, (WPS, Job height>50mm)
11	Max dry run speed	25 mm/min.

Table 2.1 (c) Voltage stabilizer specifications

1	Rating	Min 1.5 KVA, @ 415 V line to line.
2	Input voltage	310 V to 467 V line to line i.e. 180-270 V / Phase.
3	Output voltage	415V line to line i.e. 240 V phase to neutral.
4	Output voltage regulation	± 1% / phase of output voltage.
5	Voltage correction rate	35 V / sec.
6	Overload protection	With siemens contactor & 3 Ph thermal OL relay.
7	Other protections	Single phasing pre-setter, over voltage tripping.

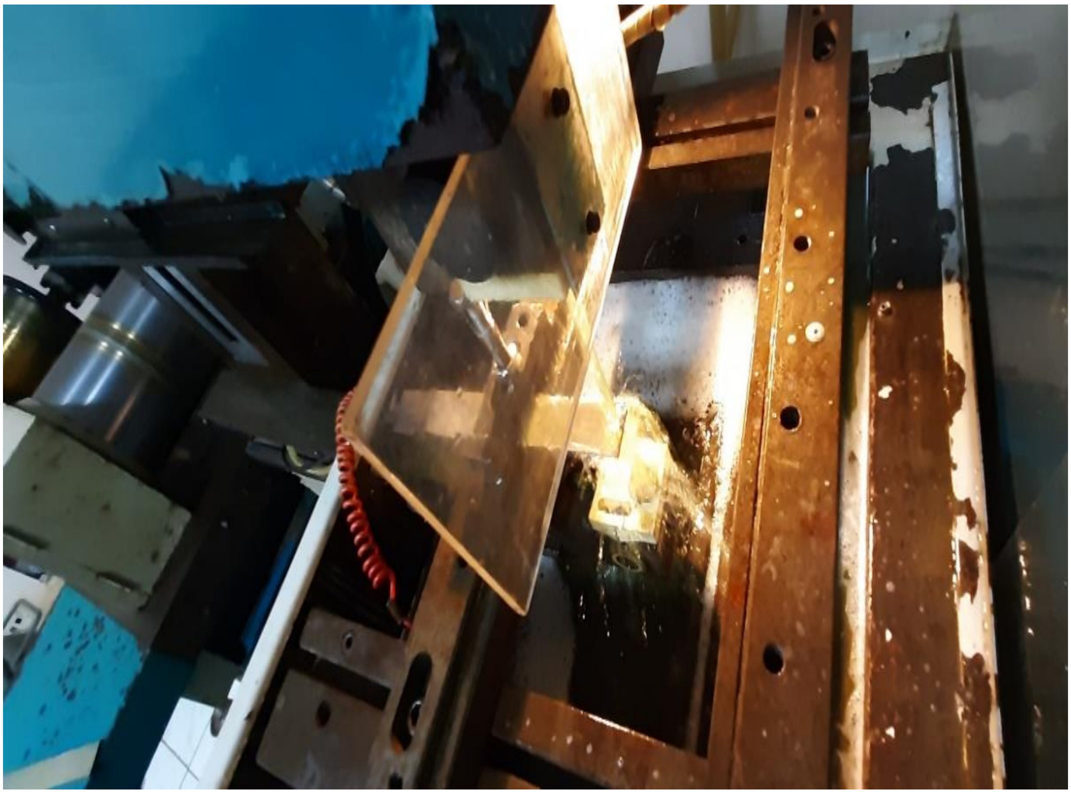


Figure 2.2. Machining view during WEDM operation

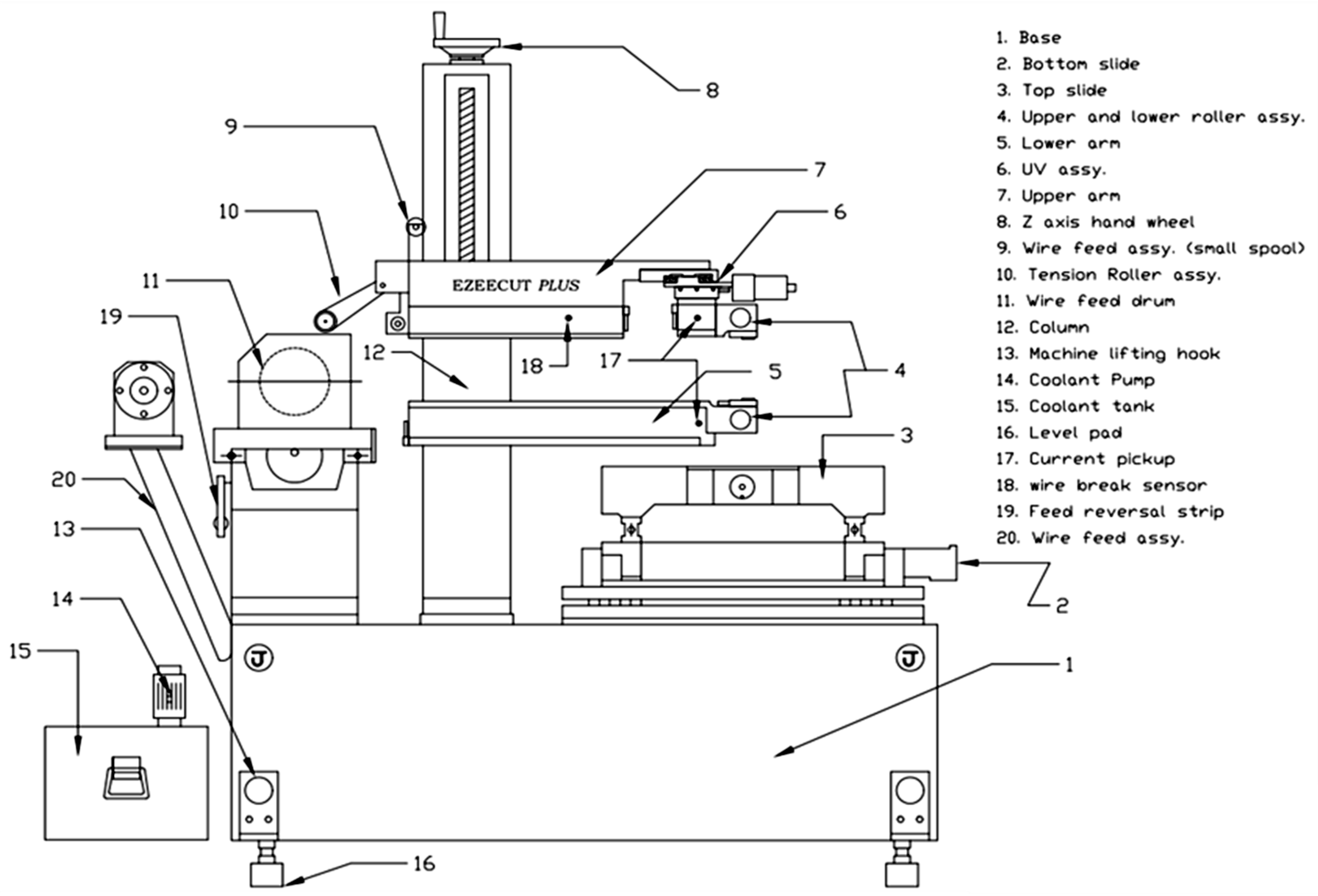


Figure 2.3. Schematic view of a wire cut EDM machine

In order to maintain proper machining procedure, following points need to be considered:

a. Wire should be perpendicular to the top surface of the work piece.

b. It is recommended to begin the machining process from a designated hole at the appropriate location. Incorrectly positioned workpiece cutouts and machining routes can lead to workpiece distortion.

- Always ensure that the start point is positioned within the workpiece.
- Arrange machining process in a way that the workpiece clamp side is machined last.
- To resist residual stress deformation, maintain an adequate wall thickness (t).
- To minimize workpiece internal stresses, consider pre-machining before the main machining process.
- Heat Treatment
  - Vacuum heat treatment.
  - Sub-zero annealing treatment, etc.
- Making of starting holes:
  - Metal, unhardened – drill
  - Metal hardened – Make hole by sink erosion.
- Clamping allowances for reliable mounting
  - Greater than 10 mm for light work pieces.
  - Greater than 35 mm for medium work pieces.
  - Greater than 50 mm for heavy work pieces to permit working without risk of collision.

c. The test should be performed on a trial piece to get exact value of over cut. The same technology/controllable parameters, viz. pulse, current, gap as used in test cut should be set while machining actual job.

d. For stable machining, workpiece clamping different cutting operation should be as shown in Figure 2.4.

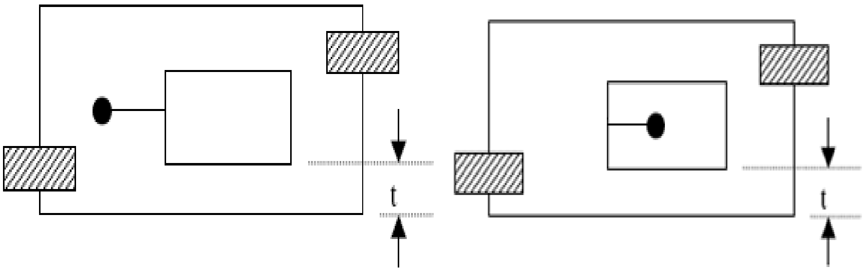


Figure 2.4. Workpiece clamping for punch and die operation

e. Corner shape accuracy is required especially for punch and die, which are often used to make thin plate product. Machining with lower spark energy can reduce deviations at corners (lower pulse and current).
f. Job may shift/tilt due to its weight just before completion. It is required to clamp or stick the job to avoid shifting.

2.1.1. Numerical Control System

The NC system refers as programmable automation that based on the method of controlling manufacturing operation by a set of program instructions. It is a discipline technique applied correctly before installing an NC machine. John Parson invented the first concept in 1947. The author showed the position control by using punched cards of a machine in an attempt to machined helicopter blade. A programmable milling machine was developed in 1949 by US Air Force and MIT. The term Numerical Control (NC) emerged in 1952 following the demonstration of a three-axis Cincinnati Hydrotel milling machine. This innovative machine combined punched cards and an electromechanical controller.

Subsequently, a new generation of machines, such as machining centers and turning centers, was developed, enabling multiple machining operations. Nowadays, NC machines are operated using both computer on board and Computer Numerical Control (CNC) systems. They can achieve impressive specifications, such as spindle speeds of 20,000 to 50,000 rpm, feed rates exceeding 600 rpm, and remarkable accuracy down to 0.0001. The decision on the type of NC machine to be installed depends on various factors, including the following;Variety and complexity of geometry of the components.

a) The tolerances to be maintained.
b) The skill of personnel or workers selected for NC training.
c) The availability of funds for purchasing the NC machines.

These machines are categorized as follows;

a. Feedback control (open loop and closed loop),
b. Motion control (positional, continuous path),
c. Power drive (hydraulic, electric and pneumatic),
d. Circuit technology (analog, digital),
e. Positioning system (absolute positioning and Incremental),

f. Axis identification (2-axis, 3-axis, 4-axis, 5-axis).

Although there are six classifications of the NC machines, the present discussion is restricted to only feedback control mode of classification, since the machine is a closed loop controlled one. In the CNC machine, it is feasible from control point of view to relate the behaviour of a particular variable (velocity/position of tool or job) to one corresponding variable.

To regulate the position or velocity of a machine slide, a servo mechanism system is employed, utilizing different components such as electro-mechanical systems, pneumatic, or hydraulic components. The data handling equipment generates output data for each axis of machine motion, which is then transmitted through separate channels to the servo systems. These servo systems, in turn, drive the respective machine slides accordingly.

2.1.2. Hardware Configuration of WEDM

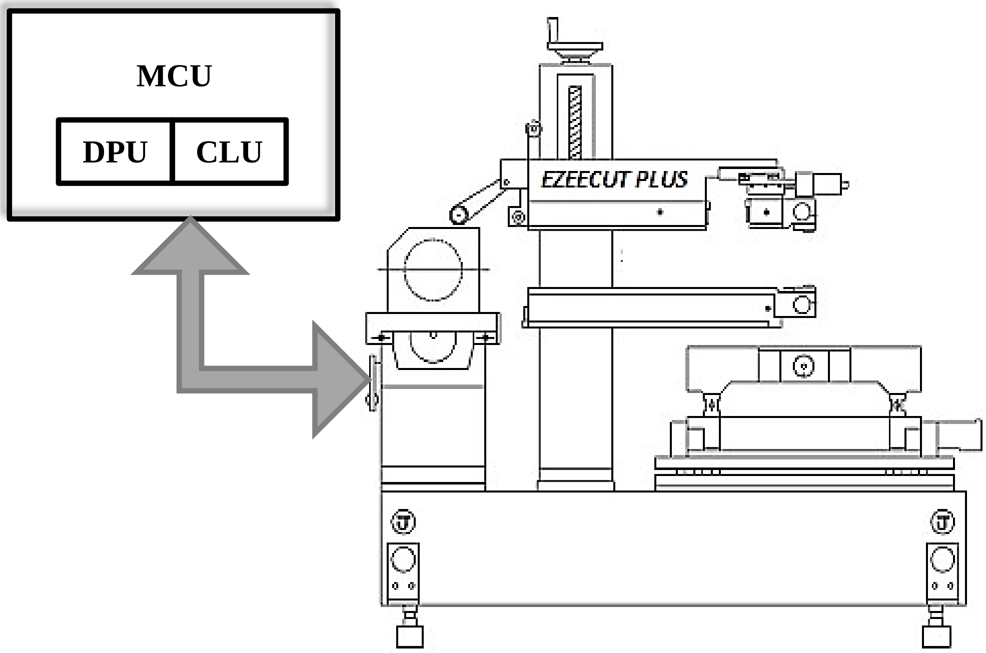


Figure 2.5. Control units in hardware configuration of CNC WEDM

The various control units illustrated in the Figure 2.5 are explained below:

1. Machine control unit (MCU) – It acts as the brain of the NC machine.
2. The Data processing unit (DPU) – It reads the part program.
3. The Control loop unit (CLU) – Its function is to control the machine tool operation, loop systems for controlling tool movement. The feedback control system, can be elaborated in following ways:

a). Open loop system

An Open Loop Control System (OLCS) is a type of control system where the output or the controlled variable is not fed back to the input or the controller for comparison. The movement of this system is done by stepping motor. Each pulse received from MCU helps to rotate a fixed value of the motor. No feedback system is available to check how close the actual machine movement comes to the exact movement programmed, as shown in Figure 2.6. Only the motor directs a signal back that representing the complete movement.

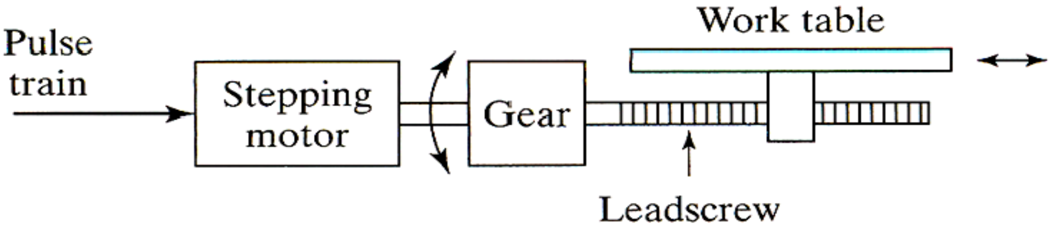


Figure 2.6. Open loop systems for controlling movement

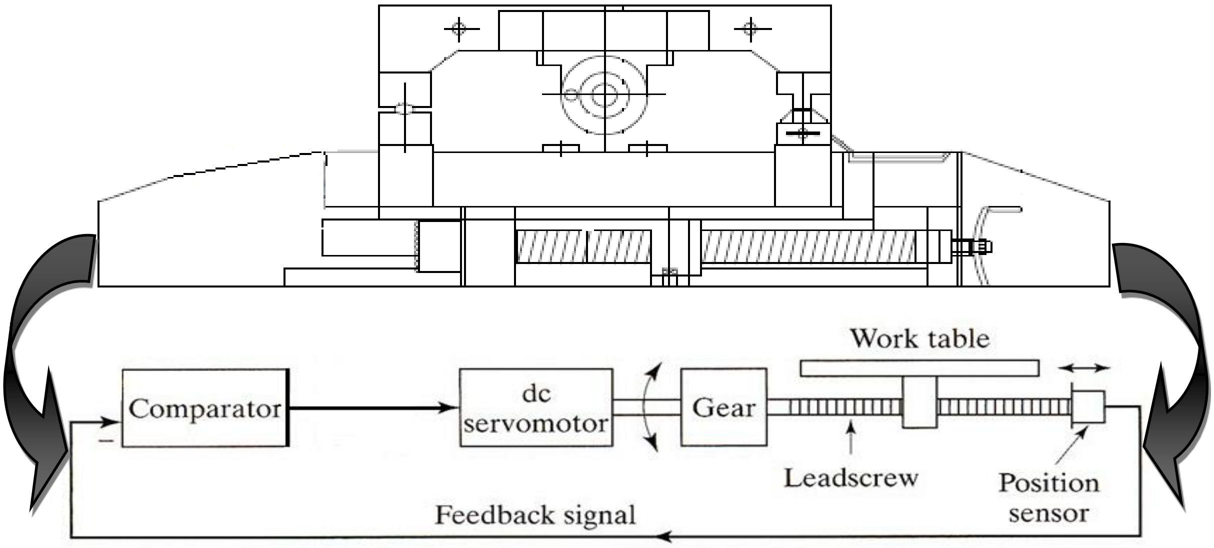


Figure 2.7. Controlling movement in CNC wire cut EDM based on closed loop systems

b). Closed loop system

With respect to input signals mainly by the signal received from feedback devices, the displacement of machine slide is balanced in a control system. It is known as closed loop control system (CLCS). Tool movement control of closed loop systems in CNC wire cut EDM is operated by AC, DC, and hydraulic servo-motors, as shown in Figure 2.7. The speed of these motors is variable and controlled by the amount of current or fluid. The motors are connected to the spindle and the table. A position sensor continuously monitors the movement and sends back a signal to the comparator to make adjustments.

2.1.3. Software Used

Here two types of software are used:

(a) Machine software (EZEECUT PLUS Ver 3.XX) for machine operation.

(b) Part Programming system (RRAPTV3.XX) installed on user PC.

One dedicated software for EZEECUT PLUS is required for running the machine. It is earlier required to reinstall software only if it gets corrupted or for software updating. In case of software reinstallation or update, so update the K factor values again. K-factor is a linear table error compensation count. Calibration for X & Y table is done in factory. K-factor for X & Y table is written on back door of control panel. There are mainly two directories (folders) – EZEECUT which contains files necessary for operation of machine and DWG_DATA which contains user programs i.e. files with RRW extension. For installation procedure, refer to the ‘readme.txt’ file present on EZEECUT PLUS software disk. Then, the detail is given in next section to transfer the program / RRW files from PC to EZ+ control panel (or machine) by CD/Pen drive.

2.1.4. Motion Program for a CNC Machine

Computerized numerical control (abbreviated as CNC) machine understands a group of commands which are called motion codes or simply G-codes (Preparatory functions / G-words) and M-codes (Miscellaneous function / M words). The sequence of these commands in a particular syntax is called NC program. This NC program changes with the size and shape of a part to be cut. Hence it is also called part program. The codes and commands of the NC program are converted into machine movements and/or settings inside the controller, which in turn produces the component according to the NC program. As the major function of this NC program is to maneuver the machine table movements it is also called motion program. Here the terms NC program, part program and motion program are used interchangeably. It explains all the G, M and E codes used in ELPULS-30 controller mastering these codes and formats will help you to exploit the power of the machine to the fullest extent.

Function: Cancels the (G41/G42) offset for wire diameter in the following blocks. Ideally, it can be called as zero diameter compensation. Application: Presence of this code assumes zero diameter wire. It cancels the modal effect of G41 / G42.To check the exact tool path.

Function: Provides the compensation to program profile for the wire radius, spark gap and finishing allowance for subsequent operations on left side of the direction of motion. Parameter: A number with parameter D indicates a variable where the offset value is stored. D variable number can vary from 00 to 10, so that 11 variables can be stored.

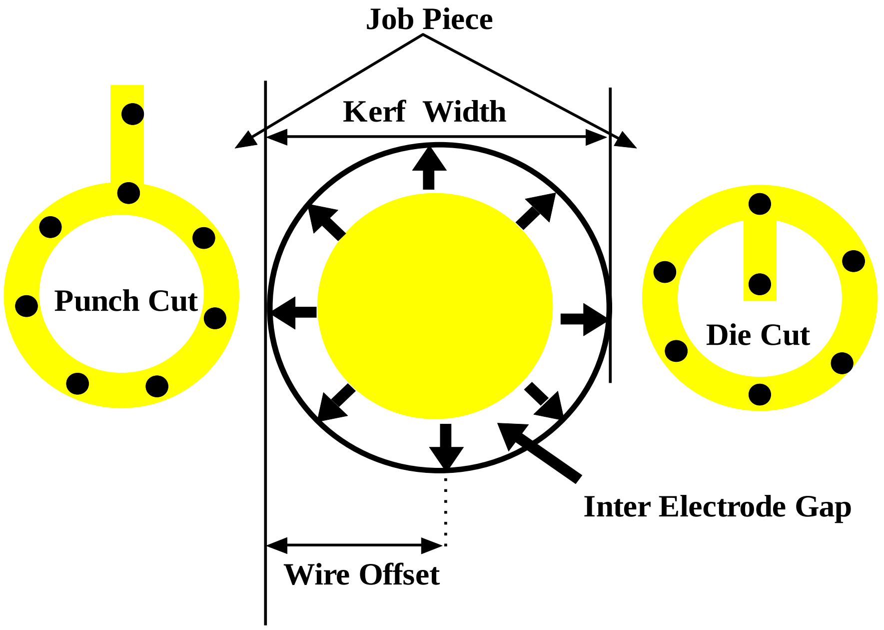


Figure 2.8. Operational/experimental concept of punch and die

In experimental setup, the brass wire diameter is 0.25 mm and spark gap is 0.030 mm, and finishing allowance is 0.010 mm and if offset has to be stored in the variable 5, then it should be done as follows:

$$\text{Offset}_{\text{(brass wire)}} = (\text{Wire dia}/2) + \text{Spark gap} + \text{Finishing allowance} \quad (2.1)$$

$$= 0.250/2 + 0.030 + 0.010$$

$$= 0.165 \text{ mm (used only brass wire)}$$

$$= 0.120 \text{ mm (used only molybdnum wire dia of 180)}$$

, and if the block is specified as D5 (brass wire) = 0.165 mm. Then a value of 0.165 is considered for the WD Comp. This value will be offset on the left side of the direction of motion as in Figure 2.8.

Application: Offers compensation for the wire radius, spark gap, and finishing allowance when performing operations on the left side of the motion direction. Eliminates the modal effect of G40 and G42.

Function: This feature enables profile compensation in the program for the wire radius, spark gap, and finishing allowance during operations on the right side of the motion direction, using the same parameters as G41. It ensures that subsequent operations on the right side are properly compensated. Additionally, it cancels the modal effect of G40 and G41.

2.2. Experimental Setup for PMWEDM

2.2.1. Development of Powder Mixing Chamber

A dielectric fluid chamber of 20L capacity with a starring system has been made to supply dielectric during machining.

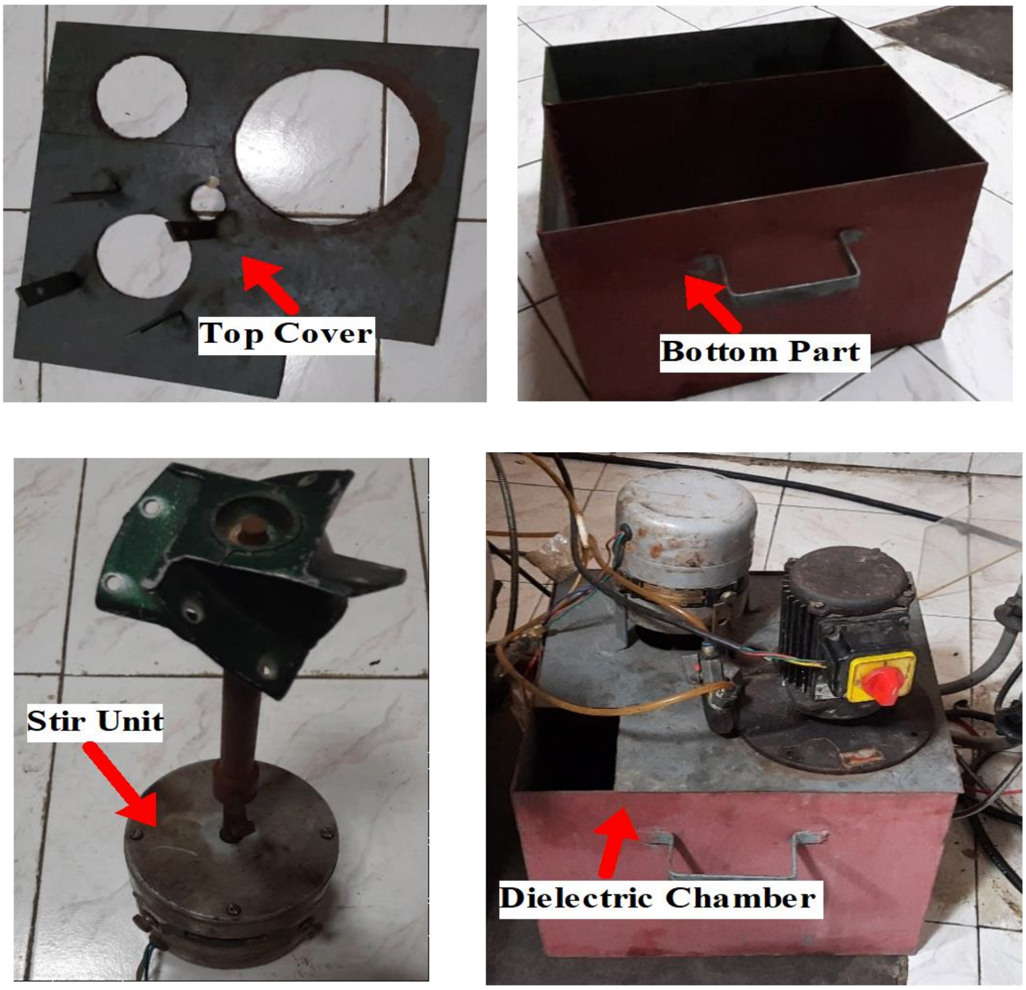


Figure. 2.9 The dielectric chamber fitting parts

The setup comprises several components: the top section, bottom section, magnate assisted section, and the stir and pump unit. A filter with a mesh size of 35 is utilized to filter the dielectric fluid and prevent bubbles from entering the pump. Figure 2.9 displays the complete configuration of the dielectric chamber.

2.2.2. Powder Selection

Apart from the variable parameteric control strategy, the addition of powder particles in dielectric can solve more than one concern related to the WEDM performances. Various types of powders, including metallic, non-metallic, and abrasive variants, possess unique characteristics that contribute to the enhanced smoothness and durability of machined surfaces. Nevertheless, degraded surface integrities such as crater, recast formation, cracks and globules, adversely affect on material properties. Powder mixed with dielectric has the most capability to recover all the surface related issues. Based on the electrical, mechanical and thermal properties, powder in dielectric provided desirable output. The powder particles must have the following criteria:

- Low density.
- High strength.
- Good high temperature strength (reaction bonded).
- Oxidation resistance (reaction bonded).
- Excellent thermal shock resistance.
- High hardness and wear resistance.
- Excellent chemical resistance.
- Low thermal expansion and high thermal conductivity.

In this study, various powder particles were employed as mixing agents in dielectric materials, specifically SiC, Al_2O_3, B_4C, and graphite powder, to enhance the capabilities of the WEDM (Wire Electrical Discharge Machining) process on superalloy. Table 2.2 to Table 2.5 present the properties of these powders.

Table 2.2 Properties of SiC powder

Name	Properties
Compound formula	SiC
Molecular weight	40.1
Appearance	Silvery
Density	3.0 to 3.2 g/cm^3
Solubility in H_2O	N/A
Electrical resistivity	1 to 4 10x Ω-m
Thermal conductivity	120 to 170 W/m-K
Thermal expansion	4.0 to 4.5 µm/m-K
Specific heat	670 to 1180 J/kg-K

Table 2.3 Properties of B_4C powder

Name	Properties
Compound formula	B_4C
Molecular weight	55.26
Appearance	Gray/black solid
Density	2.1 to 2.7 g/cm^3
Solubility in H_2O	N/A
Electrical resistivity	0 to 11 10x Ω-m
Thermal conductivity	31 to 90 W/m-K
Tensile strength	350 MPa (Ultimate)
Thermal expansion	4.5 to 5.6 µm/m-K
Specific heat	950 J/kg-K

Table 2.4 Properties of Al_2O_3 powder

Name	Properties
Compound formula	Al_2O_3
Molecular weight	101.96
Appearance	White powder
Thermal conductivity	25 W/m-K
Electrical resistivity	0 to 14 10x Ω-m
Melting point	2,072° C (3,762° F)
Boiling point	2,977° C (5,391° F)
Density	3.95 g/cm^3
Exact mass	101.948 g/mol
Monoisotopic mass	101.94782 Da

Table 2.5 Properties of Graphite powder

Name	Properties
Molecular weight	12.01
Appearance	Black powder
Melting point	3652 - 3697 °C (sublimes)
Boiling point	4200 °C
Thermal conductivity	25-470 W/m-K
Electrical resistivity	5 to 30 10x Ω-m
Density	1.8 g/cm^3
Solubility in H_2O	N/A

2.2.3. Dielectric Selection

To ensure effective machining or erosion during the WEDM process, a consistent flow of dielectric fluid is essential to flush away debris particles and provide support. During cutting operations, if red sparks are observed, it indicates inadequate water supply. To address this issue, the water flow should be increased until blue sparks appear. One of the critical factors in achieving a successful WEDM operation is the removal of molten metal particles from the machining gap. These debris must be flushed away to prevent the formation of bridges that could cause short circuits in the subsequent cycles. The dielectric medium also plays a crucial role in cooling down the machining zone by carrying away additional heat from the narrowest gap between the tool and electrode.

The Dielectric should have good mechanical and thermal properties. Maintaining the high resistivity before spark discharge, dielectric strength plays vital role and the ability to recover rapidly after the discharge. De-ionized water is commonly used as the dielectric so that high-pulse frequencies can be accomplished. The filtration of dielectric and de-ionizing systems play a crucial role in avoiding unnecessary wire breakage.

Deionized water not only pushes debris out of the wire slot but also cools both wire and work piece. Water is not the insulator that dielectric oil can be. The ionization occurs rapidly by the dielectric oil. Because of this, water will reserve current even after the voltage is in off condition. Due to the high thermal conductivity and thermal heat capacity, dielectric fluids can easily remove excess heat from the narrowest gap and lead to lower thermal loss.

Selection of dielectric is significant attention for EDM performance. Mineral oils are usually used as the dielectric for sinking EDM operations. Mineral oils demonstrate high dielectric strength and low viscosity. It is chosen for better outcomes. Concern with the safety operation, oils with a high flash point are usually used. Kerosene is also used in EDM process. Water-based dielectrics find extensive usage in the wire EDM process. This is primarily due to water's high specific heat capacity, which enables it to offer superior cooling capabilities, thus enhancing the efficiency of the WEDM process. The selection of the dielectric and its method of distribution are crucial factors that significantly influence the overall performance of the operation. Different properties such as electrical, mechanical and thermal of the dielectric effect the processes initiation of discharge, expansion of plasma, erosion of material, removal of debris, and discharge channel reconditioning.

Table 2.6 briefs the significant properties of the gas and liquid as EDM dielectrics. The properties of the liquid-gas mixture are estimated to lie in-between the properties of the base materials. To prevent chemical reactions, de-ionized water is used in such applications. In comparison to mineral oils and water, air has the lowest dielectric strength, viscosity, thermal conductivity and thermal capacity. Air with low viscosity provides higher machining accuracy and lower surface roughness. However, low dielectric constant recommends a lower removal rate with an air medium. Lower thermal conductivity insists higher thermal destruction of the machined surface. Therefore, a Complete investigation of the thermal damage must be required. The opposing effect generates by the plasma expansion channel for low viscosity. Thus, overall it reveals that air may be a better alternative dielectric for enhancing the performance measures such as surface finish and higher production rate.

Span 20 is basically applied for different purposes like pigment dispersant, carrier liquid, non-ionic surfactant, etc. Span 20 (chemical composition = $C_{18}H_{34}O_6$) is used in this study as a surfactant for developing a homogeneous powder mixture with dielectric in WEDM process. The physical and chemical properties is given in Table 2.7

Table 2.6 Comparison of electrical, thermal and mechanical properties of dielectric

Properties / Medium	Dielectric Strength	Dynamic Viscosity	Thermal Conductivity	Specific heat capacity
De-ionized water	13 MV/m	0.92 g/m-s	0.610 W/m-K	4.21 J/g-K
Kerosene	14-22 MV/m	1.64 g/m-s	0.150 W/m-K	2.20 J/g-K
Air	3.0 MV/m	0.019 g/m-s	0.026 W/m-K	1.00 J/g-K

Table 2.7 Physical and chemical properties of span-20

Molecular Formula	$C_{18}H_{34}O_6$
Molar Mass	346.459
Density	1.123g/cm^3
Boling Point	516.1°C at 760 mmHg
Flash Point	176.9°C
Vapour Pressure	8.23E-13mmHg at 25°C

2.2.4. Part Geometry Creation

The CNC wire EDM machine requires programming code for the profile geometry and generations of path descriptions for wire travell with respect to a offset position (from where the program path started) for creating the actual geometry. The part geometries or profiles employed in this research were created with RRAPT software.

RRAPT is a CAD/CAM based software for creating the NC program for the Ezee Cut Plus wire EDM machine. The profile designation in RRAPT was performed in three steps as described below;

Step – 1: Profile creation

The required part profile was created with the drawing elements (or construction elements) such as point, line, circle, line and arc. The editing comments, namely erase, undo, redo, hide and transform (copy, move, mirror, rotate, scale) are available with the RRAPT to make necessary modifications in the drawing.

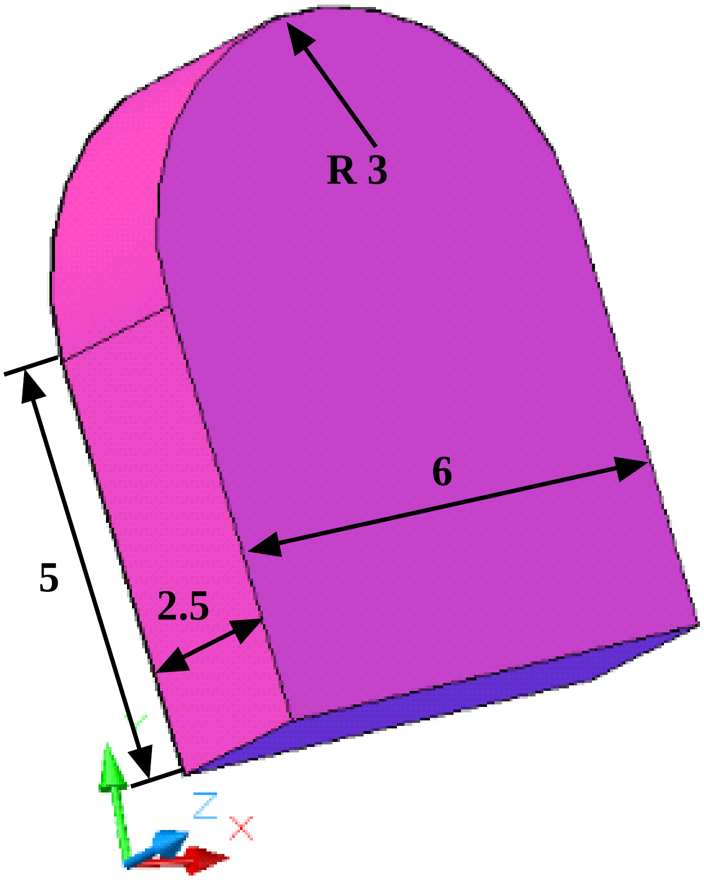


Figure 2.10. Workpiece geometry

Step – 2: Path definition

The drawing created in step-1 is connected using the comment CONNECT to define the exact wire path along with the cutting. Then save the drawing in the file dictionary. The wire path defined by connecting the drawing elements will act as a single entity though it contains many construction elements.

Step – 3: NC program generation

As soon as the sketch of the profile and path definition of wire movement are fed in to the controller, the RRAPT software start generating the NC Programming. In this step, the dimensions (inch or mm) of the profile needs to specify. Also requires other inputs such as wire compensation, taper angle (if any), corner rounding (Yes/ No), number of passes of wire, dwell time etc. The generated NC program (in RRW format) is stored in a floppy disc which can be used by the controller for the execution, when required.

By the following above three steps, NC programs for the profile has been created through RRAPT34 software. The details of the part geometry are illustrated in Figure 2.10.

2.2.5. *Materials Selection*

Wire materials: The wire EDM functions under the same principles as the sinker EDM type, but exhibits itself in a altered manner. In this case, the wire is the electrode, but since it constantly moves, it does not need to have arc erosion resistance because wire is repeatedly used during the machining process. The desired wire electrode materials should fulfill three main criteria: high conductivity, high mechanical strength, and excellent spark and flushing properties. While it is challenging for any single wire to perfectly meet all these criteria simultaneously, it is important to recognize that these factors are interconnected and reliant on each other. These ideals are supported by the those materials have relatively low melting point and high vapor pressure rating can exhibits the better performances. In the present work brass and molybdenum wire have been chosen as electrode material.

Brass emerged as a logical and early alternative to copper in the EDM process and quickly gained popularity as the primary electrode material for general wire EDM applications. Brass wire is essentially a combination of copper and zinc, typically alloyed with approximately 63% copper and 37% zinc. This composition proves beneficial in achieving improved output during the wire EDM process. The inclusion of zinc in the alloy results in significantly higher tensile strength, a lower melting point, and a higher vapor pressure rating, making the wire more versatile and suitable for WEDM operations. Commercially available in a wide range of tensile strengths (approximately 979 MPa) and hardness, brass has become a widely used and readily accessible option for wire EDM applications.

Molybdenum wire (chemical composition as in Table 2.8) is an extreme mechanical strength wire with a tensile strength of over 1896 MPa. It is widely used to create narrowest kerf width and inside sharp corner and helps reduce the number of wire breakage. The reason for this is the extremely small diameter of the wire. However, the high melting point and vaporization temperature of the material result in its relatively poor efficiency during flushing. Therefore, Molybdenum wire is typically used in medical component making industry and military applications.

Table 2.8 Chemical properties of Molybdenum wire

Element	Ni	Mg	Fe	Pb	Al	Bi	Si
Concentration (%)	0.0006	0.0006	0.001	0.0006	0.003	0.0006	0.003
Element	Ca	P	Cu	C	O	Sb	Mo
Concentration (%)	0.0006	0.001	0.0006	0.001	0.005	0.0006	≥99.95

Workpiece material: Mechanical properties of extremely hard, tough, and high corrosion resistance of Ti6Al4V alloy makes it more suitable in aerospace and biomedical applications and other advanced manufacturing industry applications. Table 2.10 exhibits the properties of Ti-6Al-4V. The composition of Ti6Al4V is given in Table 2.9. All experiments were conducted on the selected flat workpiece having a dimension of 200mm×27mm×2.5mm.

Table 2.9 Composition of Ti6Al4V

Component	Titanium Ti	Vanadium V	Aluminium Al	Iron Fe	Carbon C	Nitrogen N	Others
Weight(%)	Balance	4	6	<0.20	<0.08	<0.05	<0.12

Table 2.10 Properties of Ti6Al4V

Properties	Value (Unit)	Ti6Al4V material
Melting point	1604-1660 ºC	
Modulus of elasticity	113.8 GPa	
Ultimate tensile strength	860 MPa	
Density	4.43gm/c.c	
Shear strength	550 MPa	
Resistivity	0.000178 Ohm-cm	
Thermal conductivity	6.7W/m-K	

2.2.6. Control Factor for Experimentation

Based on literature survey and trial experiments, the control factors were chosen as input parameters as shown in Table 2.11. During trial experiments, it is observed that powder properties play an important role in machining output. Therefore, powder properties and machining inputs have been considered as input parameters.

Table 2.11 Control factors and their levels

Sl no.	Control factor	Symbol for coded value	Levels	Unit
1	Servo feed setting (SF)	A	30-90	-
2	Peak current (Ip)	B	1-4	A
3	Pulse on time (Ton)	C	20-90	µs
4	Pulse off time (Toff)	D	1-12	µs
5	Gap voltage(Gv)	E	30-90	V
6	Powder type	F	SiC, Al_2O_3, B_4C, Graphite	-
7	Powder concentration	G	2-10	g/L
8	Powder size	H	10-40	µm
9	Dielectric type	I	De-ionized water, Kerosene, Surfactant mixed De-ionized water	-
10	Fluid level	J	50-90	mm

In WEDM process, there are other factors which are anticipated to have an effect on the performance are kept constant. It may be pointed out that there are several noise factors associated with WEDM process as listed below:

(i) Ambient temperature of the tool room;
(ii) The structure of workpiece material matrix;
(iii) Variation in wire geometry;
(iv) The complex nature of wire vibration;
(v) Superimposition of sparks or craters at a particular point;
(vi) Variation of number of sparks from point to point between the wire and the workpiece;
(vii) Change in instantaneous conductivity of the dielectric fluid;
(viii) Variation of the controller performance; and so on.

2.2.7. Responses

In the present research, the following responses are considered.

(i) Metal removal rate (MRR) (mm^3/min)
(ii) Surface roughness (R_a)(μm)
(iii) Dielectric Consumption (C_D/cm^3)
(iii) Corner inaccuracy (CI)(μm^2)

2.2.8. Measuring Equipment

Figures 2.11-2.13 depict the measuring equipment utilized in the current study, while Table 2.12-2.14 provide the technical specifications of the measuring instruments.

Figure 2.11. Metallurgical microscope (model-DM 2700)

Table 2.12 Technical specification of metallurgical microscope (model-DM 2700)

Parameter	Specifications
Microscope Body/Frame/Stand	• Metallurgical Microscope for reflected/Incident light • Stabilized power supply of 100-230 V • Manual Z drive with total stroke of 25mm • Adjustable stage height stops for prevent against collision of sample with objective lenses.
Focus	3-gear focus drive (coarse, medium and fine) torque adjustment.
Illumination	White LED with intensity control and supplied with ways and means to produce constant color temperature irrespective of variation in light intensity both for Transmitted & Reflected Light.
Contrast technique	• Bright Field • Dark Field • Polarization
Nosepiece	5 Position or More
Phototube	• Beam splitting for simultaneous observation through eyepieces and live display of image on screen. • Trinocular observation tube with inclination 30 degree • Interpupillary distance should be adjustable maximum up to 75mm.
Eyepiece	Eyepieces with 10x magnification and 22mm field of view
Polarizer & Analyzer	• Analyzer rotatable with a scale. • Polarizer with switchable orientation for Reflected light • In Mount Polarizer for Transmitted Light.
Stage	Mechanical Stage with XY-movements with travel range 3"x2"
Objectives	• Semi Apochromatic 1.25X/0.04, Free working Distance 1.5 mm or better • PLAN Achromat 5x/0.12 Free working Distance 14 mm or better • PLAN Achromat 10x/0.25 Free working Distance 16 mm or better • PLAN Achromat 20x/0.40 Free working Distance 1 mm or better • PLAN Achromat 50x/0.75 Free working Distance 0.3 mm or better • PLAN Achromat 100x/0.85 Free working Distance 0.3 mm or better
Camera	· CMOS/CCD Sensor, 5 Connection: USB 3
Software for image analysis	Integrated software for image acquisition and calibration and for direct measurements. Dedicated modules for the followings: • Grain Analysis, Phase Analysis, Metallography Tools (Dendrite Arm Spacing, Banding, Layer thickness) • 2D Analysis

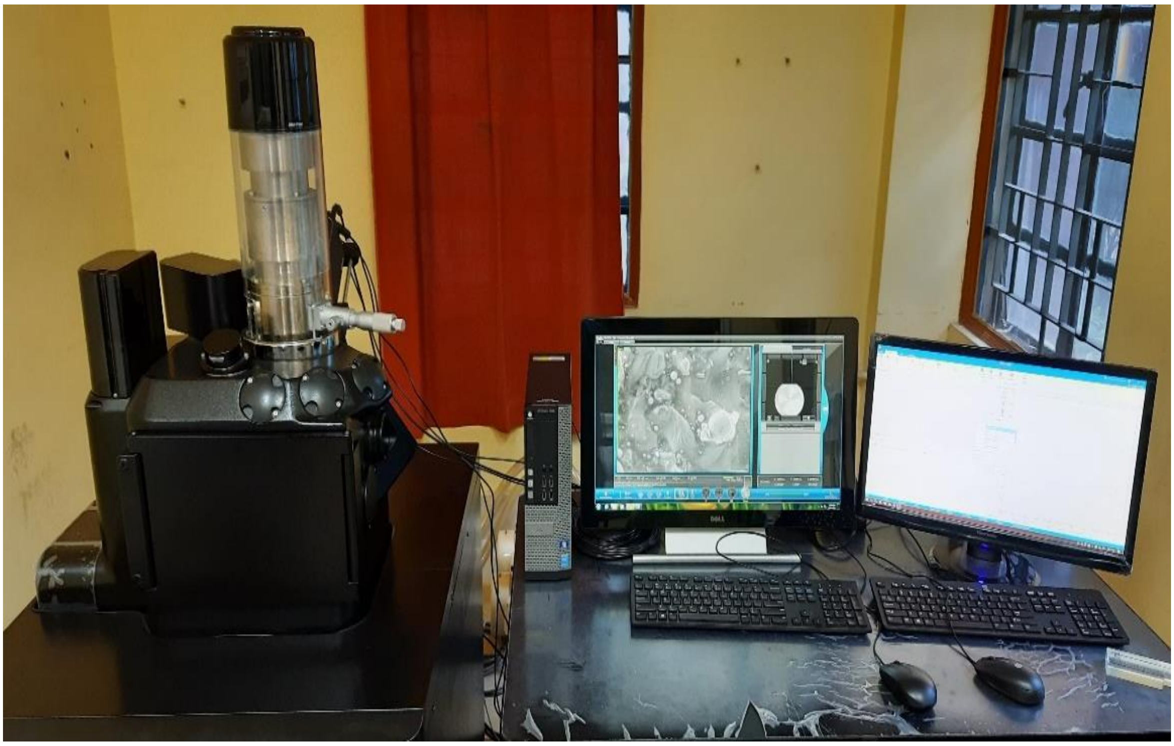


Figure 2.12. Scanning electron microscope (model- JEOL JSM IT500)

Table 2.13 Technical specification of SEM (model- JEOL JSM IT500)

Resolution	High Vacuum mode 3 nm at 30KV 20 nm at 1KV Low Vacuum mode 4 nm or better at 30 KV in BSE
Accelerating Voltage	0.3KV to 30KV (continuous)
Probe current	1 µA
Magnification	5X to 3,00,000X
Vacuum system	10- 400 Pa
Stage Specification	5 axis Fully Motorized, Eucentric / Compucentric Stage, X = 100 mm or higher, Y = 50 mm or higher, Z = 50 mm or higher, Fully motorized
Specimen size	200 mm in diameter
Image format	BMP, JPEG or TIFF

EDS (Energy Dispersive X-Ray Spectrometer)	• LN2 free SDD detector, active area 30 mm2 with 129 eV resolution • Detection from Be (4) to Am (95) • Have quantitative, qualitative analysis, mapping, Line scan, Point id , Area Analysis capabilities

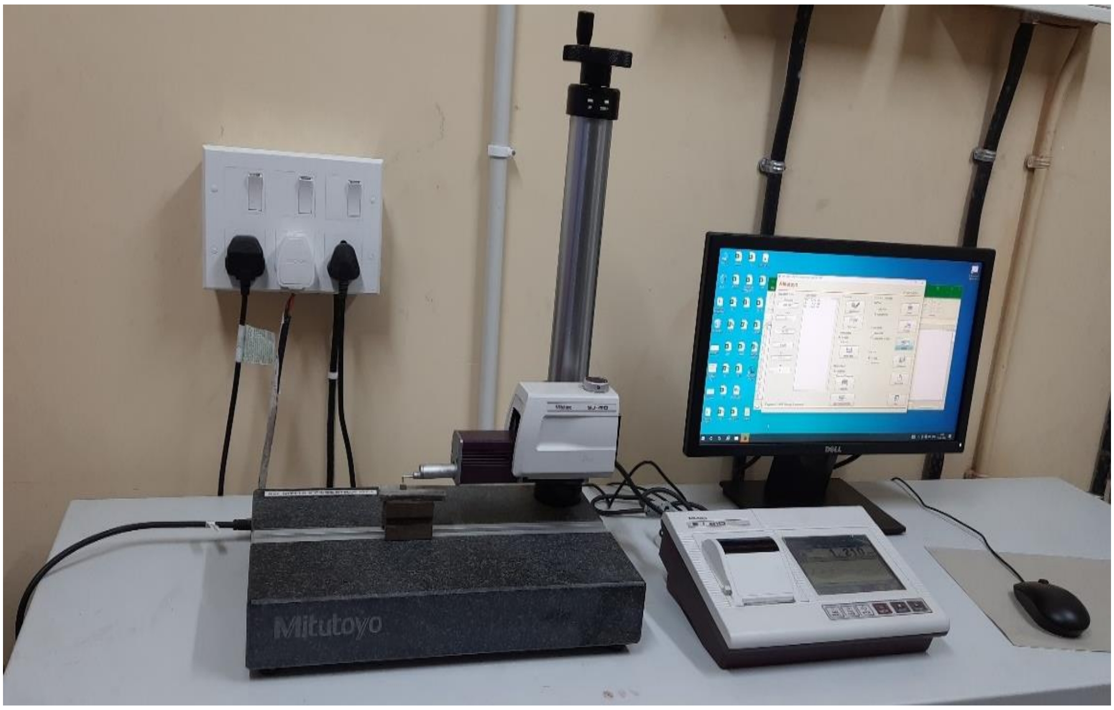


Figure 2.13. Surface roughness tester (model-SJ-410)

Table 2.14 Technical specification of surface roughness tester (SJ-410)

Measuring range	50 mm
Measuring parameters	Ra, Rq, Rz, RSm, Rmr, Rpm,
Cutoff value	0.08 mm 0.25 mm 0.8 mm 2.5 mm 8 mm
Sampling length	0.08 mm 0.25 mm 0.8 mm 2.5 mm 8, 25 mm

Measuring speed	0.05 mm/s 0.1 mm/s 0.2 mm/s 0.5 mm/s 1.0 mm/s
Analysis graph	Material ratio curve, profile height amplitude distribution curve
Applicable standards	JIS 1982/JIS 1994/JIS 2001/ISO 1997/ANSI/VDA

CHAPTER: 3

INVESTIGATION ON THE INFLUENCE OF DIFFERENT POWDERS AND DIELECTRICS ON VARIOUS MACHINING CRITERIA

3.1. Problem Statement

In the current manufacturing scenario, advanced materials like titanium alloy, Inconel, Monel, and composites with low conductivity exhibit quite low machinability and it is difficult to machine complex shapes [33,43,44,48,49]. Many innovative approaches are involved in machining these materials, but sometimes these processes are very cost effective and fail to fulfil the desired quality. WEDM is one of the most efficient machining techniques which covered all the requirement to machining macro and micro complex part of the advanced material [28-30,40]. The major problem in WEDM process is low machining rate. A hybrid machining technique of WEDM is established to overcome this issue, i.e. powder mixed WEDM. Comprehending the process mechanism and control proves to be highly challenging as well. So many researchers have discussed the significant improvement of the PMWEDM performance characteristics [26-30,40], but this process is still now in the development phase. The determination of the best solution of different metal non-metal and composites after machining which is associated with metal removal rate and critical aspects of the machined surface such as surface topography, surface morphology, and surface treatment is also in the development phase [20,29,53,54,62].

PMWEDM is a complicated hybrid thermoelectric process controlled by a large number of effective process parameters like Pulse on time (Ton), Pulse off time (Toff), Peak current (Ip) and Gap voltage (Vg), Wire feed (WF), powder properties (powder type, powder concentration and powder size) and dielectric[21, 39-41]. The wrong selection of these parameters may cause different hazards such as wire breakage, improper shape, low cutting speed.

The literature review shows that numerous research studies have focused on finding the optimal parametric setting for PMEDM using various optimization techniques [20,24,34,42,43]. However, achieving significant enhancements in performance efficiency, precision, and accuracy remains an unresolved issue. Few works have been done to improve surface characteristics [29,37,40] and performed the experiment by varying one or two powders [33-37,39-41]. Moreover, additional potential can be achieved by varying with different powder sizes and concentrations [36,43,48]. Proper selection of powder properties, process parameter and precision machining of advanced material is the main issue in this work. Some researchers have shown interest in path modification strategy and trim cutting operation of the curve profile [44-45] in the WEDM process. The generation of curve profile with the intricate shape of superalloy and composite and the low conductive material is also a concerned research area [45]. Apart from the experimental, investigation process analysis, modelling and simulation are required to get an optimal machining condition. The past research reveals that most of the research works are done on powder mixed electric discharge machining. Very few research works are involved in powder mixed WEDM.

3.2. Experimentation for Selection of Suitable Powder Type Along with Their Properties

The experimentation has been conducted using four controllable parameters and dielectric fluid levels. Based on the experimental observation, the control parameters are fixed, and further experiment has proceeded with considering powder properties as an input controlled factor. The machining setup for the present investigation has been illustrated in Figure 3.1. Table 3.1 shows the machining parameters and their considerable levels. The obtained results are given in Table 3.2.

Table 3.1 Controllable parameters.

Controllable parameters	Units	Levels/Limits		
Peak Current	A	1	2	3
Pulse-on-time	µs	40	60	80
Pulse-off-time	µs	4	6	8
Gap voltage	V	45	60	75
Fluid Level	mm	50	70	90

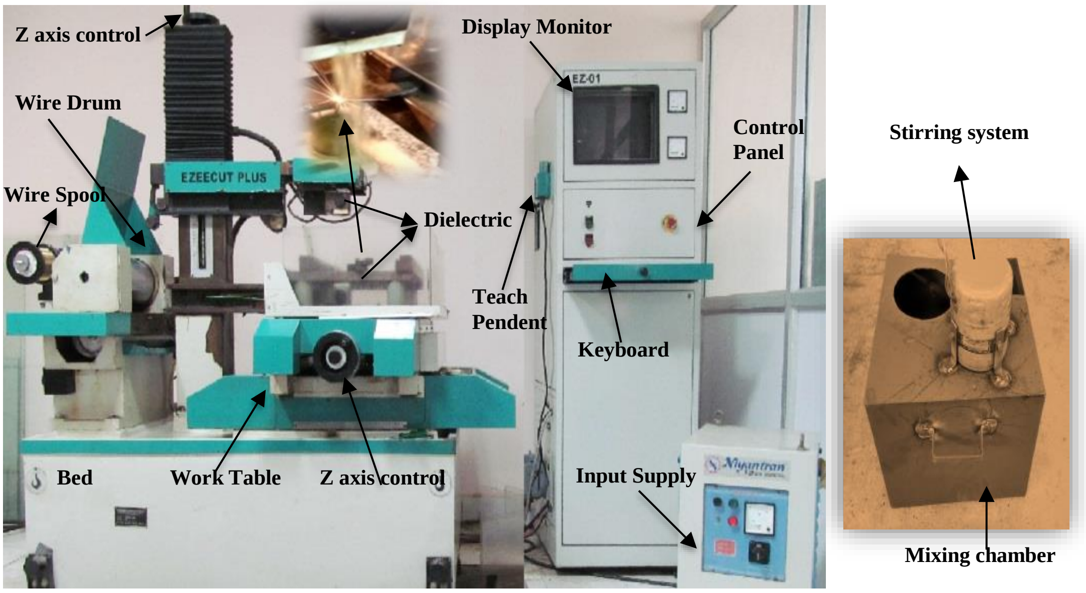


Figure 3.1. Machining setup

Table 3.2. Experimental results

EXP No.	Powder Type	Particle size (µm)	Concentration (g/l)	MRR (mm^3/min)	SR(R_a) (µm)
1	Al_2O_3	10	2	4.958	3.014
2	Al_2O_3	10	4	4.631	2.318
3	Al_2O_3	10	6	4.459	2.627
4	Al_2O_3	10	8	3.854	3.857
5	Al_2O_3	10	10	2.465	4.521
6	Al_2O_3	40	2	5.187	3.254
7	Al_2O_3	40	4	5.269	3.921
8	Al_2O_3	40	6	4.153	3.052
9	Al_2O_3	40	8	4.315	3.675
10	Al_2O_3	40	10	3.574	3.899
11	B_4C	10	2	5.024	3.256
12	B_4C	10	4	5.268	3.899
13	B_4C	10	6	4.251	2.584
14	B_4C	10	8	3.529	2.042
15	B_4C	10	10	2.685	3.245
16	B_4C	40	2	4.327	3.098
17	B_4C	40	4	3.658	2.756
18	B_4C	40	6	4.521	3.991
19	B_4C	40	8	3.104	2.785
20	B_4C	40	10	2.954	2.243
21	SiC	10	2	4.463	5.368
22	SiC	10	4	5.086	5.421
23	SiC	10	6	4.136	4.341
24	SiC	10	8	4.089	2.665

EXP No.	Powder Type	Particle size (µm)	Concentration (g/l)	MRR (mm^3/min)	SR(R_a) (µm)
25	SiC	10	10	2.301	2.428
26	SiC	40	2	2.965	3.286
27	SiC	40	4	2.843	3.869
28	SiC	40	6	2.452	3.475
29	SiC	40	8	3.416	3.892
30	SiC	40	10	3.917	4.62
31	Graphite	10	2	4.895	3.547
32	Graphite	10	4	5.032	5.019
33	Graphite	10	6	4.398	3.985
34	Graphite	10	8	2.95	4.315
35	Graphite	10	10	2.337	3.296
36	Graphite	40	2	3.407	2.267
37	Graphite	40	4	3.117	4.498
38	Graphite	40	6	4.132	3.501
39	Graphite	40	8	3.983	3.861
40	Graphite	40	10	4.632	4.622

3.3. Analysis of the Effect of Powder Characteristics on Responses

Due to the dissimilar properties of different powders, the effect of powder on process performance in WEDM is also different to each other. In addition to powder with dielectric the response measures like surface finish, reducing tool wear rate, cutting speed, material removal rate and other dimensional accuracy are influenced more. Based on the properties such as electrical and thermal conductivity, suspension capability and non-magnetic properties of different powder types, the efficiency of the machining is enhanced for better productivity.

The size of the powder is the most influential input parameter in the obtained surface topography after machining. A larger particle size increases the interelectrode gap more. Due to this, lower deionization and more contamination are found in the narrowest gap between electrode and job piece. As a result, the larger particle size of the powder increase gap, but at the same time, it decreases surface finish and material removal rate.

The discharge gap increases by using conductive powder with dielectric. So, the conductivity of powder is reasonably connected with WEDM performances. The nature of conductivity improves the flashing criteria and spark frequency. A higher amount of heat is confiscated from the machining gap by the particle because of the high thermal conductivity of the powder. As a result, shallow craters are produced on the machined surface.

Upon combining the powder with the dielectric, the particles become energized by the supplied current, leading to the creation of a bridging effect within the spark gap. This bridging effect results in a decrease in gap voltage and dielectric strength, subsequently initiating a sequence of spark discharges. An increase in powder concentration results in higher MRR and lower surface roughness. But the higher value of powder concentration reduces performance. While higher powder concentrations can initially offer advantages like improved MRR and surface roughness, the negative effects of agglomeration, clogging, increased friction, heat generation, and process instability eventually outweigh the benefits, resulting in reduced performance. It is required to find the optimum powder concentration for a proper supply of discharge energy to the workpiece.

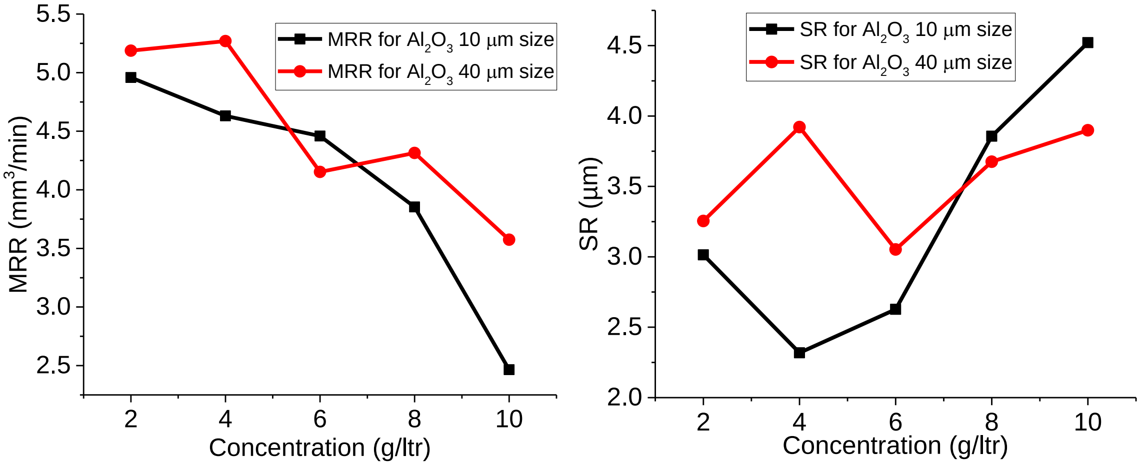


Figure 3.2. Influence of different powder concentration of Al_2O_3 on MRR and SR

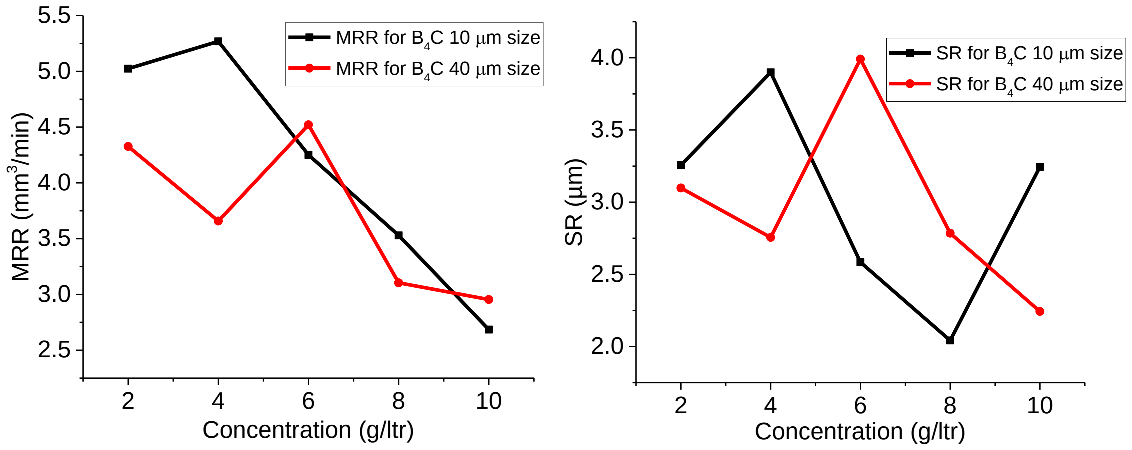


Figure 3.3. Influence of different powder concentrations of B_4C on MRR and SR

The density of the powder particles plays a significant role in influencing surface forces, which, in turn, contributes to achieving a uniform distribution of powder particles within the dielectric. When the density is low, it helps balance the surface forces, leading to a more even distribution. Additionally, the lower density ensures that a smaller quantity of powder accumulates at the bottom of the dielectric chamber, thereby minimizing the amount of power needed. In this investigation, several powders like SiC, Al_2O_3, B_4C and graphite powders are used to modify the WEDM process capability on superalloy material. With respect to the powder properties of type, size, and concentration, suitable powders are selected as the best performer for the next experimentations.

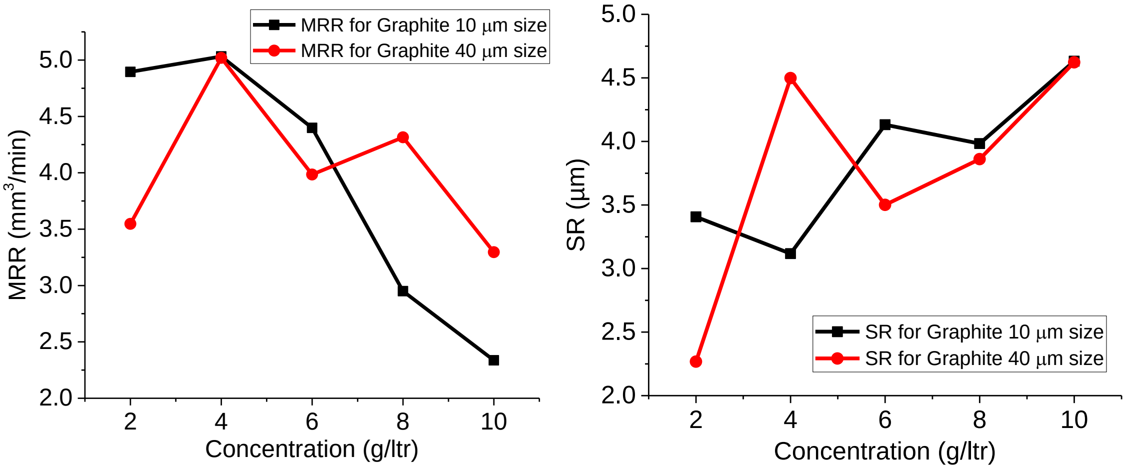


Figure 3.4. Influence of different powder concentration of graphite on MRR and SR

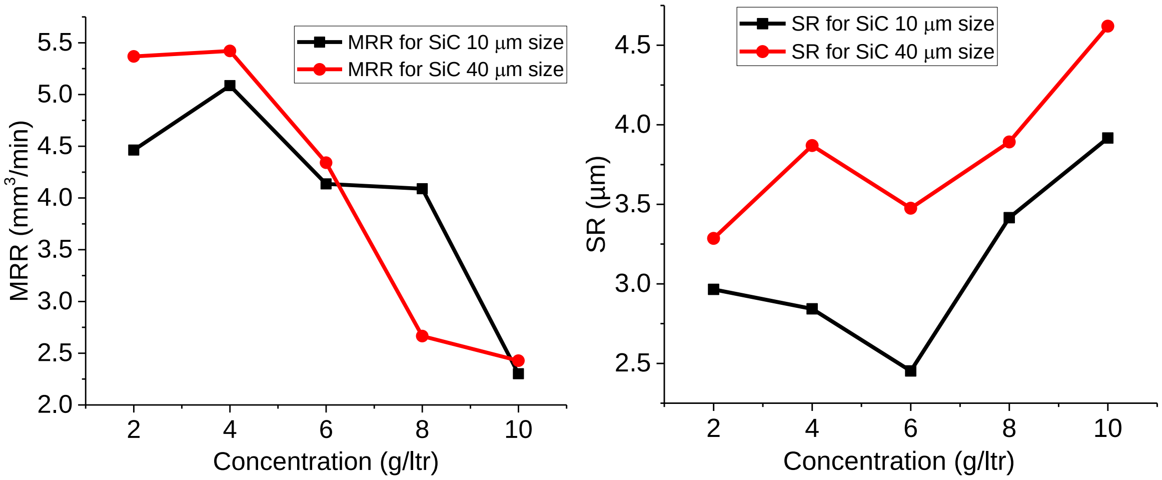


Figure 3.5. Influence of different powder concentration of SiC on MRR and SR

In this section, PMWEDM operation is done by varying powder concentration and size while machining controllable parameters are fixed, i.e. I_p=2A, T_{on}=30μs and T_{off}=8μs and

Gv=75V. The size of all types of powder is selected as 10 µm and 40 µm, respectively. The range of powder concentration is 2g/L-10g/L. The obtained results are presented in Table 3.2. The result shows that 10µm particle size gives a better result as compared to 40 µm particle size. From Figure 3.2 and Figure 3.3, it is clear that 10µm size of both powders (Al_2O_3 and B_4C) provides the best surface finish for a concentration of 4g/L and 8g/L, respectively. But, the average performance of SiC with a concentration of 4g/L is closer to the performance of the Al_2O_3 powder as shown in Figure 3.5. Figure 3.4 and Figure 3.5 show the impact of graphite and SiC powder in dielectric on MRR and SR during WEDM process. From the experimental results, the size 10 µm and concentration of 4g/L show the best value of MRR and SR.

The Surface roughness decreases with an increase in B_4C powder concentration up to 8g/L. For other powders, the surface roughness increases with an increased powder concentration up to 10g/L. B_4C powder has a low density as compared to the other powders. The balanced surface force, brought about by the low density, leads to an improved surface finish. Due to the increase of powder concentration, the material removal rate is decreased. High powder concentration slows down the process because of discrete sparks in the plasma channel. During machining, a larger amount of particles absorb the discharge energy. As a result, the next cycle spark discharge is affected due to the availability of lower fraction energy. Thus machining efficiency is decreased with a selection of improper powder concentration. Based on the results, it is clear that Al_2O_3 provides a better outcome for MRR and surface finish together. In terms of dimensional accuracy, B_4C gives the best performance. Moreover, the next investigation is carried out with these two powders adding to the dielectric.

3.4. Study of Microstructure of WEDM Surface

Figure 3.6 (a) and Figure 3.6 (b) presents a visual representation of the machined sample using two different powders, Al_2O_3 and B_4C, in the WEDM process. The surface of the machined sample, when B_4C powder was mixed in the dielectric, displayed a more uniform and improved crater formation compared to the sample with Al_2O_3 added dielectric. This resulted in a R_a value of 2.042 µm when using 8 g/L B_4C powder in the dielectric. On the other hand, a surface roughness of 2.318 µm was observed when using a lower concentration of Al_2O_3 added dielectric. These findings indicate the significance of powder selection for the PMWEDM process. Further investigation and study are necessary to accurately determine the optimal powder properties for achieving desired surface characteristics and overall performance in the machining process.

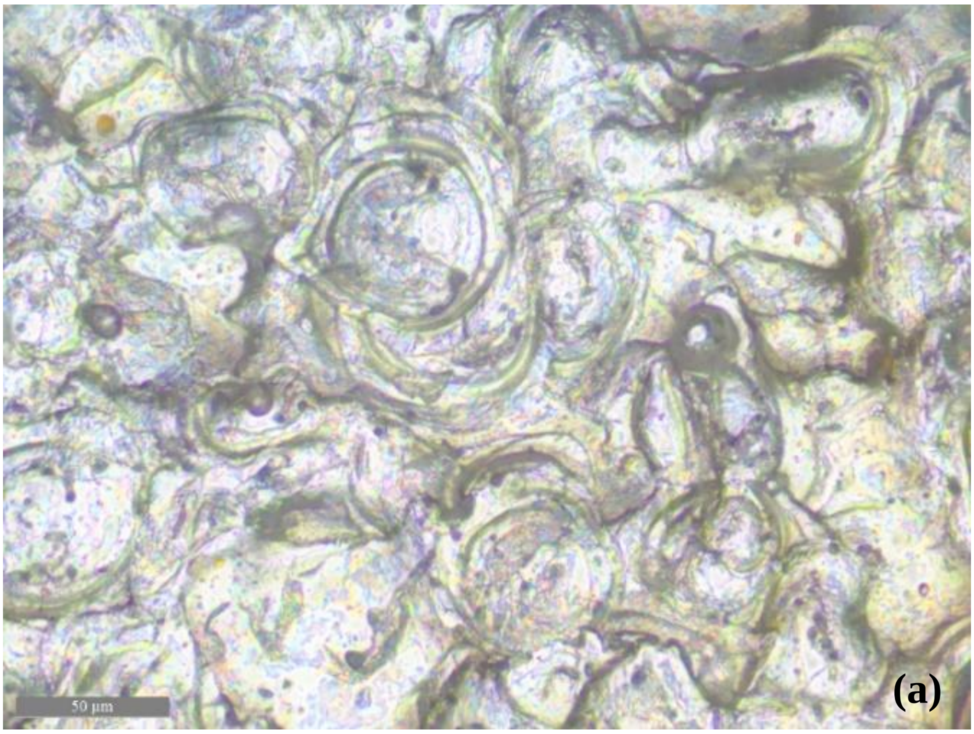


Figure 3.6. (a) Microstructure of PMWEDM sample with Al_2O_3 powder size 10µm and concentration 4g/L

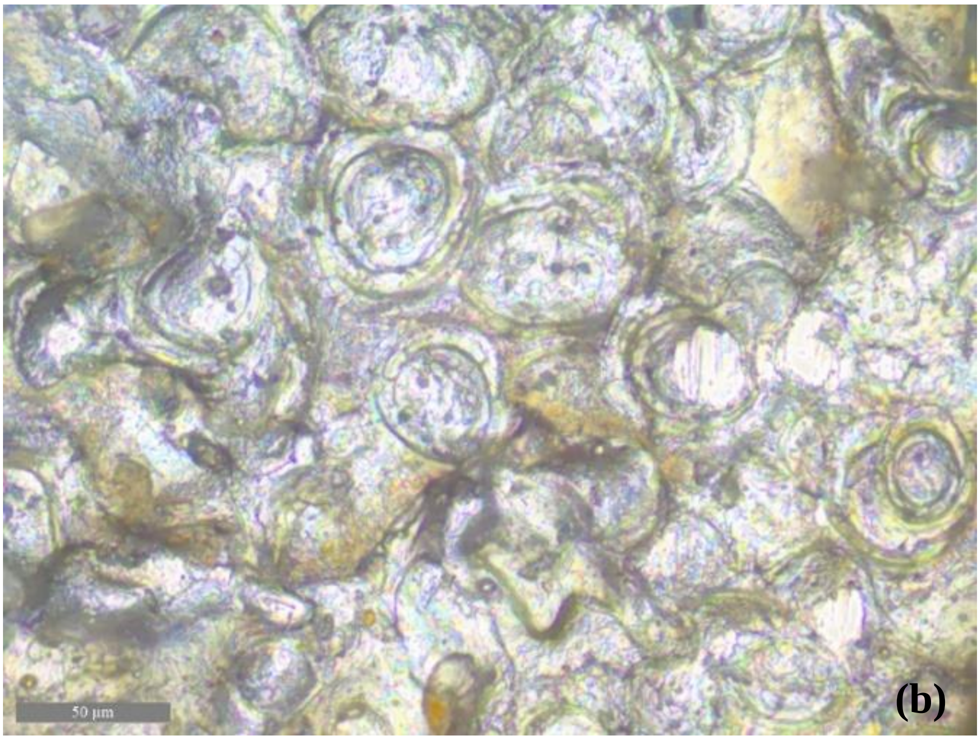


Figure 3.6. (b) Microstructure of PMWEDM sample with B_4C powder size 10µm and concentration 8 g/L

3.5. Experimentation with Different Dielectrics

In this study, total experiments have been conducted by Ezee Cut Plus wire EDM machine. The machining dielectric tank of size 20 liters capacity was made with a stirring system for proper mixing of the powder particle. During machining, the selected powder B_4C of 10 µm size mixed with the dielectric fluid. Ti6Al4V alloy was chosen for machining purposes, which has a high hardness value of 34 HRC and melting point of 1660℃. The size of the work material was 200 mm×27 mm×2.5 mm. The electrode material was brass of 250 µm diameter. The experimental machine setup with powder mixing chamber is shown as in Figure 3.1. In the present study, two dielectric fluids i.e. deionized water and kerosene) are used for the first experimentation phase. Second phase experimentation has been conducted by adding surfactant in the dielectric. Span 20 (chemical composition = $C_{18}H_{34}O_6$) is used as a surfactant for developing a homogeneous powder mixture in the dielectric.

3.6. Control Factors and Responses

Design of experiment has demonstrated in Table 3.3. Table 3.4 shows the selection of variable parameters and their levels as machining inputs like pulse on time, pulse off time, gap voltage and fluid level. Experimental design has been shown in Table 3.5 for conducting the experimentation. The effectiveness of these machining variables are investigated for better responses such as material removal rate, surface roughness and dielectric consumption

Table 3.3 Input parameter and their levels

Controllable parameters	Units	Levels/Limits		
		1	2	3
Pulse-on-time	µsec	40	60	80
Pulse-off-time	µsec	4	6	8
Gap voltage	Volts	45	60	75
Fluid Level	mm	50	70	90

The metal removal rate has been measured by dividing the total weight loss during machining by the total machining time and density of the workpiece, as in Equation (3.1).

$$MRR = \frac{(w_i - w_f) \times 60 \times 1000}{T \times \rho} \tag{3.1}$$

where W_i and W_f are the weight (gm)of the job piece before machining and after machining. T is the total time, and ρ represents the density of the job piece (gm/mm^3)

Average surface roughness in terms of Ra has been measured through Surftest SJ-410 series. Measurement of dielectric consumption has been calculated by dividing the volume of dielectric consumption after machining and before machining by total time and MRR as in Equation (3.2).

$$C_D = \frac{(c_a - c_b)}{t_m \times MRR} \tag{3.2}$$

Where, C_D represents dielectric consumption, c_a and c_b represents the dielectric volume after machining and before machining in cm^3. t_m is the total machining time.

Table 3.4 Experimental plan

Sl.No.	Pulse on Time (µs)	Pulse off Time (µs)	Gap Voltage (V)	Fluid Level (mm)
1	80	8	75	90
2	80	8	75	70
3	80	8	75	50
4	80	8	60	90
5	80	8	45	90
6	40	4	75	50
7	40	4	60	50
8	40	4	45	50
9	80	6	75	90
10	80	4	75	90
11	60	8	75	90
12	40	8	75	90

3.7. Influence of Process Parameters on Performance Measures

The powder particle acts as an insulator in the dielectric medium of powder mixed wire electric discharge machining. Here, the powder particles modernize the dielectric flow; as a result, agglomeration of vaporized material breakup occurs and modifies the plasma channel [46]. During machining, powder particles get energized by the discharge current, and early explosion passes through the channel. Powder particles reduce the insulating strength of dielectric with an increasing the spark gap. Due to these reasons, the overall process becomes more stable and improves process efficiency. As a result, the machined surface quality and metal removal rate of PMWEDM enhanced more than the conventional WEDM process [47]. In the present study, four adjustable input variables are selected to obtain the response measure such as MRR, SR and dielectric consumption. The individual interaction of each process parameters are concentrated on responses at a same time. A detailed discussion has been elaborated in next section in the domain of PMWEDM process parameter and environmental contamination with the help of new approach i.e. one factor at a time (OFAT).

Table 3.5. Experimental results

Sl. No.	Pulse on Time	Pulse off Time	Gap Voltage	Fluid Level	MRR (mm^3/min)		SR (R_a) (µm)	
	(µs)	(µs)	(V)	(mm)	Deionized Water	Kerosene	Deionized Water	Kerosene
1	80	8	75	90	7.548	7.948	4.221	3.540
2	80	8	75	70	8.752	7.711	3.254	2.229
3	80	8	75	50	6.324	5.217	2.540	3.254
4	80	8	60	90	6.014	4.136	2.847	2.610
5	80	8	45	90	5.891	4.995	3.015	4.571
6	40	4	75	50	2.504	3.254	2.109	3.286
7	40	4	60	50	3.529	3.685	3.549	3.445
8	40	4	45	50	2.547	1.988	2.596	2.164
9	80	6	75	90	7.526	8.213	3.288	2.542
10	80	4	75	90	5.854	7.836	2.553	2.310
11	60	8	75	90	6.015	6.751	4.452	2.559
12	40	8	75	90	5.857	3.766	2.139	3.985

3.7.1. Study of the Effect of Machining Parameters and Dielectric Fluid on Material Removal Rate

In the present study, two recognized dielectric like deionized water and kerosene are used to find out the impact on responses. A strong relationship is established between the performance efficiency and dielectric of powder mixed WEDM when current passes through the dielectric. So the conductivity of the dielectric play a key role in PMWEDM process [48]. The dielectric insulation simply breakdowns by high conductivity and generates a large machining gap. Changing with various dielectric, Figure 3.7 displays the influence of the machining inputs on MRR. It is evident in Figures 3.7 (a) and 3.7 (b) that a greater MRR is found in kerosene dielectric, whereas 3.7 (c) and 3.7 (d) deionized water clearly show the maximum MRR. Therefore, MRR continuously improved with the increases of gap voltage and pulse on time.

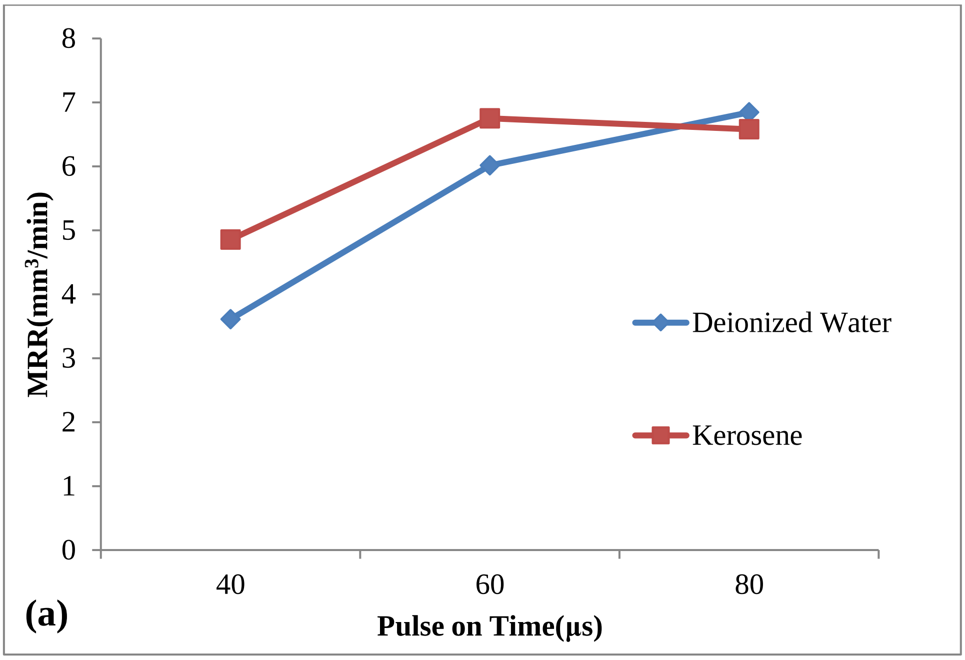


Figure 3.7. (a) Influence of pulse on time on MRR

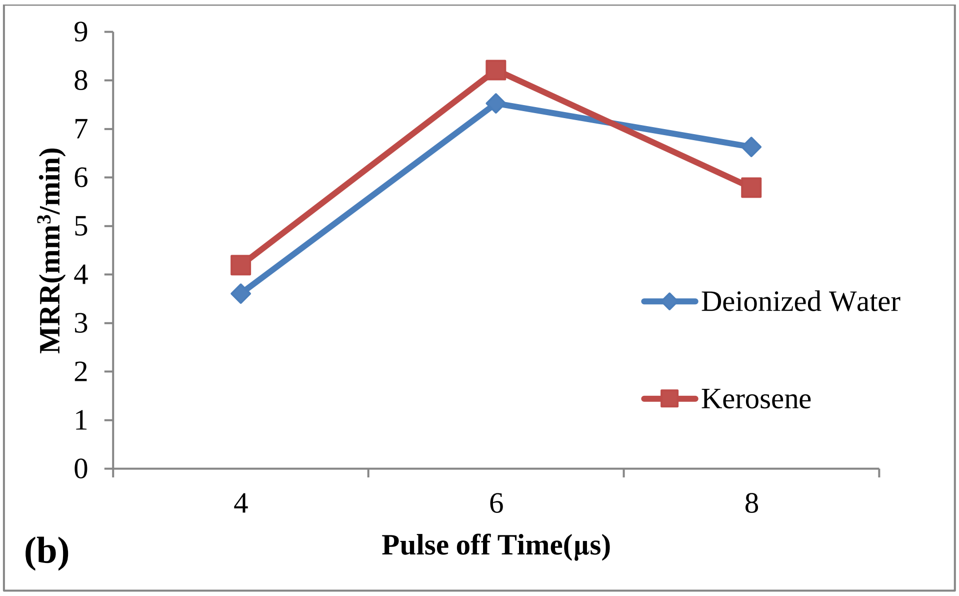


Figure 3.7. (b) Influence of pulse off time on MRR

Although the open voltage is worked in the narrowest machining gap, discharge did not occur then. The discharge only happen after the ignition delay time. A discharge current is also passing through the machining zone during the breakdown of dielectric. The discharge energy increases with the increases of both parameters like gap voltage and pulse on time.

Figures 3.7 (b) and 3.7 (d) demonstrate that the highest metal removal rate is achieved when the pulse off time and fluid level are set to their middle values. The deionized water has a greater impact on MRR than kerosene dielectric.

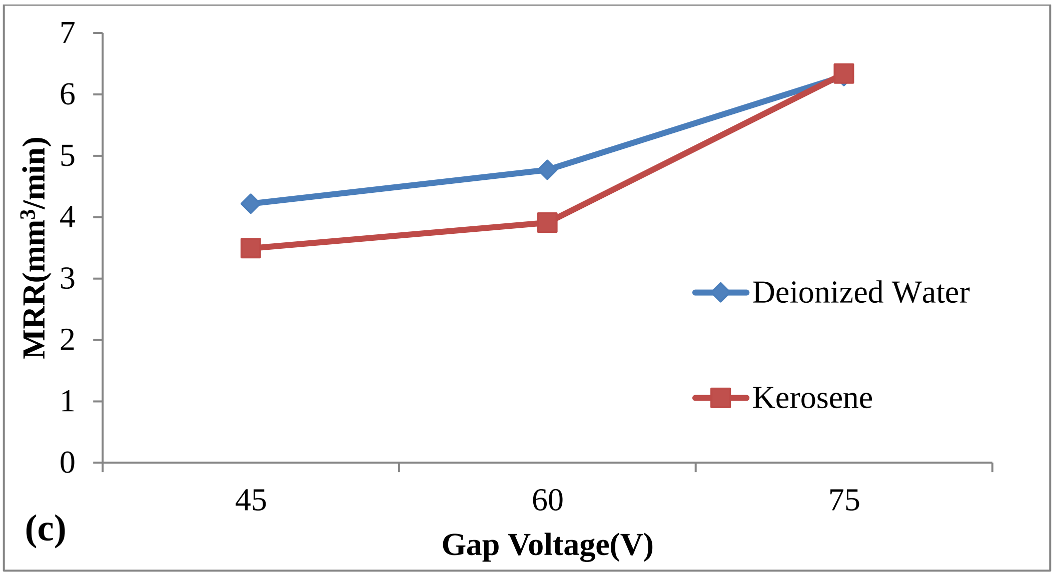


Figure 3.7. (c) Influence of gap voltage on MRR

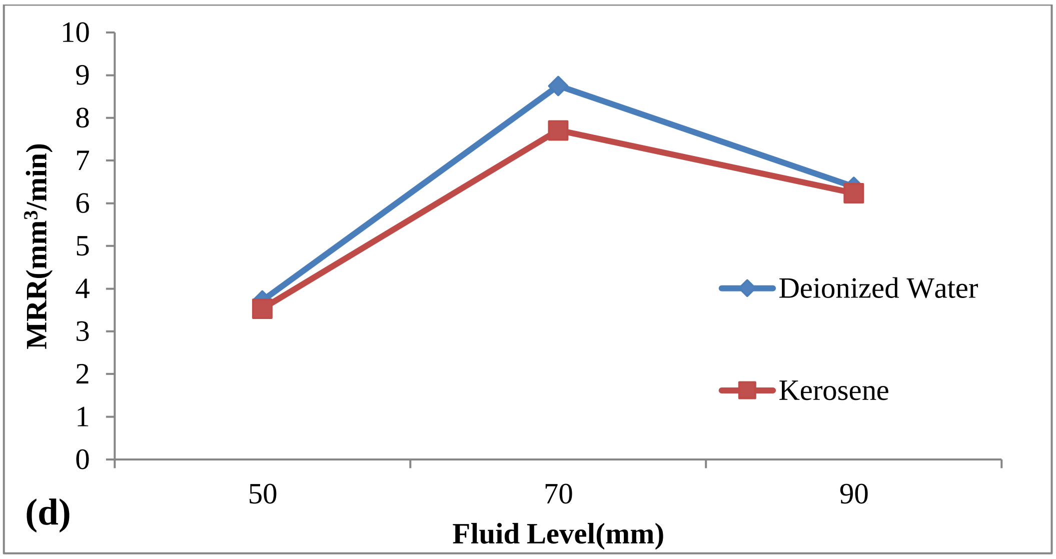


Figure 3.7. (d) Influence of fluid level and dielectric fluid on MRR

3.7.2. Study of the Effect of Machining Parameters and Dielectric Fluid on Surface Roughness

Heating and cooling processes are continued during machining of the WEDM process. Therefore overheating causes a high degree of metal erosion from the workpiece, resulting in a deeper crater on the machining surface. On the other side the effect of cooling action generates micro crack on surface. Pulse on time is the greatest dominating factor which directly promotes the supply of high discharge density. A shallow and minimal size crater formation on the job surface leads to superfine surface topography [49]. Thereby, it is important to produce a continuous with a small amount of discharge energy during machining so that massive discharge can be discarded. At the same time, removing the molten metal from the machining zone in the form of debris particles is required to avoid ultimate recast layer formation on the machined surface.

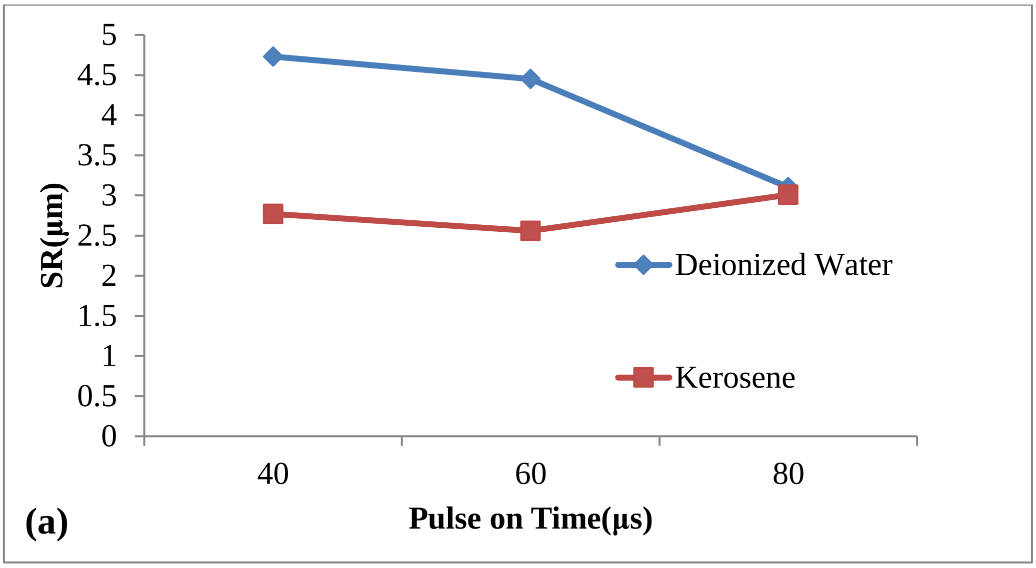


Figure 3.8. (a) Influence of pulse on time on SR

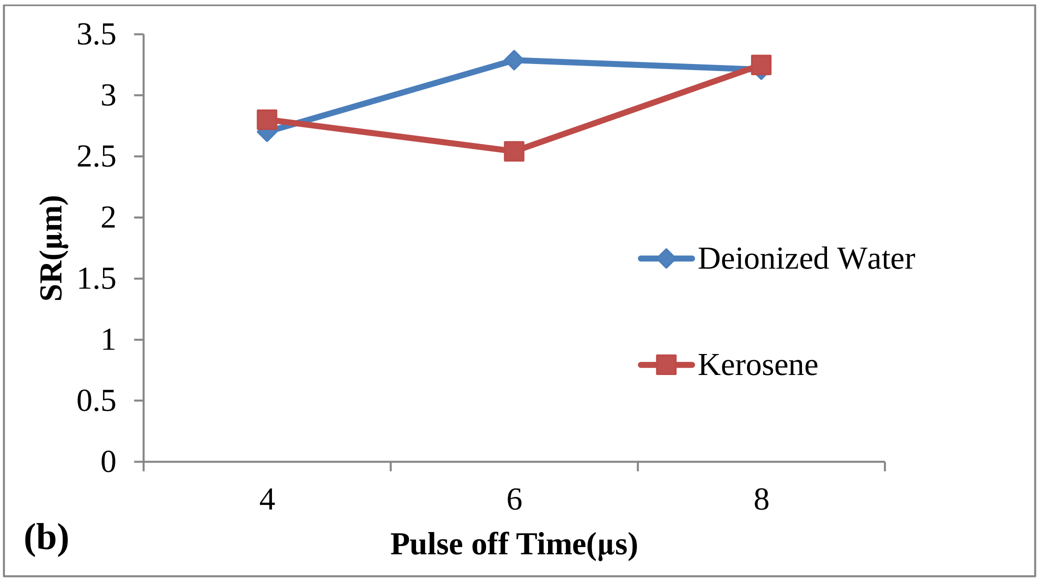


Figure 3.8. (b) Influence of pulse off time on SR

Figure 3.8 shows the influence of the input parameter followed by different dielectric on surface roughness. Figures 3.8 (a) and 3.8 (b) illustrate a trend where the surface roughness (SR) first increases and then decreases with variations in the pulse on time and fluid level. Additionally, Figure 3.8 (c) indicates intentionally higher surface roughness at low gap voltage settings. This is due to low intensity of the spark energy. Figures 3.8 (a), 3.8 (b) and 3.8 (d) show that the middle value provides the best surface finish. With an increase in pulse on time from 40-80 µs, deionized water delivers a better surface finish. This is due to suspended B_4C powder into dielectric as it breakdowns the insulation and reduces the impulse force.

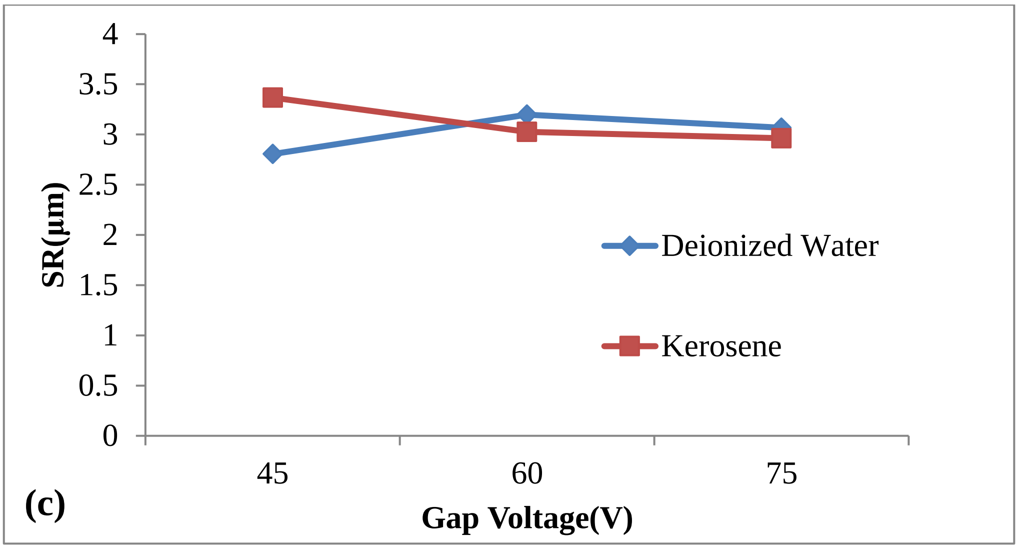


Figure 3.8. (c) Influence of gap voltage on SR

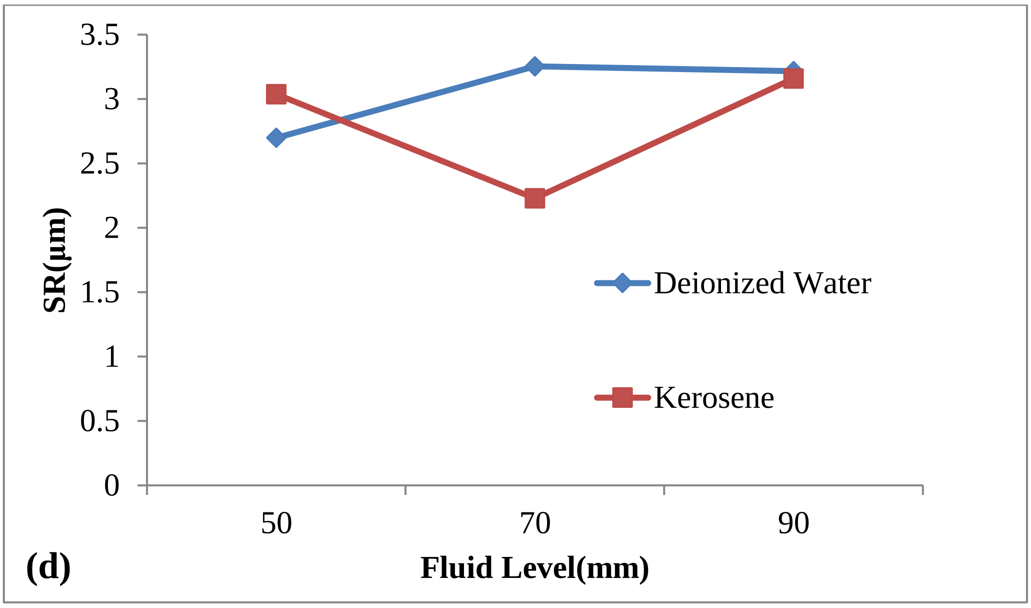


Figure 3.8. (d) Influence of fluid level and dielectric fluid on SR

As a result, high pressure energy during increasing Ton helps to create small craters and voids, resulting a smooth surface finish. For surface roughness, the most significant parameters are pulse on time, pulse off time and fluid level. From the experimental results in Table 3.5, a comparison among these dielectric indicates that deionized water has a greater effect followed by kerosene on surface roughness as well as MRR for both conditions i.e. single or multi-response criteria. In the next section, experimentation is performed with surfactant added PMWEDM. Surfactant helps to mix the powder in dielectric homogeneously and retards to an agglomeration of eroded material and carbon layer that increases the efficiency of the process. The addition of surfactant increases the conductivity of the dielectric in the machining zone [48]. The influence of the parametric effect is elaborated in the next section.

3.7.3. Study of the Effect of Machining Parameters and Surfactant Added Dielectric on Material Removal Rate

The modification process of wire electric discharge machining (WEDM) has been effectively implemented on alloy materials. To further enhance the machining process, the addition of a surfactant to the dielectric, along with the powder particles in the PMWEDM process, is recommended. The surfactant not only improves the dielectric conductivity but also facilitates proper mixing of the powder within the dielectric medium. This enhancement results in improved machining capabilities and a higher quality of the finished product.

Table 3.6. Experimental results at surfactant added dielectric condition

Sl No.	MRR(mm^3/min)		SR(R$_a$) (µm)		Dielectric Consumption/cm^3	
	Without Powder Deionized Water	With Powder Surfactant Added Deionized Water	Without Powder Deionized Water	With Powder Surfactant Added Deionized Water	Without Powder Deionized Water	With Powder Surfactant Added Deionized Water
1	6.391	7.562	3.534	2.223	0.634	0.569
2	8.42	9.201	2.591	1.862	0.419	1.632
3	5.442	6.547	2.232	2.568	0.587	0.872
4	7.385	8.225	3.085	2.054	0.271	0.386
5	4.773	6.852	3.682	3.252	0.342	1.234
6	3.227	2.587	2.197	2.061	0.169	2.790
7	2.739	2.358	3.094	2.117	0.285	0.382
8	3.098	3.254	2.470	2.336	0.410	0.380
9	6.783	7.890	2.567	1.962	0.399	1.005
10	5.775	6.378	2.351	2.572	0.289	1.984
11	7.406	6.837	3.724	3.339	0.336	2.110
12	3.967	4.001	2.812	2.104	2.864	3.457

Based on the pilot experiment, it is established that a concentration of surfactant up to 6g/l provides better outcomes. But, a concentration of surfactant up to 10 g/l decreases MRR continuously. Experimental results at surfactant added dielectric condition with considering the outputs MRR, SR and dielectric consumption are shown in Table 3.6. Figure 3.9 demonstrates the effect of the machining variables of the surfactant added PMWEDM of Ti6Al4V alloy.

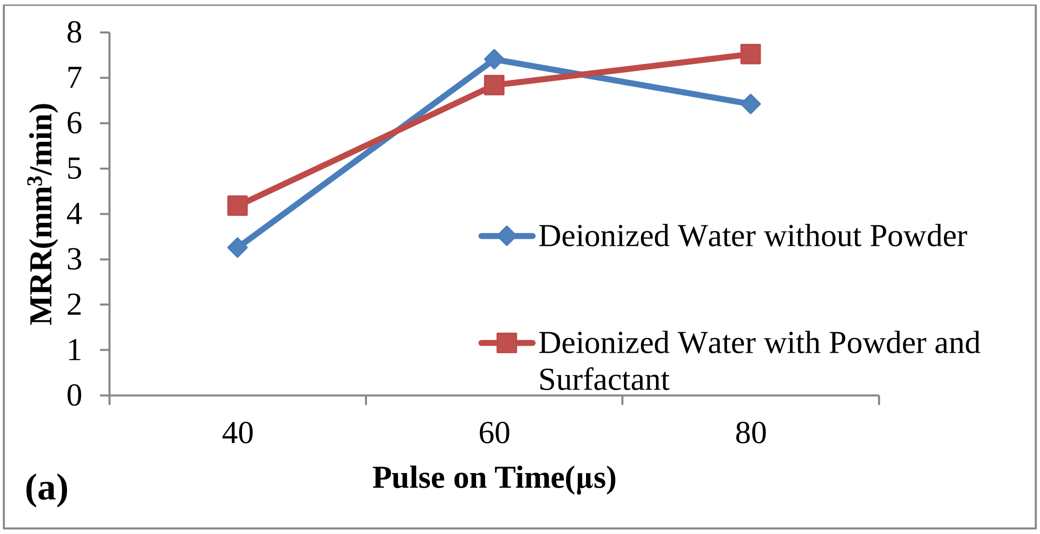


Figure 3.9. (a) Influence of pulse on time on MRR

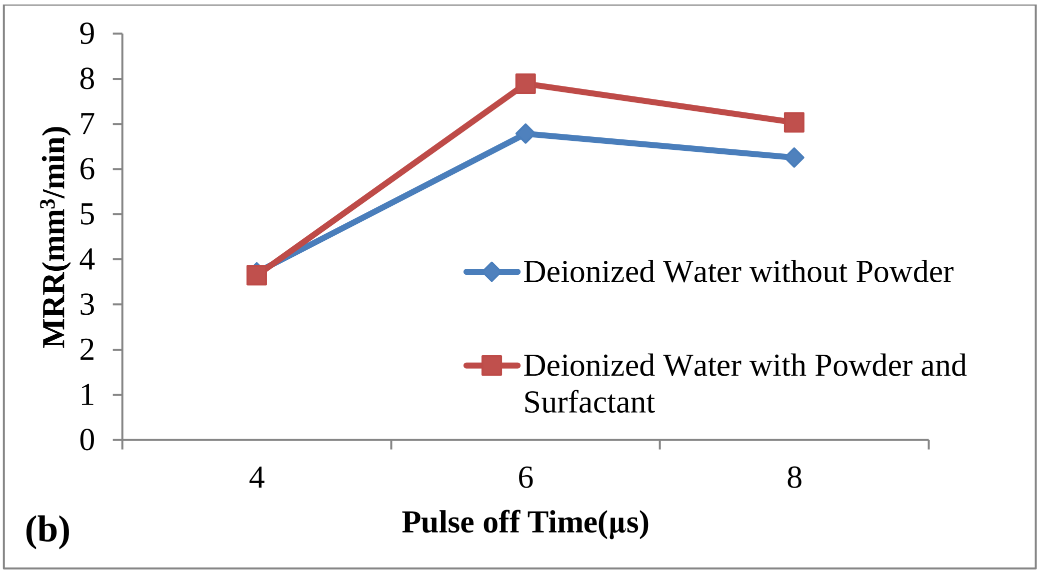


Figure 3.9. (b) Influence of pulse off time on MRR

Figures 3.9 (a) and 3.9 (c) explain that material removal rate is improved during increase of both parameters i.e. pulse on time and gap voltage. According to the Figures 3.9 (b) and 3.9 (d), Maximum MRR is seen at the middle value of pulse off time and fluid level respectively. During machining without adding powder with deionized water, lesser amount of MRR is initiated. WEDM process becomes more stable in surfactant added condition than normal condition. In presence of surfactant, a uniform discharge energy is distributed in the machining gap by developing the dielectric fluid conductivity leading to better MRR.

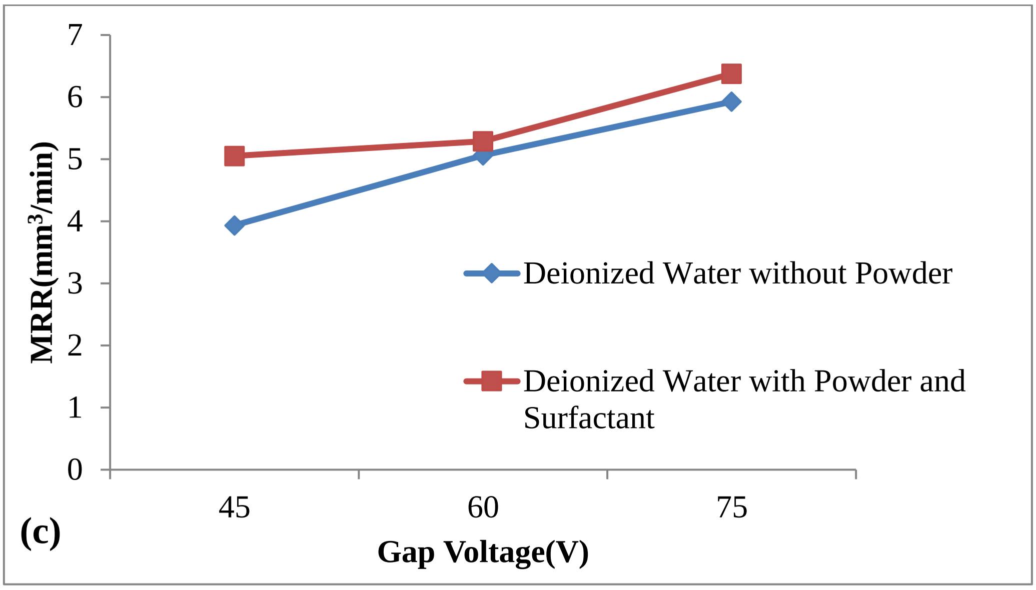


Figure 3.9. (c) Influence of gap voltage on MRR

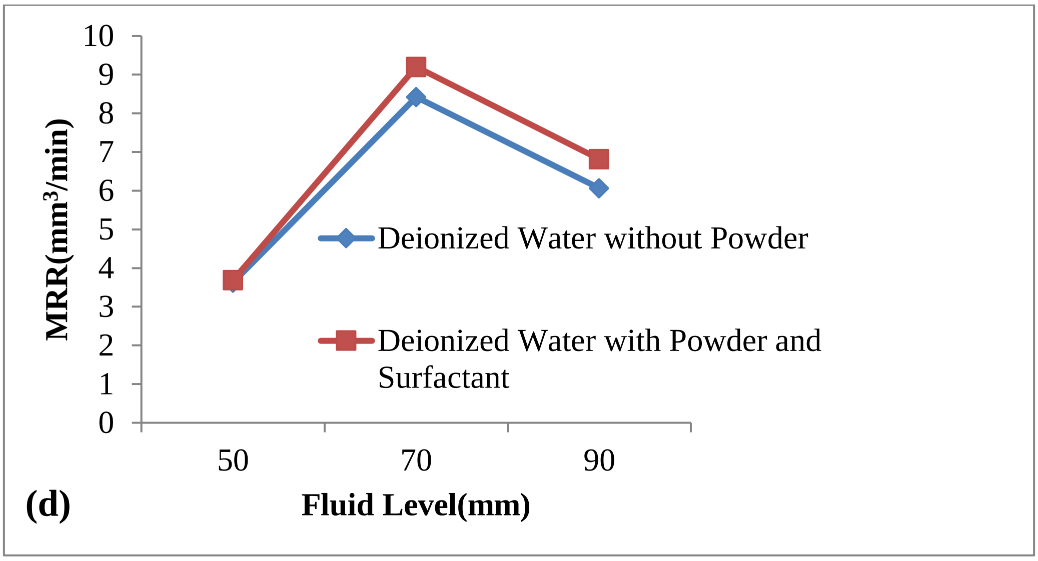


Figure 3.9. (d) Influence of fluid level and surfactant added dielectric on MRR

3.7.4. Study of the Effect of Machining Parameters and Surfactant Added Dielectric on Surface Roughness

The effect of the machining variables and surfactant mixed dielectric in PMWEDM on machined surface roughness in the terms of R_a is presented in Figure 3.10.

The surface roughness in PMWEDM is influenced by various factors, including the uniform distribution of powder particles within the narrowest gap, an increase in dielectric conductivity, and a decrease in dielectric strength [50-51]. Nonetheless, the inclusion of a surfactant in the dielectric results in an increase in impulse force within the machining gap. This rise in impulse force is a consequence of the higher discharge energy, which, in turn, causes shallower erosion and the generation of cracks on the workpiece.

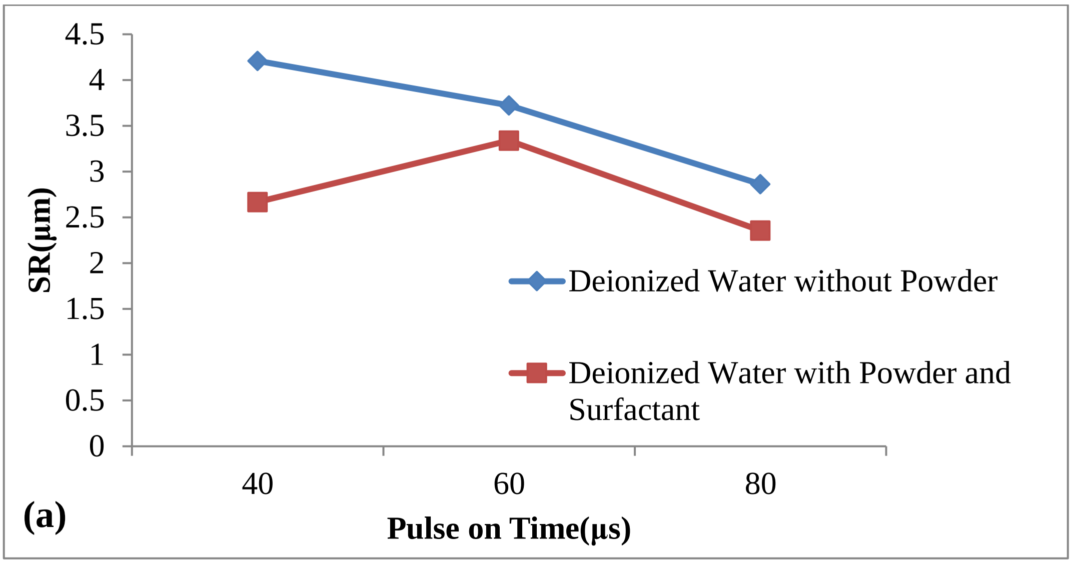


Figure 3. 10. (a) Influence of pulse on time on SR

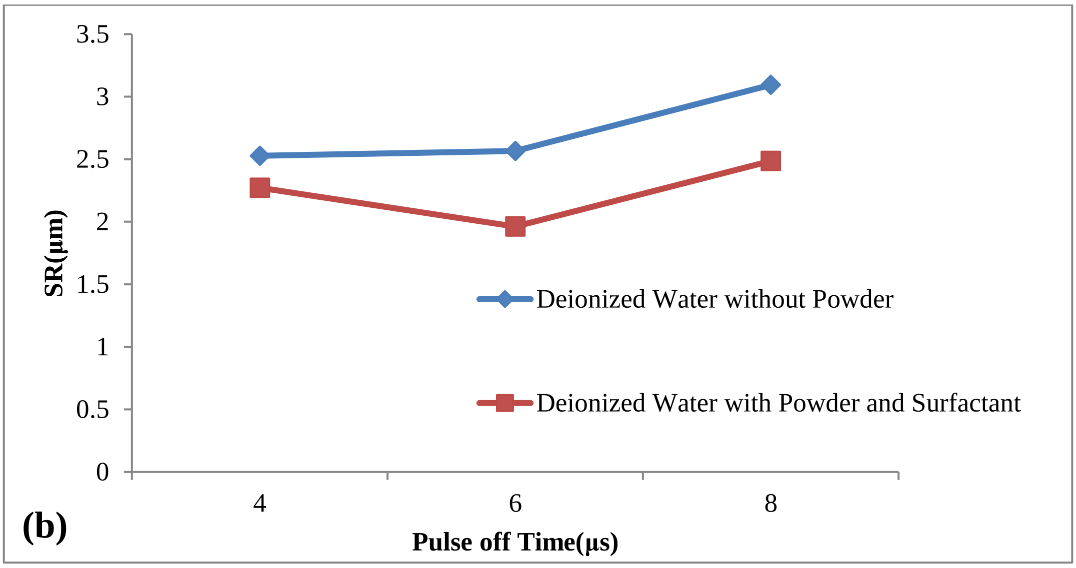


Figure 3. 10. (b) Influence of pulse off time on SR

Due to high heat energy, more smoke is generated in the dielectric supply unit, leading to harmful consequences on the atmosphere. Figure 3. 10 (b), 3. 10 (c) and 3. 10 (d) signify that first, Surface roughness decreases and then increases by varying lower to a higher value of two inputs such as pulse off time and fluid level with addition of surfactant in the dielectric fluid. Surface roughness continuously decreases with the increase of pulse on time as shown in Figure 3. 10 (a). Fluid level mostly influences on SR as it provides the lowest output.

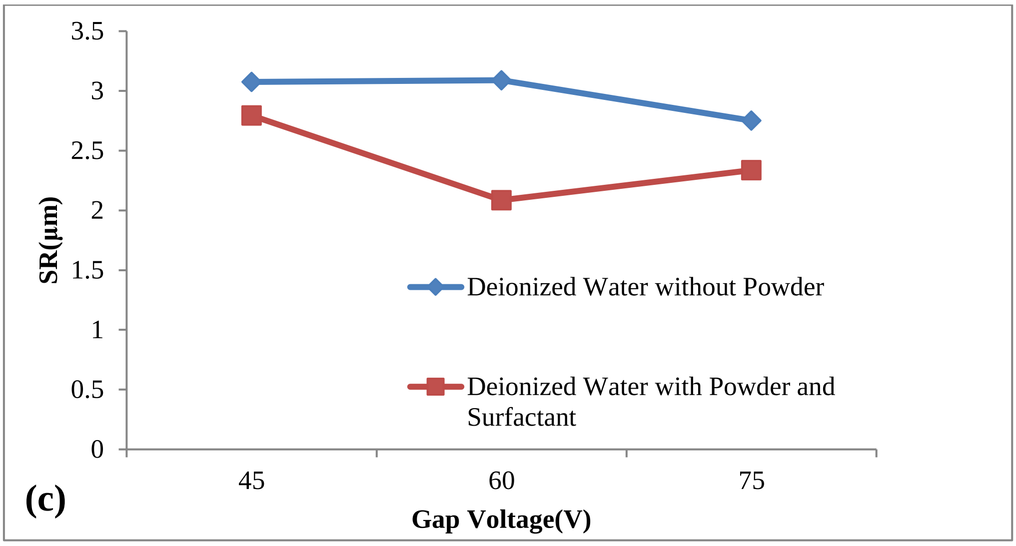


Figure 3. 10. (c) Influence of gap voltage on SR

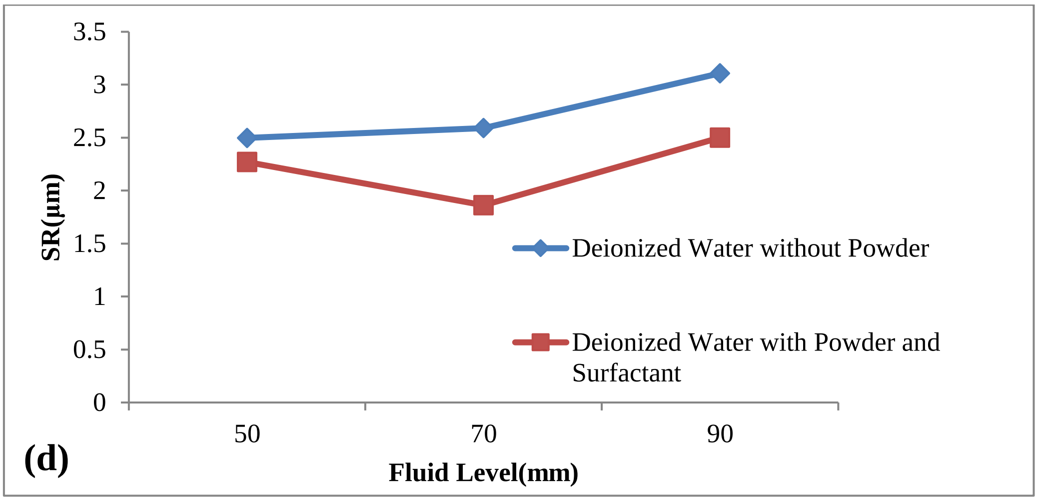


Figure 3. 10. (d) Influence of fluid level and surfactant added dielectric on SR

The dielectric fluid is typically reused in the WEDM process to enable longer machining durations until the job is completed. Changing the dielectric fluid during machining is not feasible. However, if the fluid level is not adequately maintained, it can lead to a rough surface finish. When a surfactant is added to the dielectric, the conductivity increases, but this comes at the cost of a decrease in dielectric strength, resulting in an enlarged spark gap. This enlarged spark gap aids in effectively removing debris particles from the machining zone, creating a comfortable area for the next spark cycle to erode the material. As a result of this smooth spark cycle operation, a superior surface topography is achieved.

Furthermore, employing low pulse energy and maintaining the appropriate fluid level contribute to achieving a superfine surface topography.

3.7.5. Study of the Effect of Machining Parameters and Surfactant Added Dielectric on Dielectric Consumption

Dielectric consumption is a significant factor linked to pollution and hazards for the operator. Figure 3.11 illustrates how the input factor affects dielectric consumption. Increased dielectric consumption leads to environmental contamination and health concerns for machine workers. This ultimately impacts the overall product cost as it results in the loss of dielectric material.

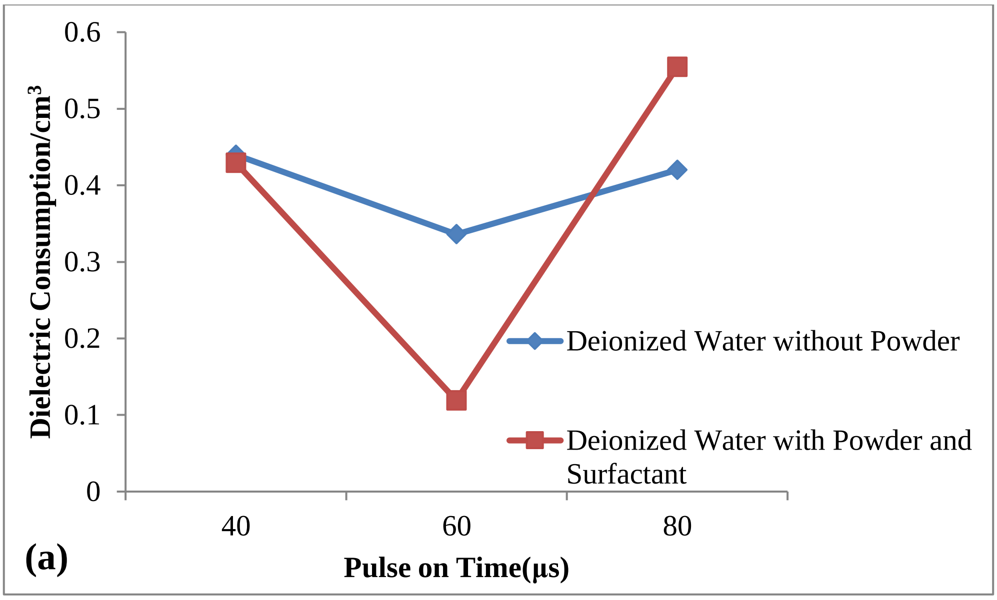


Figure 3.11. (a) Influence of pulse on time on dielectric consumption

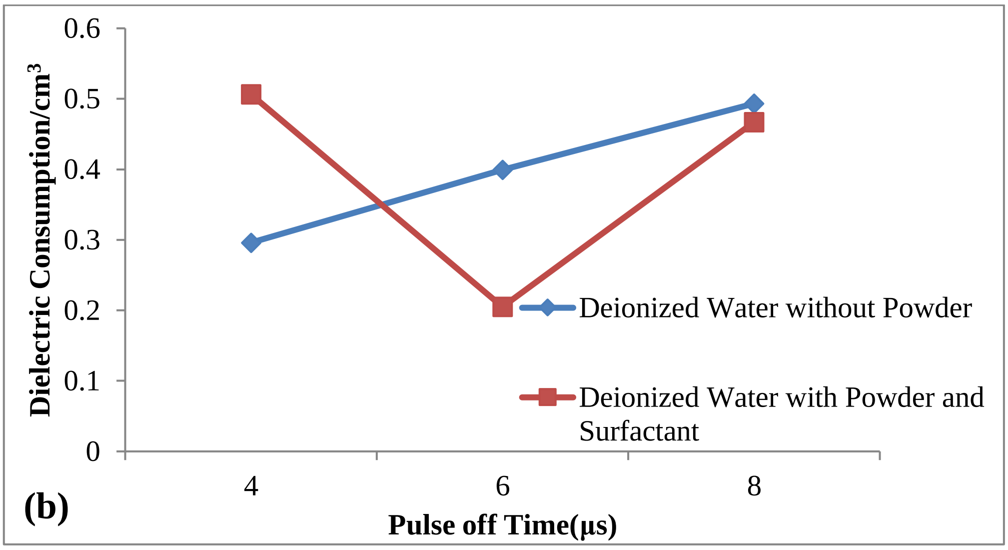


Figure 3.11. (b) Influence of pulse off time on dielectric consumption

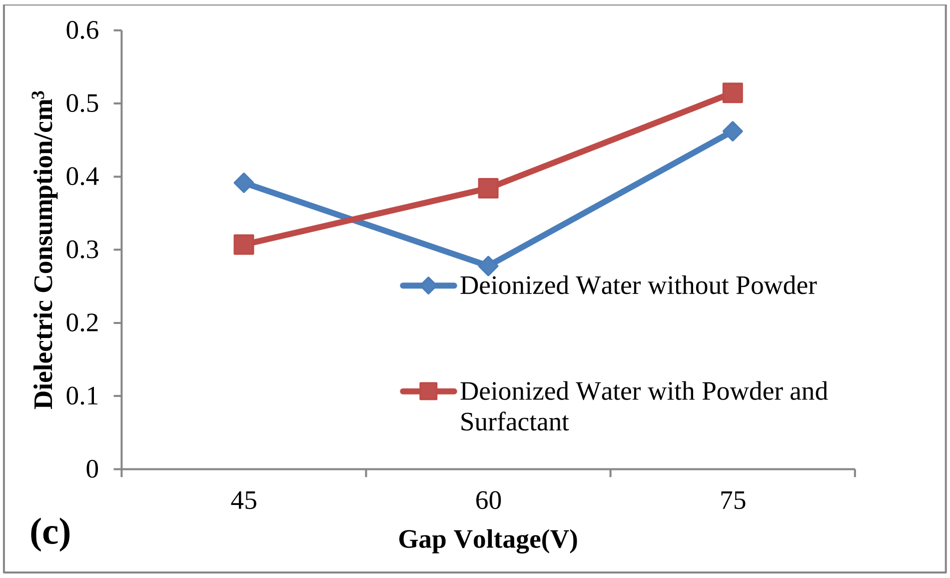


Figure 3.11. (c) Influence of gap voltage on dielectric consumption

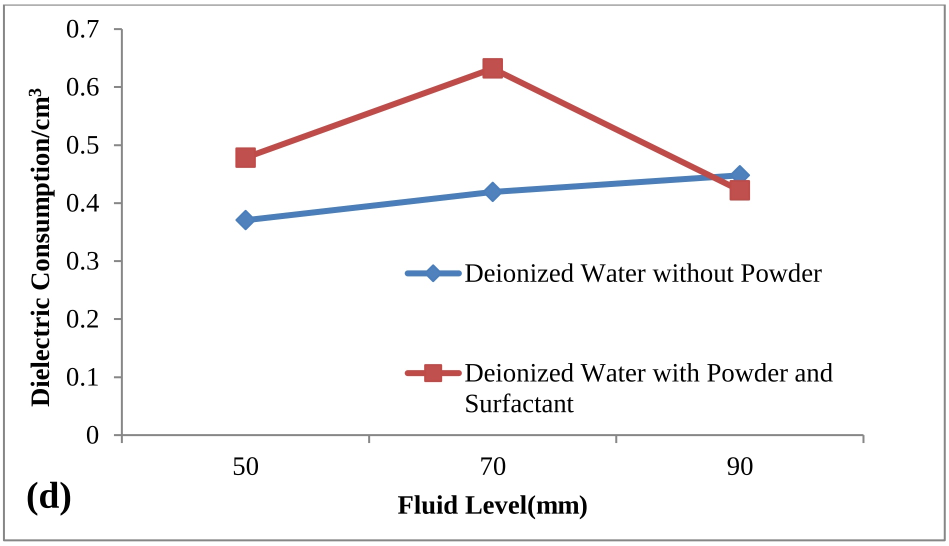


Figure 3.11. (d) Influence of fluid level and surfactant added dielectric on dielectric consumption

Figures 3.11 (a) and 3.11 (b) show that dielectric consumption firstly decreases and then increases due to extensive evaporation of the dielectric by surfactant added deionized water with powder mixed. At the same time, middle value of pulse on time and pulse off time provide the lowest dielectric consumption. This is due to stable discharging and not discrete sparking in machining zone. Reduced dielectric consumption is observed in deionized water when the fluid level is minimal, as depicted in Figure 3.11 (d). However, an increase in fluid level results in higher dielectric consumption for deionized water, as illustrated in Figure 3.11 (d).

3.8. Analysis of Hazard and Operability Study

In the practical point of view, plenty of process parameters influencing have not verified yet in the field of powder mixed wire EDM process. According to the complexity of nature in this process, all possible data are collected by the HAZOP study [52] for enhancing the machining efficiency and avoid environment contamination and low powder in the PMWEDM process. Figure 3.12 displays the procedural steps of HAZOP study.

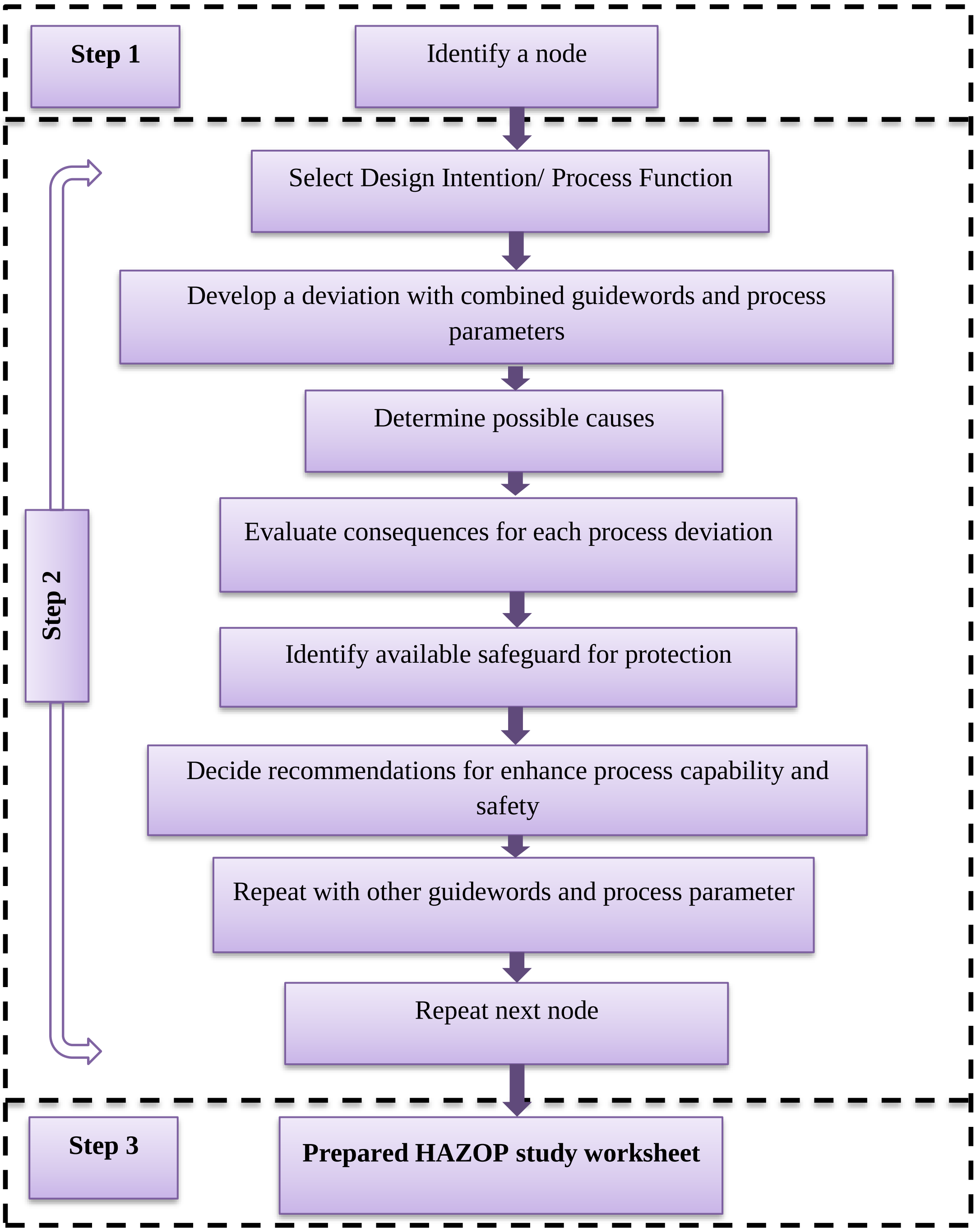


Figure 3.12. Different steps of HAZOP study

Besed on the all possible parameters, i.e. mechanical, electrical and environmental, the worksheet with major objectives are given as follows:

- Objective (a)-Influence of process parameter and dielectric on metal removal rate
- Objective (b)-Influence of process parameter and dielectric on surface roughness
- Objective (c)-Influence of process parameter on dielectric consumption
- Objective (d)-Influence of process parameter on surfactant
- Objective(e)-Influence of process parameter on the environment

Table 3.7 represents the HAZOP analysis worksheet for the PMWEDM process and the surfactant added PMWEDM process. High pulse on time leads to the rise in pressure energy by controlling the current flow per cycle. Simultaneously, other parametric settings also play a crucial role in the plasma channel. Within a specific range of pulse on time, the material erodes from the workpiece at a reduced rate due to the absorption of a certain amount of energy by the interface B4C powder particles. When the current value is high, the discharge energy increases, leading to greater evaporation and impulse force acting on the gap zone. This causes a higher amount of eroded material to accumulate in the narrowest machining zone, slowing down the process and resulting in a low Material Removal Rate (MRR), which, in turn, increases time consumption and product cost. Considering the dielectric fluids and their levels should be done with a guiding role, as they can significantly impact the process. It's important to be cautious about toxic emissions from the dielectric, which can be harmful to both humans and the environment.

Surface Roughness is increased with an increase in gap voltage. Higher gap voltage causes a higher ionization rate of dielectric; as a result, larger craters are created on the machining surface, showing the reduction of surface finish. A high amount of powder concentration in dielectric also causes lower surface finish. This is due to the fact that bombarding force is generated on the machine surface with an increase in pulse on time and powder concentration up to a specified value.

Fire hazards can arise when using hydrocarbon-based dielectric fluids. To ensure smooth and safe functioning, it is strongly advised to opt for natural EDM oil instead, as it helps prevent potential fire issues and associated hazards. Proper selection of dielectric and their level may causes high amount of fluid consumption. Also, it creates the chemical distribution around the machining area. Therefore, skilled operator, room ventilation, and schedule maintenance is essential for environment friendly machining operation.

Table 3.7. HAZOP analysis worksheet for PMWEDM:

Table 3.7(a)-Influence of process parameters and dielectric on metal removal rate in PMWEDM

Deviation	Guide words	Causes	Consequences	Recommendation
High energy consumption and cost of production	High	1.High pulse off time(11 µs) and gap voltage 2.Low Dielectric pressure 3.Low wire tension 4.Selection of dielectric 5.Unskilled worker	1.Large time taken 2.Fast wire breakage 3.Reduce machining efficiency 4.Low profit	1.Skilled operator 2.Advance precision machine 3.Hybridization of process 4.Selection of proper input parameter 5. Selection of proper electrode material and dielectric

Table 3.7(b)-Influence of process parameters and dielectric on surface roughness in PMWEDM

Deviation	Guide words	Causes	Consequences	Recommendation
Low quality, wastage of product and cost of production	High	6.High pulse on time-(100µs) 7.High peak current-11A 8.Low gap voltage and wire tension 9.Low fluid pressure 10. Kerosene or deionized water	5.Fast wire breakage 6.Wastage of time 7.Required another process for further machining 8.Reduce machining efficiency 9.Low profit	6.Skilled worker 7.Advance precision machine 8.Hybridization of process 9.Selection of proper input parameter 10. Proper selection of electrode material and dielectric 11.Replace abrasives with Nano-size

Table 3.7 (c)-Influence of process parameters on dielectric consumption in PMWEDM

Deviation	Guide words	Causes	Consequences	Recommendation
High Risk and cost of production	High	11. Low level volume of dielectric 12. Poor flashing system 13. Improper selection of dielectric 14. High current	10. Health problem 11. Loss of dielectric 12. Effect on eye skin and lungs 13. High generation of vapour	12. Skill operator 13. Proper maintenance 14. Choose other natural dielectric 15. Machine room ventilator 16. Avoid high concentration of surfactant 17. Safety protector for operator like mask, eyeglass, gloves

Table 3.7(d)- Influence of process parameters on surfactant in PMWEDM

Deviation	Guide words	Causes	Consequences	Recommendation
High wastage	High	15. Powder selection 16. Wrong selection of dielectric 17. Dielectric pressure 18. Surrounding cover	14. Desecration of active environment 15. Skin irritation 16. High reaction	18. Proper mixing with dielectric 19. Skill operator 20. Proper maintenance before and after machining 21. Suitable stirring system 22. Surfactant concentration 23. Input parameter selection 24. Safety protector for operator like mask, eyeglass, hand gloves

Table 3.7(e)- Influence of process parameters on the environment in PMWEDM

Deviation	Guide words	Causes	Consequences	Recommendation
High hazard creation and low process efficiency	Low	19. Unskilled operator 20. Unstable input supply voltage 21. High room temperature and humidity 22. Improper machining operation 23. Less competency toward the machine operation	17. Low productivity 18. Higher production cost 19. Hazard on machine maintenance 20. Desecration of environment 21. Uncertain machine failure	25. Skill operator 26. Proper ventilation 27. Install AC in the machine room 28. Periodically maintenance of the overall machine 29. Clean machine environment after and before machining.

3.9. Summary

In the present investigation, the abrasive mixed dielectric in wire EDM process has been employed to evaluate the best possible output so that the process becomes more efficient to machine low machinability materials. The obtained results are tremendously helpful in order to predict the best parametric condition for machining Ti6Al4V alloy. Based on the proposed methodology and experimental observation, the following conclusions are drawn.

1. In this investigation, PMWEDM process efficiency significantly improves by adding Al_2O_3 and B_4C with 10 µm size abrasive powder in dielectric.
2. Higher MRR can be achieved by increasing pulse on time, and with a value of 6 µs pulse off time results best output. Gap voltage has an inverse relationship towards the surface roughness. Thus lower discharge intensity leads to a higher surface finish.

3. As compared to the various dielectric, kerosene has a slightly higher impact on responses. Due to some disadvantages of kerosene, such as carbon layer formation on machine surface, more generation of toxic vapour emission during machining and creation of fire hazard, deionized water is used in the WEDM process instead of kerosene.
4. The next improvement of the process is surfactant added PMWEDM and the obtained result proves that surfactant help to increase the modified plasma channel as a result best output is achieved. At the same time, the chemical composition of the surfactant has created serious health problems and polluted the environment rigorously, so it is required to follow the proper recommendation for safe operation.
5. The dielectric consumption is significantly influenced by the fluid level. In surfactant mixed PMWEDM, dielectric consumption tends to increase with higher fluid levels.
6. A Hazard and Operability Study (HAZOP) has been conducted to ensure a superior quality product, lower product cost, enhanced safety measures, and reduced environmental contamination during the WEDM process.

CHAPTER: 4

PARAMETRIC ANALYSIS AND OPTIMIZATION

4.1. Introduction

The best performance measures depend on Precision machining characteristics, which makes the material more flexible. However, the enhancement in machining efficiency of Ti6Al4V alloy is still a complicated job for the research community. Recently, the advancement of the WEDM process has developed as a potential machining process for machining very low conductive material. In the present investigation, the powder mixed wire EDM (PMWEDM) process has been employed to improve the performance efficiency of Ti6Al4V alloy. The past research revealed that limited work had been done on Ti6Al4V alloy using the PMWEDM process. The present problem has been formulated and analysed with four machining inputs of pulse off time (T_{off}), pulse on time ($T_{on)},$ peak current (I_p), and powder concentration (PC) under the domain of MRR and surface roughness. The impact of powder characteristics in dielectric with all other machining settings has been discussed. Finally, the machining inputs are optimized using RSM, GRA and PSO-GRA to obtain the best output.

4.2. Material and Methodology

The exceptional mechanical properties, including high hardness, toughness, and corrosion resistance, make Ti6Al4V alloy highly suitable for aerospace, biomedical applications, and advanced manufacturing industries. In this research, Ti6Al4V is chosen as the workpiece material with a composition of 4% vanadium, 6% aluminium, less than 0.05% nitrogen, less than 0.08% carbon, less than 0.20% iron, less than 0.12% of other elements, and the remaining portion being titanium.

In the present study, deionized water is worked as a dielectric fluid, and Al_2O_3 powder with different concentration levels has been taken into consideration of powder characteristics as an input variable. Separately a mixing chamber (20 lits capacity) was made for supply dielectric to the WEDM machine. Also, a stirring system was used in the dielectric chamber for the proper mixing of powder in the dielectric during the machining operation. Ezeecut plus wire electric discharge machining was used to perform the experiments. MRR was calculated by the weight-based method, as given in Equation (4.1).

$$MRR = \frac{(w_{initial} - w_{final}) \times 60 \times 1000}{T_m \times \rho} \tag{4.1}$$

where,

W_{initial} = Initial weight of the work-piece before machining (gm)

W_{final} = Final weight of the work-piece after machining (gm)

T_m = Total machining time consumed (sec)

ρ = Density of the job (g/mm^3)

Surface roughness was measured in terms of R_a by Mitutoyo Surftest SJ-410 with 0.08 mm cut off length. The mean surface roughness is the final obtained data by taking R_a values of five different points on the machined surface. One sample measurement of R_a is illustrated in Figure 4.1. Based on the past research work, pilot experiments and machine limitations, four parameters are considered for analyzing the responses such as MRR and SR in the present investigation. The selected input settings were T_{off}, T_{on}, I_p, and PC, and their range was given in Table 4.1.

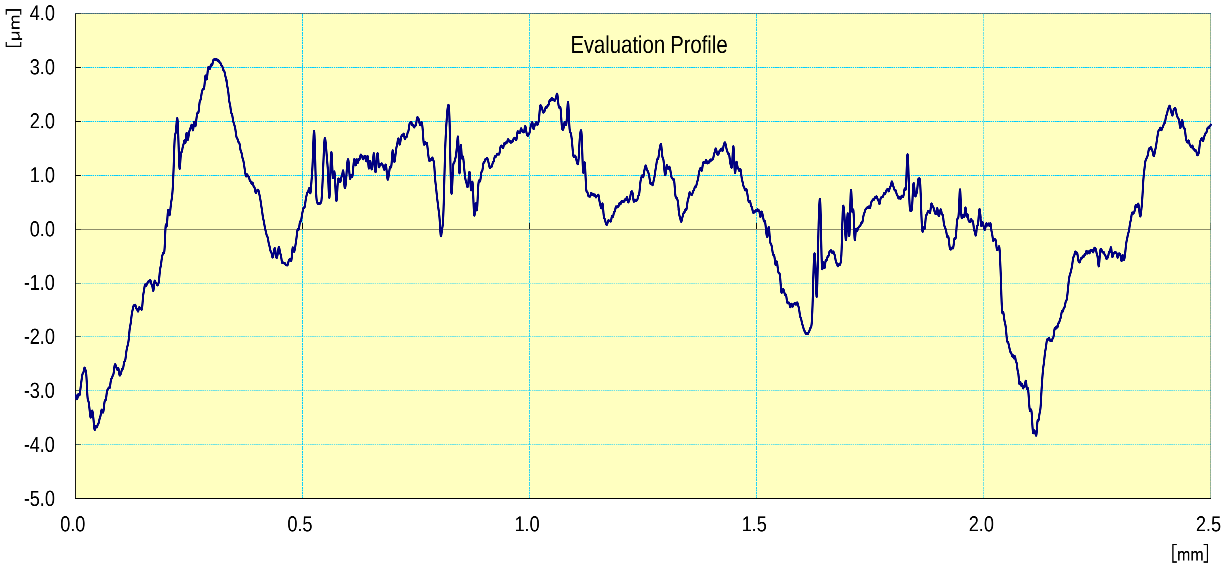


Figure 4.1. Measurement of surface roughness (Experiment No.7)

Table 4.1. Selected control factor and their values

Input parameter with symbol	Unit	Notation	Value
Pulse off time (A)	μs	T_{off}	4, 8, 12
Pulse on time (B)	μs	T_{on}	30, 60, 90
Peak current (C)	A	I_p	2, 3, 4
Powder Concentration(D)	g/L	PC	4,6,8

A robust empirical modelling approach to optimize the process variable and determine the correlation between the dependent and independent variables is commonly known as Response Surface Methodology [53]. The quadratic modelling equation is derived in terms of the statistical method as in Equation (4.2).

In the present study, the most influential parameters are identified and optimized through RSM methodology.

$$Y_u = \beta_0 + \sum_{i=1}^{n} \beta_i X_{iu} + \sum_{i=1}^{n} \beta_{ii} X_{iu}^2 + \sum_{i=1}^{n-1} \sum_{j=2}^{n} \beta_{ij} X_{iu} X_{ij} + e_u \tag{4.2}$$

Where regression coefficients are denoted as $\beta_0, \beta_i, \beta_{ij}$ and interaction terms are denoted as X_{iu}, X_{ij}.

For further analysis, particle swarm optimization (PSO) coupled with grey relation analysis (GRA) has been introduced to determine the best output. GRA converted multi-objective in a single objective. In the GRA method, firstly, all data are normalized within the value from 0 to 1. The terms ‘higher is better’ and ‘lower is better’ for the selected responses are calculated using Equations (4.3) and (4.4). Two responses in the PMWEDM process, such as MRR and SR have been considered as ‘higher is better’ and ‘lower is better’, respectively.

$$\text{For HIB} \quad j_i^n(k) = \frac{j_i^*(k) - \min j_i^*(k)}{\max j_i^*(k) - \min j_i^*(k)} \tag{4.3}$$

$$\text{For LIB} \quad j_i^n(k) = \frac{\max j_i^*(k) - j_i^*(k)}{\max j_i^*(k) - \min j_i^*(k)} \tag{4.4}$$

where $j_i^n(k)$ is the normalised value; $j_i^*(k)$ is the original data; the maximum value among all original data is $\max j_i^*(k)$, and the minimum value among all original data is $\min j_i^*(k)$.

The equivalent GRA coefficient has been determined using Equation (4.5). The identification coefficient is considered as 0.5, which indicates that both responses have equal importance.

$$\varepsilon_i(k) = \frac{\Delta_{\min} + \gamma\Delta_{\max}}{\Delta_{oi}(k) + \gamma\Delta_{\max}} \tag{4.5}$$

After determining the grey relation grade, Particle swarm optimization (PSO) is incorporated in the present investigation to find out the maximum GRG value. PSO was firstly introduced by Eberhart and kennedy [63], which is based on the combined features of GA and evolution strategies. PSO is initialized with a set of random particles, which offers an individual solution. All particle positions and velocities are updated during the process run. The best position with the best fitness value of a particle is called local best, and the best position among all swarm particles is called global best. Therefore, PSO starts with generating particles that have random velocities and positions. From the beginning, the particle velocity and position in each interaction are updated. The governing equation for updating the particle velocity and position has been given in Equation (4.6).

$$\mathrm{V}_{id}{}^{j+1} = w * \mathrm{V}_{id}{}^{j} + c_1 * rand_1\left(P_{best} - \mathrm{X}_{id}{}^{j}\right) + c_2 * rand_2\left(G_{best} - \mathrm{X}_{id}{}^{j}\right) \tag{4.6}$$

$$\mathrm{X}_{id}{}^{j+1} = \mathrm{X}_{id}{}^{j} + \mathrm{V}_{id}{}^{j+1}$$

Where $\mathrm{V}_{id}{}^{j}$ represents the particle velocity of the i term at j interaction. The weight is taken as w. The acceleration coefficient is termed as c_1 and c_2. Two random numbers are created, such as $rand_1$ and $rand_2$

Some critical phases are required to generate the PSO algorithm. The phases are as follows:

1. Define the objective function
2. Select proper PSO parameters
3. Initialization of each particle’s velocity and position
4. Determine the function evaluation
5. Determine the G_{best} and P_{best}
6. Updating the velocity and position for each agent
7. Handling boundary violations
8. Accumulation of best output

4.3. Design of Experiment

The experimental design is carried out by the face-centred central composite design (CCD) method, which is generated by design expert software. The central composite design is very useful for built up a quadratic model for each response and analysing the experimental data. Therefore, the design of experiment and obtained results are presented in Table 4.2.

Table 4.2. Experimental results

Sl No.	Factors				Responses	
	Pulse off Time	Pulse on Time	Peak Current	Powder Concentration	MRR	SR (R_a)
	µs	µs	A	g/L	mm^3/min	µm
1	4	30	2	4	5.318	1.987
2	8	60	3	6	3.732	2.862
3	8	60	3	6	3.745	2.874
4	8	60	3	6	3.987	2.921
5	12	30	2	4	6.023	2.777
6	4	90	2	4	3.527	2.033
7	8	60	4	6	4.101	3.242
8	8	60	2	6	4.226	2.547
9	8	60	3	8	3.778	2.444
10	4	90	4	4	5.791	2.353
11	8	60	3	6	3.874	2.879
12	8	60	3	6	4.139	2.785
13	12	30	2	8	5.107	2.806
14	4	90	2	8	4.419	1.732
15	12	90	2	8	4.622	3.138
16	4	30	4	8	4.872	5.435
17	12	30	4	8	2.593	3.077
18	4	90	4	8	6.041	3.061
19	12	90	4	8	3.564	2.284
20	4	60	3	6	4.428	3.715
21	12	60	3	6	3.542	3.721
22	8	30	3	6	3.565	2.778
23	8	90	3	6	3.155	2.605
24	8	60	3	4	4.111	2.375
25	4	30	2	8	4.706	2.581
26	12	90	2	4	4.034	4.205
27	4	30	4	4	6.126	3.731
28	8	60	3	6	3.778	2.645
29	12	90	4	4	3.618	2.541
30	12	30	4	4	4.151	2.538

A total of six numbers of experiments of the same control factor setting is performed for evaluating the data. Based on the experiment design, the outcomes of the test of experiment no. 2, 3, 4, 8, 27, and 28 are exposed in Table 4.3. The percentage of the error is calculated by the given Equation (4.7).

$$\text{Percentage of error} = \left(\frac{\textit{Average value} - \textit{Experimental value}}{\textit{Average value}}\right) \times 100 \tag{4.7}$$

From the obtained result in Table 4.3, MRR and SR show the tolerance limit ± 5%. Furthermore, the experimental standard deviation is evaluated for response measures in repetitive experiments.

Table 4.3. Reproducibility with error percentage for MRR and SR

Sl No.	Standard order	T_{off} (µs)	T_{on} (µs)	I_p (A)	PC (g/L)	MRR (mm^3/min)		SR (R_a) (µm)	
						Exp. Value	% of Error	Exp. Value	% of Error
2	27	8	60	3	6	3.778	2.428	2.645	4.167
3	26	8	60	3	6	3.874	-0.552	2.879	-4.312
4	28	8	60	3	6	4.139	-6.896	2.785	-0.906
8	25	8	60	3	6	3.732	3.616	2.862	-3.696
27	29	8	60	3	6	3.745	3.280	2.874	-4.130
28	30	8	60	3	6	3.987	-2.970	2.921	-5.833

4.4. Empirical Modelling for Response Measures

The relative experiment has been conducted with a set of selected parameters, i.e., pulse on time of 30 µs, pulse off time of 4 µs, peak current of 2 A, gap voltage 60 volts and wire feed rate 50 m/min. Al_2O_3 abrasive powder of 10 µm size is selected as a mixing agent in dielectric during the PMWEDM process, while other machining parameters are similar to the WEDM process. It is observed that the performance-wise PMWEDM process is highly recommended for greater productivity and high dimensional accuracy compared to the conventional Wire EDM process.

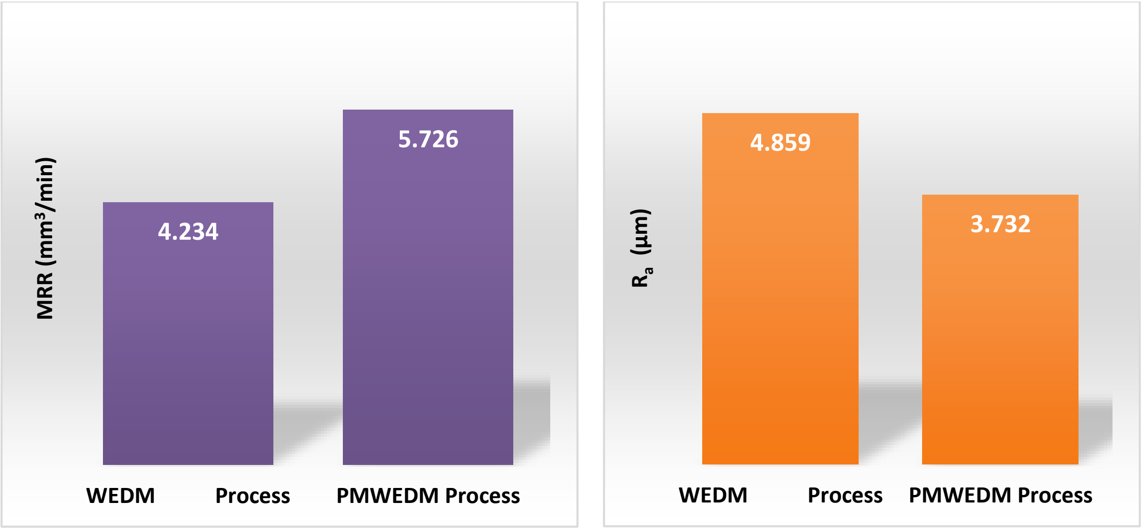


Figure 4.2. Variation in a) MRR and b) SR of WEDM and PMWEDM process

Identifying the optimal input variables in the PMWEDM process while minimizing noise is a challenging task. To address this, the Response Surface Methodology (RSM) is employed as the most effective approach to assess the mathematical relationship and analyze the quadratic effects between input and output variables. The statistical technique known as Analysis of Variance (ANOVA) is utilized in this study to identify the most suitable input variables.

The quadratic modelling equations established in the present investigation can predict the response variable for every input variable's specified value.

$$MRR = 11.7125+0.13093*T_{off}-0.039876*T_{on}-2.09542*I_p-1.04871*PC-0.0004125*T_{off}*Ton-0.1675*T_{off}*I_p-0.0095*T_{off}*PC+0.0121333*T_{on}*I_p+0.00626667*T_{on}*PC-0.08025*I_p*PC+0.0214106*T_{off}^2-0.000313811*T_{on}^2+0.52107*I_p^2+0.0755175*PC^2 \quad (4.8)$$

$$SR= -5.18774-0.390126*T_{off}+0.0588406*T_{on}+1.55011*I_p+1.72558*PC+0.0028776*T_{off}*T_{on}-0.136453*T_{off}*I_p-0.0270391*T_{off}*PC-0.0114563*T_{on}*I_p-0.00394063*T_{on}*PC+0.107469*I_p*PC+0.0497149*T_{off}^2-0.000256735*T_{on}^2-0.0280614*I_p^2-0.128265*PC^2 \quad (4.9)$$

Also, it is worthwhile to detect a comparative influence of factors by equating factor coefficients. For amalgamating the dimensions of every single element, the ratio is scaled. The quadratic equations of the proposed model for MRR and SR are given in Equations (4.8) and (4.9), respectively.

4.5. Parametric Analysis

4.5.1. Analysis of Variance (ANOVA) for Material Removal Rate

The Analysis of Variance (ANOVA) technique is based on different test procedures to judge the significant difference among the variables. The obtained results of ANOVA for MRR are shown in Table 4.4. The backward elimination rule examines the influential parameters. From Figure 4.3, it is seen that residuals are located around a straight line. It indicates that the error deviation between predicted and actual values are normally distributed. Moreover, a good agreement between actual and predicted values proves that the ANOVA model is reasonably satisfied the desired criteria. The quadratic model is evaluated with a sequential sum square and statistical tests to improve the current investigation.

Table 4.4. ANOVA for MRR

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	22.14	14	1.58	73.44	< 0.0001	significant
A-T_{off}	3.53	1	3.53	164.01	< 0.0001	
B-T_{on}	0.7565	1	0.7565	35.12	< 0.0001	
C-I_p	0.0703	1	0.0703	3.26	0.0909	
D-PC	0.499	1	0.499	23.17	0.0002	
AC	7.18	1	7.18	333.48	< 0.0001	
BC	2.12	1	2.12	98.43	< 0.0001	
BD	2.26	1	2.26	105.02	< 0.0001	
CD	0.4122	1	0.4122	19.14	0.0005	
A^2	0.3041	1	0.3041	14.12	0.0019	
B^2	0.2067	1	0.2067	9.6	0.0074	
C^2	0.7035	1	0.7035	32.66	< 0.0001	
D^2	0.2364	1	0.2364	10.98	0.0047	
Residual	0.3231	15	0.0215			
Lack of Fit	0.1941	10	0.0194	0.7523	0.6728	not significant
Pure Error	0.129	5	0.0258			
Cor Total	22.47	29		R^2		0.98562
Std. Dev.	0.146758			Adjusted R^2		0.972198
Mean	4.2891			Predicted R^2		0.968898
C.V. %	3.421657			Adeq Precision		34.04521

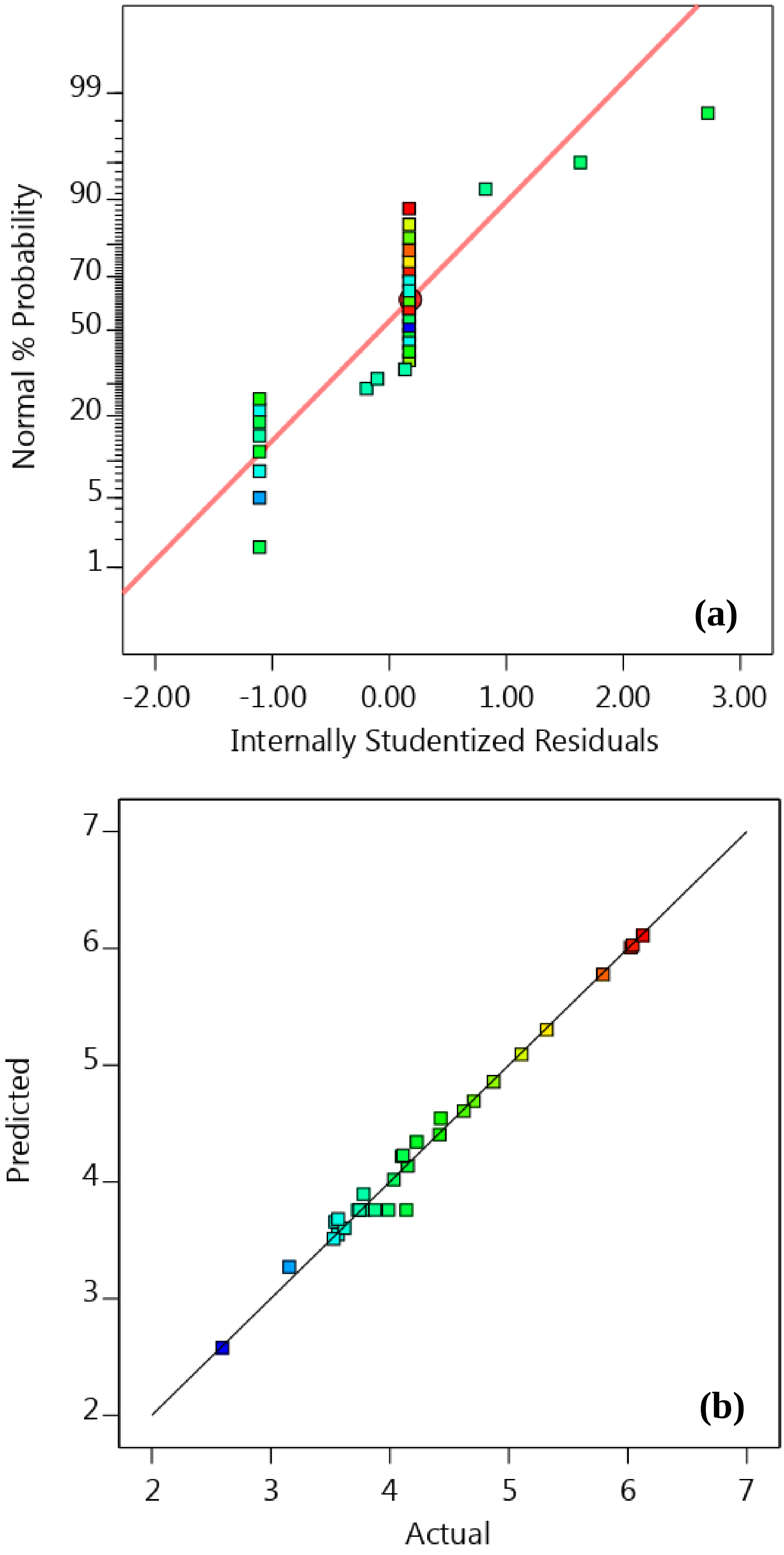


Figure 4.3. a) Normal plot for residual b) predicted vs. actual on MRR

In the ANOVA for MRR, an F-value of 73.44 of the model exposes that the selected model is significant. Therefore, a 0.01 percent possibility of a larger F-value can be found due to the noise. P-values less than 5% imply that the model terms are in the acceptable region, as the model is considered to predict a 95% confidence level. In this model, A, B, D, AC, BC, BD, CD, A^2, B^2, C^2, and D^2 are effective model terms**.** The percentage of contribution of each factor is calculated by dividing model sum squares with individual model term sum square value. The factor contributions are determined such as 15.94, 3.42, 2.25, 32.43, 9.58, 10.21, 1.86, 1.37, 0.93, 3.18 and 1.07%, respectively.

Other non-significant terms are found with a greater than values of 0.1000. Due to many insignificant model terms, the quadratic model may improve by model reduction. In the present investigation, the Lack of Fit with a value of 0.75 exposes its non-significance as compare to the pure error. There is a 67.28% chance that a larger lack of fit F-value will occur due to noise. It is clear that a non-significant lack of fit is decent for a worthy model term.

The Predicted R^2 of 0.9689 is in a feasible covenant with the Adjusted R^2 of 0.9722, i.e., the variation is below 0.2. In addition, Adeq Precision quantifies the signal to noise ratio with a desirable value of 4. In the present model, the S/N ratio of 34.045 indicates a necessary signal into the model. Thus the model is functioned to predict the MRR with maximum and minimum considered factor. The coefficient evaluation signifies the estimated modification in MRR with one factor at a time when other factors are detained constant.

4.5.2. Analysis of Variance (ANOVA) for Surface Roughness

Table 4.5 displays ANOVA for surface roughness and conformity of the quadratic model suggested by design expert software. Figure 4.4 depicting surface roughness demonstrates a strong alignment between the actual and predicted values, satisfying the criteria set by the ANOVA model. Most effective parameters are inspected by the backward elimination rule and fit the summary in Table 4.5. The model for SR, F-value of 74.59, exhibited the significance as the model implies. A possibility of 0.01%, the F-value enormously could happen because of noise.

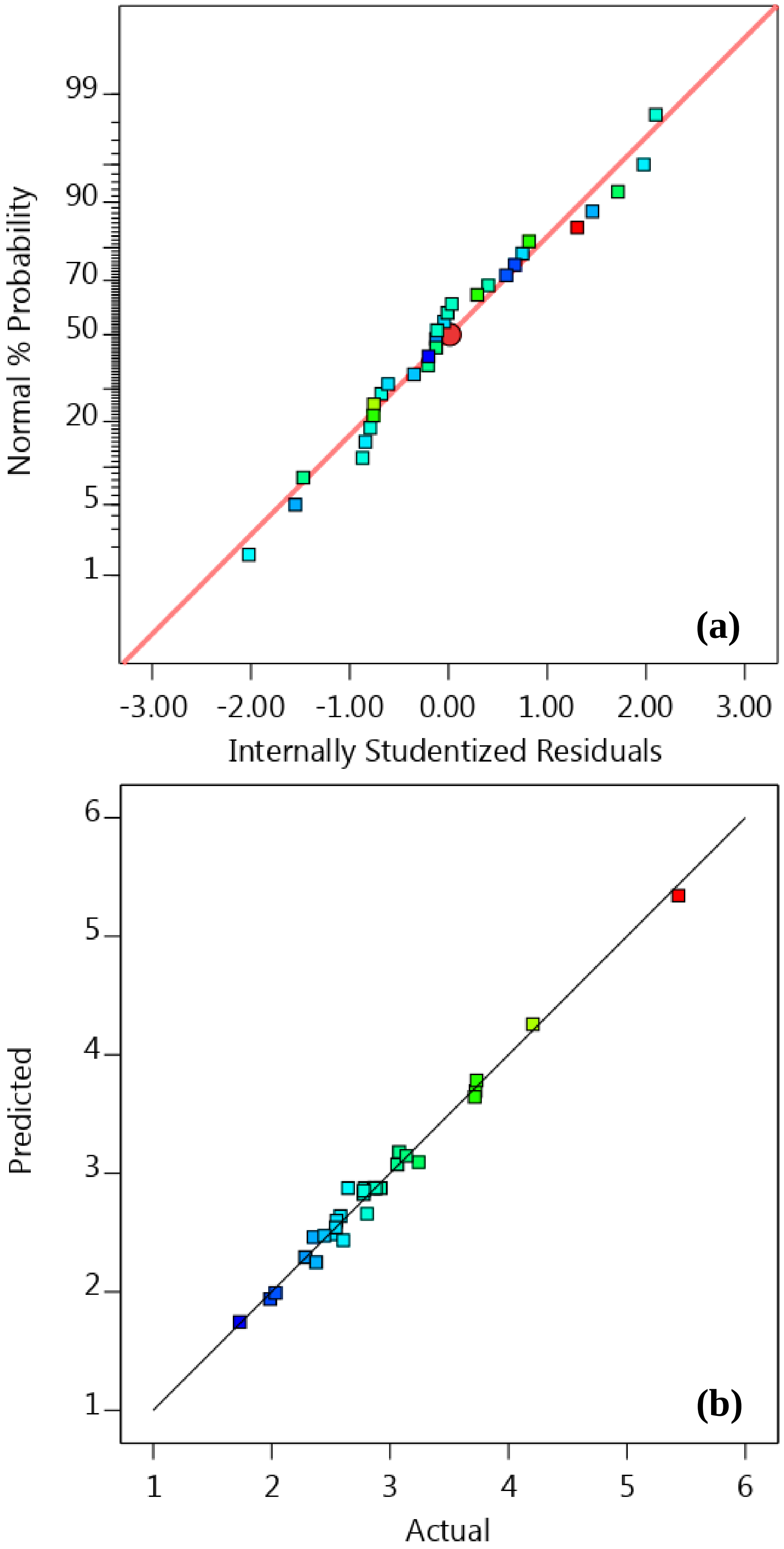


Figure 4.4. a) Normal plot for residual b) predicted vs. actual on SR

Table 4.5. ANOVA for SR

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	14.98	14	1.07	74.59	< 0.0001	significant
A-T_{off}	0.0117	1	0.0117	0.8161	0.3806	
B-T_{on}	0.7846	1	0.7846	54.71	< 0.0001	
C-I_p	1.1	1	1.1	76.92	< 0.0001	
D-PC	0.2262	1	0.2262	15.78	0.0012	
AB	1.91	1	1.91	133.03	< 0.0001	
AC	4.77	1	4.77	332.36	< 0.0001	
AD	0.7487	1	0.7487	52.2	< 0.0001	
BC	1.89	1	1.89	131.78	< 0.0001	
BD	0.8944	1	0.8944	62.37	< 0.0001	
CD	0.7392	1	0.7392	51.54	< 0.0001	
A^2	1.64	1	1.64	114.31	< 0.0001	
B^2	0.1383	1	0.1383	9.65	0.0072	
D^2	0.682	1	0.682	47.55	< 0.0001	
Residual	0.2151	15	0.0143			
Lack of Fit	0.1653	10	0.0165	1.66	0.3005	not significant
Pure Error	0.0499	5	0.01			
Cor Total	15.19	29		R^2		0.9858
Std. Dev.	0.1198			Adjusted R^2		0.9726
Mean	2.89			Predicted R^2		0.9348
C.V. %	4.15			Adeq Precision		42.4852

Therefore, a 30.05% chance more substantial lack of fit F-value could occur due to noise. P values of below 0.05 specify the importance of model terms. Here the terms B, C, D, AB, AC, AD, BC, BD, CD, A^2, B^2, D^2 have a percentage of contribution of each factor such as 5.24, 7.34, 1.51, 12.75, 31.84, 5.00, 12.62, 5.97, 4.93, 10.95, 0.92 and 4.55% respectively. Significant model terms are shown with a value of greater than 0.1 for improving the model summary. The coefficient estimation characterizes the expected change in SR with a single factor at a time when all other remaining factors are detained constant.

The reasonably close proximity between the Predicted R^2 (0.9348) and the Adjusted R^2 (0.9726) indicates a good fit of the model. Furthermore, the Adeq Precision, with an S/N ratio value of 42.485, exceeds the desired threshold of 4, confirming the model's adequacy in predicting the surface roughness. As a result, this model can effectively predict the surface roughness values for both maximum and minimum considered factors.

4.5.3. Parametric Study on Material Removal Rate

The present study exposed the relative impact of machine control factors on the MRR of Ti6Al4V material through powder mixed wire EDM process in the perturbation graph as in Figure 4.5. By the design-Expert software, the midpoint of all factors is kept as a reference point.

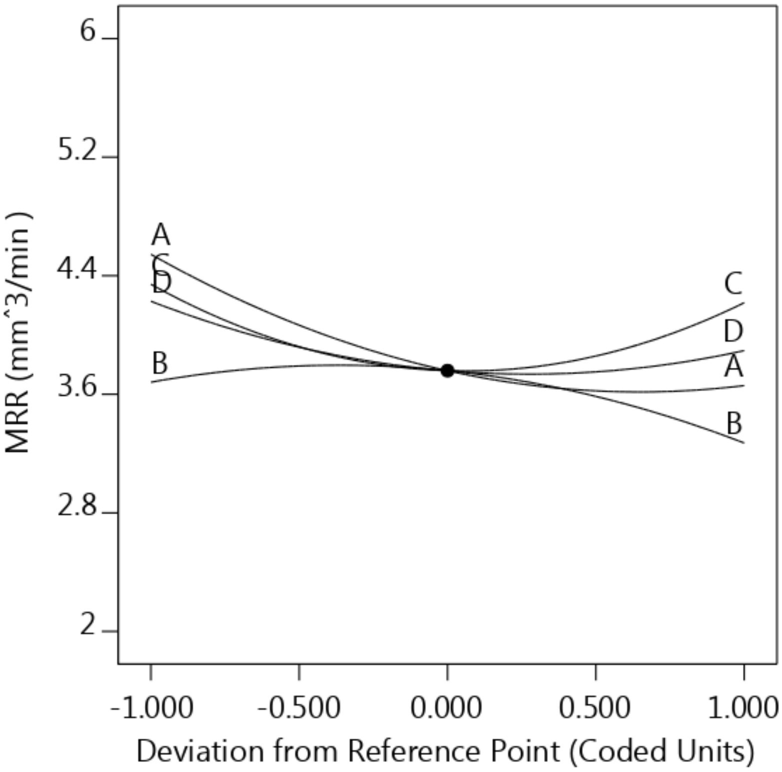


Figure 4.5. Perturbation graph for metal removal rate

The intense slope, including all significant parameters such as T_{off} (A), T_{on} (B), and PC (D), indicates that MRR is highly sensible towards these parameters while the selected I_p (C) parameter has less sensitive as compared to other parameter settings. The effect of gas explosion, ion generation, and bridging effect of powder mostly influences MRR for a specific value of discharge energy. The contribution of the significant interactions between input variables like T_{off} and I_p (AC), T_{on} and I_p (BC), T_{on} and PC (BD), and I_p and PC (CD) are shown in Table 4.4. The surface plot of these parameter interactions is illustrated in Figure 4.6a-4.6d, respectively. Figure 4.6a represents the interaction effects at the middle point of T_{off} and I_p. It is observed in Figure 4.6a that with an increase in T_{off} and $I_{p,}$ MRR increases smoothly. This is due to the high discharge energy produced by higher peak current and availability of higher time to remove the debris particle from the gap by the higher pulse off time.

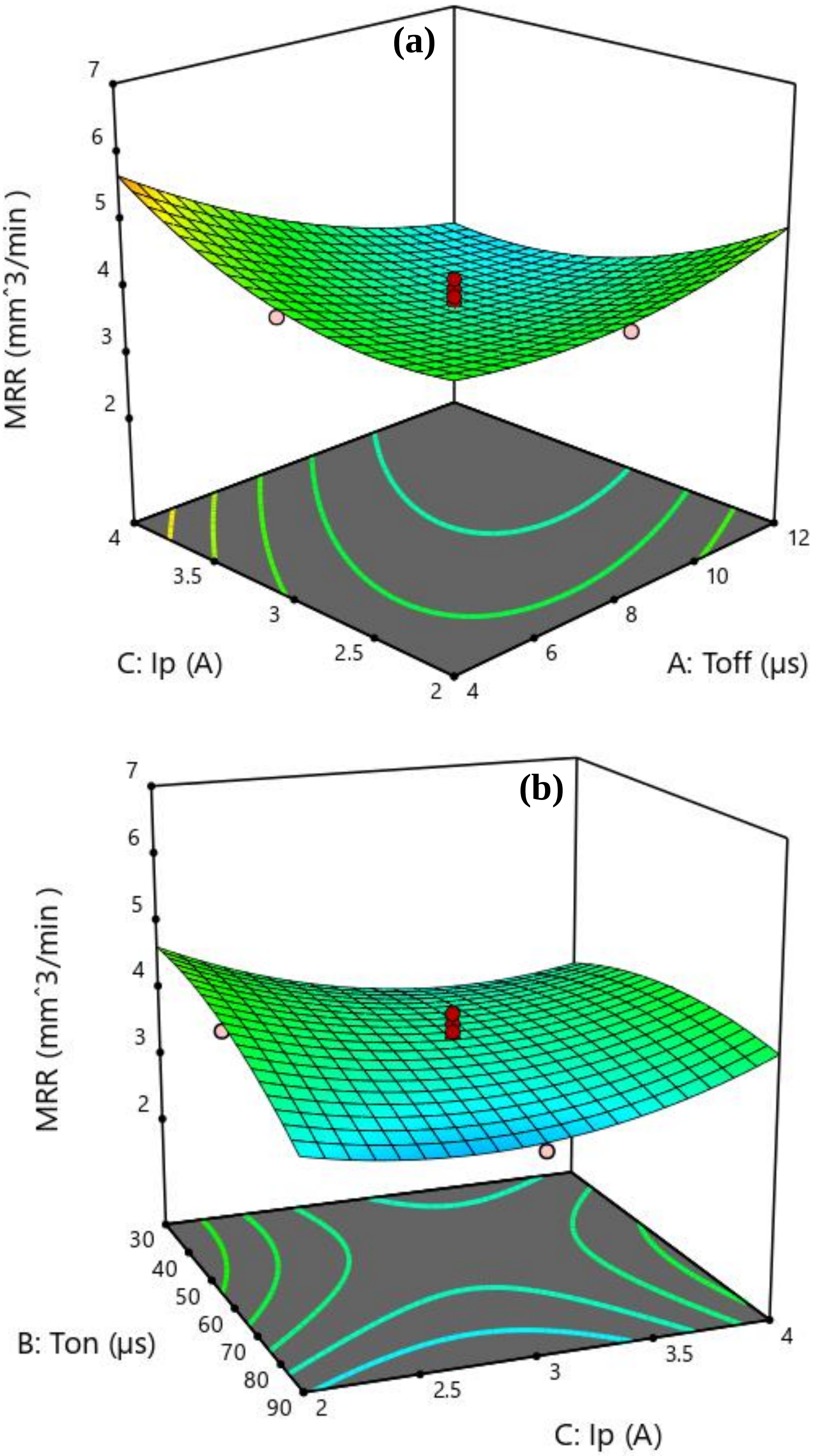
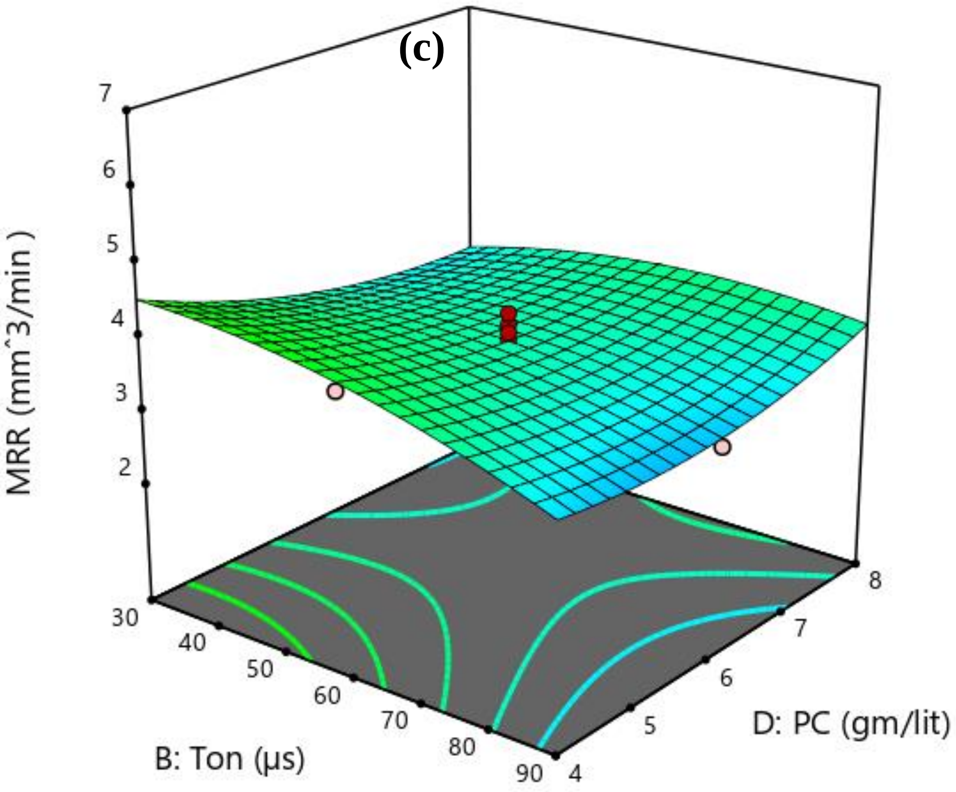


Figure 4.6. Interaction plot a) I_p Vs T_{off} and b) I_p Vs T_{on} on MRR



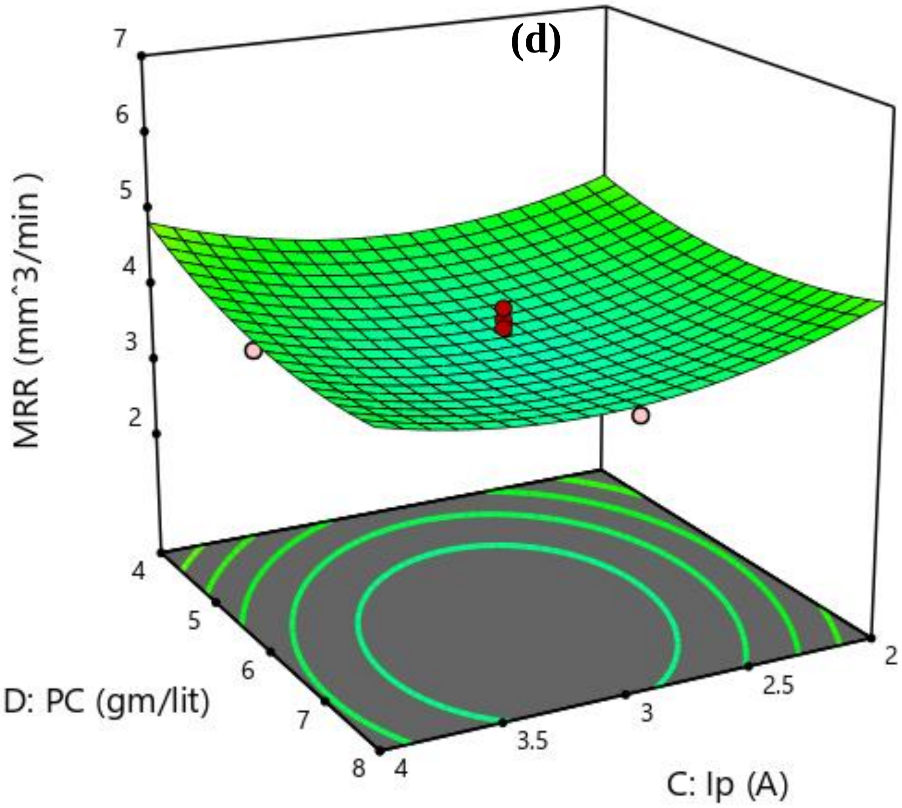


Figure 4.6. Interaction plot c) T_{on} Vs PC and d) I_p Vs PC on MRR

Figures 4.6b and 4.6c demonstrate the combined impact of I_p, T_{on}, and PC on the process. As illustrated, MRR initially decreases with increasing PC and I_p, but later increases. In the case of T_{on}, MRR follows a pattern of increase followed by decrease. This behavior is attributed to variations in PC, which directly influence the plasma channel and its characteristics. Higher powder concentration disrupts the smooth spark generation process. Consequently, the discharge energy is governed by I_p and T_{off}, allowing control over the melting and evaporation of the machining surface.

Proper powder concentration helps to create a continuous robust bridging effect in the gap zone. Due to this, an early explosion is placed and enlarges the spark gap in the plasma channel. A series of sparks is produced, which provides better MRR. The overall process depends on the weightage value of the PC. MRR increased with the increase of powder concentration because of the consistency of discharge energy which results in large and deeper craters. Consequently, the swift removal of debris from the gap zone results in reduced machining time. When there is a lower amount of powder mixed with the dielectric, the bridging effect is not adequately formed, leading to a decrease in MRR. On the other hand, an excessive amount of powder accumulation in the plasma channel results in discrete sparks, leading to lower MRR and surface finish quality. Hence, adopting a low pulse setting enhances process efficiency while achieving lower-cost productions.

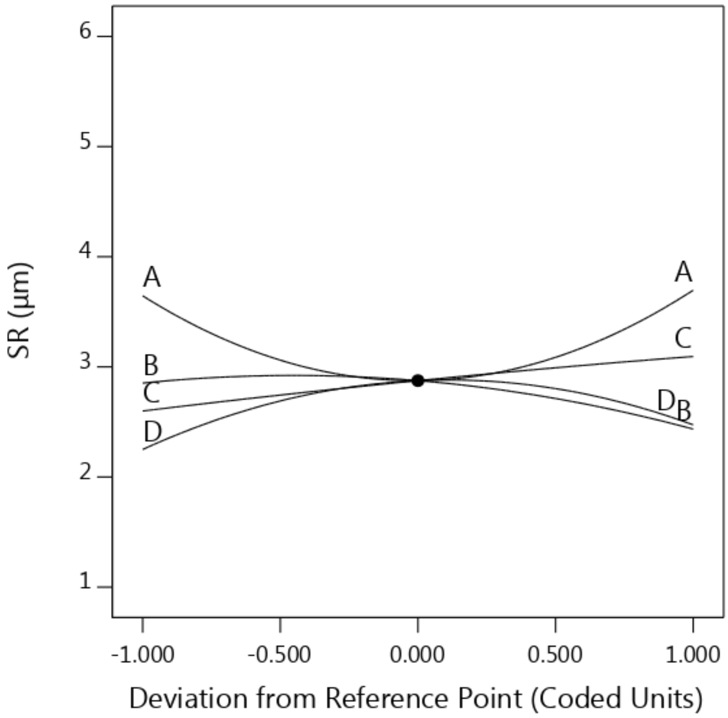


Figure 4.7. Perturbation graph for surface roughness

The augmentation of MRR is seen with an increase in PC as well as pulse off time. The spark frequency depends on pulse off time variation. Spark frequency decreases with an increase in T_{off} that leads to minimize the gas eruption. At the same time, higher T_{off} provides sufficient time to reduce debris from the gap zone and initiates the next series of spark discharges. In addition to powder with dielectric, the discharge energy is enhanced, resulting in faster erosion from the job surface. The optimum setting for all input variables, including PC, is required; otherwise, a larger or smaller amount of PC selection reduces the MRR.

4.5.4. Parametric Study on Surface Roughness

The most influencing parameters are shown in Table 4.5. Figure 4.7 represents the perturbation plot with four parameters, i.e., T_{off} (A), T_{on} (B), I_p (C), and PC (D) for surface roughness of the machine surface. The intense slope, including the most significant parameters such as T_{off} (A) and PC (D), indicates that SR is highly sensible towards these parameters. PC helps to decrease dielectric strength and avoid discrete sparks, and T_{off} provides more time to remove debris from the gap zone. Due to this, machining performance is improved, and the process becomes more stabilized. In contrast, selected T_{on} (B) and I_p (C) parameters have less sensitivity than other parameters settings. Ion generation and discharge energy are controlled by T_{on} and I_p. The best surface finish has been achieved when the machined surface shows fewer craters, voids and micro-cracks, which are mostly affected by T_{off} and PC.

According to the ANOVA Table 4.5, the contribution of the significant interactions between input variables is T_{off} and T_{on} (AB), T_{off} and I_p **(**AC), T_{off} and PC (AD), T_{on} and I_p (BC), T_{on} and PC **(**BD), I_p and PC (CD)**.** The surface plot of these parameter interactions is illustrated in Figure 4.8a-4.8f, respectively.

Figures 4.8a and 4.8c demonstrate that surface roughness initially decreases and then increases as T_{off} increases. In contrast, Figures 4.8c, 4.8e, and 4.8f show that surface roughness increases up to a PC of 6g/L. This is due to the abrasion action and characteristics of the powder and pulse delay time. Figures 4.8b, 4.8d and 4.8f show that higher peak current leads to higher surface roughness produced on the machining surface. Higher current converts to high discharge energy; as a result, more evaporation transpires from the workpiece.

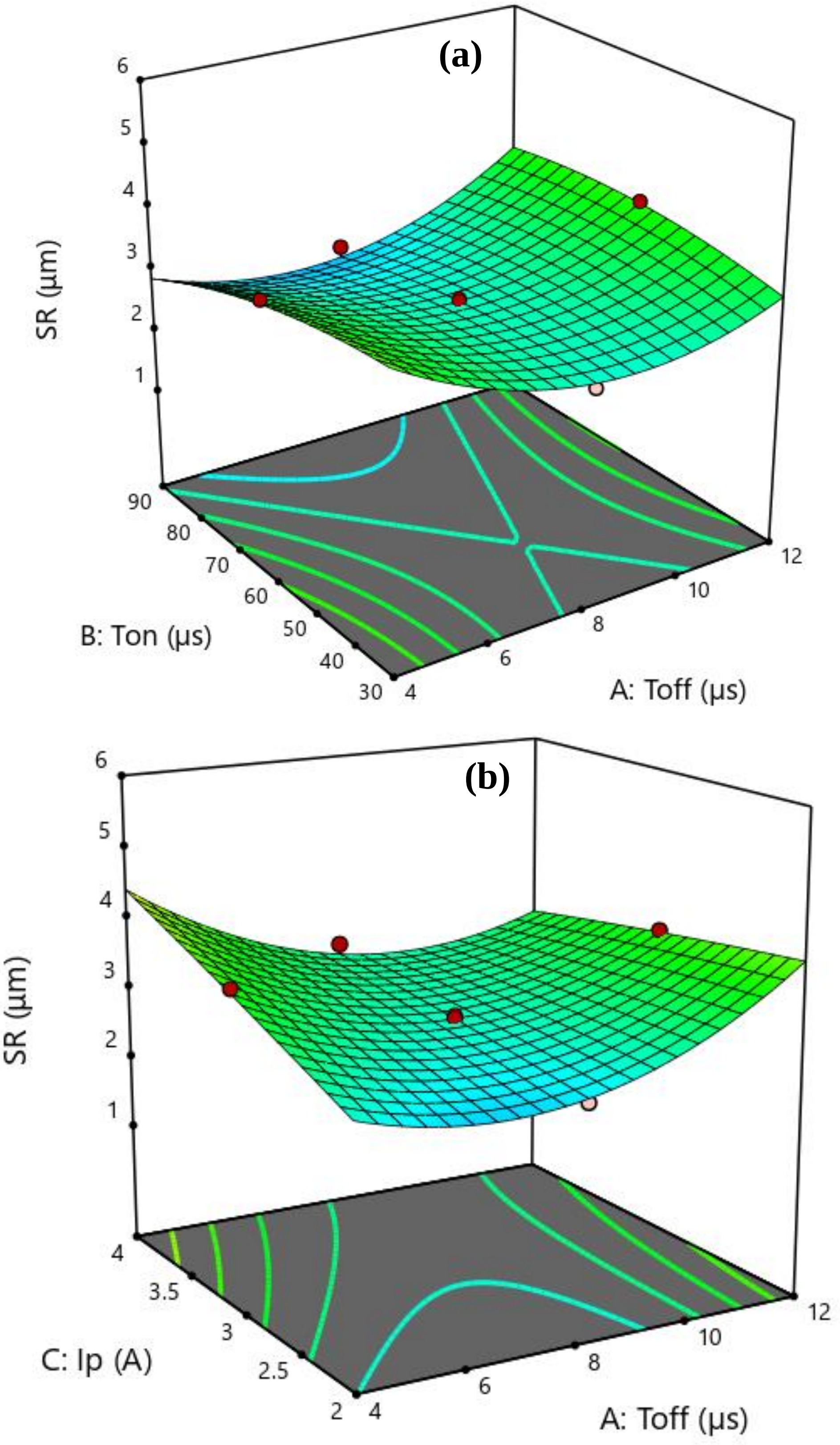


Figure 4.8. Interaction plot a) T_{on} Vs T_{off} and b) I_p Vs T_{off} on SR

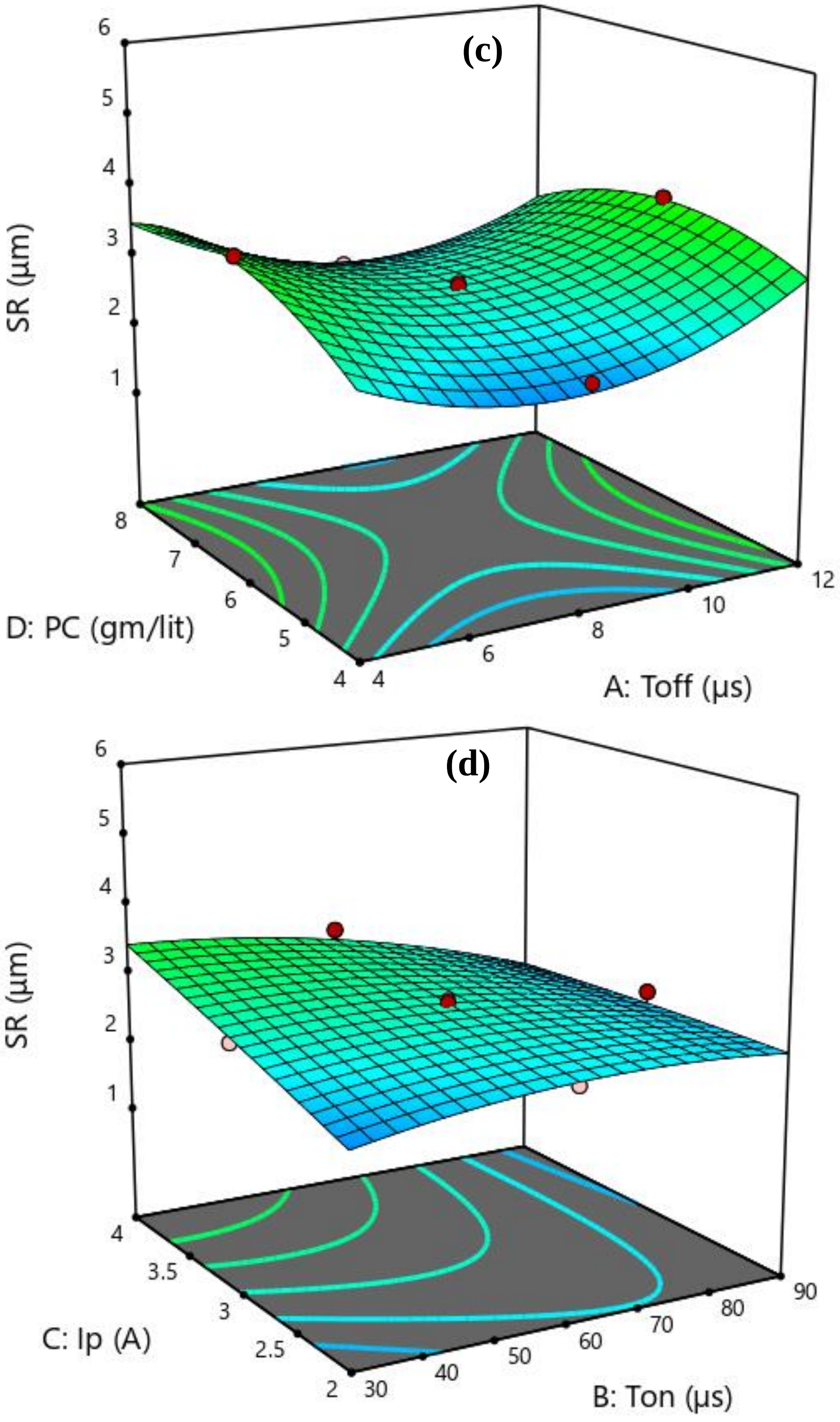
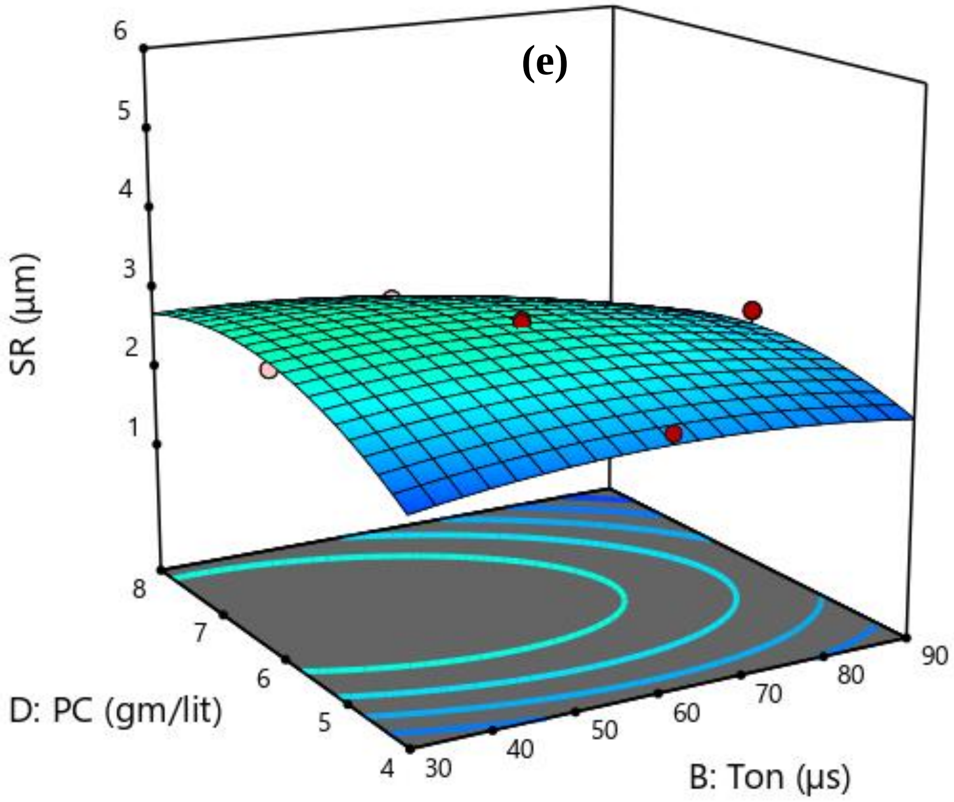


Figure 4.8. Interaction plot c) PC Vs T_{off} and d) I_p Vs T_{on} on SR



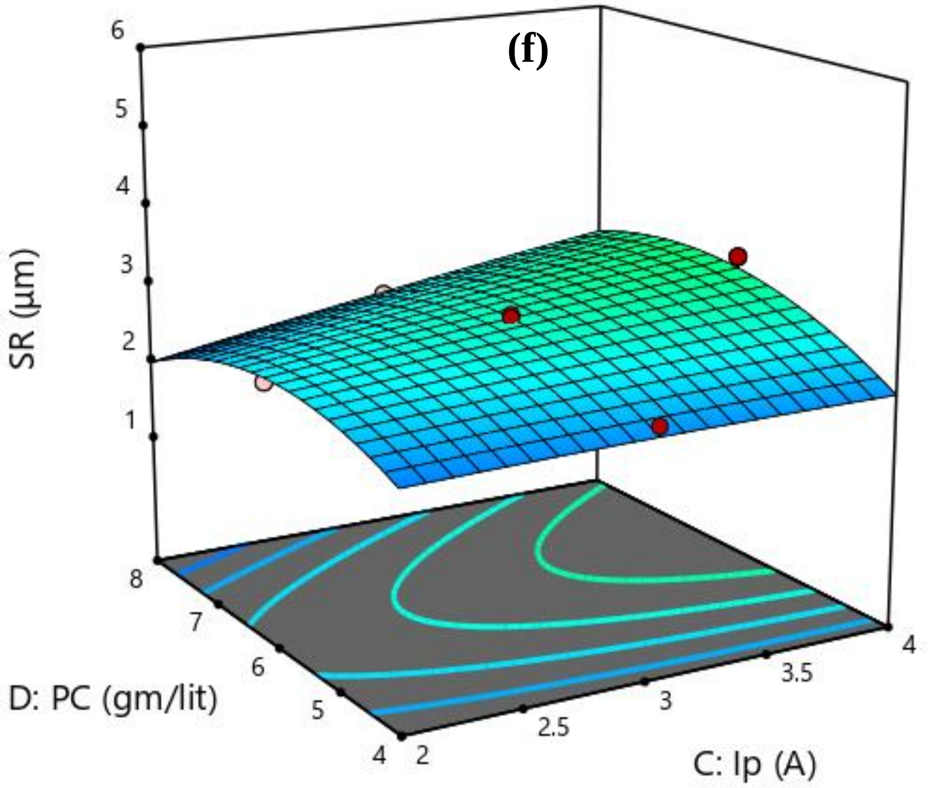


Figure 4.8. Interaction plot e) T_{on} Vs PC and f) I_p Vs PC on SR

Debris particles are not removed well and attached to the machine surface, which leads to poor surface finish. It is clearly understood from Figure 4.8d - 4.8f that the surface roughness increases initially with an increase in PC and then starts to decrease for a further rise in abrasive concentration. This is due to the discrete spark generation in the narrowest gap. A sufficient amount of PC with dielectric helps to reduce the electrical resistivity of the dielectric. As a result, reduced impulse force established a high plasma channel that provides higher MRR and surface finish. But, a higher amount of suspended powder leads to low MRR and creats even large debris and massive craters on the machine surface, resulting in higher SR. However, higher T_{off} may cause wire breakage that degrades the overall process efficiency. Consideration of optimal T_{off} setting is then essential to avoid this obstructed situation.

4.6. Multi-objective Optimization

4.6.1. Multi Response Optimization with Desirability Approach

An objective function is commonly known as desirability that expanses from zero to one at the target. The characteristics of the goal are rehabilitated by modifying the weight or importance. High desirability value indicates that the lower and upper limits are how much closer to the most favourable value (desirability value of 1.0). The desirability approach is a concrete methodology to solve a single objective and multi-response optimization problem. For multi-responses and factors, all goals are combined into a single desirability function.

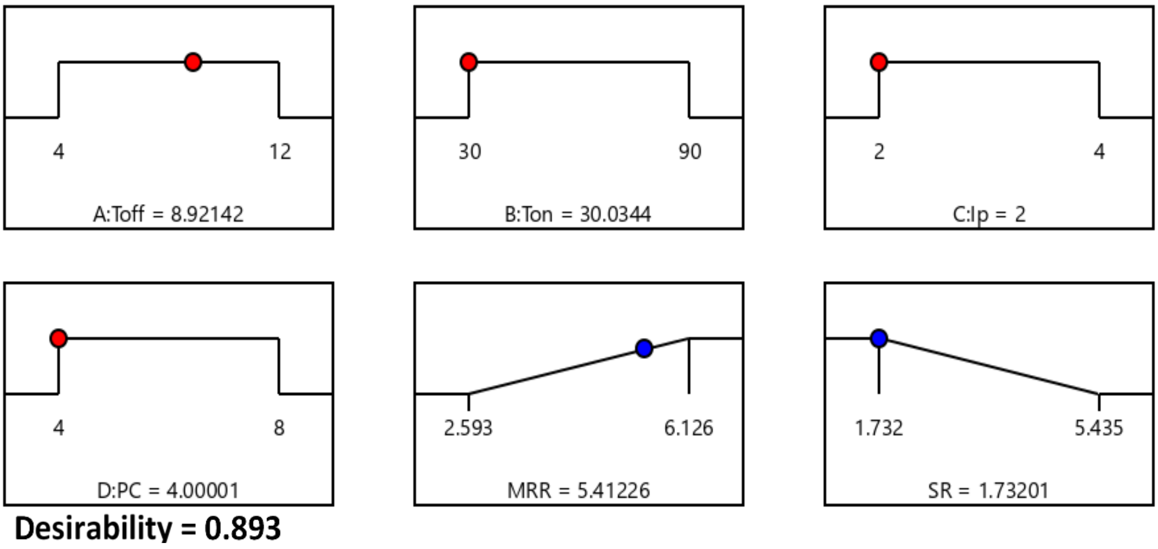


Figure 4.9. Numerical optimization ramps view for Ti6Al4V

In this investigation, desirability- based multi optimization is used with a set of input factors such as I_p, T_{on}, $T_{off,}$ and PC, that satisfies the constraints executed on machining factors and response measures as shown in Table 4.6. In the numerical optimization ramps view, the desirability of MRR and R_a are illustrated as ramp function diagram and bar graph, as shown in Figure 4.9 and Figure 4.10, respectively.

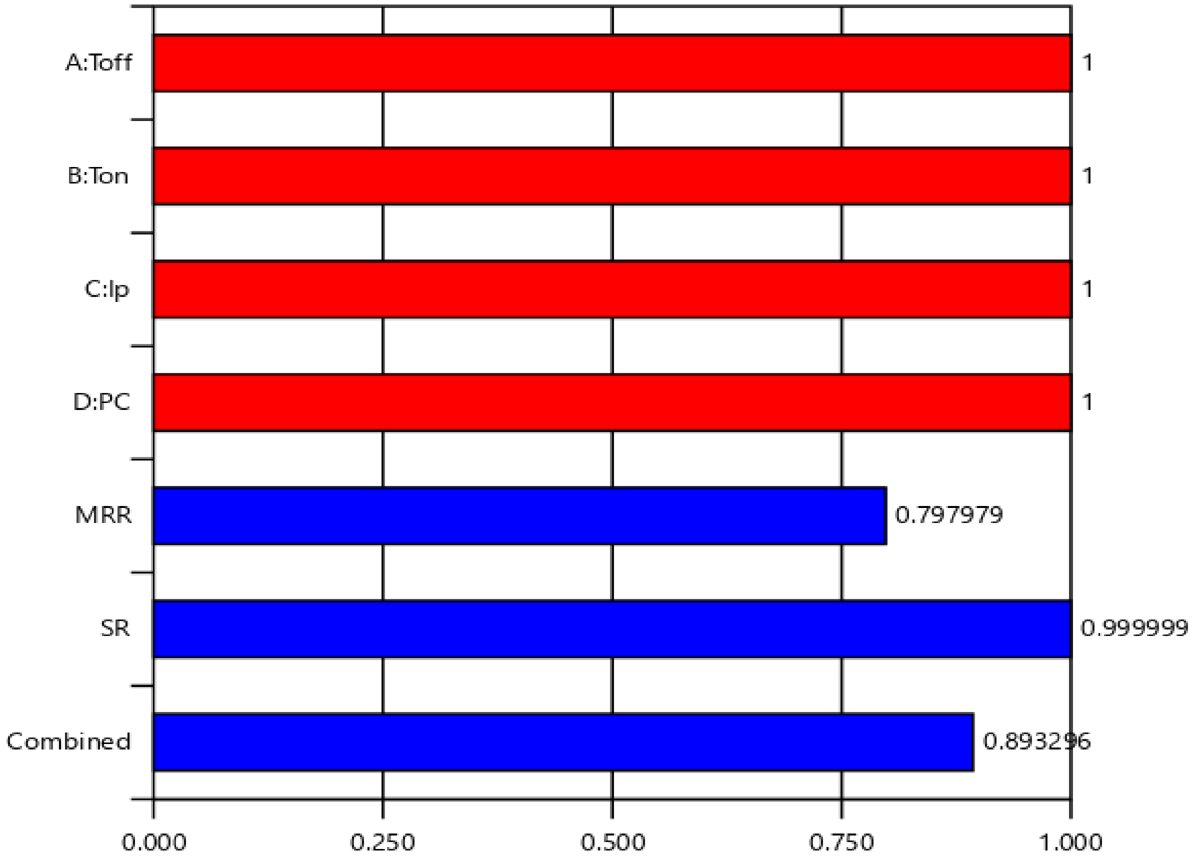


Figure 4.10. The solution to multiple response optimization (desirability bar graph)

The point on the ramp view graph showed the estimation value for machining parameter and response measure. Therefore, the peak point leads to its desirability. In the bar graph, the MRR value is closer to 1, which indicates satisfactory constraints. Table 4.6 presents the limitations imposed on the input and output variables for achieving desirability. The combined case takes into account both performance measures, MRR and SR, ensuring that they are kept close to the desired values. Under the current design constraints of output measures, a set of 100 optimal solutions has been identified.

Table 4.6. Contraints of input and output variable for desirability

Name	Target	Lower Range	Upper Range	Lower Weightage	Upper Weightage	Significance
A:Toff	within range	4	12	1	1	3
B:Ton	within range	30	90	1	1	3
C:Ip	within range	2	4	1	1	3
D:PC	within range	4	8	1	1	3
MRR	maximize	2.593	6.126	1	1	3
SR (R_a)	minimize	1.732	5.435	1	1	3

4.6.2. Multi Response Optimization with GRA-PSO

The second optimization technique is framed with particle swarm optimization (PSO) coupled with the GRA approach. Many researchers have used GRA approach in their investigation to optimize the process parameters. Due to certain limitations to compute optimal solutions, additional tools are required for the best possible output after using GRA in complex problems. GRA can be sensitive to the initial data used in the analysis. The choice of reference series and the normalization method can significantly impact the results, making it challenging to achieve consistent and robust solutions. GRA is a distance-based method that is more suitable for linear relationships between variables. It may not effectively capture nonlinear relationships, limiting its applicability to certain complex problems. Hence particle swarm optimization technique has a higher ability to provide a better result. PSO employs a population of candidate solutions (particles) that interact and move through the search space together. This approach allows it to explore a wide range of potential solutions simultaneously, increasing the chances of finding better solutions.

In the present investigation, the GRA approach converts the multi objectives into a single objective. Then PSO is employed to obtain global optimal solution as an alternate of quasi-optimal solution. In the first step of GRA computation, all experimental data are normalized, and then the grey relation coefficient (GRC) has been generated using Equations (4.3), (4.4) and (4.5), respectively. Finally, the grey relation grade has been computed simply by taking the average value of GRC. The calculated data by using the GRA method has been given in Table 4.7.

Table 4.7. Computational value for grey relation grade

Sl No.	Grey relation generating		Grey relation coefficient		GRG
1	0.771	0.931	0.686	0.879	0.783
2	0.322	0.695	0.425	0.621	0.523
3	0.326	0.692	0.426	0.619	0.522
4	0.395	0.679	0.452	0.609	0.531
5	0.971	0.718	0.945	0.639	0.792
6	0.264	0.919	0.405	0.860	0.632
7	0.427	0.592	0.466	0.551	0.508
8	0.462	0.780	0.482	0.694	0.588
9	0.335	0.808	0.429	0.722	0.576
10	0.905	0.832	0.841	0.749	0.795
11	0.363	0.690	0.440	0.617	0.529
12	0.438	0.716	0.471	0.637	0.554
13	0.712	0.710	0.634	0.633	0.634
14	0.517	1.000	0.509	1.000	0.754
15	0.574	0.620	0.540	0.568	0.554
16	0.645	0.000	0.585	0.333	0.459
17	0.000	0.637	0.333	0.579	0.456
18	0.976	0.641	0.954	0.582	0.768
19	0.275	0.851	0.408	0.770	0.589
20	0.519	0.464	0.510	0.483	0.496
21	0.269	0.463	0.406	0.482	0.444
22	0.275	0.718	0.408	0.639	0.524
23	0.159	0.764	0.373	0.680	0.526
24	0.430	0.826	0.467	0.742	0.605
25	0.598	0.771	0.554	0.686	0.620
26	0.408	0.332	0.458	0.428	0.443
27	1.000	0.460	1.000	0.481	0.740
28	0.335	0.753	0.429	0.670	0.550
29	0.290	0.782	0.413	0.696	0.555
30	0.441	0.782	0.472	0.697	0.584

After generating the regression analysis of GRA, the fitness function for PSO is employed to obtain the best solution. The main objective of PSO is to solve the maximise problem and determine a maximum GRA value. In the present investigation, the fitness function has been given in Equation (4.10) to evaluate the parametric fitness of a set of machining inputs in the PMWEDM process. The proposed fitness function evaluates the individual agent fitness. G_{best} represents the best fitness position among the agents in the PSO optimisation, whereas P_{best} represents the individual best position. For each agent, the velocity and positions are updated using the governing equation in the PSO algorithm.

$$\text{Maximize GRG} = 2.226+0.0422*T_{off}-0.01156*T_{on}-0.307*I_p-0.3142*PC-0.00218*T_{off}^2+0.000022*T_{on}^2+0.0431*I_p^2+0.02129*PC^2-0.000350\,T_{off}*T_{on}-0.00330\,T_{off}*I_p+0.001624*T_{off}*PC+0.001897*T_{on}*I_p+0.001012*T_{on}*PC-0.00980*I_p*PC \quad (4.10)$$

The maximize problem is subjected to the selected parametric setting as follows:

Subjected to: $4 \leq T_{off} \leq 12$

$30 \leq T_{on} \leq 90$

$2 \leq I_p \leq 4$

$4 \leq PC \leq 8$

The convergence characteristic graph generated by the PSO optimization technique has been illustrated in Figure 4.11. The diagram has been presented the maximum GRA value of 0.897, which is nearest to the value of 1. This value indicates that the obtained result satisfies the desired criteria.

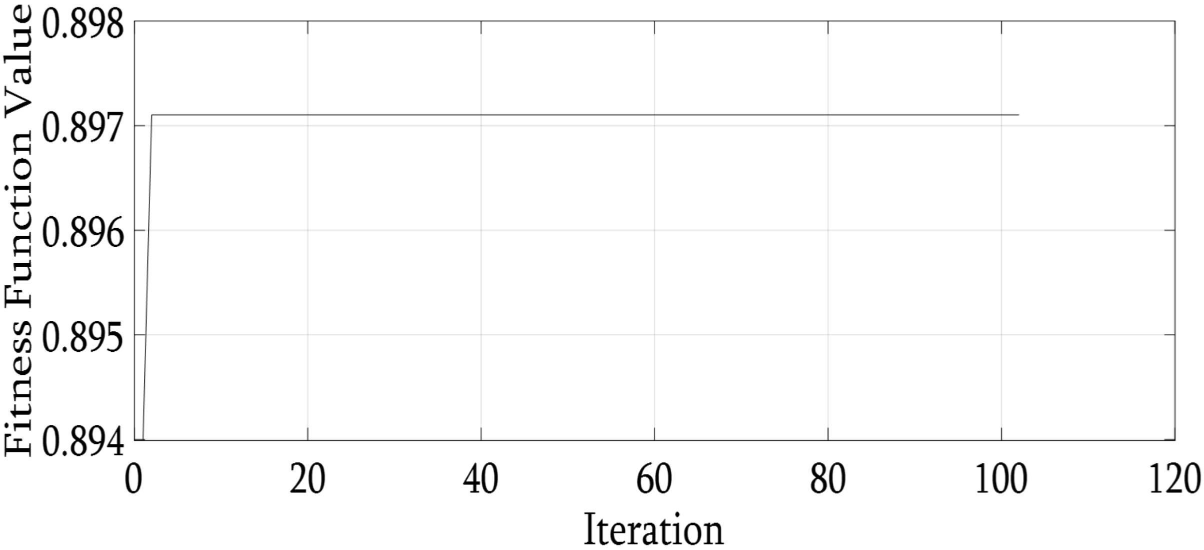


Figure 4.11. PSO convergence characteristic curve

Table 4.8. Optimum parameter setting

Methods	T_{off} (µs)	T_{on} (µs)	I_p (A)	PC (g/L)
RSM	8.921	30	2	4
GRA	4	90	2	4
PSO-GRA	7.247	30	2	4

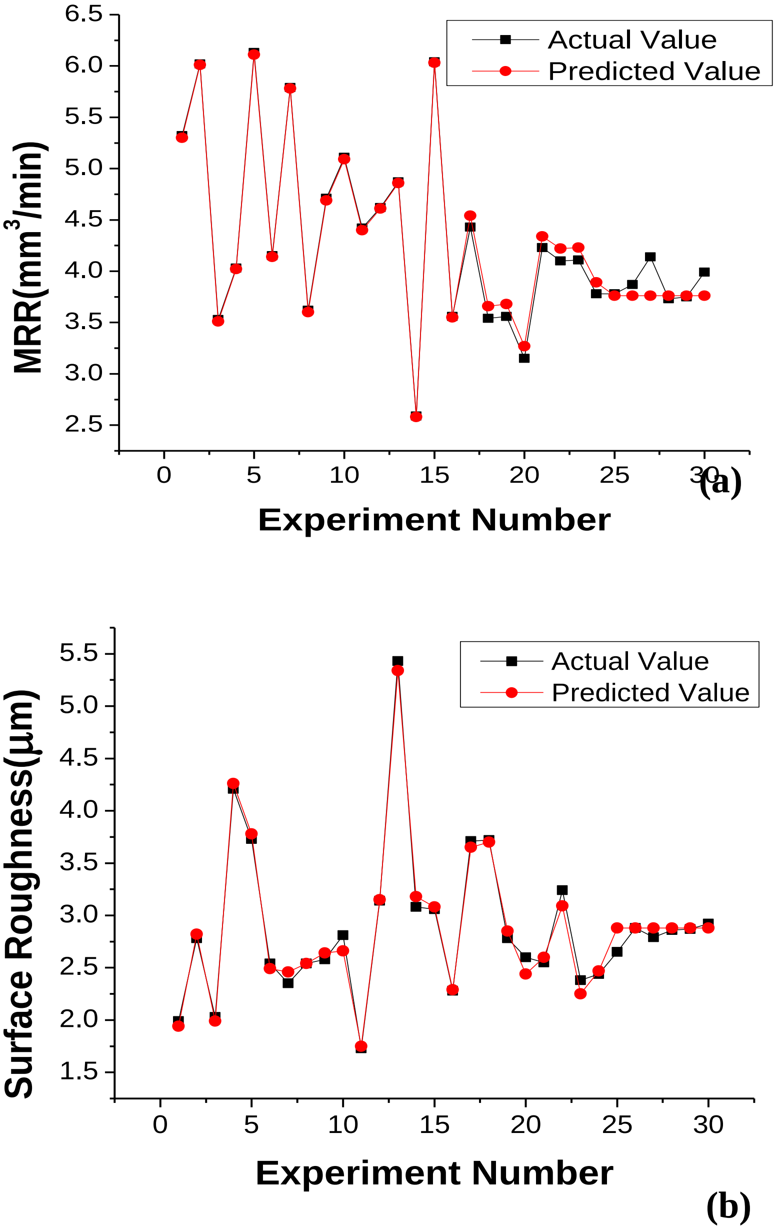


Figure 4.12. Actual vs. predicted graph for a) MRR and b)SR

As in Table 4.8, a confirmation test is performed with different optimization techniques with the setting of an optimal solution. It is evident from the confirmation test that the error is within ± 5, which reveals the close attachment between predicted and experimental values in the RSM methodology. In RSM, the error is found at 2.85% and 4.80% for MRR and SR, as shown in Table 4.9. The best-predicted value is obtained in hybrid PSO from the other alternating optimization techniques such as GRA and PSO-GRA. It is achieved that the best output of 9.79 % higher adequate potency is obtained from PSO-GRA than the GRA technique. Therefore, an optimum result for machining Ti6Al4V using the PMWEDM process can satisfy bright promises with achievable performances.

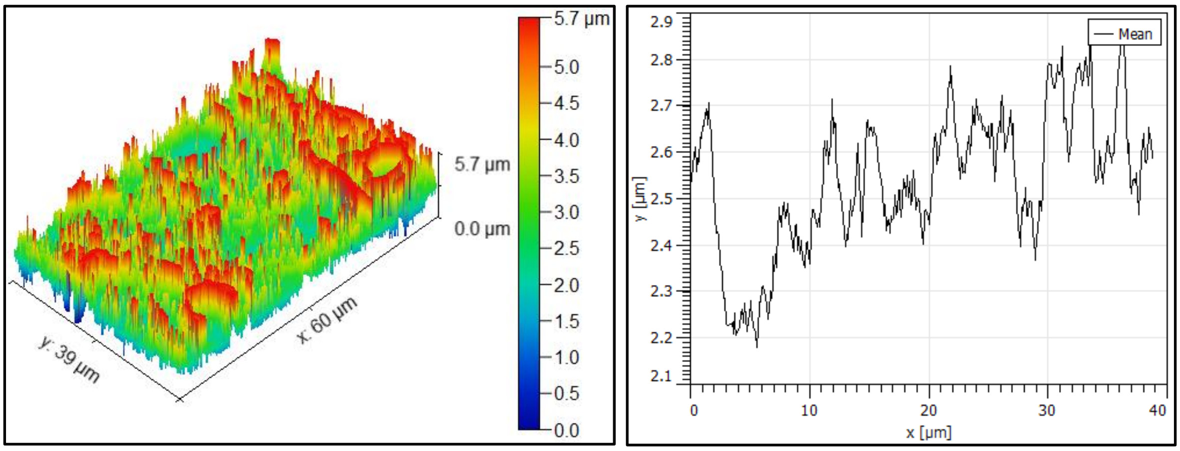
Figure 4.12 illustrates that the experimental values and RSM prediction results are nearly closer 2.28% & 1.63% for SR and MRR, respectively. Thus, the proposed RSM model predicts appropriately, and the model can be used for predicting time and cost reduction manufacturing. A concentration of 4 g/L abrasive powder mixed with dielectric, including other sets of machining parameters, plays a significant role in enhancing the hybrid process of wire electric discharge machining.

Table 4.9. Confirmation test for the final predicted value

Methods	Response	Target	Predicted	Experimental	Error %
RSM	MRR(mm^3/min)	maximize	5.480	5.328	2.85
	SR(μm)	minimize	1.843	1.936	4.80
GRA		maximize	0.817	0.831	1.68
PSO-GRA		maximize	0.897	0.916	2.07

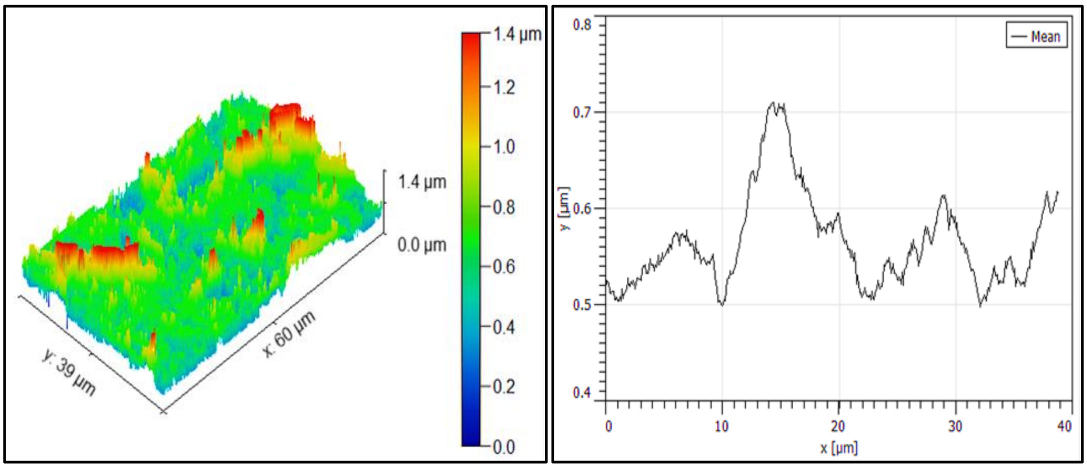
4.7. Analysis of Machined Surface Topography

3D and 2D topography of machining surface have been analyzed with two conditions: experimental plan No 16 which has maximum surface roughness and optimum setting obtained by GRA-PSO. The Figure 4.13 (a) illustrates that the molten metal deposited massively on the machined surface. Thus an inferior surface finish is highlighted. During the evaluation of all data set, it is evident that better surface topography has been achieved in an optimum condition of the PMWEDM process as in Figure 4.13 (b). This is due to the elimination of deposited recast layer, crater and voids formation, and globules.



(a)

Figure 4.13. a) 3D and 2D topography of the machine surface (maximum obtained surface in Exp. No. 16: T_{off} = 4 µs, T_{on}= 30 µs , I_p =4 A, PC = 8 g/L)



(b)

Figure 4.13. b) 3D and 2D topography of the machine surface (optimum machining setting T_{off} = 7.247 µs, T_{on}= 30 µs, I_p =2 A, PC = 4 g/L)

The surface morphology is presented at the optimum parametric combination in Figure 4.14. Larger massive craters are formed with high peak current and low pulse on time. This is due to the usage of powder in dielectric while machining. Discharge sparks get distributed over a large area, increasing the mean distance of the craters. Also, a lower amount of recast layer formation, micro globules, and cracks enhance machined surface quality. The heating and cooling effects have a prominent role in WEDMed surface profile.

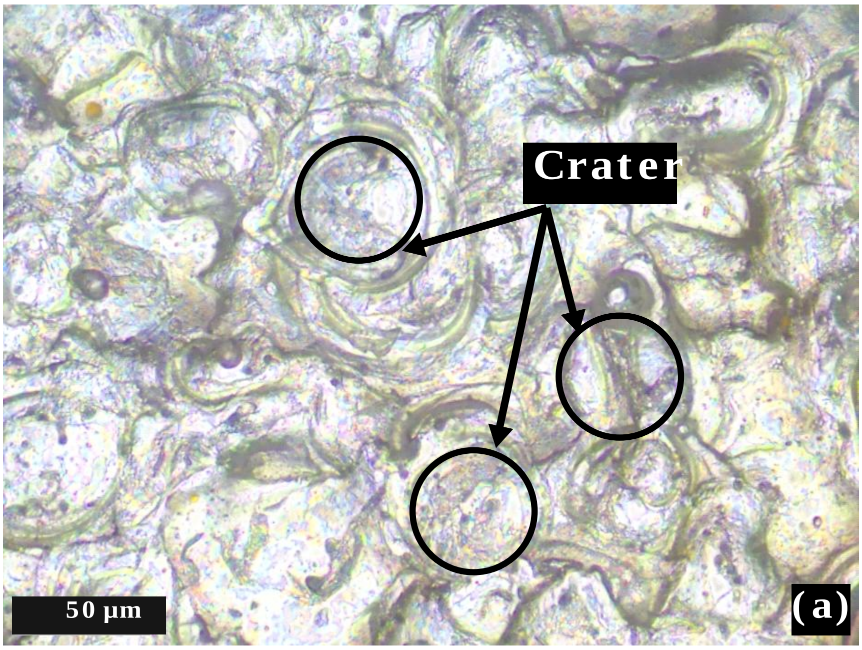


Figure 4.14. a) Microstructure of the machine surface in optimum condition T_{off} = 7.247 µs, T_{on}= 30 µs, I_p =2 A, PC = 4 g/L

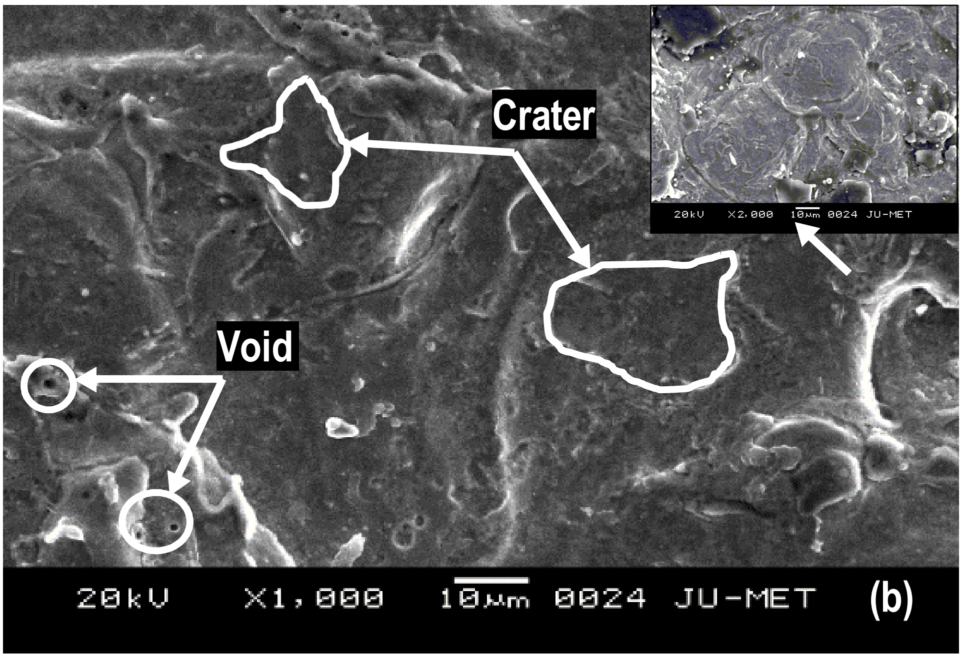


Figure 4.14. b) SEM image of the machine surface in optimum condition T_{off} = 7.247 µs, T_{on}= 30 µs, I_p =2 A, PC = 4 g/L

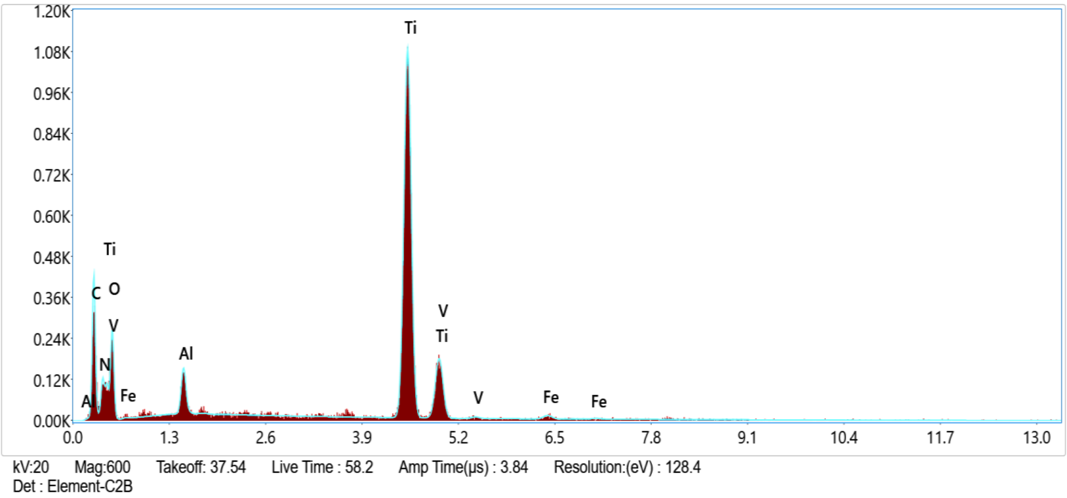


Figure 4.14. EDS plots of the machine surface in optimum condition

The effects of heating and cooling are directly proportional to residual stress. If the discharge is less intense, the residual stress is also less. Therefore, the high thermal conductivity of the power help to carry away additional heat, undermining the heating and cooling phenomena. As a result, low residual stress affects the machined surface. Low residual stress and low spark intensity make the process more stable using Al_2O_3 mixed dielectric in WEDM process. The presence of carbide form on machined surfaces justifies the enhancement of micro-hardness. The elements on the machined surface have been illustrated in Figure 4.15. Thereby increasing in surface finish as well as the hardness of the surface of Ti6Al4V alloy is achieved.

4.8. Summary

The present study can be summarised as follows:

1. The stochastic nature and process behaviour of the PMWEDM are successfully analyzed, and the critical importance of each parameter is determined by RSM methodology. The multiobjective optimisation shows that the GRA-PSO technique has the highest adequate capability to predict the best responses compared to other techniques.
2. The maximum MRR and surface finish for Ti6Al4V alloy is found at a concentration of 4 g/L of Al_2O_3 powder. At this concentration level, the consistency of discharge energy is appropriate, and the recast layer formation is significantly less, which results in excellent output.
3. Increasing T_{off} and I_p result in higher MRR due to the higher discharge energy and the availability of adequate time to remove the debris particle inside the machining gap.
4. The obtained result reveals that I_p, $T_{on,}$ and PC have a more considerable influence on MRR. Therefore, an enormous contribution of I_p is found at 15.94%. Interaction of I_p followed by T_{off} impacts mostly on MRR.
5. The highest achievable surface finish can be obtained by low pulse setting and high peak current. The impact of I_p followed by PC, T_{on} followed by PC and T_{off} followed by PC have the nearly same on the machine surface characteristics.
6. The parametric analysis states that discharge energy is controlled by the most influential parameters, i.e. I_p and T_{off}, followed by PC in the proposed machining domain.
7. Finally, the obtained optimal solution for each technique is experimentally verified. Confirmation test established that the PSO-GRA approach has a value of 9.79 % higher adequate potency than the GRA approach.

CHAPTER: 5

EXPERIMENTAL INVESTIGATION ON DIMENSIONAL ACCURACY

5.1. Introduction

The limitations of the normal WEDM process are overcome by using a hybrid WEDM process [54]. Powder mixed wire EDM (PMWEDM) is one type of hybrid WEDM process by which the machining efficiency is improved for any variety of conductive materials. In the PMWEDM process, metal, non-metal and abrasives powders are added with dielectric fluid. The suspended powder in dielectric gets energized by applying supply voltage and withstand to particle’s accumulation. The energized particle creates a bridging effect during machining that helps to an early explosion. The insulating strength of the dielectric is reduced by increasing the spark gap. A large amount of spark energy is distributed evenly during the machining operation. Due to this, the operation becomes more stable and results in achievable responses. This hybrid technique can be incorporated into WEDM process for making micro dimension profile with better efficiency.

Nowadays, micromachining is very much needed where the micro-precision dimension is intensely dependent [55-56]. Micro-WEDM is widely accepted in technically advanced industries like nuclear plants, aerospace, and biomedical components making companies. In the micro-WEDM process, a thin electrode wire is used, which is continuously travelling [57]. The machining performances of micro-WEDM are greatly influenced by the input machining variables. The level selection of machining parameters is challenging work for micromachining. For low machinability with higher mechanical properties material, micro-machining is extremely challenging research work.

In the last few years, researchers have attempted many hybrid techniques of electric discharge machining for processing the alloy materials. Further, to enhance the machining efficiency of the EDM technique, different hybrid machining processes such as rotary assisted EDM, gas-assisted EDM, ultrasonic-assisted, magnetic-assisted and powder mixed EDM have been incorporated in research work [58-61]. Among all the hybrid processes of WEDM, the more efficient machining process is powder mixed wire EDM, which provides better dimensional accuracy than conventional WEDM processes [62].

5.2. Motivation of the Problem

Therefore, many past investigations are carried on the WEDM process to enhance the MRR, kerf width, surface finish, and dimensional shift. However, little work has been performed on powder mixed wire EDM. No such investigation is carried out in the surfactant added PMWEDM process with considering the machining outputs such as surface roughness and corner inaccuracy in micron dimension. In the present investigation, a central composite RSM model has been developed to predict the interrelationship among the input variables of five-level with performance measures, i.e. surface roughness and corner inaccuracy for processing Ti6Al4V alloy. The adequacy of the predicted model has been checked by the ANOVA technique. Further, sensitivity analysis has been conducted to find out the most hazardous inputs which affecting on micro profile. Finally, a multi-objective optimization, namely genetic algorithm, has been used to determine the optimal input parameters to achieve the best output, i.e. surface roughness and corner inaccuracy.

5.3. Experimentation

Ti6Al4V alloy of a dimension of 200×27×4 mm^3 has been selected for making 90° corner profiles. All the experiments have been conducted using an Ezeecut Plus CNC wire electric discharge machine, which consists of three major axes: X, Y and Z. As per the experimental setup, a mixing chamber of powder with dielectric has been made for the machining purpose. Molybdenum wire of a dimension of 180 µm is used as electrode material. A schematic diagram of PMWEDM setup and corner profile during machining has been presented in Figure 5.2. The major input variable of B_4C powder concentration of a range of 2 g/L to 10 g/L adding with deionized water, including other parameters, is considered to achieve better dimensional accuracy during the PMWEDM process. Apart from that, surfactant (SPAN 20) is added with dielectric constant throughout the experiments. Surfactant is used for proper mixing powder with dielectric, which results in better output. The machining parameters are selected as pulse on time (ranges from 30 µs to 90 µs), pulse off time (ranges from 3 µs to 11 µs) and gap voltage (ranges from 40 V to 80 V). The selected input parameters are nominated in the present investigation by the pilot experiment and previous work already done on the domain of WEDM performances. The selection of input variables and their levels are shown in Table 5.1. A photographic view of PMWEDM has been illustrated in Figure 5.1.

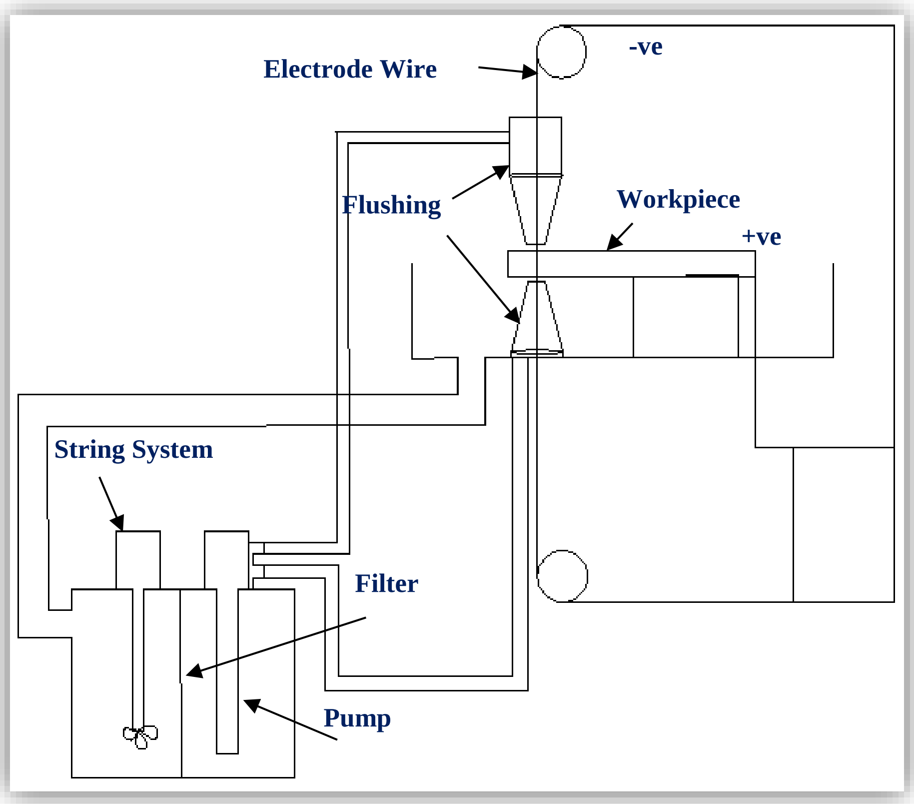


Figure 5.1. Schematic view of the experimental setup

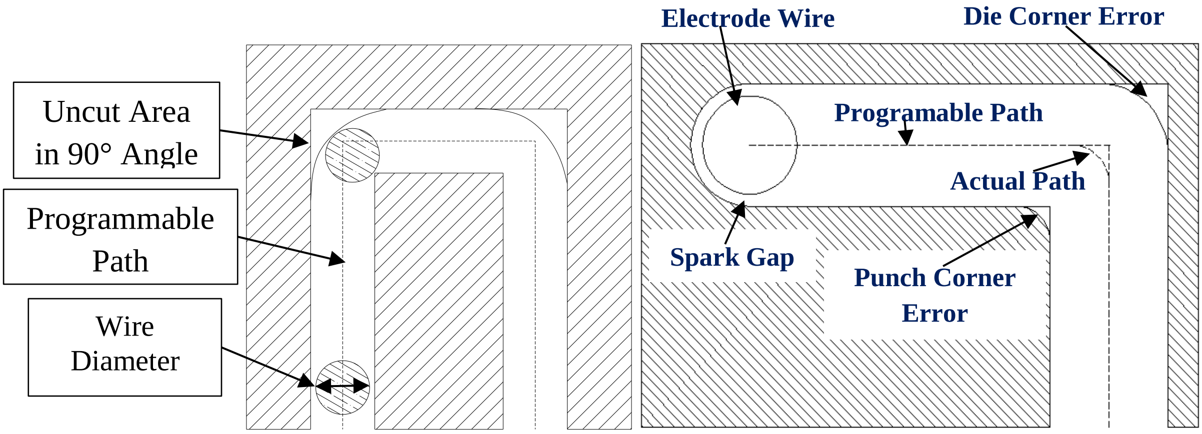


Figure 5.2. Details of the profile produced by the wire in WEDM process

5.4. Impact of Variable Input Parameters on Dimensional Accuracy

The experimental plan, modelling, and analysis have been carried out by response surface methodology (RSM). A set of Statistical and mathematical methods are used for solving the problem using the RSM technique [64]. In RSM, a second-order polynomial modelling equation is determined, which represents as in Equation (4.2).

Table 5.1. Obtained results from the experimentation

Run Order	T_{on}	T_{off}	GV	PC	SR (R_a)	CI
	X_1 (μs)	X_2 (μs)	X_3 (V)	X_4 (g/L)	Y_1 (μm)	Y_2 (μm^2)
1	60	7	60	6	3.185	17276
2	60	7	80	6	3.072	18862
3	90	7	60	6	3.085	19263
4	75	5	70	8	3.813	27871
5	60	7	60	6	3.676	17568
6	45	9	70	4	2.558	19434
7	75	9	70	4	2.732	17579
8	75	9	70	8	3.979	31262
9	45	5	50	4	2.463	18973
10	60	7	40	6	3.641	20643
11	45	9	50	4	2.689	20425
12	45	5	50	8	4.465	25748
13	60	7	60	6	3.163	17856
14	75	5	50	4	3.033	20815
15	60	7	60	6	3.144	17347
16	75	9	50	4	2.726	18334
17	30	7	60	6	2.474	19272
18	75	5	70	4	2.542	15287
19	60	11	60	6	3.239	26463
20	45	5	70	4	1.521	12837
21	60	7	60	6	3.165	17112
22	60	7	60	6	3.152	17579
23	60	3	60	6	2.848	22441
24	75	9	50	8	3.562	27592
25	60	7	60	10	4.863	38783
26	75	5	50	8	3.929	28738
27	45	5	70	8	3.114	23825
28	45	9	50	8	3.889	26735
29	45	9	70	8	3.828	29361
30	60	7	60	2	2.354	19159
31	60	7	60	6	3.154	17751

A total 31 number of experiment has been carried out by the full factorial central composite design method. The value of α has been considered as 2. Four inputs, including powder concentration and their five levels, were selected for the investigation as per the different pilot experiments. Design of experiment with the actual value of selected inputs have been depicted in Table 5.1.

All the experimental results are evaluated through the ANOVA test procedure and modelled for further analysis. There are four inputs, including powder concentration with their five levels, as presented in Table 5.1. Based on the 31 experimental designs and the obtained results, the RSM methodology establishes the empirical model. The main focus is to correlate the input variables with the response measures of surface roughness (Y_1) and corner inaccuracy (Y_2). The regression equations are shown in Equations (5.1) and (5.2), respectively.

$$\begin{aligned} Y_1 = {} & 5.21 + 0.0609\,X_1 - 0.042\,X_2 - 0.1831\,X_3 + 0.324\,X_4 - 0.000519\,X_1{*}X_1 - 0.01272\,X_2{*}X_2 \\ & + 0.000274\,X_3{*}X_3 + 0.02259\,X_4{*}X_4 - 0.00358\,X_1{*}X_2 + 0.000959\,X_1{*}X_3 - 0.00378\,X_1{*}X_4 \\ & + 0.00978\,X_2{*}X_3 - 0.0189\,X_2{*}X_4 + 0.00140\,X_3{*}X_4 \end{aligned} \tag{5.1}$$

$$\begin{aligned} Y_2 = {} & 116803 - 189.4\,X_1 - 7474\,X_2 - 1477\,X_3 - 10470\,X_4 + 1.736\,X_1{*}X_1 + 421.7\,X_2{*}X_2 \\ & + 5.119\,X_3{*}X_3 + 704.1\,X_4{*}X_4 - 26.07\,X_1{*}X_2 + 1.227\,X_1{*}X_3 + 19.68\,X_1{*}X_4 + 59.39\,X_2{*}X_3 \\ & + 14.2\,X_2{*}X_4 + 52.86\,X_3{*}X_4 \end{aligned} \tag{5.2}$$

5.4.1. Analysis of Variance (ANOVA)

After the selection of the model, individual terms and the whole model are tested using ANOVA analysis. The interaction of each parameter has been computed to identify the significance level. P values are computed to determine the significance level of each parameter. A limit value of P (≤ 0.05) has been considered for each response measure. Therefore, a lack-of-fit test is performed to check the adequacy of the present model. The ANOVA analysis results of surface roughness (SR) and corner inaccuracy (CI) have been presented in Tables 5.2 and 5.3. The ANOVA result shows that the p-value for the lack-of-fit of SR and CI is 0.704 and 0.023, respectively. These lack-of-fit result values indicate that the model is adequate for all responses. The goodness-of-fit values for R^2, R^2 (adj) and R^2 (pred) are closer to the value of 1. Thus, the ANOVA analysis result concludes that the desired criteria for SR and CI are satisfied and can be used for further analysis and optimization.

Table 5.2. Analysis of Variance for SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	13.1593	0.93995	30.28	0.000
Linear	4	10.9224	2.73061	87.95	0.000
Ton	1	0.3778	0.37776	12.17	0.003
Toff	1	0.1449	0.14493	4.67	0.046
GV	1	0.6039	0.60389	19.45	0.000
PC	1	9.7959	9.79587	315.52	0.000
Square	4	0.7988	0.19971	6.43	0.003
Ton*Ton	1	0.3906	0.39064	12.58	0.003
PC*PC	1	0.2335	0.23354	7.52	0.014
2-Way Interaction	6	1.4380	0.23967	7.72	0.001
Ton*Toff	1	0.1847	0.18469	5.95	0.027
Ton*GV	1	0.3309	0.33091	10.66	0.005
Ton*PC	1	0.2059	0.20589	6.63	0.020
Toff*GV	1	0.6127	0.61270	19.73	0.000
Error	16	0.4967	0.03105		
Lack-of-Fit	10	0.2680	0.02680	0.70	0.704
Pure Error	6	0.2288	0.03813		
Total	30	13.6560			

Table 5.3. Analysis of Variance for corner inaccuracy

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	943770604	67412186	243.86	0.000
Linear	4	604602168	151150542	546.78	0.000
Ton	1	4268954	4268954	15.44	0.001
Toff	1	25362816	25362816	91.75	0.000
GV	1	7555548	7555548	27.33	0.000
PC	1	567414851	567414851	2052.61	0.000
Square	4	282749084	70687271	255.71	0.000
Ton*Ton	1	4363763	4363763	15.79	0.001
Toff*Toff	1	81360207	81360207	294.32	0.000
GV*GV	1	7493066	7493066	27.11	0.000
PC*PC	1	226843547	226843547	820.60	0.000
2-Way Interaction	6	56419352	9403225	34.02	0.000
Ton*Toff	1	9790641	9790641	35.42	0.000
Ton*PC	1	5579044	5579044	20.18	0.000
Toff*GV	1	22572001	22572001	81.65	0.000
GV*PC	1	17884441	17884441	64.70	0.000
Error	16	4422973	276436		
Lack-of-Fit	10	3998260	399826	5.65	0.023
Pure Error	6	424714	70786		
Total	30	948193578			

5.4.2. Parametric Analysis

In the present investigation, the experimental result shows PMWEDM that the maximum and minimum surface roughness has been achieved with a value of 4.863 µm and 1.521 µm, respectively. At the same time, the maximum and minimum corner inaccuracy has been achieved as a dimension of 38783 μm^2 and 12837 $\mu m^{2,}$ respectively. Lower powder concentration (4 g/L) combined with the middle range of gap voltage (60 V) provides maximum surface finish and minimum corner inaccuracy. A higher or lower value of powder concentration has produced more elevated surface roughness and corner inaccuracy. Pulse intensity also involves in changing all the responses. Higher pulse on time increases the amount of thermal discharge energy, whereas lower pulse off time increases the spark frequency. Due to this, a large melting point and shortage timing for removing the debris is generated in the gap zone. As a result, a reduction of surface finish is found. Powder particle mixed with dielectric helps to minimize the micro corner error by decreasing the dielectric strength and initiating a continuous spark on a point. Thus, powder with deionized water followed by machining inputs provides a better control strategy to get the best micro dimensional accuracy in the PMWEDM process.

5.4.3. Analysis of Sensitivity

The sensitivity analysis is performed in order to explore the contribution of machining input to the performance measure of the different samples carried out in the research study. Sensitivity analysis has a critical importance for a system design [65]. It is performed by partial derivatives of the objective function concerning its design variables. Y_1 and Y_2 in Equations (5.1) and (5.2) represent the quadratic equation for surface roughness and corner inaccuracy. To evaluate the relative sensitivity of each factor, equations Y_1 and Y_2 are differentiated to input variables, e.g., $\frac{\partial Y_1}{\partial X_1}$ in equation (5.3) is the differential form of Equation (5.1) for pulse on time on surface roughness. The sensitivity of pulse on time on surface roughness has been carried out with different selected parametric levels (i.e., 30 µs, 45 µs, 60 µs, 75 µs and 90 µs) along with the middle value of other parameters. The sensitivity of surface roughness for pulse on time, pulse off time, gap voltage and powder concentration is presented in Equations (5.3), (5.4), (5.5), (5.6), respectively.

$$\frac{\partial Y_1}{\partial X_1} = 0.0609 - 0.000519\, X_1 - 0.00358\, X_2 + 0.000959\, X_3 - 0.00378\, X_4 \quad (5.3)$$

$$\frac{\partial Y_1}{\partial X_2} = - 0.042 - 0.01272\, X_2 - 0.00358\, X_1 + 0.00978\, X_3 - 0.0189\, X_4 \quad (5.4)$$

$$\frac{\partial Y_1}{\partial X_3} = -\ 0.1831 + 0.000274\ X_3\ + 0.000959\ X_1 + 0.00978\ X_2 + 0.00140\ X_4 \qquad (5.5)$$

$$\frac{\partial Y_1}{\partial X_4} = 0.324 + 0.02259\ X_4 - 0.00378\ X_1 - 0.0189\ X_2 + 0.00140\ X_3 \qquad (5.6)$$

The proposed Equation in (5.7), (5.8), (5.9), (5.10) represents the sensitivity of corner inaccuracy for pulse on time, pulse off time, gap voltage and powder concentration, respectively.

$$\frac{\partial Y_2}{\partial X_1} = -\ 189.4 + 1.736\ X_1 - 26.07X_2 + 1.227X_3 + 19.68\ X_4 \qquad (5.7)$$

$$\frac{\partial Y_2}{\partial X_2} = -\ 7474 + 421.7\ X_2 - 26.07X_1 + 59.39X_3 + 14.2\ X_4 \qquad (5.8)$$

$$\frac{\partial Y_2}{\partial X_3} = -\ 1477 + 5.119X_3 + 1.227X_1 + 59.39\ X_2 + 52.86\ X_4 \qquad (5.9)$$

$$\frac{\partial Y_2}{\partial X_4} = -\ 10470 + 704.1X_4 + 19.68\ X_1 + 14.2\ X_2 + 52.86\ X_3 \qquad (5.10)$$

5.4.4. Sensitivity Analysis of Pulse on Time for PMWEDM Performances

During sensitivity calculation of pulse on time for PMWEDM performances, the input parameters of pulse off time of 7 µs, gap voltage of 60 V and powder concentration of 6 g/L are taken as constant. The graphical representation of sensitivity analysis of pulse on time on surface roughness and corner inaccuracy has been illustrated in Figure 5.3. It is clearly seen in Figure 5.3 that the sensitivity of surface roughness on pulse on time is a positive value. In comparison, the sensitivity of corner inaccuracy is observed to be a negative value.

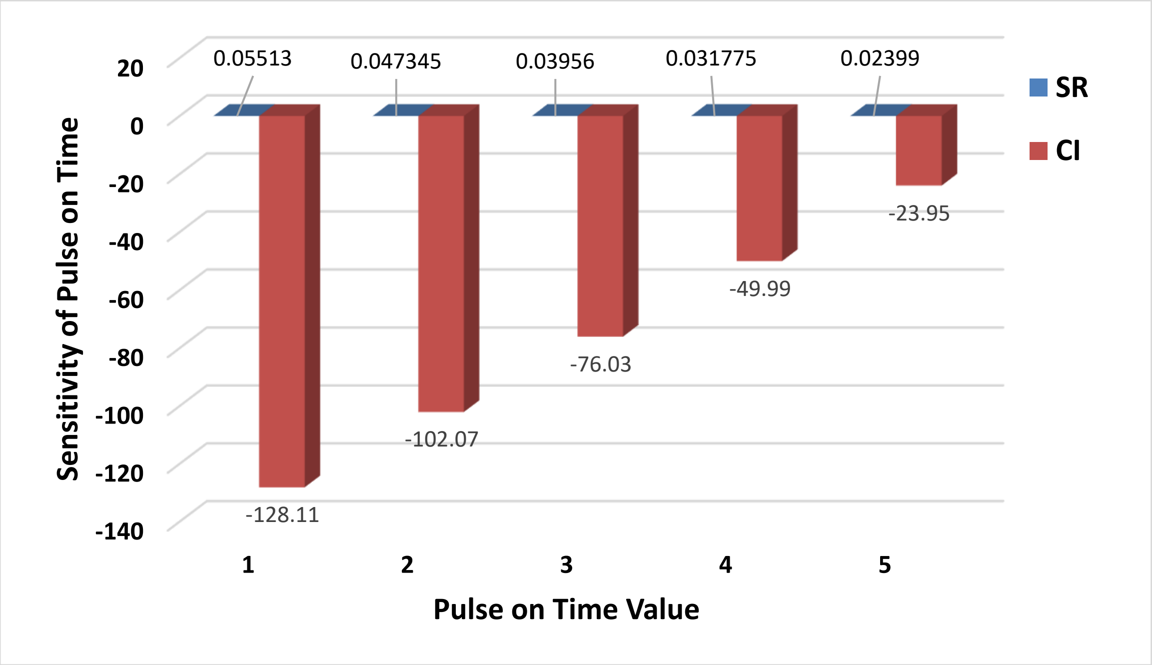


Figure 5.3. Sensitivity analysis of pulse on time for surface roughness and corner inaccuracy

Therefore, with an increase in pulse on time, the surface roughness is significantly increasing. Higher pulse on time leads to a higher amount of ions generation, which causes higher motion in the gap zone. Due to that, the kinetic energy of more ions is converted into higher thermal energy leading to more material erosion from the workpiece. At the same time, the pressure energy is also higher with the increase in pulse on time at a moderate gap voltage of 60 volts. Due to the short interval of time, the debris particles are attached to the machined surface. It is also creating large massive craters and voids that result in higher surface roughness. Lower pulse on time leads to a higher surface finish. The control of current flow per cycle is executed by controlling the pulse on time. In the PMWEDM process, proper selection of pulse on time is very much essential for better surface topography.

In the graph of sensitivity analysis of corner inaccuracy on pulse on time, it is clear that lower pulse setting is required to achieve a lower material removal rate at the corner portion because of dimensional shift. During corner cutting, the path of the wire is always shifted from its original programmable path. On the other hand, a higher pulse on time leads to a high amount of intense bubble creation in the gap zone. Due to this, a large amount of wire deflection is produced; as a result, the trend of corner inaccuracy is increasing manner.

5.4.5. Sensitivity Analysis of Pulse off Time for PMWEDM Performances

Figure 5.4 illustrates the sensitivity of pulse off time on micro profile processing, i.e. surface roughness and corner inaccuracy. During sensitivity computation, the input parameters of pulse on time of 60 µs, gap voltage of 60 V and powder concentration of 6 g/L are considered as constant inputs. The sensitivity of pulse off time is positive for surface roughness and negative for corner inaccuracy. Therefore, the sensitivity of surface roughness on pulse off time is higher than the sensitiveness of corner inaccuracy. With an increment in pulse off time, both the response surface roughness and corner inaccuracy tend to increase. Higher pulse off time leads to a decrease in spark frequency that minimizes the creation of gas exploration. When pulse off time increases up to 9µs, the surface roughness marginally decreases. At the same time, corner inaccuracy also reduces. This is due to the time availability for flushing away the eroded material from the gap zone during machining. Thus machine stability can be improved, which is very essential in corner profile generation. At the time of micro corner processing, a prolonged machining rate is required at the corner section. Higher pulse off time results in a higher cooling effect and higher flushing rate, decreasing the metal removal rate. Due to this, the dimensional shift becomes lesser using a specific limit of pulse off time value, resulting in lower corner inaccuracy. Moreover, the maximum pulse off time value leads to higher profile inaccuracy.

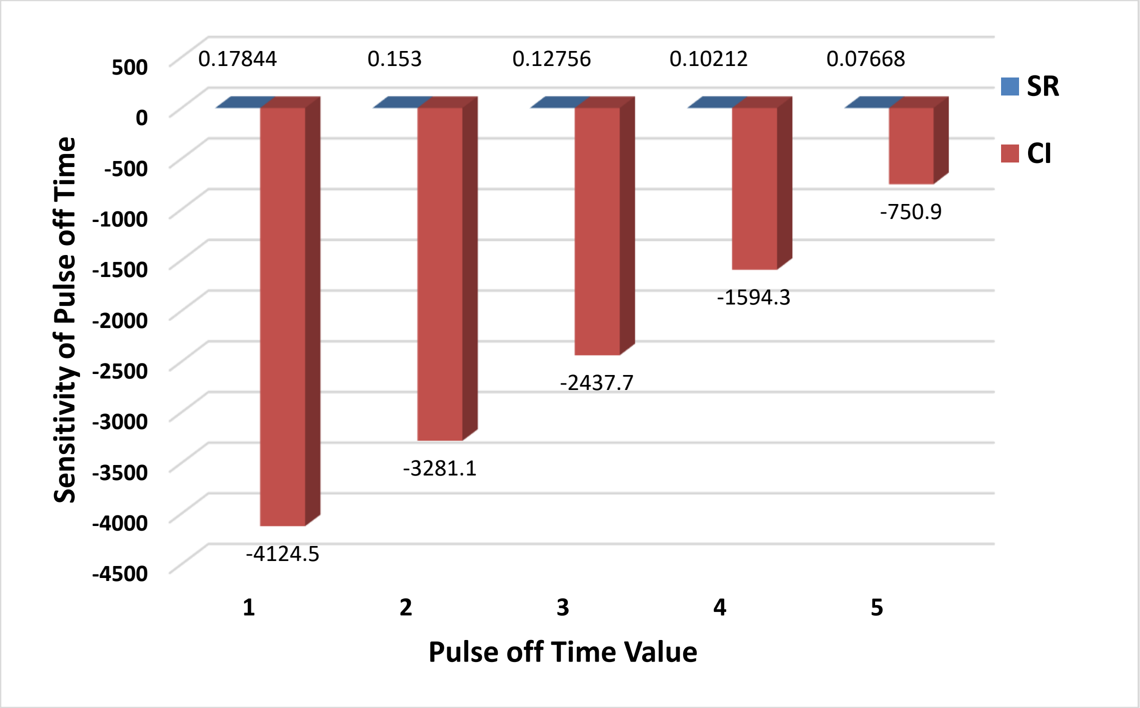


Figure 5.4. Sensitivity analysis of pulse off time for surface roughness and corner inaccuracy

5.4.6. Sensitivity Analysis of Gap Voltage for PMWEDM Performances

Figure 5.5 illustrates the sensitivity analysis of gap voltage for PMWEDM performance criteria such as surface roughness and corner inaccuracy. Other selected constant parameters are Pulse on time of 60 µs, pulse off time of 7 µs and powder concentration of 6 g/L. The value of sensitivity of gap voltage is minimal and negative, as in Figure 5.5. It is clearly seen in Figure 5.5 that corner inaccuracy gradually increases with an increase in gap voltage due to high discharge energy. From the experimentation, up to 70 V of gap voltage, both responses show a better result. Material removal rate tremendously increases by higher erosive power. Higher discharge energy increases the arc discharge; as a result, the insulating circumstance in the narrowest gap zone is very much affected. Due to this high amount of wire vibration occurs, which is directly involved in increasing corner inaccuracy. The surface roughness marginally increases with an increase in gap voltage. A higher metal removal rate with an incremental gap voltage leads to increased surface roughness. This is due to high spark energy, resulting in large explosive forces strike on the machining surface. Therefore, both the response measures are increased with an increase in gap voltage.

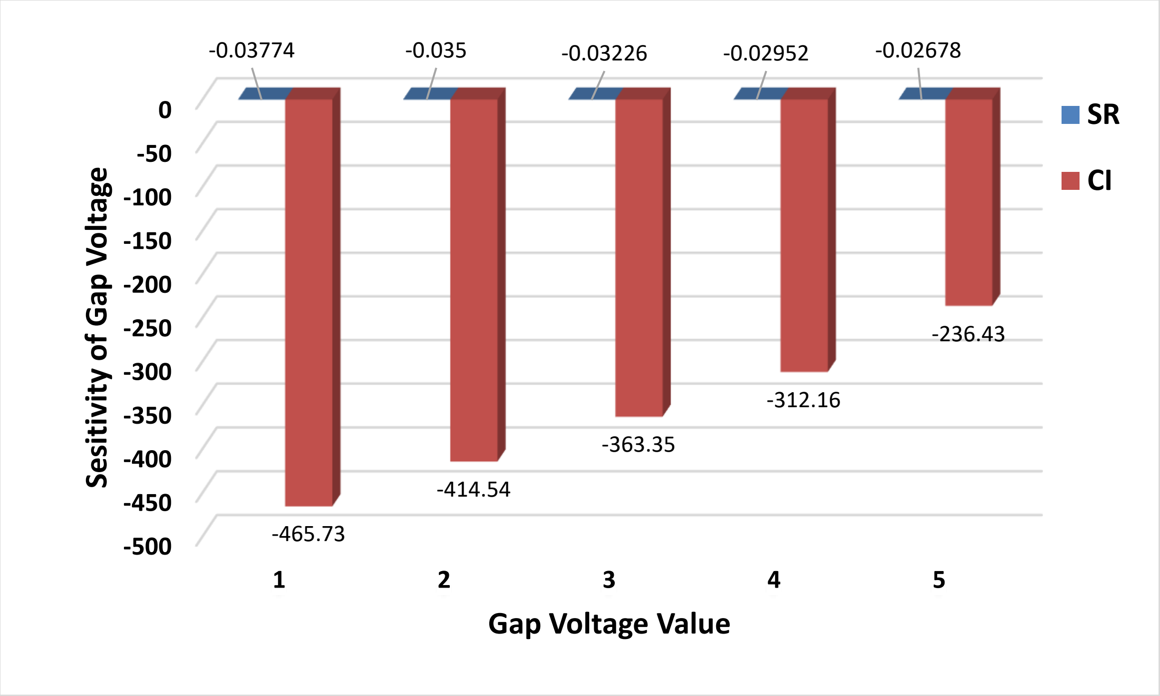


Figure 5.5. Sensitivity analysis of gap voltage for surface roughness and corner inaccuracy

5.4.7. Sensitivity Analysis of Powder Concentration for PMWEDM Performances

Figure 5.6 illustrates the sensitivity of powder concentration in dielectric on micro profile processing, i.e. surface roughness and corner inaccuracy. During sensitivity computation, the input parameters of pulse on time of 60 µs, pulse on time of 7 µs, gap voltage of 60 V are considered as constant inputs. The sensitivity of surface roughness and corner inaccuracy is very high on powder concentration in the dielectric. In comparison with other machining parameters, the sensitivity impact of both responses on powder concentration is maximum. The sensitivity of surface roughness is positive, whereas the first four levels are negative, and the fifth level is positive for corner inaccuracy.

With the increment of B_4C powder concentration from 2 g/L to 6 g/L, the surface roughness is decreased. Above 6 g/L value, surface roughness is increased. During machining, suspended powder in dielectric breakdowns the insulation. Thus, dielectric resistivity becomes poor, and the discharge gap rises. As a result, an explosive force from the plasma channel tends to reduce. Due to the increase in discharge gap, a large amount of heat is transferred from job to electrode, resulting increase in MRR. At the same time, machined surfaces are produced with smaller craters, less voids, and uneven eroded particles, proving the surface roughness reduction.

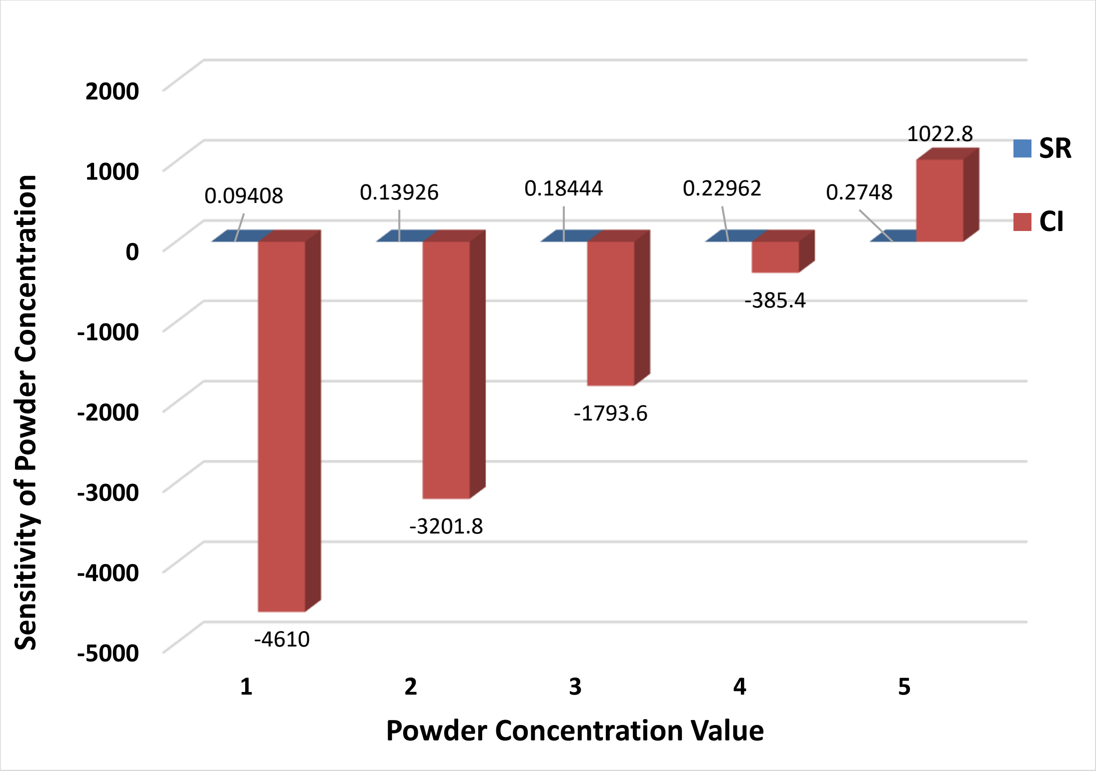


Figure 5.6. Sensitivity analysis of powder concentration for surface roughness and corner inaccuracy

5.5. Multi-objective Optimization of PMWEDM

Multi objective optimization has been carried out in the present investigation to find out the optimal solution using genetic algorithm (GA). The genetic algorithm is an exploratory search based algorithm, which imitates the natural evaluation. GA optimization has been performed by MATLAB software. The first step in GA is to create the initial population which is based on the combined set of chromosomes. By the fitness function, each of the individual chromosomes is evaluated. Then the ranking order of individuals is established. For the next generation, few numbers of maximum fitness value of individuals are considered. The remaining individuals are nourished by crossover and mutation. Fitness evaluation to the last step has to apply repeatedly until the solution is reached to the final stage [66]. The minimized multi-objective problem for both the responses, i.e. surface roughness and corner inaccuracy, are subjected to the following parametric settings:

Subjected to: $30 \leq \text{Ton} \leq 90$
$3 \leq \text{Toff} \leq 11$
$40 \leq \text{GV} \leq 80$
$2 \leq \text{PC} \leq 10$

Table 5.4. Input parameter setting for GA

Tuning Parameter settings	Selective values
Population type	Double vector
Population size	200
Creation function	Uniform
Crossover fraction	0.8
Selection function	Tournament
Tournament size	2
Mutation function	Adaptive feasible
Maximum generation	100
Selection	Stochastic uniform
Crossover function	Scattered
Migration direction	Forward

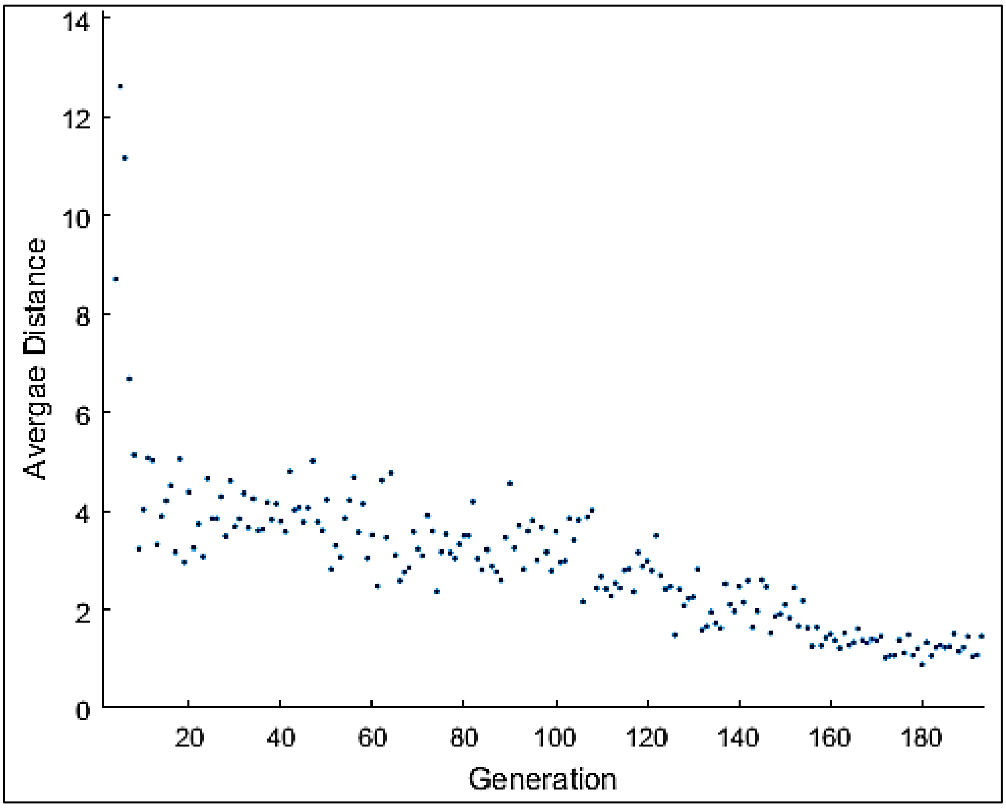


Figure 5.7. The graphical view between average distance and generation in GA

Table number 5.4 represents the parameters setting during the process of GA optimization. The GA results show that the diversity of the population is very low because of the lower value of the average distance between the individuals. Figure 5.7 illustrates the graphical view between the average distance of individuals and generation. It is clear that the GA has performed well and is suitable for measuring the right amount of population diversity. The Pareto front generated by using MATLAB has been displayed in Figure 5.8. The Figure suggests that an appropriate solution for the present study is found for two objectives, i.e. surface roughness ≈1.199 µm and corner inaccuracy ≈12982.67 µm^2. The outcome has been found as an optimal parametric setting by the GA optimization such as pulse on time (Ton) of 30.23 µs, pulse off time (Toff) of 3.02 µs, gap voltage(GV) of 79.99 V and powder concentration (PC) of 3.01 g/L. Lastly, a confirmation test was conducted with this optimal setting and checked the adequacy of the result data compared with predicted values.

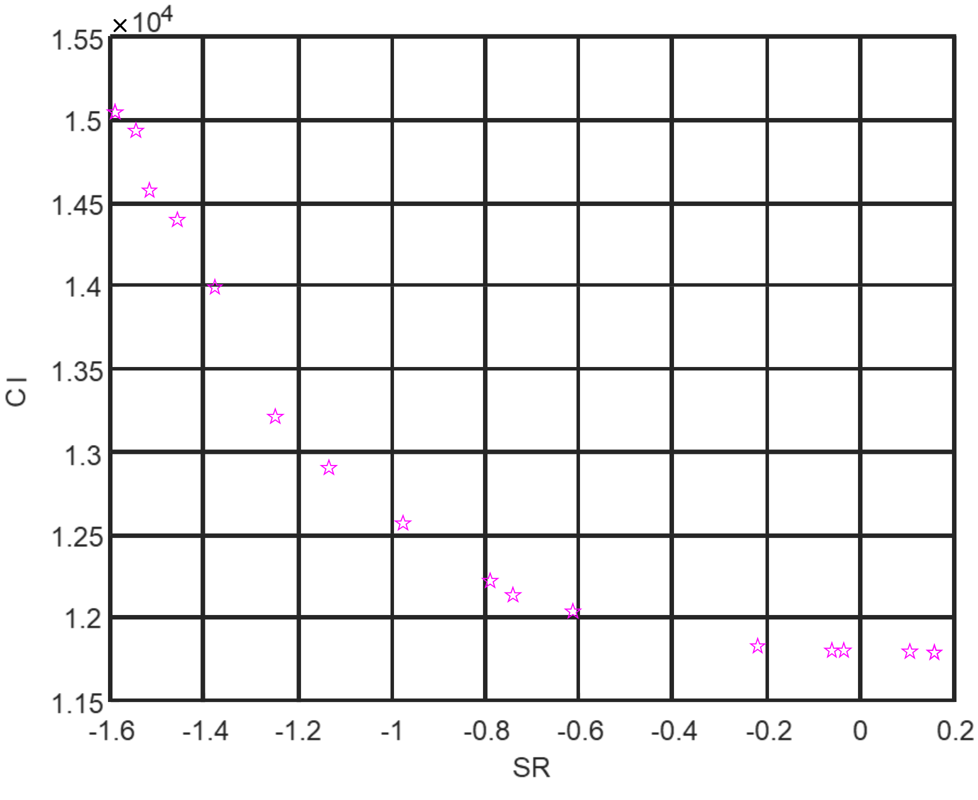


Figure 5.8. Pareto front generated by MATLAB software

A total of five experiments in the confirmation test have been performed using the optimal parametric setting. The mean result from the experimental values is taken as the final obtained value, as in Table 5.5. Also, a separate experiment has been carried out without powder, whereas the other optimal input settings are fixed. It is revealed that powder mixed WEDM shows a higher degree of dimensional accuracies, such as surface finish and corner accuracy. The error has been found for SR and CI from the obtained result, i.e. 3.46% and

4.14%, respectively. Therefore, the confirmation test results have established a good agreement between prediction and experimental value. Also, the PMWEDM process can increase surface finish of 50.77% and corner accuracy of 23.01% compared with the conventional WEDM process. Due to this, a hybrid process, namely PMWEDM, is highly applicable for micro geometry processing. The pictorial view of the corner profile as in Figure 5.9 shows that a value of 10190.81µm^2 is present as the actual corner error at optimum condition.

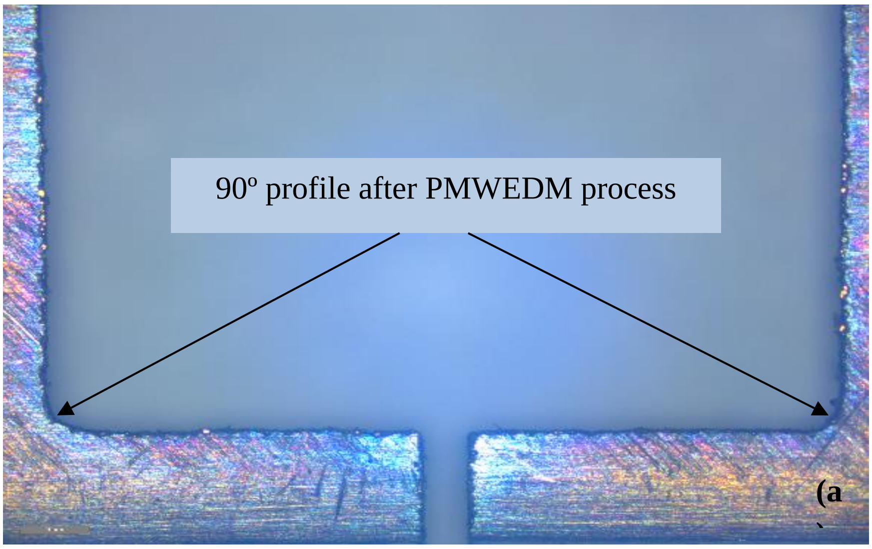


Figure 5.9. (a) Pictorial view of 90º corner profile at the optimum condition (Ton = 30.23 µs, Toff = 3.02 µs, GV = 79.99 V and PC = 3.01 g/L)

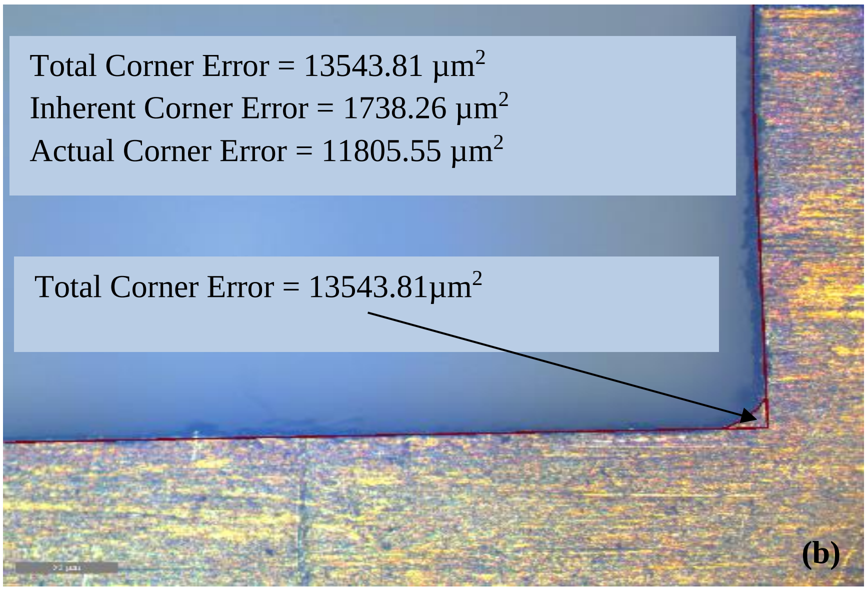


Figure 5.9. (b) The detail dimension of corner profile at the optimum condition (Ton = 30.23 µs, Toff = 3.02 µs, GV = 79.99 V and PC = 3.01 g/L)

With the help of the optimum machining control setting, confirmation experiments were conducted with powder and without powder mixed in the dielectric. It is seen that better kerf width is generated in the PMWEDM process, as shown in Figure 5.10. In terms of surface topography, the SEM image for the machining surface of PMWEDM shows an improvement in surface texture compared to the simple WEDM process, as in Figure 5.11.

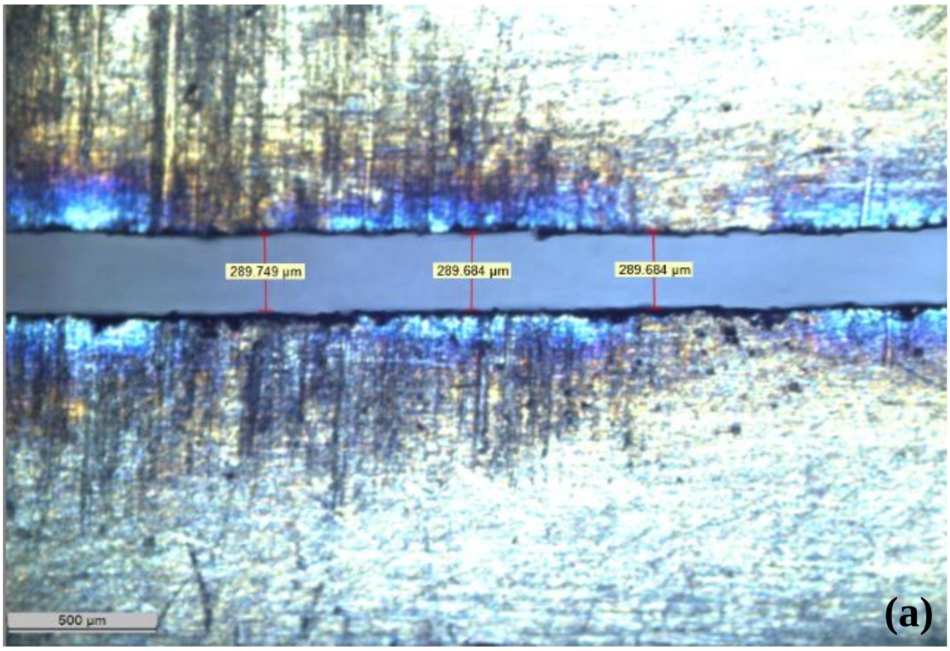


Figure 5.10. (a) Pictorial view of kerf width at optimum condition (Ton = 30.23 µs, Toff = 3.02 µs, GV = 79.99 V) with powder (PC = 3.01 g/L)

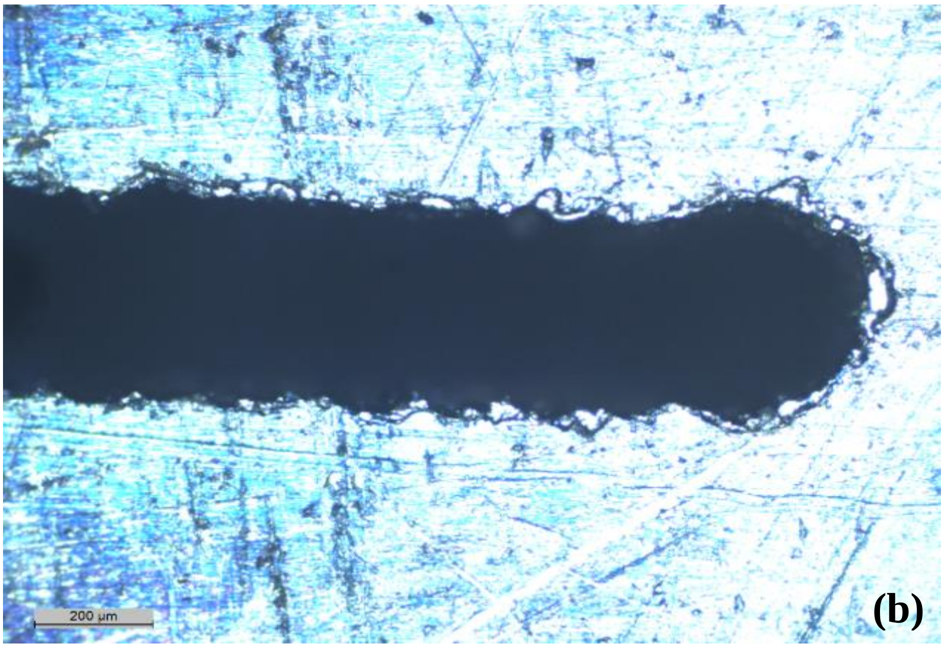


Figure 5.10. (b) Pictorial view of kerf width at optimum condition (Ton = 30.23 µs, Toff = 3.02 µs, GV = 79.99 V) without powder

The presence of cracks, void, globule, and recast layer with uneven surface texture displays the damage to the machined profile. In Figure 5.11 (a), poor surface quality is seen by using the conventional WEDM process. This is due to the high intensity of the spark discharge. In case of powder mixed WEDM, the discharge intensity is reduced due to increase in spark gap; as a result, a refinement on the machined surface is established.

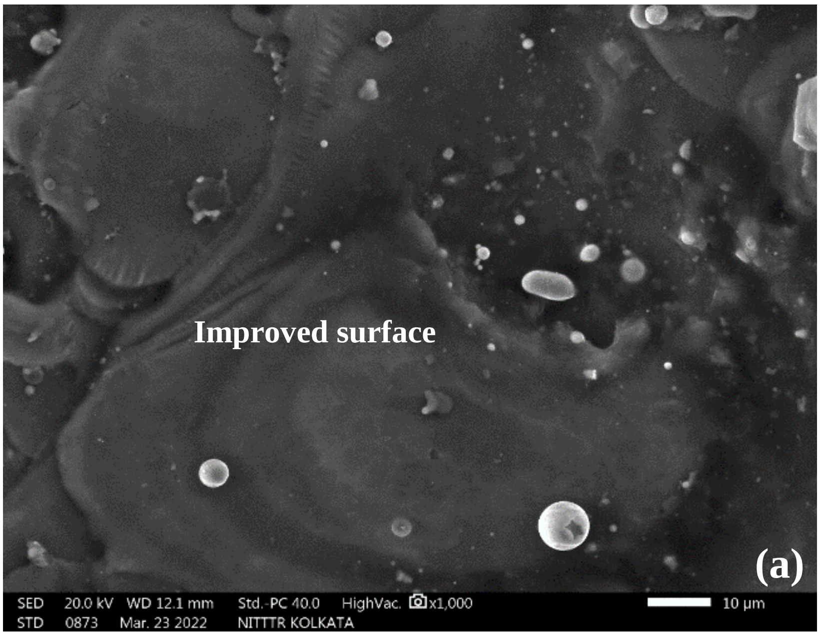


Figure 5.11. (a) SEM image of machined surface at (Ton = 30.23 µs, Toff = 3.02 µs, GV = 79.99 V) with powder (PC = 3.01 g/L)

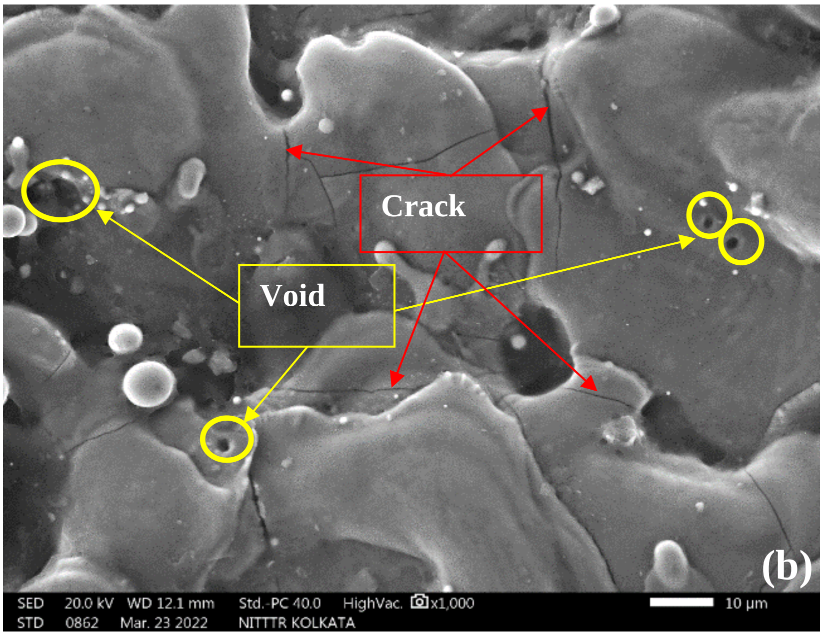


Figure 5.11. (b) SEM image of machined surface at (Ton = 30.23 µs, Toff = 3.02 µs, GV = 79.99 V) without powder

Table 5. Confirmation test

Input parameter		SR			CI		
		Predicted	Experimental	Error	Predicted	Experimental	Error
With powder	(Ton) 30.23 µs (Toff) 3.02 µs (GV) 79.99V (PC) 3.01 g/L	1.199	1.242	3.46%	12982.67	13543.81	4.14%
Without powder	(Ton) 30.23 µs (Toff) 3.02 µs (GV) 79.99V		2.523			17593.45	

5.6. Research Outcome from the Modular Experiment

In the present investigation, a parameters control strategy has been utilized for analyzing the performance efficiency of Ti6Al4V material during micro geometry processing. A hybrid technique, namely PMWEDM, is used for machining the material. The highest contribution of input variables has been determined through sensitivity analysis. Finally, multi-objective optimization is carried out to achieve the best optimal surface finish and corner accuracy. From the obtained results and analyzing data, the following conclusions were made:

1. Surfactant added PMWEDM plays an important role in micro geometry creation. Here, a surfactant used for proper amalgamation of powder with dielectric so that the continuous spark improved machining efficiency,
2. Achievable corner accuracy and surface finish have been determined by using the hybrid technique.
3. The experimental result shows a good agreement with predated results for SR and CI. The predicted mathematical model is perfectly validated through ANOVA analysis.
4. Sensitivity analysis reveals that powder concentration is the highest sensible parameter compared to other micro geometry processing parameters in PMWEDM. Moreover, pulse on time, pulse off time and powder concentration have contributed to positive sensitivity to surface roughness, whereas only powder concentration has contributed to positive sensitivity on corner inaccuracy.

5. The outcome of the multi-objective optimization is achieved, such as surface roughness ≈1.199 µm and corner inaccuracy ≈12982.67 µm^2. The optimal parametric settings are pulse on time of 30.23 µs, pulse off time of 3.02 µs, gap voltage of 79.99V and powder concentration of 3.01 g/L.
6. The error for both the responses is seen below 5%, which conveys the decent adequacy of the predicted result. Therefore, the improvement of the PMWEDM process is found to be 50.77% of surface finish and 23.01% of corner accuracy compared with the conventional WEDM process
7. SEM figure highlights an enhancement in machined surface geometry in the presence of powder in dielectric fluid.

CHAPTER: 6

GENERAL CONCLUSIONS & FUTURE SCOPE OF RESEARCH

6.1. General Conclusions

Due to the complexity of the process behaviour of powder mixed WEDM, manufacturing of intricate shapes with high precision is a challenging task. The interaction of plenty process parameters makes the process more complicated. As of now, little research has been done on powder mixed WEDM to find the suitable powder and its properties and dielectric, which will vary with material types. The present research is focused on the PMWEDM for machining the Ti6Al4V. An extensive experimental study has been carried out to find dielectric and powder properties by considering of the machine other electrical and mechanical properties. In this investigation, machining inputs are analysed and optimized with a unique approach to characterize better outputs of dielectric fluid consumption, MRR, SR, and corner accuracy. In terms of dimensional accuracy, corner inaccuracy is quantified by the uncut area between the actual profile and the programmable profile. The sensitivity of all inputs along with powder characteristics has been explored in the study. Based on the experimental observation, subsequent modelling, analysis and optimization of powder mixed WEDM, the following conclusions are drawn:

(i) In the present investigation, the machining inputs such as peak current, pulse-on-time, pulse-off-time, gap voltage, dielectric fluid type, fluid level and additive powder type, concentration and size are considered for conducting the WEDM process. Powder properties such as type, size and concentration are not machine controllable parameters rather it is mixed with the dielectric in the fluid chamber to understand their influences on responses. The response measures, namely material removal rate, dielectric consumption, surface roughness and corner accuracy were successfully modelled. Moreover, the recent innovation of powder mixed with dielectric technique in wire EDM has been successfully adopted in this investigation, and the process significantly improves process efficiency.

(ii) Based on the experimental observation and the parametric analysis using OFAT, it is revealed that B_4C and Al_2O_3 powder has a higher impact on responses measure. The size of powder 10µm influences more on SR and MRR. As considered to the various dielectric, kerosene has a slightly higher impact on responses. Due to certain drawbacks of kerosene, a carbon layer formation on machine surface and toxic vapour emission during machining create a fire hazard, deionized water is preferred in this investigation. The subsequent enhancement of the process involves incorporating a surfactant into PMWEDM. The outcomes reveal that the surfactant plays a beneficial role in augmenting the modified plasma channel by effectively blending the powder within the dielectric material. Hazard and operability study is demostrated for superior quality product, lower product cost, safety features, and environmental contamination during WEDM process.

(iii) Dielectric fluid consumption of the PMWEDM process is highly dependent on the fluid level. The major machine controllable inputs such as peak current, pulse on time, pulse off time are influenced more on surface roughness and machining rate. Gap voltage shows an average effect on both the responses. The continuous variation of output measure with respect to different control settings and powder properties shows that the analysis and optimization are conflicting in nature for these performance variables simultaneously. Therefore, incorporating multi-objective optimisation techniques is necessary for this study.

(iv) The complicated process behaviour of PMWEDM is analysed by response surface methodology and optimized by a hybrid technique of GRA-particle swarm optimization. Based on the face-centred central composite design (CCD) method in RSM, a total of 30 experiments are carried out to predict a quadratic model for further analysis. The multi-objective optimisation shows that the GRA-PSO technique has the highest adequate capability to predict the best responses compared to other techniques.

(v) The maximum MRR and surface finish for Ti6Al4V alloy can be obtained using 10 µm average size of Al_2O_3 abrasive powder properties at a concentration of 4 g/L when the consistency of discharge energy is appropriately matched and the recast layer on machined surface significantly less.

(vi) From the analysis it is proved that increasing trends of pulse on time, peak current and pulse off time leads to higher discharge energy and adequate time for removing eroded particles from gap as the process provides a result of higher MRR at that condition. The combination effect of pulse on time, peak current and powder concentration impact more on MRR. The maximum surface finish can be obtained by low pulse setting and high peak current with little sacrifice with MRR. The impact of I_p followed by PC, T_{on} followed by PC and T_{off} followed by PC have nearly the same on the machine surface characteristics.

(vii) Corner inaccuracy is the major drawback in the wire electric discharge machining due to the use of the circular shape of wire. A parametric control strategy is used to improve corner error (especially die corner inaccuracy) during powder mixed micro WEDM process and to predict a model to determine the best output, such as die corner accuracy and surface roughness.

(viii) Surfactant added PMWEDM plays a vital role in micro dimensional accuracy. Due to the proper amalgamation of powder with dielectric, a continuous spark is generated in the machining gap, breaking the insulation. Thus, dielectric resistivity becomes poor, and the discharge gap rises. As a result, the explosive force from the plasma channel tends to reduce. With the increase in discharge gap, a better continuous discharge form results in improved corner accuracy. The sensitivity analysis has been utilized to determine the highest contribution of input variables. The experimental results agree well with predated SR and CI results. The predicted mathematical model is ideally validated through ANOVA analysis.

(ix) Sensitivity analysis reveals that powder concentration is the highest sensible parameter compared to other micro geometry processing parameters in PMWEDM. Moreover, pulse on time, pulse off time and powder concentration have contributed to a positive sensitivity to surface roughness. In contrast, only powder concentration has contributed to positive sensitivity on corner inaccuracy. The parametric modification strategy obtains a lower corner accuracy of 17593.45 μm^2 using the conventional WEDM method. Using powder with a dielectric WEDM process provided a better corner accuracy of 13543.81µm^2. Thus the improvement of the PMWEDM process is found to be 23.01% in corner accuracy compared with the conventional WEDM process. Also, the improvement of 50.77% of surface finish is seen during the hybrid process

(x) The characteristic features of the machined surface of Ti6Al4V have been studied through the scanning electron microscope under the optimal machining setting. This reveals that powder mixed WEDM surfaces show smaller size craters, less voids, and unevenly eroded particles. Whereas micro-cracks, multiple numbers of void and recast layers on the machining surface are found during the WEDM process. Hence powder mixed WEDM technology is highly recommended for precision job processing.

It is expected that the present research will open new insight into the fundamental and applied research on wire EDM. It is a fruitful technology for efficient product development and is helpful to the advanced manufacturing industry. Also, the effort can be used to analyse plenty of machining settings for the best outputs comprehensively.

6.2. Scope of Future Work

. The scope of the future research includes:

I. The domain of the WEDM process can encompass an experimental study involving diverse metal and non-metal powders in the dielectric. This experimentation comprises the use of nanopowders such as B4C, SiC, Al2O3, along with metal powders like Cu, Al, Si, and graphite. The objective is to explore their potential application in micro-manufacturing through the WEDM process.

II. The study of machined surface topography and path modification strategies with hybrid techniques can be included in future work by considering different significant machining parameters. Other dielectrics such as natural oils with different powders can be applied for harmless operation towards environmentally conscious production.

III. Investigation can be done on changing the electrode polarity to acheive better output responses.

IV. A detailed analysis can be incorporated of surface characteristics of the machined samples, such as surface topography, microhardness, crack growdth fatigue strenght.

V. Use of various optimization techniques to understand the process efficiently.

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Performance characterization of powder mixed wire electrical discharge machining technique for processing of Ti6Al4V alloy

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Abstract

Precision machining characteristics with high-dimensional accuracy make the material more adaptable towards the applications. The present study employs the powder mixed wire electrical discharge machining process to machine Ti6Al4V alloy material. In spite of limited drawbacks and enhanced output in the powder mixed wire electrical discharge machining process, the present problem has been formulated for improving the machining efficiency of Ti6Al4V. The impact of suspended powder characteristics on responses, that is, material removal rate and surface roughness, is examined throughout the process. The current investigation also focuses on the interaction effect of machining constraints along with Al_2O_3 abrasive mixed dielectric to achieve economical machining output for the Ti6Al4V material. An effort has been presented to obtain optimal solutions using the different methodologies, namely response surface methodology, grey relation analysis, and particle swarm optimization. The study reveals that discharge energy is deeply influenced by the peak current and pulse off time followed by powder concentration in the powder mixed wire electrical discharge machining process. The maximum material removal rate of 6.628 mm^3/min and average surface finish of 1.386 μm are the outcome of the present study for a set of optimal machining settings, that is, pulse off time (T_{off}) of 7.247 μs, pulse on time (T_{on}) of 30 μs, peak current (I_p) of 2 A, and powder concentration of 4 g/L. Finally, the proposed model has been verified that the hybrid particle swarm optimization technique has the highest adequate capability to achieve maximum output. Thus, the approach offered an enhancement on performance measures of Ti6Al4V alloy in the powder mixed wire electrical discharge machining process.

Keywords

Powder mixed wire electrical discharge machining, Ti6Al4V, material removal rate, surface roughness, response surface methodology, particle swarm optimization-grey relation analysis

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Introduction

Since the last decade, the most active research field is the machining characteristics of advanced alloy material because of their massive demand and hazard issues associated with their machining criteria.[1,2] Ti6Al4V alloy is primarily used to manufacture biomedical parts and aerospace components due to its outstanding mechanical properties. Machining of Ti6Al4V is an immensely challenging task as it attributes high temperatures during the conventional method. The necessity of the non-conventional process becomes an appropriate alternate solution for the machining of this low conductive material. Wire electrical discharge machining is the best choice for through cutting operation of complex shapes profile with high accuracy.[3] In wire electrical discharge machining (WEDM), the performance depends on the substance of the thin wire (ϕ 50–300 μm).[4] Due to the spark discharge by the high pulse frequency, materials are removed from the interelectrode gap and shape the material.[5] Therefore, the WEDM process has quite limitations during operation despite excellent machining capabilities, such as low material removal rate (MRR) and poor surface finish.

The limitations of the electrothermal process are overcome by applying several hybrid techniques. Electrical discharge surface grinding and high-speed EDM drilling are examples of hybrid machining processes where one conventional and one spark erosion process is involved.[6,7] A recent approach termed powder mixed wire EDM (PMWEDM) has been introduced in existing research work where conductive or non-conductive powders are

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Optimisation of machining performance in PMWEDM of titanium alloy using the hybrid technique (GRA-PCA)

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ABSTRACT
Ti6Al4V plays a prominent role in manufacturing component production due to tremendous mechanical and engineering properties. The present investigation focuses on the impact of machining input constraints and the advancement of robust optimisation technique during powder-mixed wire electric discharge machining (PMWEDM) of Ti6Al4V alloy. The machining inputs are figured out for experimentation such as pulse on time (Ton), pulse off time (Toff), peak current (Ip), gap voltage (GV), and powder concentration (PC) based on preliminary observation and existing research work on that area. Another attention is to reach the optimal value of the metal removal rate, surface roughness, and cutting speed. A comparative study is executed between GRA and GRA-PCA in the present research work. It is found that GRA-PCA has an adequate capability of 23.04% larger than the GRA technique. ANOVA analysis is revealed that powder concentration and pulse on time are the most significant parameter whereas pulse off time and gap voltage are the significant parameter for surface roughness. Therefore, the confirmation test is validated through experimentation and surface topography analysis.

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PMWEDM; B_4C; Ti6AL4V; GRA-PCA; Taguchi L_{27}

1. Introduction

Due to broad application in manufacturing sectors, electric discharge machining has become a widespread non-traditional method for machining of technically advanced materials. EDM process is commonly known as the spark erosion process where the discharge energy generates a series of spark. The material removal mechanism is continuously occurred by exploiting spark energy using thermoelectric decomposition of dielectric in the EDM process [1,2]. It can easily be machined with complex shapes by the EDM process of any conductive material even though their superior toughness, hardness, and corrosion resistance [3]. With the same mechanism, wire EDM is also extensively used for versatile capability in making irregular through cutting geometry of hard and tough material like Ti6Al4V [4]. There is no confusion in the thermal-assisted WEDM process that the surface of the machined area is greatly affected by transforming the surface morphology, i.e. crater, recast layer, and Heat affected Zone (HAZ) [5]. But the

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ORIGINAL ARTICLE

Performance Analysis on Eco-friendly Machining of Ti6Al4V using Powder Mixed with Different Dielectrics in WEDM

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ABSTRACT – The recent scenario of modern manufacturing is tremendously improved in the sense of precision machining and abstaining from environmental pollution and hazard issues. In the present work, Ti6Al4V is machined through wire EDM (WEDM) process with powder mixed dielectric and analyzed the influence of input parameters and inherent hazard issues. WEDM has different parameters such as peak current, pulse on time, pulse off time, gap voltage, wire speed, wire tension and so on, as well as dielectrics with powder mixed. These are playing an essential role in WEDM performances to improve the process efficiency by developing the surface texture, microhardness, and metal removal rate. Even though the parameter's influencing, the study of environmental effect in the WEDM process is very essential during the machining process due to the high emission of toxic vapour by the high discharge energy. In the present study, three different dielectric fluids were used, including deionised water, kerosene, and surfactant added deionised water and analysed the data by taking one factor at a time (OFAT) approach. From this study, it is established that dielectric types and powder significantly improve performances with proper set of machining parameters and find out the risk factor associated with the PMWEDM process.

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INTRODUCTION

Electrical discharge machining and wire electrical discharge machining are the most efficient non-traditional machining applicable to machine advance materials. Therefore, controlling the process behaviour of EDM is an arduous task. Plenty process parameters are associated with electric discharge machining process such as pulse on time, pulse off time, peak current, gap voltage, wire-speed, wire tension, flushing pressure, dielectrics etc. along with other machines non-controllable parameters [1]. The exploration of complex interaction with all concern parameters is the most anfractuous research field in modern engineering applications. In the present scenario of modern manufacturing, a minimal micron error is not accepted for a specific application where the precise dimension is highly demanded. In this situation, the development of the process characterisation is the major key point of research for enhancing process capability. In this study, authors have used an effective technique of WEDM process for improving the machining efficiency as well as analysing the effect of different dielectric on eco-friendly machining so that the process becomes efficient and inoffensive. Machining characterisation of titanium and its alloy through the non-traditional process is the most challenging research field due to its high hardness and toughness value. Among all the grades of Ti alloy, Ti6Al4V has unique properties such as low thermal conductivity and high weight to strength ratio, which makes it's difficult to cut material. Ti6Al4V comes under the α-β titanium alloy, and it has exceptionally high chemical, mechanical, and metallurgical properties [2]. Owing to high hardness, toughness and superior corrosion properties its low conductivity nature somehow restricted the machining performance of the material.

Well known non-traditional process, namely wire EDM is the most preferred for complex through cutting operation. The main negative feedback of the thermal erosion process is the creation of rough surface and low MRR. As the WEDM process is coming under this group (thermal process), high oxide layers and crack formation also thrust into fatigue failure [3]. Due to high heating and cooling in WEDM process, the inferior machined surface becomes brittle and generates micro-crack, which causes an unexpected result. Then process control strategy is massively essential for enhancing machining efficiency. Several critical process parameters are involved in the WEDM process like mechanical, electrical, dielectric and electrode parameters [4, 5]. Performance efficiency of WEDM process is also strongly dependent on the material characterisation properties based on their thermal, electrical and physical properties. The comparative study was made for modelling and optimisation on different materials using Buckingham pi, RSM, Genetic algorithm and other methodology to model the WEDM responses such as MRR and SR [6-11]. The selection of wire electrodes in the WEDM process also plays a vital role in enhancing the outer response characterisation [12]. Based on the physical and mechanical properties such as tensile strength, conductivity, melting point and fracture toughness, an appropriate wire is selected for machining [13, 14].

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Parametric Influences on Powder Mixed Dielectric in Wire EDM for Processing Ti6Al4V

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Abstract Owing to brilliant mechanical properties, Ti6Al4V alloy is used in the advanced manufacturing sector broadly. Machining of the alloy is created many inherent issues by the conventional methods. Due to this, proper machining process selection is very much necessary for processing the Ti6Al4V alloy. The present investigation illustrated a hybrid machining process of wire EDM where the abrasive powder is mixed with the dielectric to achieve better accuracy in dimensional criteria. With powder in dielectric, the process becomes more stable and improves the machining performance of Ti6Al4V alloy such as MRR and surface roughness. Therefore, the study of the influence of powder properties along with other machining settings in wire EDM has been explored. Sensitivity analysis has been adopted in the present work to find out the significance level of each parameter. For modeling and optimizing the process variable, RSM is used. The relation between the input parameters such as peak current, pulse-off time, pulse-on time, and powder concentration is established to find the best optimal solution for the proposed work. The result concludes that Al_2O_3-mixed deionized water can improve surface roughness upto 61.37% and metal removal rate increased upto 31.52% compared with the conventional WEDM process.

Keywords Hybrid machining · Ti6Al4V · MRR · SR · Sensitivity analysis · RSM

1 Introduction

As per the structure of the metallurgical view of Ti6Al4V, it is known as α–β titanium alloy, and it has a high weight ratio, corrosion resistance, and wear resistance at elevated temperature. Those mechanical properties and other metallurgical properties make the material exceedingly more rigid and more stringent. Also, Ti6Al4V is

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An investigation on dimensional accuracy and surface topography in powder mixed WEDM using RSM and GRA-PCA

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ABSTRACT

The dimensional accuracy in terms of corner error is the critical concern in the wire EDM (WEDM) process where the minor error is not acceptable in the advance manufacturing industry. Superfine Surface topography has also similar importance for application to avoid further machining and lower machining cost. WEDM process is become more efficient to machine any conductive material when powder particles mixed with dielectric during machining. The present work aims at the analysis of the influence of several WEDM parameters by varying pulse on time (Ton) of 30–75 μs, pulse off time (Toff) of 2–11 μs, peak current (Ip) of 1-4A, and B_4C powder concentration (PC) of 2–8 gm/lit on output measures like surface roughness and corner profile error. The grey relation analysis coupled with principal component analysis (GRA-PCA) is considered for analyzing and optimizing the process parameter for better dimensional accuracy. The present investigation recommends an optimal setting in achieving the best possible output during powder mixed wire EDM of Ti6Al4V alloy. Therefore, a comparative study between RSM and GRA-PCA is executed to verify potential that shows GRA-PCA is more efficient than RSM methodology in terms of 17.57% improvement for both the parameters.

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1. Introduction

Due to attractive development in non-traditional machining processes, wire electric discharge machining (WEDM) is widely used for machining of newer superalloy material as it is difficult to machine with the conventional method. As the WEDM process is an electro-thermal erosion process, the demerits always come up in terms of profile inaccuracy and machined surface defects [1],. The present investigation focuses on the improvement of the machining efficiency of WEDM by adding powder into the dielectric during machining. Ti6Al4V material is considered for machining with desirable output. Ti6Al4V alloy has numerous applications in the advance manufacturing industry. Low machinability, superior mechanical and thermal properties of Ti6Al4V alloy makes the material difficult to machine with precise dimension. Machining with high potential of Ti6Al4V, powder mixed wire EDM (PMWEDM) is playing a crucial role.

During thermal erosion, machining process stability is highly required to control the overall process. Hence powder particle with dielectric has been solved the common issues mostly by modifying the plasma channel [2,4]. Several powders are used in EDM and WEDM processes in past research work. Different metallic, non-metallic, and abrasives powder such as Cu, Ti, Graphite, Al, Al_2O_3, SiC, B_4C, and Nanopowders shows their significant effect on performances [3],. Powder properties like size and concentration along with types of powder particles in dielectric play a key role on responses. Thus, proper selection of powder properties followed by the machining parameter is very essential for the best outcome for the process.

In the WEDM process, the most substantial response parameters are surface roughness (SR), material removal rate (MRR), kerf width (KW), dimensional shift (DS). The major input parameters are peak current, pulse on time, pulse off time, gap voltage, wire tension, and servo speed by which responses are mostly influenced [5],. The best optimal solution of proposed input parameters and their levels are found with the help of different optimization techniques such as ANN, GA, RSM, GRA-PCA, and PSO. The individual optimization technique has its unique process characteristics.

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Modeling & Analysis of B_4C Powder Mixed Wire EDM Process for Improving Performance Criteria of Ti6Al4V

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Abstract. The present investigation represents the effect of B_4C powder properties on performance characteristics of Ti6Al4V material. Boron carbide has good chemical resistance, low density and non-oxide properties. Due to that, it has a great impact on powder mixed wire EDM. The machining of Ti6Al4V is very difficult by other non-conventional processes when it is considered particularly through cutting operation with desired surface quality and strong economically. In this study pulse on time, pulse off time, peak current and gap voltage are considered as input parameter and analyzed the performance characteristics such MRR and SR. B4C Powder concentration and size in the dielectric are analyzed to get significant output. The optimum result is obtained from machining condition i.e. powder size 10µm and concentration 6gm/lit as for both performances like MRR and SR while machining controllable parameters are fixed i.e. Ip=2, Ton=30 and Toff=8. The machined surface is studied through microstructure image

1. Introduction

Electrically and thermally conductive materials are machined through the EDM process. The basic mechanism of metal removal Wire electric discharge machining is same as EDM process. In this process tool and workpiece always maintain a constant gap, say 0.05-0.50mm and flooded the gap area with a dielectric medium. The rate of metal removal is depending upon the workpiece material properties i.e. melting point, thermal conductivity and density as well as polarity and discharge intensity. In the modern manufacturing industry, a lot of advanced materials and superalloys are used for their enormous applications. Ti6Al4V is an alpha-beta titanium alloy which has excellent corrosion resistance and high strength to weight ratio. Ti6Al4V has numerous applications in aerospace and marine industry. Machining of this material is very difficult by other non-conventional when it is considered through cutting operation with a complex profile. WEDM is one of the best choices for perfect machining with precision dimension for its practical advantages. Alternatively, powder mixed wire EDM is the best options for high accuracy machining of advance alloys with desired product quality. In this process, powder is added with dielectric and during machining powder properties are varied as well as changing the machining parameter. Several machining inputs are involved in powder mixed technology in WEDM process.

1.1. Literature Review

Kumar et al [1] studied the multi-objective optimization through Grey Relation Analysis. The influence parameters such as peak current, pulse on time, duty factor and SI powder concentration and showed that silicon powder of 2gm/ltr in kerosene dielectric has the best effect on performance. Kumar et al [2] focused on the tool material (copper, copper-chromium and graphite) and powder

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Experimental investigation on enhancing die corner accuracy during powder mixed wire EDM of Ti6Al4V

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ABSTRACT

Owing to increase demand and machining capability, wire electric discharge machining (WEDM) is one of the promising machining processes to make precision geometry specially for dies and machine tools. The present investigation focused on hybridization of the process by integrating power into dielectric to achieve desired die corner accuracy of the 'hard to cut' material. The presence of abrasive powder in flushing dielectric considerably improve plasma channel so that better outcome has been achieved. The effect of process parameters, as well as different powders, mixed dielectric has been analyzed on the measured responses such as corner accuracy and metal removal rate to reduce the uncut area in terms of corner error. Obtained results established that adding powder in dielectric enhances the corner accuracy with a proper setting of input parameter. Therefore, 43.66% improvement of corner accuracy is achieved in the proposed hybrid technique. B_4C abrasive powder particle mixed with dielectric shows the highest impact on corner error and MRR. Moreover, high discharge energy and the addition of powder in dielectric increase the productivity that is more preferable for manufacture excellent quality of the product with low cost and large quantity. At the same time, the low discharge energy provides better corner accuracy with lower productivity.

1. Introduction

High consistent of the prosperity of modern manufacturing industry like a biomedical, nuclear plant, aerospace, automobile industry, etc., the demand of superalloy materials having high corrosion resistance, weight to strength ratio, superior wear resistance, and high melting point is increasing unexpectedly [1,2]. Ti6Al4V is basically titanium-based super alloy and it has a wide range of applications [3]. But machining of this material is too challenging to create a complex curve profile with optimum corner accuracy [4].

In the modern days, remarkable improvement has arrived in the non-traditional machining process. Among all the thermal erosion non-traditional machining processes, wire electric discharge machining (WEDM) has more capability to produce an intricate shape with high accuracy profile [5]. Specially die making is depended on the material design aspect so that the product would be at a lower cost as well as eliminated the application of further machining operation. Need for the high demand for precision tool and die making manufacturing industry, WEDM is the most priority technique to solve the issues after machining [6]. In the WEDM process, a thin flexible wire electrode is used. During machining, a deformation has taken place on the electrode material by the electrostatic and explosive force; as a result, profile inaccuracy generates on the work surface [7].

The product of spark energy in the WEDM process is controlled by several restrainable machining parameters and non restrainable parameters [8]. The error in corner profile cutting is always present in the WEDM process due to the use of a small radius circular wire electrode. Zhi chen et al. [9] stated that this issue is mainly occurred by the deflection of the wire from the original programmable path. For reducing workpiece corner error, authors have established a mathematical model. Discharge energy and

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Assessing the Effect of Powder Mixed with Dielectric in Wire EDM of Ti6Al4V using RSM

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ABSTRACT

Titanium based superalloy, Ti6Al4V, is termed as hard to cut material, owing to its excellent fatigue properties, superior strength and corrosion resistance, it has a large application in technically advance manufacturing industry. Due to extreme work hardening tendency, some restricted inherent problems occurred during conventional machining of Ti6Al4V. Therefore, in the present investigation, a hybrid machining process named powder mixed wire EDM has been established. In PMWEDM, abrasive powder particles are mixed with de-ionized water and performed a comparative experiment for better of Ti6Al4V performance such as MRR and Surface roughness. A suitable technique (RSM) has been used for modeling analyzing the experimental result to find out the set of optimal solution including of four input parameter like peak current, pulse off time, pulse on time and powder concentration. The obtained model established by RSM is found as very trustworthy. From the experimental result, it is evident that powder concentration in dielectric plays an important role on both output measures. Maximum MRR of 8.347 mm3/min and average surface finish of 2.543 μm are the outcome of the present study for a set of optimal machining setting, viz. peak current of 80A, pulse off time of 70μs , pulse on time of 8.8 μs and abrasive concentration of 2.9gm/l.

1. Introduction

With the advancement of new technology in the field of newer super alloy and hydride material, such as Ti based, Nickel based and chromiun based, Ti6Al4V alloy becomes very popular in different applications. Recently Ti6Al4V alloy is being utilized in not only technically advance manufacturing industrybut also in medical surgical equipment[1, 2]. According to the metallurgical structure of Ti6Al4V, it is basically known as α-β titanium alloy and it has high weight ratio, corrosion resistance and wear resistance at elevated high temperature. These types of mechanical properties, as well as other metallurgical properties, make the material extremely harder and tougher. Ti6Al4V is known as a hard to cut material due to its low machinability and poor conductivity [3-5].

Therefore, machining of this material is a challenging task in the manufacturing field. Planty thermal assisted non-conventional machining is available like EDM, LBM, EBM, which have more capability to cut the hard material very smoothly. Among of them, electric discharge machining is one of the most effective machining processes for cut Ti6Al4V material very precisely [6]. However, many researchers have discussed how to improve the machining capability of EDM with the help of different methodology.

Sadananda chakraborty