

**“Optimization Of Quality Characteristic In Wire Electric
Discharge Machining Of Aluminium Alloy-Based Metal
Matrix Composites”**

**A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY**

**In
PRODUCTION AND INDUSTRIAL ENGINEERING
by**

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JULY, 2020

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CERTIFICATE

This is to certify that the thesis work entitled “**Optimization of quality characteristic in wire electric discharge machining of Aluminium Alloy-Based Metal Matrix Composites**” submitted by ABDUL REHMAN, Enrollment No. 1500100179 in partial fulfillment for the award of **Master of Technology** degree in **Mechanical Engineering Department** with specialization in **Production and Industrial Engineering**, to Integral University, Lucknow (U.P.). He has carried out his thesis work under my supervision and guidance and to the best of my knowledge; the matter embodied in this thesis has not been submitted to any other University/Institute for award of any degree to the candidate or to anybody else.

A handwritten signature in blue ink, appearing to read 'Anas', is located above the name of the supervisor.

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ABSTRACT

Wire EDM is an emerging technology in the field of non-conventional machining to fabricate very complex products with very high degree of precision. Wire EDM is a very complex process involving the different process parameters. In the present investigation an optimization of wire EDM has been carried out using Taguchi optimization method. The parameters involved are pulse-on time, pulse-off time, peak current and servo voltage. Cutting rate, Surface Roughness, Dimensional Deviation and Wire Wear Ratio are taken as the responses. Experimental investigation has been carried out on SPRINTCUT Wire-EDM machine.

Wire electrical discharge machining process is a highly complex, time varying & stochastic process. The major applications of this process are in the fields of dies, molds, precision manufacturing and contour cutting etc. Any complex shape can be generated with high grade of accuracy and surface finish using CNC WEDM. The output of the process is affected by large no of input variables. Hence a suitable selection of input variables for the wire electrical discharge machining (WEDM) process depends heavily on the operator's technology & experience.

WEDM is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in wire EDM is very challenging one because improvement of more than one performance measures viz. Metal removal rate (MRR), surface finish are quite challenging task. The study demonstrates that the WEDM process parameters can be adjusted so as to achieve better metal removal rate, surface finish, electrode wear rate and dimensional deviation.

ACKNOWLEDGEMENT

I would like to express my deep sense of gratitude and respect to my supervisor **Dr. Mohd. Anas** for his invaluable guidance, motivation, constant inspiration and above all for his ever co-operating attitude that enabled me in bringing up this thesis in the present form. I consider myself extremely lucky to be able to work under the guidance of such a dynamic personality.

I am also thankful to **Dr. P.K. Bharti**, Head of Department, Mechanical Engineering, for his support and motivation.

I would also like to thank to “**Mohd. Saif** (SHUATS, ALLAHABAD)” who also guided me throughout the experiments and provided all the facilities for successful completion of experimental work.

My very special thanks go to all my family members. Their love, affection and patience made this work possible and the blessings and encouragement of my beloved parents greatly helped me in carrying out this research work.

Place: Lucknow

Date: 11-09-2020

Abdul Rehman



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INTRODUCTION

INTRODUCTION

Recent developments in the manufacturing industry have fueled the demand for materials having higher strength, hardness and toughness. These materials pose a problem while machining with conventional machines available. The new materials available are lightweight combined with greater hardness and toughness. Sometimes their properties may create major challenges during their machining. Hence, non-conventional machining methods including electrochemical machining (ECM), ultrasonic machining (USM), electrical discharging machine (EDM) and the newly developed hybrid machining etc. are applied to machine such difficult to machine materials. The most generalized machine tool to machine these materials is WEDM. Wire Electric Discharge Machining (WEDM) is a process by which a conductive material is cut by means of a thin wire electrode (generally brass) which follows a CNC controlled path. WEDM leaves a totally random pattern on the surface as compared to tooling marks left by milling cutters and grinding wheels.

Since its inception in 1960's by the contributions from Lazarenko Brothers, it has revolutionalised the tool and die making industry to a much wider extent. WEDM has evolved over time from being just used for manufacturing tools and dies to the machine of exotic spaceage alloys including Hastelloy, Inconel, titanium, Carbide, Polycrystalline diamond compacts and Conductive ceramics. Figure 1.1 shows the schematic of WEDM. It can machine anything regardless of its hardness, the only condition being the material should be electrically conductive. It is probably the most exciting and diversified machine tool developed by the manufacturing industry in the last fifty years and has numerous advantages to offer.

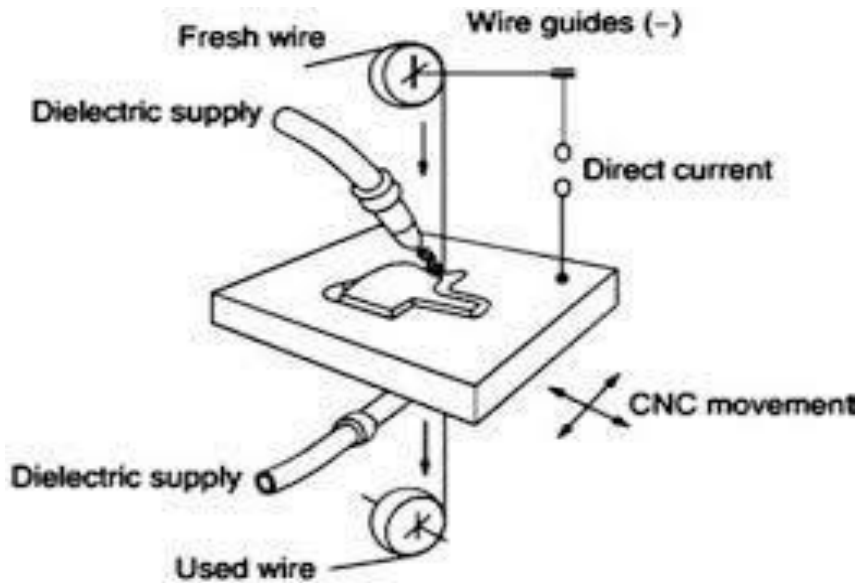
Machining on WEDM is initiated by drilling a hole on the work-piece or starting from the edge. Here, the electrical energy is transformed into thermal energy by a series of discrete sparks being generated by spark generator. Sparks are formed through a sequence of rapid electrical pulses generated by the machine's power supply and these are thousands of times per second.

Each spark forms an ionization channel under extremely high heat and pressure, in which particles flow between the wire electrode and the work-piece, resulting in vaporization of localized sections.

WEDM is a special adoption of EDM process for removal of material from the work-piece surface. The only difference between WEDM and EDM process is the type of tool being employed.

The shape of the tool in EDM is the replica of the product to be obtained while in WEDM it is a continuously moving thin brass wire (generally diameter 0.25mm). The wire is fed through a pair of tensioning rollers. Both the work piece and the tool are immersed in a continuously flowing pressurized dielectric fluid (deionized water). The dielectric fluid serves two purposes: a) It acts as an insulator till a threshold voltage is reached; b) it acts as a cooling agent. It also flushes away the debris from the machining zone. Since there is no contact between the tool and work piece, the process is free from any forces. This significantly reduces the need for special

fixtures to support the work piece as required in conventional processes. The process leaves no residual burrs, thus eliminating the need for any finishing process.



Wire EDM also gives designers more latitude in designing dies, and management more control of manufacturing, since the machining is completed automatically. Parts that have complex geometry and tolerances don't require you to rely on different skill levels or multiple equipment. Substantial increases in productivity are achieved since the machining is unattended, allowing operators to do work in other areas. Most work pieces come off the machine as a finished part, without the need for secondary operations. It's a one-step processed

HISTORY

Erosion of craters left by electric discharges on the cathode surface was first discovered by Joseph Priestley, an English theologian, and chemist, in 1766. Since then, arcs have been used for a variety of purposes and not necessarily for the removal of metal. The first use of arc for removing metal was attempted by the **Russian scientists Boris and Natalya Lazarenko at the Moscow University in 1943**. They were investigating the wear caused by sparking between tungsten electrical contacts which were critical for maintenance of automotive engines during Second World War under an assignment from the Soviet Government. They have noted that during the experimentation the sparks were more predictable in oil than in air. Then they came up with the idea of using this controlled sparking as a method of removing metal. They developed the "**Lazarenko Circuit**" which is a relaxation circuit based on the resistance-capacitance circuit that remained the standard EDM generator for years. The first EDM machine that used wire as an electrode became commercially available in 1967 in the Soviet Union.

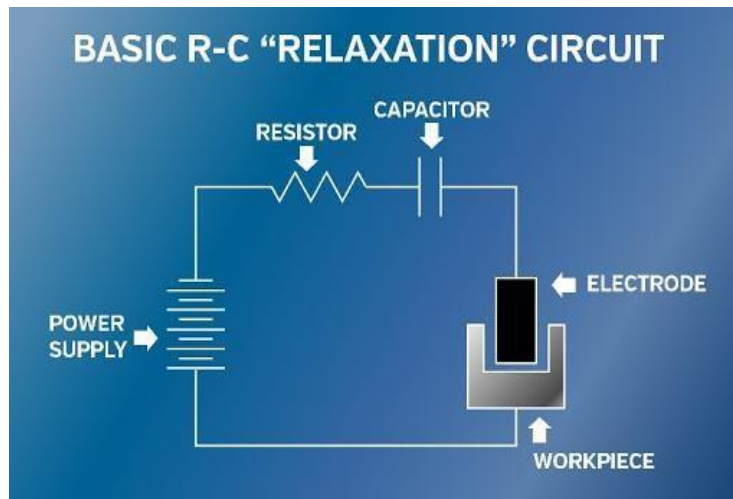


Fig 1.2 Relaxation Circuit as used by Lazarenko

BASIC PRINCIPLE OF WEDM PROCESS

Wire-cut machines are available in two, four, and five-axis variations. The axes are identified as X axis, Y axis, U axis, V axis, and Z axis as shown in Figure 1.3. In operation, the X and U axes are parallel to each other, the Y and V axes are parallel in their operation, while the Z axis is perpendicular to the X-U and Y-V axes. The U and V axes offset the electrode wire from the vertical position. This offset allows the wire cut machine to produce vertical machined surfaces on the work piece when the U and V axes locate the top wire guide, directly above the bottom wire guide. Surfaces with tapers are machined on the work piece by using the U and V axes to offset the top wire guide from a position directly above the bottom wire guide. The conical shape surrounding the electrode wire illustrates this offsetting.

Z-axis operation may be manually operated or computer controlled. This axis is used to position the top wire guide in close proximity to the work piece's top surface. The positioning of the top wire guide is necessary to ensure proper flow of dielectric fluid into the sparking area and to maintain WEDM-chip removal. Adjustment of the Z axis is necessary at any time during the sparking cycle when a change of contour in the work piece's top surface is encountered. Should the work piece surface project into the path of the top wire guide, the units could be damaged in a collision.

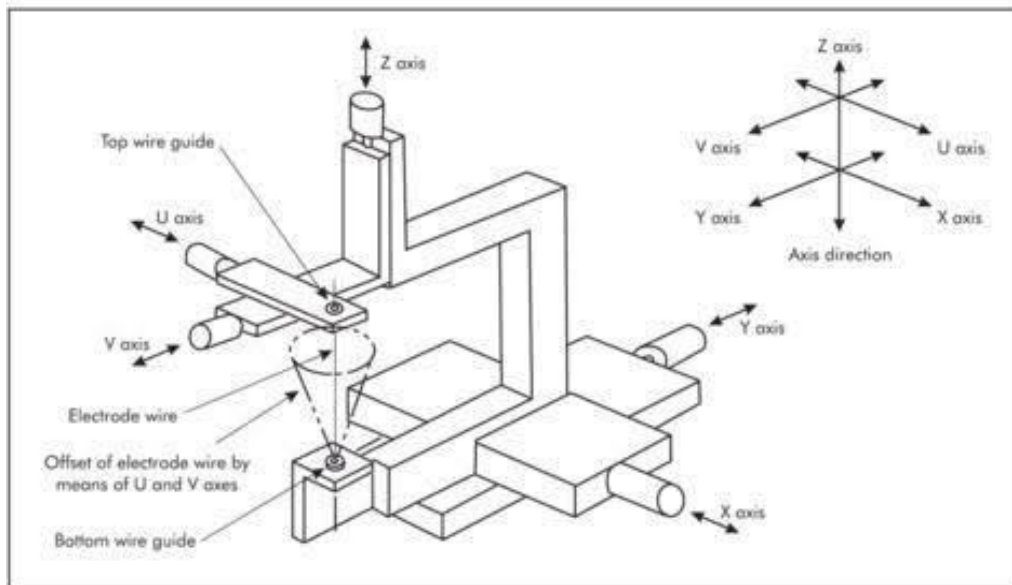


Figure 2-14. Five-axes wire-cut-machine design.

Fig 1.3 Five axes wire-cut-machine design

The machine tool also includes the wire-feed unit. This unit controls wire-traverse speed as it passes through the sparking area. When the wire passes too slowly through the area, the sparking will erode and eventually break the wire. Passing the wire too quickly through the sparking area is wasteful. In addition to controlling the wire-traverse speed, the wire-feed unit must hold the electrode wire under proper tension and keep it taut and straight. Without proper tensioning, the machine servo system will not function properly and the machined surface will be distorted. Wire-traverse speed is a computer-controlled function that uses settings recommended by the manufacturer. The settings consider items such as the electrode wire's material, diameter, and metallurgy. The work piece material and thickness also will affect wire-traverse speed.

MECHANISM OF MATERIAL REMOVAL IN WEDM PROCESS

In WEDM, there are numerous mechanisms involved in material removal viz. heat conduction and radiation, phase changes, electrical forces, bubble formation and collapse, rapid solidification etc. The most appropriate theory for the explanation of the electrical discharge machining process is a thermoelectric phenomenon as shown in Figure 1.4

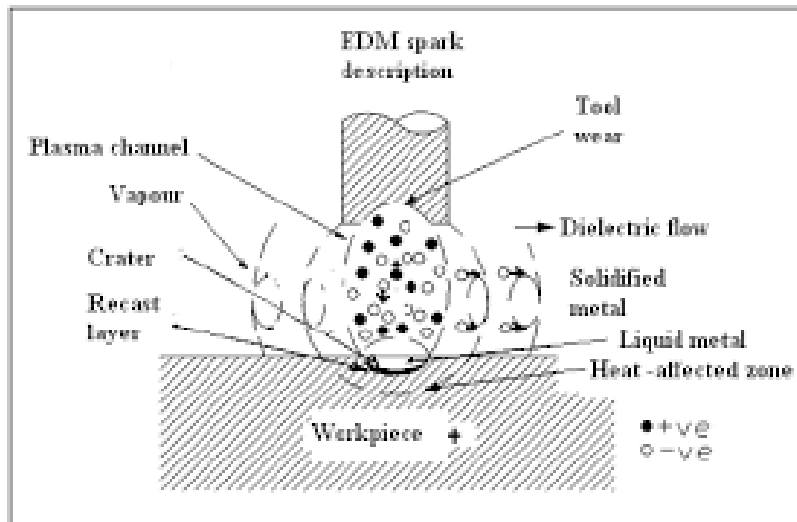


Figure 1.4: Schematic of Material Removal Phenomenon in WEDM (EC Jameson)

The material removal takes place due to melting and vaporization caused by the number of discrete sparks being generated by spark generator. The material is removed both from the cathode and anode in the presence of pressurized flowing dielectric fluid. The dielectric fluid gets ionized after a threshold voltage, in between the tool-electrode gap. This creates an ionization channel which helps the ions to move to oppositely charged electrodes at very high velocities. The area wherein discharge takes place gets heated to very high temperatures such that the surface gets melted and removed. The temperature of electrodes can locally rise to a very high value which reaches beyond the melting point of the work material due to the transformation of the kinetic energy of electrons into heat. The high energy density erodes a part of the material from both the wire and work piece by locally melting and vaporizing. The removed particles (debris) get flushed away by the continuously flowing dielectric fluid. In the WEDM process, the motion of wire is slow. It is fed in the programmed path and material is removed from the work piece accordingly.

ADVANTAGES OF WEDM PROCESS

- > The process is capable to machine metals, alloys and carbides irrespective of their hardness, strength, toughness and microstructure.
- > Any materials that are electrically conductive can be machined by WEDM.
- > The tool (electrode) and work piece are free from cutting forces thus eliminating the need for special fixtures.
- > Edge machining and sharp comers are possible in WEDM process.
- > The process produces a good surface finish, accuracy and repeatability.
- > Hardened work pieces can also be machined since the deformation caused by it does not affect the final dimensions.

- > It is a burr free process.
- > Hard die materials with complicated shapes can be easily machined with good surface finish and accuracy through WEDM process.
- > Due to the presence of dielectric fluid, there is very little heating of the bulk material.
- > Since there is no mechanical contact between the work piece and tool, small work pieces can be machined.

DISADVANTAGES OF WEDM PROCESS

- > Material removal rates are low, making the process economical only for very hard and difficult to machine materials.
- > Re-cast layers and micro-cracks are inherent features of the WEDM process, thereby making the surface quality poor.
- > WEDM process is not suitable for non-conductors.
- > Rapid electrode wear makes the process more costly.

The surfaces produced by WEDM generally have a matte type appearance, requiring further polishing to attain a glossy finish.

APPLICATIONS OF WEDM PROCESS

Wire EDM is used for cutting aluminum, brass, copper, carbides, graphite, steels and titanium. The wire material varies with the application requirements. For quicker cutting action, zinc-coated brass wires are used while for more accurate applications, molybdenum wires are used. The process is used in the following areas:

- > Aerospace, Medical, Electronics and Semiconductor applications
- > Tool & Die making industries.
- > For cutting the hard Extrusion Dies
- > In making Fixtures, Gauges & Cams
- > Cutting of Gears, Strippers, Punches and Dies
- > Manufacturing hard Electrodes.
- > Manufacturing micro-tooling for Micro-EDM, Micro-USM and such other micro-machining application

CHAPTER 2

LITERATURE REVIEW

Literature Review

Harshdeep and Ishu Monga (2015) used Taguchi L16 Orthogonal Array for developing robust design while machining H11 steel. The design was used for optimization of input parameters (Pulse on time, Pulse off time, wire feed, wire tension and Peak current) and output parameters (material removal rate, wire wear ratio, surface flatness). Furthermore multi-response (signal to noise ratio) approach was applied to measure the performance characteristics deviating from the actual value.

Nagaraja et.al (2015) presented an investigation on the optimization of parameters in WEDM of bronze-alumina MMC. The main objective was to find the optimum cutting parameters to achieve a low value of Surface roughness. The input parameters considered in this experimental study were pulse on time (TON), pulse off time (TQFF) and wire feed rate. The settings of cutting parameters were determined by using Taguchi L9 orthogonal array. Signal to Noise ratio (S/N) and analysis of variance (ANOVA) were used to analyze the effect of the parameters on surface roughness. The contribution of each cutting parameter towards the surface roughness is also identified. The results indicated that the wire feed rate (39.4%) is the most dominant factor affecting the surface roughness. The study shows that the Taguchi method is suitable to solve the stated problem with a minimum number of trials as compared with a full factorial design.

Rao and Venkaiah (2015) used the central composite face centered design of Response Surface Methodology (RSM) for planning their experimentation while optimizing various process parameters on Nimonic-263 alloy. The input parameters taken were pulse on time, pulse off time, peak current and servo voltage. The significance of process parameters is estimated by ANOVA technique. They also developed models for predicting the values of MRR and Surface Roughness. The optimal values for MRR and SR from RSM were 3.59856 mmVmin and 0.363162 μ m respectively. Similarly, the optimal values found from PSO for MRR and SR were 3.6713 mmVmin and 0.261 μ m.

The results were optimized with the help of Particle Swarm Optimization (PSO) algorithm. Results of both RSM technique and PSO algorithm were compared and PSO algorithm gave better results.

Kubade et.al (2015) optimized the process parametric combinations of pulse on time, pulse off time and wire speed using Taguchi L27 Orthogonal Array each at 3 levels on Titanium Dibromide TiB₂. Signal to Noise ratios of the Material removal rate, Surface roughness and Overcut for all

experiments were calculated. The results were analyzed using analysis of variance (ANOVA) and response graphs.

Dewangan et al. (2015) machined AISI P20 tool steel on EDM and investigated the effect of various input parameters on surface integrity of the material. The experiments were designed with the help of Response Surface Methodology (RSM). The input parameters selected were discharge current (IP), pulse-on time (TON), tool-work time (Tw) and tool-lift time (Tup). Grey Relational Analysis (GRA) and fuzzy logic were used to evaluate Grey Fuzzy Reasoning Grade (GFRG). The main findings of their study were that pulse on time followed by discharge current were mostly influencing the results of surface integrity. The optimal settings obtained were IP = 1 A, TON = 10 ms, Tw = 0.2 s, and TUP = 0.0 s.

Azhiri et al. (2014) focused on the effect of machining Al/SiC metal matrix composite using dry WEDM process. In the experimentation, the liquid dielectric is replaced with a gaseous medium to enhance the quality of machining environment. Oxygen gas and brass wire were selected as gaseous medium and tool electrode through a series of experiments as they guaranteed superior cutting velocity. The effect of the pulse on time, pulse off time, gap voltage, discharge current, wire tension and wire feed were studied on cutting velocity (CV) and surface roughness (SR) using Taguchi's orthogonal array. The relationship between process inputs and responses were correlated using adaptive neuro-fuzzy inference system. At last, Grey Relational analysis had been used to optimize CV and SR simultaneously. Pulse on time and discharge current were found to have a significant effect on CV and SR.

Rao et al. (2014) used the Taguchi method and Hybrid Genetic Algorithm with the aid of linear regression models to optimize surface roughness and material removal rate while machining Aluminum 2014T6 alloy. Peak current, pulse on time, spark gap significantly influence both SR and MRR. At last white layer thickness measurement of specimens was done which showed quite high values.

Saedon et al. (2014) conducted the experiments to determine the effects of pulse on time, pulse off time, wire feed and wire tension on the surface roughness (Ra), cutting rate and material removal rate (MRR) in machining of titanium alloy. Combined approach of the orthogonal array and Grey Relational Analysis (GRA) was used for multi-objective optimization of response variables. The optimal machining settings were pulse-off time at 3 μ s, peak current at 12A, wire tension at 16 N and wire feed at 4 mm/min.

Abinesh et al. (2014) showed that WEDM process parameters can be altered to achieve the betterment of Material removal rate (MRR), Surface Roughness (SR) and Electrode Wear. The objective was to investigate and optimize the potential process parameters influencing the MRR, SR and Electrode Wear while machining of Titanium alloys. The work involved the study of the

relation between the various input process parameters like Pulse-on time(ToN), Pulse off time(ToFF), Pulse Peak Current(IP), Wire material and Workpiece material. Based on the chosen input parameters and performance measures L-16 orthogonal array was selected to optimize the best-suited values for machining for Titanium alloys by WEDM.

Equbal et al. (2014) used the Taguchi method and Grey Relational Analysis (GRA) to optimize the process parameters while hot forging of spring saddle. Input parameters like flash thickness, billet temperature, die temperature and friction coefficient along with their interactions were studied with L27 OA. Analysis of variance (ANOVA) is employed to determine significant parameters. For forging load, flash thickness, billet temperature and interaction between the two are found to be the most significant parameters.

Goswami and Kumar (2014) in their investigation on Nimonic-80A used Taguchi's methodology to design the experiments. The response was seen on surface integrity, material removal rate and wire wear ratio. All the input parameters and two-factor interactions were found to be significant. Scanned Electron Microscopy was performed on machined surfaces to investigate their microstructure. It was observed that thick recast layer was formed while using higher pulse on time settings. Also, lower values of wire deposition were observed when low values of pulse on time and high values of pulse off time was used as settings.

Baig and Venkaiah (2014) machined Hastelloy C276 by using Taguchi and Grey Relational Analysis. MRR and Kerf width were taken as response variables. Discharge current (IP) was found to be the most significant factor affecting the MRR and kerf width.

Sudhakara and Prasanthi (2014) dealt with optimization of process parameters (pulse on time, pulse off time, servo voltage, peak current, wire tension and water pressure) of WEDM with performance response of Surface Roughness while machining Powder Metallurgical Cold worked Tool Steel VANADIS 4e. Experiments were performed on Mitsubishi WEDM and optimum factors are found out using Taguchi method and ANOVA. Pulse on time followed by spark gap set voltage had a significant effect on SR. Wire feed and Pulse off time had almost no effect on material removal rate.

Rajyalakshmi and Ramaiah (2013) conducted the experiments on Inconel 825 under combined approach of orthogonal array design L36 (I³S³?) and Grey Relational Analysis. The main objective of the research was to find the improvised values of MRR, surface roughness and spark gap. Material removal rate showed an increased value of 119.625 to 126.85 mmVmin, the surface roughness shows a reduced value of 1.68 to 1.44 nm and the spark gap shows a reduced value of 0.015 to 0.013 mm.

Shah et al. (2013) reported the optimization of operating parameters of WEDM during machining Inconel-600 using Response Surface Methodology (RSM). Four input parameters (Pulse on time,

Pulse off time, Peak Current, Wire feed rate) were chosen to study their effect experimentally on performance response of Material Removal Rate. Taguchi with mixed LI 8 array was used for designing the experiment and ANOVA was used for analysis and finally RSM was used to develop surface models for response parameters. ResuUs showed that effect of Pulse on time, pulse off time and Peak current had a significant effect on MRR.

Sharma et al. (2013) conducted experiments to investigate the effect of process parameters on cutting speed and dimensional deviations in cutting high-strength low alloy steel (HSLA). Response Surface Methodology (RSM) was used to optimize the parameters while central composite rotatable design to design them. ANOVA was used to determine the significant factors. Experiments showed that pulse-on time was the most prominent factor for cutting speed and dimensional deviation.

Nourbakhsh et al (2013) reported the effect of seven process parameters on the responses while machining titanium alloy. The influence of zinc coated brass wire was compared with high-speed brass wire. The seven process parameters include pulse width, servo reference voltage, pulse current and wire tension. The response was seen on cutting speed, wire rupture and surface integrity. The experiments were designed based on Taguchi LI 8 design of experiment (DOE). Observations showed that the cutting speed increases with pulse width, peak current and pulse interval. Pulse width, wire tension and peak current had a direct impact on surface roughness. Voltage, injection pressure, wire feed rate and wire tension were found to be insignificant for cutting speed. Zinc coated brass wire resulted in higher cutting speed and smoother surface finish as compared high-speed brass wire. Also, SEM photographs proved that uncoated wire produces a surface finish with more cracks, craters and meUed drops. Scanning Electron Microscopic (SEM) examination of machined surfaces was performed to understand the effect of different wires on workpiece material surface characteristics. On the side of wire rupture, the most influencing factors were pulse width and pulse interval.

Fard et al. (2013) designed the experiments based on L27 Taguchi's orthogonal array. Analysis of variances (ANOVA) has been performed to identify significant factors. The workpiece material used was Al/SiC metal composite. The machining was done under dry dielectric conditions using a gaseous medium. In order to correlate the relationship between process inputs and responses, an adaptive neuro-fiizzy inference system (ANFIS) has been employed to predict the process characteristics. The process variables under study were pulse on time, pulse off time, gap voltage, discharge current, wire tension and wire feed and their effects were calculated on cutting velocity (CV) and surface roughness (SR). After the application of ANFIS, Artificial Bee Colony (ABC) algorithm technique was applied to optimize the values of cutting rate and surface roughness. Results indicated that oxygen gas and brass wire guaranteed superior cutting velocity while

ANOVA indicated that pulse on time and discharge current had a significant effect on CV and SR.

Shandilya et al. (2013) described the response surface methodology (RSM) and artificial neural network (ANN) based mathematical modeling for the average cutting speed of 10% SiCp/6061 Al metal matrix composite (MMC) during wire electric discharge machining (WEDM). Servo voltage (SV), pulse-on time (TON), pulse-off time (TOFF) and wire feed rate (WF) were chosen as input factors. A back propagation neural network model was developed with the help of Box-

Behnken design (BBD) of experiments. The performance of the developed ANN models was compared with the RSM mathematical models. The prediction accuracy of ANN model was about three times better than RSM. Voltage was a more significant parameter on average cutting speed than wire feed rate and pulse-off time. On the basis of the correlation coefficient, the prediction accuracy of ANN model is higher than RSM model.

Shayan et al. (2013) employed Central composite rotatable design (CCRD) to design experiments based on response surface methodology (RSM). Empirical models were developed to create relationships between input factors and their responses by considering the analysis of variances (ANOVA). Intelligent models were developed based on back-propagation neural network (BPNN) and these models were compared with mathematical models based on the root mean square error (RMSE) and prediction error percent (PEP). These models developed were integrated with optimization approaches namely desirability function and particle swarm optimization. The optimal solution of both the approaches was compared and validity tests were conducted. Results showed that air at inlet pressure at Ibar leads to higher MRR and lower Surface Roughness and oversize.

Kumar and Agarwal (2012) optimized the machining parameters for maximum material removal rate and minimum surface finish by multi-objective genetic algorithm while machining high-speed steel (M2, SKH9). Experiments were designed based on Taguchi's L27 parameter design. Pulse peak current, pulse on time, pulse off time, wire feed, wire tension and flushing pressure and their interaction were seen on material removal rate and surface finish. Zinc coated copper wire was used as a tool. The mathematical models were developed between input parameters and responses by using non-linear regression analysis. These mathematical models were then optimized by using multi-objective optimization technique based on Non-dominated Sorting Genetic Algorithm-II to obtain a Pareto-optimal solution set. The results indicated that the MRR and surface finish were influenced more by pulse peak current, pulse duration, pulse-off period and wire feed than by flushing pressure and wire tension. The best parametric combination with highest possible MRR, while maintaining the specified surface finish

requirement of 3.69 *\im*, were: pulse peak current=30 A, pulse duration=37 us, pulse-off time=50 us, wire feed=7 m/min, wire tension=1260 g, flushing pressure =2.1 kg/cm².

Shandilya et al. (2012) optimized the process parameters of SiCp/6061 Al metal matrix composite (MMC) by wire electrical discharge machining (WEDM) using response surface methodology (RSM). The input parameters considered were voltage, pulse-on time, pulse-off time and wire feed rate and their effect was studied on cutting width (kerf). Voltage and wire feed rate were found to be significant factors during the analysis. SEM images of the cut surfaces have revealed that the fine surface finish was obtained when machining was done at a combination of lower levels of input process parameters.

Yang et al. (2012) tried to analyze variations in metal removal rate MRR, surface roughness Ra, and corner deviation CD while machining pure tungsten with WEDM. This research proposes an effective process parameter optimization approach that integrates Taguchi's parameter design method, response surface methodology (RSM), back-propagation neural network (BPNN), and simulated annealing algorithm (SAA) on WEDM processes. Furthermore, the field-emission SEM images showed that a lot of built-edge layers were present on the finished surface after the WEDM process. With the increase in pulse on time, the MRR was increased due to increase in number of sparks per second thus deteriorating the surface profile rougher surfaces. Also, increasing the wire tension resulted in the decrease of corner deviation.

SatishKumar et.al (2011) presented a performance of WEDM parameters while machining A16063/SiCp composite. In this experiment, four process parameters (Pulse on time, Pulse off time, gap voltage, wire feed) and two response (MRR and Ra values) were selected. For this, SiC was mixed as 5%, 10% & 15% in Al using stir casting method and then machining of pure A16063 and Al-MMC was done. L9 orthogonal array was used to design the experiment and after that values are analyzed using ANOVA and response graph. The results of different fractions were compared with unreinforced A16063 for MRR. MRR was found to decrease with increased fractions of SiC in MMC. SR also increased with increased fractions of SiC in MMC. Gap voltage showed more significance than other parameters.

Jangra et al. (2011) illustrated a case of the optimization of two quality characteristics viz: Material Removal Rate and Surface Roughness while machining a composite of Tungsten Carbide and Cobalt. The parameters used in the study were taper angle, peak current, pulse on time, pulse off time, wire tension and dielectric flow rate. Grey Relational Analysis (GRA) along with Taguchi

method was employed for simultaneous optimization of responses. Optimal settings of process parameters were evaluated with Grey Relational Grade. ANOVA showed that pulse on time and taper angle were most significant factors affecting the results.

Antar et al. (2011) presented experimental data for workpiece productivity and integrity while machining nickel-based super alloy Udimet-720 and Ti-6Al-2Sn4Zr-6Mo titanium alloy, using Cu core coated wires (ZnCuSO and Zn-rich brass). It was reported that up to a 40% for Udimet-720 and 70% for Ti-6Al-2Sn4Zr-6Mo titanium alloy increase in productivity was possible compared to when using uncoated brass wires with the same operating parameters.

Muthu Kumar et al. (2010) used Grey-Taguchi method for optimizing multiple parameters while machining Aluminium alloy based metal matrix composites superalloy. The output of the experiment was seen on MRR, SR and kerf. The optimal settings obtained were 50 V-Gap Voltage, 10 μ s pulse on-time, 6 μ s pulse off time and 8 mm/minute wire feed rate.

Newton et al. (2009) tried to find the parameters which affect the formation of recast layer in Inconel 718. They found that average thickness of re-cast layer increased when energy per spark, current pulse duration and peak discharge current were increased. The average thickness of re-cast layer was found varying from 5 to 9 μ m. Wire diameter and spark cycle time had an insignificant impact on the formation of recast layer.

Singh and Garg (2009) investigated the effect of various process parameters of WEDM like pulse on-time (Ton), pulse off time (TOFF), servo voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) on hot die steel(H-1 1) using one variable at a time approach. The optimal set of process parameters was predicted to maximize the material removal rate (MRR). It was noticed that the pulse on time and peak current had a direct impact while pulse off time had an indirect impact on MRR. Wire feed and wire tension had little effect on MRR.

Mahapatra and Patnaik (2007) used Taguchi's L27 OA and non-linear regression analysis to design the experiment on various operating parameters. D2 tool steel was used as workpiece material and the response parameters were MRR, surface roughness and kerf width. Finally, a genetic algorithm was employed to optimize multiple quality characteristics in WEDM. The conclusion was that the discharge current, pulse duration, dielectric flow rate and the interaction between discharge current and pulse duration were most significant parameters for cutting operation.

Chiang and Chang (2006) machined Al₂O₃ particle reinforced material (6061 alloy) on WEDM and investigated the effects of various input parameters on surface roughness and surface removal rate. Taguchi's L₈ mixed OA and Grey Relational Analysis design technique was applied to optimize the results. The wire electrode used was made of pure copper of diameter 0.20mm. The main findings of their study were that the arc on-time of discharging, arc off-time of discharging, the on time of discharge and the servo voltage have a greater influence on cutting rate and surface roughness.

Ramakrishnan and Karunamoorthy (2006) used the robust design of experiment for achieving multi-response optimization of parameters while machining heat treated tool steel. Zinc coated wire with a diameter of 0.25 mm is used as tool electrode. The study revealed that the pulse on time and ignition current intensity were most significant factors in affecting the various responses.

Manna and Bhattacharyya (2006) offered an experimental investigation to determine the parameters setting during the machining of aluminum-reinforced silicon carbide metal matrix composite (Al/SiC-MMC). On the basis of the experimental results, several conclusions were drawn for the effective machining of Al/SiC- metal matrix composites by the CNC wire-cut EDM. Taguchi's L18 ($2^4 \times 3^4$). Mathematical models relating to the machining performance are established using the Gauss elimination method. OA design was used in formulating the experiment. Open-gap voltage was found as the most significant influencing machining parameter for controlling the MRR. The pulse-on period was second important influencing parameter. The open gap voltage influences the cutting speed significantly. Wire tension and wire feed rate are the most significant and significant machining parameters influencing the surface roughness. Similarly, wire tension and spark gap voltage setting were found as the significant parameters for controlling spark gap. Mathematical models were developed and also verification tests for developed models were carried out. The test results were analyzed for the selection of an optimal combination of parameters for the proper machining of Al/SiC-MMC. The research work investigated the relative importance of parameters affecting different machining characteristics.

IDENTIFIED GAPS IN THE LITERATURE

After a comprehensive study of the existing literature, a number of gaps have been observed in machining of WEDM.

- > Most of the researchers have investigated the influence of a limited number of process parameters on the performance measures of WEDMed parts.
- > Literature review reveals that the researchers have carried out most of the work on WEDM developments, monitoring and control but very limited work has been reported on optimization of process variables.
- > The effect of machining parameters on Aluminium alloy based metal matrix composites has not been fully explored using WEDM with brass wire as an electrode.
- > Multi-response optimization of WEDM process is another thrust area which has been given less attention in past studies.

CHAPTER – 3

EXPERIMENTAL SET-UP AND PROCESS PARAMETER SELECTION

MACHINE TOOL

The experiments were carried out on a wire-cut EDM machine (ELEKTRASPRINTCUT 734) of Electronica Machine Tools Ltd. installed at Advanced Manufacturing Laboratory of Mechanical Engineering Department, N.I.T. Kurukshetra, Haryana, India. The WEDM machine tool (Figure 3.1) specifications are given in the following table.

Table 3.1: WEDM Machine Specifications

Design	Fixed column, moving table
Table size	440 X 650 mm
Max. workpiece height	200 mm
Max. workpiece weight	500 kg
Main table traverse (X, Y)	300, 400 mm
Auxiliary table traverse (u, v)	80, 80 mm
Wire electrode diameter	0.25 mm (Standard) 0.15, 0.20 mm (Optional)
Generator	ELPULS-40 A DLX
Controlled axes	X Y, U, V simultaneous / independent
Literpolation	Linear & Circular
Least input increment	0.0001mm
Least command input (X, Y, u, v)	0.0005mm
Input Power supply	3 phase, AC 415 V, 50 Hz
Connected load	10KVA
Average power consumption	6 to 7 KVA

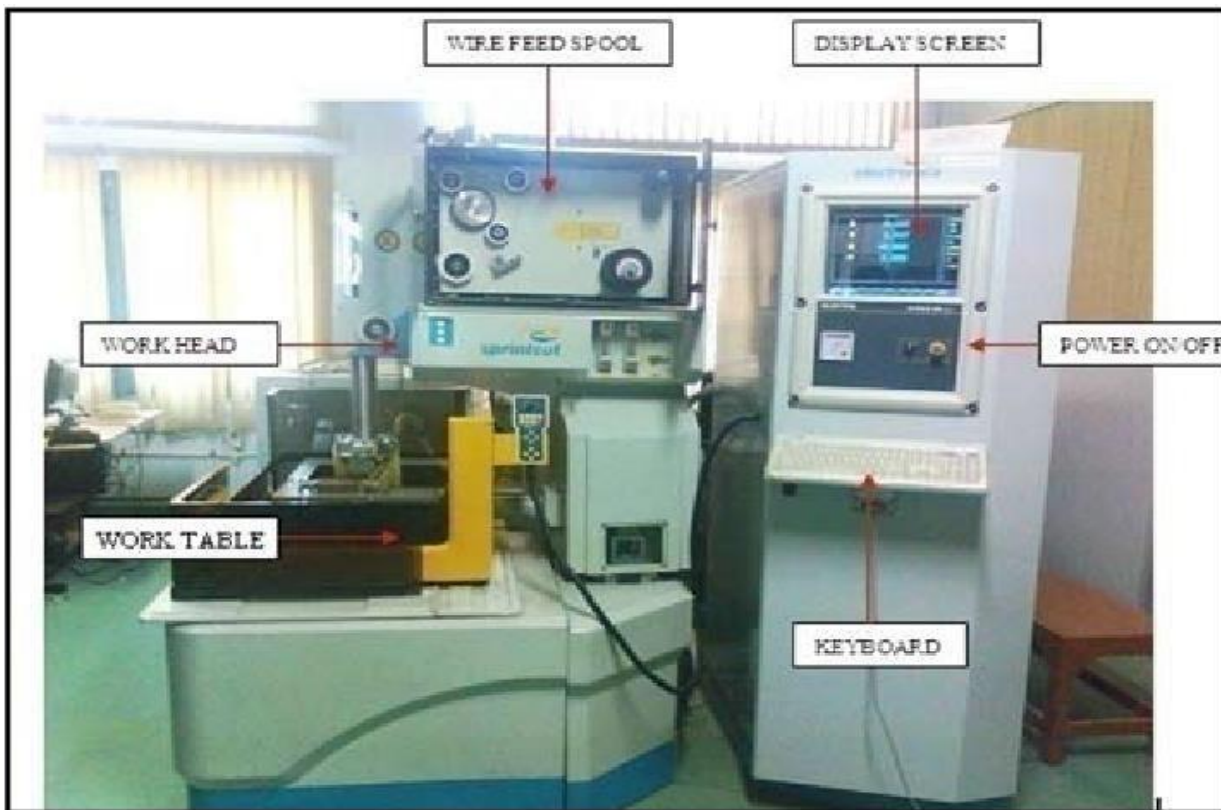


Fig. 2: Pictorial View of WEDM Machine Tool

Figure 3.1: Pictorial View of WEDM Machine Tool

WORKPIECE MATERIAL

Aluminium matrix composites find a wide range of popularity in transportation sector because of lower noise and lower fuel consumptions over another material. Composite materials are old as our human civilization but commercialized after 2nd world war. A composite is a material that consists of constituents produced by a physical combination of pre-existing monolithic compounds to obtain a new material with unique properties when compared to the base composition. Current definition distinguishes a composite from other multiphase materials which are produced by bulk processes where one or more phases result from phase transformation. In general, two phases are present in any composite (a) matrix and (b) reinforcement. Composite is defined as a material which consists of two or more physically and chemically distinct parts which are suitably arranged and are having different properties with respect to those of each constituent part. Industry and material scientist define composite as a material that consists of constituents produced by a physical combination of already existing compound to yield a new material with different properties as compared to the base composition. In general matrix is continuous and surrounds the discontinuous reinforcement phase present in the composite material. The composites are classified according to: (1) their [matrix \(polymer, ceramic, metal and carbon\)](#) (2) their reinforcement, which includes their chemical nature (oxides, [carbides](#) and nitrides), (3) the shape (continuous fibres, short fibres, whiskers and particulates) and (4) the orientation and (5) the processing routes. The other two classes are (d) [carbon-carbon composites](#) and (e) hybrid matrix composites. In a composite, when the matrix is a metal or an alloy of metal, we have a [metal matrix composite](#) (MMC), which forms the percolating network. Other constituent embedded in this metal/metal alloy matrix serves as reinforcement. It is usually non-metallic and are commonly ceramic such as SiC, C, Al₂O₃, SiO₂, B, BN, B₄C, [AlN](#).

Many factors influence the selection of the processing technique, which include the type of reinforcement and matrix, their mechanical and thermal properties and the extent of microstructural integrity desired. The type of reinforcement, variation of reinforcement in matrix

and interaction of matrix with reinforcement plays a vital role in determining the final properties of the composite. Various investigations have been carried out using the different type of matrix materials.

Magnesium based composites has gained a lot of attention due to improved mechanical and corrosion properties. It serves as a potential candidate for application in light weight components. Most Mg–Al alloys contain 8–9% Al with small amount of Zn to give increase in [tensile strength](#). 0.1–0.3 wt% addition of Mn improves [corrosion resistance](#). Composite materials based on Mg alloys reinforced by dispersion particles of [silicon carbide](#) (SiC) shows very low density in the range of 2.0–2.1 g/cm³ and are characterized by 30–40% better mechanical properties than unreinforced [magnesium alloys](#). High reactivity of Mg leads to significant problems in synthesis of Mg-based [MMCs](#). Improper fabrication process can also cause degradation rather than improvement of the mechanical properties. Thus, special attention should be given to the reaction products at the interface between SiC particles and the Mg matrix.

Iron based metal matrix composites are used for heavy duty applications such as railway wagon wheels, braking system etc. Synthesis of iron based composites is carried out using [powder metallurgy](#) technique since it leads to the generation of homogenous phase along with least interaction between the matrix and reinforcement phase. Gupta et al. reported that for Fe-Al₂O₃ metal matrix composites the various properties such as density, hardness, wear, deformation and corrosion is found to improve. Improvement in the properties is found due to iron aluminate (FeAl₂O₄) phase formation. Iron aluminate phase forms as a result of reactive sintering between iron and alumina particles.

Table 3.2: Chemical Composition of In coloy-800

Element	Ni	Cr	Fe	C	Mn	Si	Cu	Al	S
% value	30-	19-	39.5	0.10	1.50	1.0	0.75	0.15-	0.0015
	35	23	min	max	max	max	max	0.60	max

Table 3.3: Physical and Mechanical Constants of Aluminium alloy based metal matrix composites

Density	7.94 gm/cm- [^]
Melting Range	1357-1385T
Specific Heat	460 J/KgT
Tensile Modulus(@ 20»C)	196.5 GPA
Shear Modulus(@ 20»C)	73.4 GPA
Poisson Ratio	0.339
Electrical Resistivity	0.989 [^] nm
Thermal Conductivity	11.5 W/m°C

PREPARATION OF SPECIMENS

Rectangular specimens of 5mm X 5mm X 10mm were prepared from the workpiece using brass wire electrode of 0.25mm diameter.

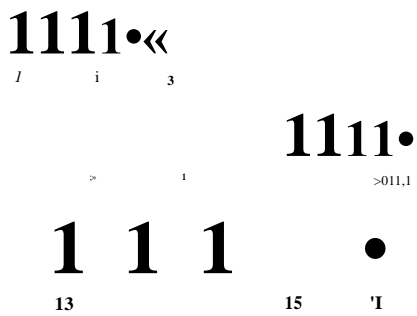


Figure 3.2a: The Specimens Shown Lying Horizontally

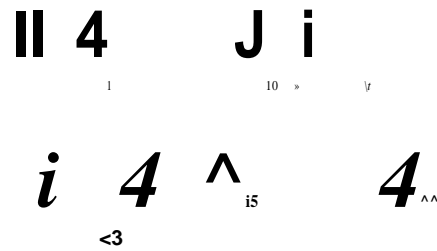


Figure 3.2b: The Specimens Shown Lying Vertically

MEASUREMENT OF EXPERIMENTAL PARAMETERS

The discussions related to the measurement of WEDM experimental parameters e.g. cutting rate, surface roughness, wire wear ratio and dimensional accuracy, are presented in the following subsections.

Cutting Rate

For WEDM, cutting rate is an important characteristic and it should be as high as possible to increase the productivity of machine and also to make the process economical. Cutting rate provides information about the Material Removal Rate (MRR) thus defining the efficiency of the machine. However, in this study, cutting rate which is digitally displayed on the screen of the machine is calculated and is given quantitatively in mm/min. Digital stopwatch was used for precise calculation of the time taken to cut the specimen.

Surface Roughness

Surface roughness is a good predictor of the performance of a mechanical component since irregularities in the surface may form nucleation sites for cracks or corrosion. It depends on the type of contact, accuracy, friction and deformation. Roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if small, the surface is smooth. Roughness is typically considered to be the high frequency, short wavelength component of a measured surface.

Surface roughness is defined by the Ra value. The average roughness is measured by comparing all the peaks and valleys to the mean line, and then averaging them all over the entire cut-off length. Cut-off length signifies the length that the stylus is dragged across the surface; a longer cut-off length will give a more average value, and a shorter cut-off length might give a less accurate result over a shorter stretch of the surface. The surface roughness was measured by Surfcom Roughness Tester available in the Metrology Lab of our institute (Figure 3.3). The tester displays the results in μm . The stylus moves across the specimen and traces the minute in-

egularities of the surface. The vertical stylus displacement during the trace is displayed on the screen of the tester. Condition for Surface Roughness Measurement

- > Cut-off Length: 0.25mm
- > Evaluation Length: 5.00mm
- > Measuring Speed: 0.3mm/sec

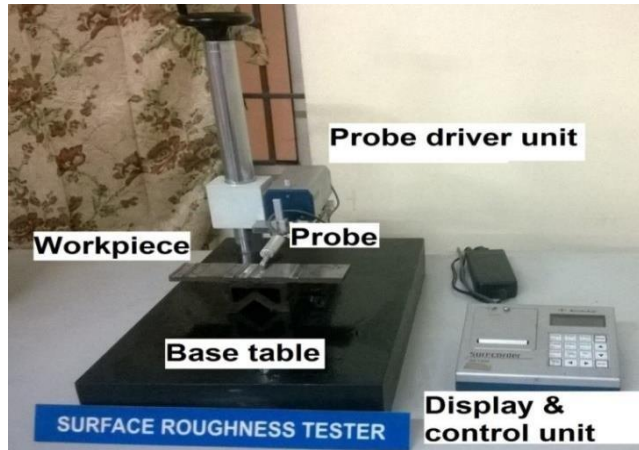


Figure 3.3: Set Up for Surface Roughness Measurement

Dimensional Deviation

In WEDM process, profile traced by the wire and the job profile are not same. Thus, the actual job produced by WEDM is either undersized or oversized. The specimen cross-section is measured with the help of a Mitutoyo's digital micrometer (Figure 3.4) having the least count of 0.001 mm and the deviation of the measured dimension is calculated in percentage using the following expression:

$$\text{Dimensional Deviation} = \frac{\text{Observed Value} - \text{Actual Value}}{\text{Actual value}} \times 100$$



Figure 3.4: Digital Micrometer to measure Dimensional Deviation

Wire Wear Ratio

First, the wire was rolled without machining for one minute and then its weight was measured, which was obtained 3.912 gm. After performing the experiment on Aluminium alloy based metal matrix composites material of 10 mm thickness for cutting each of 5mm*5mm square, the weight

of wire was measured (Final Weight). The time for the experiment was also observed and was multiplied with the weight of one-minute wire roll to obtain the initial wire weight. And the difference in weight was calculated. Then the wire wear rate was found by taking the ratio of wire wear loss to the initial weight of the wire. For weight measurement, the electronic weight balance available in the Civil Engineering **Department of our institute** was used.

$$\text{Wire Wear Ratio} = \frac{\text{Initial Wire Weight} - \text{Final Wire Weight}}{\text{X 100 Initial Wire Weight}}$$

SELECTION OF PROCESS PARAMETERS

In order to identify the process parameters that may affect the machining characteristics of WEDM machined parts Ishikawa cause and effect diagram was constructed and is shown in Figure 3.5

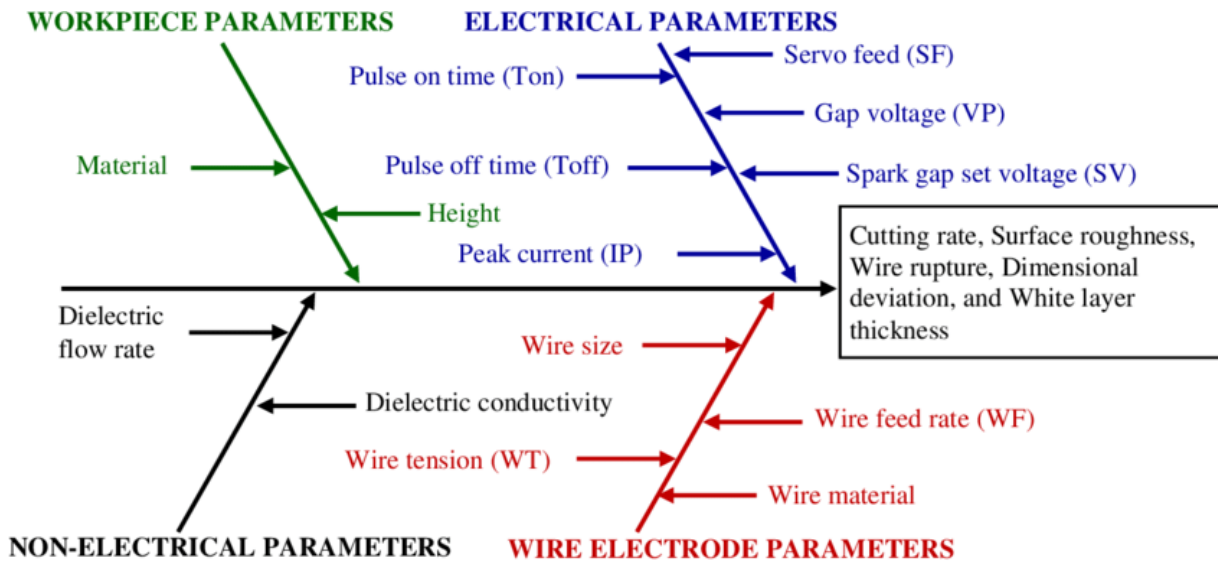


Figure 3.5 Ishikawa Cause and Effect Diagram for WEDM Process

Pulse on time (TON)

Electric discharge machining must occur (ON time) and stop (OFF time) alternately during machining. The Pulse on time is the time in microseconds during which actual electrical discharge occurs between the workpiece and electrode wire (gap). The current flows only in this part of the cycle and voltage is also applied across the electrodes. For getting a long discharge, a large value of ON time must be selected. It is expressed as TON. The discharge energy increases with increase in the TON period, resulting in higher cutting rate. A higher value of discharge may

cause short circuit leading to wire breakage. However, the surface profile tends to deteriorate with higher values of TON levels.

Pulse off time (TOFF)

The Pulse off time is the time in microseconds during which no voltage is applied consequently no electric discharge takes place between workpiece and wire electrode. It is the time between the occurrences of two consecutive sparks. It is expressed as T_{off} . When the values of T_{off} are lower, more number of discharges takes place in a given time, resulting in an increase in the sparking efficiency. As a result, the cutting rate also increases. Low values of discharge may cause wire breakage and due to this cutting efficiency also reduces.

Peak Current (IP)

It is the maximum amount of current flowing through the circuit during pulse on time. It is measured in amperage. This parameter actually reveals how much power is used in WEDM. A higher value of peak current is required for roughing operations and in cavities or details with large surface areas. Cutting rate also increases with increase in peak current. It is expressed as I_p .

Servo voltage (SV)

Servo voltage actually controls the advancing and retracting of the wire. During machining, the mean machining voltage varies depending on the state of the machining between the workpiece and the electrode. If the mean machining voltage is higher than the set voltage level, the wire advances, and if it is lower, the wire retracts (to be precise, the work table advances or retracts instead of wire). So if SV is applied more, than the gap between the wire electrode and the workpiece will be wider and hence electric spark will be less and machining rate will be low. If SV is less, then the gap is less, so electric sparks are more, hence automatically machining/cutting rate will be more. But, the state of machining at the gap may become unstable, resulting in wire breakage. It is expressed as SV.

Duty Cycle

This parameter gives the value of average machining amperes value during a wire EDM process. It is defined as the ratio of pulse-on time to the sum of pulse-on and pulse-off time during a cycle

$$\text{DUTY CYCLE} = \frac{\text{Pulse On time}}{\text{Pulse on time} + \text{Pulse off time}}$$

After calculating the duty cycle, average machining amperes can be calculated as

$$\text{IA} = \text{Ip} \times \text{Duty Cycle}$$

IA = Average amperes

Ip = Peak amperes

Wire Tension

This parameter reveals about the straightness of the electrode wire. That means if wire tension is high then the wire will remain straight otherwise wire might drag behind or even bent. This is the gram equivalent load with which the continuously fed wire is kept under tension so that it remains straight between the wire guides. While the wire is being fed continuously appropriate wire tension avoids the wire deflection from its straight path. The wire deflection is caused due to spark-induced reaction forces and dielectric pressure. Improper setting of tension may result in the job inaccuracies as well as wire breakage.

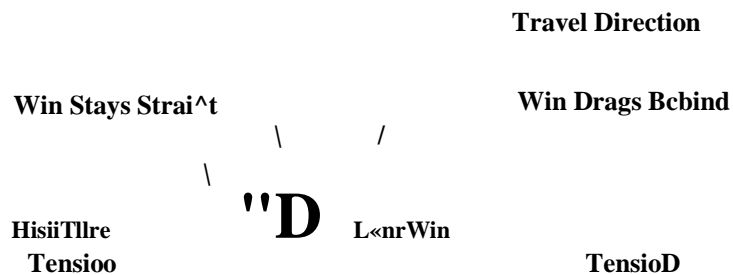


Figure 3.7 Relation between Wire Tension and Wire Drag [Ghodsiyeh et al. 2013]

Wire Feed

Wire Feed tells about the actual speed at which the wire is fed between the guides. If wire feed is high, more wire will be consumed leading to increase in the cost of machining. If speed of wire is less, then wire breakage can occur at high cutting speeds.

Flushing Pressure of Dielectric

Flushing Pressure is an essential parameter of WEDM. The flushing pressure range on this machine is either 1 (High) or 0 (low). High input pressure of water dielectric is necessary for cutting with higher values of pulse power and also while cutting the workpiece of more thickness. Low input pressure is used for thin workpiece and in trim cuts. Commonly used dielectric fluid for WEDM is deionized water because of its environmental friendly characteristic. Electro discharge can occur in the air; however, it is not predictable and can't be used for rough cut machining. To obtain a stable electric discharge, dielectric fluid is required. Within the dielectric

fluid, electric discharge machining can be stabilized with efficient cooling and chip removal. A high-velocity gas jet would lead to better flushing of debris from the discharge gap thus improving surface finishing values. This leads to higher process stability.

PILOT EXPERIMENTS

The purpose of the pilot experiments is to study the variations of the WEDM process parameters on performance measures such as cutting rate, surface roughness, wire wear ratio and dimensional deviation. Also, it is intended to ascertain the range of different parameters required for the experimental design methodology used in this work. The pilot experiments were performed on ELEKTRA SPRINTCUT 734 WEDM machine (Figure 3.1). Various input parameters varied during the experimentation are pulse on-time (TON), pulse off time (TOFF), servo voltage (SV) and peak current (IP). The effects of these input parameters are studied on cutting rate, surface roughness, wire wear ratio and dimensional deviation.

Apart from the parameters mentioned above following parameters were kept constant at a fixed value during the experiments:

- > Workpiece Material: Aluminum alloy based metal matrix composites
- > Cutting Tool: Brass wire of diameter 0.25 mm
- > Conductivity of Dielectric: 15 mho
- > Workpiece Height: 10 mm
- > Servo Feed: 2050 unit

Flushing Pressure: High

CHAPTER – 4

EXPERIMENTAL DESIGN METHODOLOGY

A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. By the statistical design of experiments the process of planning the experiment is carried out, so that appropriate data will be collected and analyzed by statistical methods resulting in valid and objective conclusions. When the problem involves data that are subjected to experimental error, statistical methodology is the only objective approach to analysis. Thus, there are two aspects of an experimental problem: the design of the experiments and the statistical analysis of the data. These two points are closely related since the method of analysis depends directly on the design of experiments employed. The advantages of design of experiments are as follows:

- > Numbers of trials is significantly reduced.
- > Important decision variables which control and improve the performance of the product or the process can be identified.
- > Optimal setting of the parameters can be found out.
- > Qualitative estimation of parameters can be made.
- > Experimental error can be estimated.
- > Inference regarding the effect of parameters on the characteristics of the process can be made.

In the present work, the Taguchi's method has been used to plan the experiments and subsequent analysis of the data collected.

HISTORICAL BACKGROUND OF TAGUCHI APPROACH

Dr. Genichi Taguchi, a Japanese engineer was born on 1st Jan, 1924. He was active in the improvement of Japan's industrial products and processes since the late 1940's. After the Second World War, the allied forces found that the quality of Japanese telephone system was extremely poor and totally unsuitable for long distance communication purposes. To improve the system the allied command recommended that Japan establish research facilities similar to the Bell Laboratories in the US in order to develop state-of-the-art communication systems. The Japanese founded the ECL with Dr. Taguchi in charge of improving R&D productivity and enhancing product quality. He observed that a great deal of money and time was being spent on engineering experimentation and testing. Dr. Taguchi started to develop new methods to optimize the process of engineering experimentations. He developed techniques which are now known as '*Taguchi Techniques*'.

TAGUCHI'S PHILOSOPHY

Dr. Genichi Taguchi, a Japanese scientist dedicated his entire life for generating methods that could tremendously improve the performance of manufacturing systems, while working on limited number of resources. The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce low cost products while maintaining its high quality. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process that in turn defines how well the process is functioning. For this he developed a method based on orthogonal arrays (OA). In this method quality is measured by the deviation of a characteristic, from its target value. A loss function is developed from this deviation. Uncontrollable factors which are also known as noise factors cause such deviations. Taguchi method seeks to minimize the effect of noise because the elimination of noise factors is impractical.

Instead of testing all possible combinations like the full factorial design, the Taguchi method tests selective pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. The Taguchi method is best used when there is an intermediate number of variables (3 to 50), few interactions between variables, and when only a few variables contribute significantly.

The arrays are selected on the basis of number of parameters (input variables) and the number of levels (states). Analysis of variance on the collected data from the Taguchi design of experiments can be used to select new parameter values to optimize the performance characteristic. The data from the arrays can be analyzed by plotting the data and performing ANOVA to test significance. Taguchi's philosophy is founded on the following three very simple and fundamental concepts (Ross, 1988; Roy, 1990):

- > Quality should be designed into the product and not inspected into it.
- > Quality is best achieved by minimizing the deviations from the target. The product or process should be so designed that it is immune to uncontrollable environmental variables.
- > The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi proposes quality in two main areas, which are, off-line and on-line quality control (QC). Off-line quality control encompasses all those activities that are performed before the actual manufacturing of the product or service rendered. On-line quality control activities start from the manufacturing of a product till it goes in the field and also after sale service.

Taguchi refers "off-line" strategy of more importance as these are carried out in the design stages of the product. He observes that poor quality cannot be improved by the process of inspection, screening and salvaging. No amount of inspection can put quality back into the product. Taguchi recommends a three-stage process: system design, parameter design and tolerance design (Ross, 1988, Roy, 1990). In the present work Taguchi's parameter design approach is used to study the effect of process parameters on the various responses of the WEDM process.

EXPERIMENTAL DESIGN STRATEGY

Taguchi recommends orthogonal array (OA) for laying out of experiments. These OA's are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. The array forces all experimenters to design almost identical experiments (Roy, 1990). In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives (Ross, 1988);

- > To establish the best or the optimum condition for a product or process
- > To estimate the contribution of individual parameters and interactions
- > To estimate the response under the optimum condition

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trends of influence of each parameter. The knowledge of contribution of individual parameters is a key in deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control (Ross, 1988). Taguchi suggests (Roy, 1990) two different routes to carry out the complete analysis. First, the standard approach, where the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal- to- noise ratio (S/N) for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function (Barker, 1990). By maximizing the S/N ratio, the loss associated can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. The S/N ratio is treated as a response (transform of raw data) of the experiment. Taguchi recommends (Ross, 1988) the use of outer OA to force the noise variation into the experiment i.e. the noise is intentionally introduced into experiment. However, processes are often times subject to many noise factors that in combination, strongly influence the variation of the response. For extremely noisy systems, it is not generally necessary to identify specific noise factors and to deliberately control them during experimentation. It is sufficient to generate

repetitions at each experimental condition of the controllable parameters and analyze them using an appropriate S/N ratio (Byrne and Taguchi, 1987).

In the present investigation, the raw data analysis and S/N data analysis have been performed. The effects of the selected WEDM process parameters on the selected quality characteristics have been investigated through the plots of the main effects based on raw data. The optimum condition for each of the quality characteristics has been established through S/N data analysis aided by the raw data analysis.

LOSS FUNCTION

The heart of Taguchi method is his definition of the nebulous and elusive term "quality" as the characteristic that avoids loss to the society from the time the product is shipped. Loss is measured in terms of monetary units and is related to quantifiable product characteristic.

Taguchi defines quality loss via his "loss function". He unites the financial loss with the functional specification through a quadratic relationship that comes from a Taylor series expansion. The quadratic function takes the form of a parabola. Taguchi defines the loss function as a quantity proportional to the deviation from the nominal quality characteristic (Roy, 1990). He has found the following quadratic form to be a useful workable function (Roy, 1990):

$$L(y) = k(y-m)^2 \quad (4.1)$$

Where,

L = Loss in monetary units
m - value at which the characteristic should be set
y = actual value of the characteristic

k = constant depending on the magnitude of the characteristic and the monetary unit involved

The loss function represented in Eq. 4.1 is graphically shown in Figure 4.1. The characteristics of the loss function are:

- > The farther the product's characteristic varies from the target value, the greater is the loss.
The loss must be zero when the quality characteristic of a product meets its target value.

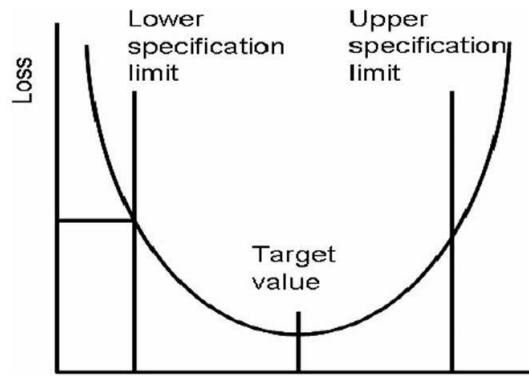


Figure 4.1 Taguchi Loss Function

SIGNAL TO NOISE RATIO (n)

Taguchi's signal to noise ratio is the logarithmic function of desired output. S/N ratio is the ratio of the mean to standard deviation. Here mean refers to signal and standard deviation refers to noise. The ratio depends on the quality characteristic of the product process to be optimized.

A high value of S/N implies that signal is much higher than the random effects of noise factors. Process operation consistent with highest S/N always yields optimum quality with minimum variation.

STEPS IN EXPERIMENTAL DESIGN AND ANALYSIS

The Taguchi experimental design and analysis flow diagram is shown in Figure 4.3. The important steps are discussed in the subsequent article.

Selection of orthogonal array (OA)

In selecting an appropriate OA, the pre-requisites are (Ross, 1988; Roy, 1990):

- > Selection of process parameters and/or interactions to be evaluated
- > Selection of number of levels for the selected parameters

The determination of which parameters to investigate hinges upon the product or process performance characteristics or responses of interest (Ross, 1988). Several methods are suggested by Taguchi for determining which parameters to include in an experiment. These are (Ross, 1988)

- a) Brainstorming
- b) Flowcharting
- c) Cause-Effect diagrams

The total Degrees of Freedom (DOF) of an experiment is a direct function of total number of trials. If the number of levels of a parameter increases, the DOF of the parameter also increases

because the DOF of a parameter is the number of levels minus one. Thus, increasing the number of levels for a parameter increases the total degrees of freedom in the experiment which in turn increases the total number of trials. Thus, two levels for each parameter are recommended to minimize the size of the experiment (Ross, 1988). If curved or higher order polynomial relationship between the parameters under study and the response is expected, at least three levels for each parameter should be considered (Barker, 1990). The standard two level and three level arrays (Taguchi and Wu, 1979) are:

Two level arrays: L4, L8, L16 and L32

Three level arrays: L9, L18 and L27

Selection of Orthogonal Array (OA)

Decide: Number of parameters
 Number of levels
 Interactions of interest
 Degrees of freedom (DOF) required

OA Selection Criterion
 Total DOF of OA > DOF required for parameters and interactions

Assign parameters and interactions to columns of OA using linear graph and/or Triangular tables

• < ^ Noise? J^{\wedge}

Consider noise factors and use
 ^proinate outer array

T

Decide the number of r^etitions
 (at least two repetitions)

T

- > Run the expaiment in random order
- > Record the responses
- > Determine the S/N ratio

Conduct ANOVA on raw data

Identify control parameters which affect mean of the quality characteristics

Conduct ANOVA on S/N data

i :
 Identify control parameters which affect mean and variation of the quality characteristics

±

*

Classify the factors
 Class I: affect both average and variation
 Class II: afTect variation only
 Class m: affect average only
 Class IV: affect nothing

t

Select proper levels of Class I and Class II factors to reduce variation and Class m factors to adjust the mean to the target and Class IV to the most economic levels

- > Predict the mean at die selected levels
- > Determine confidence intervals
- > Determine optimal range
- > Conduct confirmation experiments
- > Draw conclusions

Figure 4.3 Taguchi Experimental Design and Analysis Flow Diagram

The number as subscript in the array designation indicates the number of trials in that array. The total degrees of freedom (DOF) available in an OA are equal to the number of trials minus one (Ross, 1988):

Degrees of Freedom (F) = N-1

N=No. of trials

When a particular OA is selected for an experiment, the following inequality must be satisfied (Ross, 1988):

$F > \text{Total degree of freedom required for parameters and interactions}$

Depending on the number of levels of the parameters and total DOF required for the experiment, a suitable OA is selected.

Assignment of parameters to the OA

The OA's have several columns available for assignment of parameters and some columns subsequently can estimate the effect of interactions of these parameters. Taguchi has provided two tools to aid in the assignment of parameters and interactions to arrays (Ross, 1988; Roy, 1990):

- a) Linear graphs
- b) Triangular tables

Each OA has a particular set of linear graphs and a triangular table associated with it. The linear graphs indicate various columns to which parameters may be assigned and the columns subsequently evaluate the interaction of these parameters. The triangular tables contain all the possible interactions between parameters (columns). Using the linear graphs and /or the triangular table of the selected OA, the parameters and interactions are assigned to the columns of the OA.

Experimentation and data collection

The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried out to reduce bias in the experiment. The data (raw data) are recorded against each trial condition and S/N ratios of the repeated data points are calculated and recorded against each trial condition

Data analysis

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average response curves, interaction graphs etc. (Ross, 1988).

Parameters Design Strategy

Parameter classification

When the ANOVA on the raw data (identifies control parameters which affect average) and S/N data (identifies control parameters which affect variation) are completed, the control parameters may be put into four classes (Ross 1988):

- > Class I: Parameters which affect both average and variation (Significant in both i.e. raw data ANOVA and S/N ANOVA)
- > Class II: Parameters which affect variation only (Significant in S/N ANOVA only)
- > Class III: Parameters which affect average only (Significant in raw data ANOVA only)
- > Class IV: Parameters which affect nothing. (Not significant in both ANOVAs)

The parameters design strategy is to select the proper levels of class I and class II parameters to reduce variation and class III parameters to adjust the average to the target value. Class IV parameters may be set at the most economical levels since nothing is affected.

Prediction of the mean

After determination of the optimum condition, the mean of the response (\bar{y}) at the optimum condition is predicted. The mean is estimated only from the significant parameters. The ANOVA identifies the significant parameters. Suppose, parameters A and B are significant and A2B2 (second level of A, second level of B) is the optimal treatment condition. Then, the mean at the optimal condition (optimal value of the response characteristic) is estimated as (Ross, 1988):

$$\bar{y} = \bar{y} + (A_2 - \bar{y}) + (B_2 - \bar{y})$$

Where,

\bar{y} = Overall mean of the response

A2, B2 = Average values of response at the second levels of parameters A and B respectively.

Determination of confidence interval

The estimate of the mean (\bar{y}) is only a point estimate based on the average of results obtained from the experiment. Statistically this provides a 50% chance of the true average being greater than \bar{y} . It is therefore customary to represent the values of a statistical parameter as a range within which it is likely to fall, for a given level of confidence (Ross, 1988). This range is termed as the confidence

interval (CI). In other words, the confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence (Ross, 1988).

The following two types of confidence interval are suggested by Taguchi in regards to the estimated mean of the optimal treatment condition (Ross, 1988).

- a) Around the estimated average of a treatment condition predicted from the experiment. This type of confidence interval is designated as CIpop (confidence interval for the population).
- b) Around the estimated average of a treatment condition used in a confirmation experiment to verify predictions. This type of confidence interval is designated as CICE (confidence interval for a sample group).

$$CIPOP = jF \sqrt{\frac{V}{n/e} * g}$$

Where,

V = variance of error

n = degree of freedom of factor

e = degree of freedom of error term

$Ngff$ = effective number of replications

$$TV^{jJ} = \frac{\text{Total no. of results}}{\text{DOF of mean (always 1) + DOF of all the factors included to estimate mean performance}}$$

CHAPTER - 5

EXPERIMENTAL RESULTS AND ANALYSIS

INTRODUCTION

The present chapter gives the application of the Taguchi experimental design method. The scheme of carrying out experiments was selected and the experiments were conducted to investigate the effect of process parameters on the output parameters e.g. cutting rate, surface roughness, wire wear ratio and dimensional deviation. The experimental results are discussed subsequently in the following sections.

SELECTION OF ORTHOGONAL ARRAY AND PARAMETER ASSIGNMENT

For the present experimental work four process parameters each at four levels have been decided. It is desirable to have minimum three levels of process parameters to reflect the true behavior of output parameters under study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in Table 5.1.

Table 5.1: Process Parameters and their Levels

Factors	Parameters	Units	Level 1	Level 2	Level 3	Level 4
A	TON	\sqrt{s}	106	112	118	124
B	TOFF	\sqrt{s}	36	44	52	60
C	IP	A	100	130	160	190
D	SV	V	40	55	70	85

As per Taguchi experimental design philosophy a set of four levels assigned to each process parameter has three degrees of freedom (DOF). This gives a total of 12 DOF for four process parameters selected in this work. The nearest four level orthogonal array available satisfying the criterion of selecting the OA is L16 having 15 DOF (Ross 1988). For each trial in the L16 array, the levels of the process parameters are indicated in Table 5.2.

Table 5.2 Calculation of S/N ratio for Delamination factor

Table 5.2: Taguchi's L16 Standard Orthogonal Array

Trial No.	A	B	C	D
1.	1	1	1	1
2.	1	2	2	2

3.	1	3	3	3
4.	1	4	4	4
5.	2	1	2	3
6.	2	2	1	4
7.	2	3	4	1
8.	2	4	3	2
9.	3	1	3	4
10.	3	2	4	3
11.	3	3	1	2
12.	3	4	2	1
13.	4	1	4	2
14.	4	2	3	1
15.	4	3	2	4
16.	• 4	4	1	3

EXPERIMENTAL RESULTS

The WEDM experiments were conducted to study the effect of process parameters over the output response characteristics with the process parameters assigned to columns as given in Table 5.2. The experimental results for cutting rate and surface roughness are given in Table 5.3 and Table reports the same for wire wear ratio and dimensional deviation. 16 experiments were conducted using Taguchi experimental design methodology for obtaining S/N values.

In the present study all the designs, plots and analysis have been carried out using Minitab 17 statistical software.

Table 5.3: Experimental Results of Cutting Rate and Surface Roughness

Trial No.	TON (fis)	TOFF (us)	IP (A)	SV (V)	Cutting Rate (mm/min)	S/N Ratio (dB)	Surface Roughness (fim)	S/N Ratio (dB)
1.	106	36	100	40	1.4105	2.9875	2.394	-7.5825
2.	106	44	130	55	0.8455	-1.4577	2.270	-7.1205
3.	106	52	160	70	0.3545	-9.0077	2.240	-7.0050
4.	106	60	190	85	0.1895	-14.4478	1.850	-5.3434
5.	112	36	130	70	0.9260	-0.6678	3.750	-11.4806
6.	112	44	100	85	0.9005	-0.9103	3.540	-10.9801
7.	112	52	190	40	1.9840	5.9508	3.125	-9.8970
8.	112	60	160	55	0.9905	-0.0829	2.820	-9.0050
9.	118	36	160	85	2.4725	7.8627	4.210	-12.4856
10.	118	44	190	70	2.8965	9.2375	3.980	-11.9977
11.	118	52	100	55	1.7210	4.7156	3.500	-10.8814
12.	118	60	130	40	1.5635	3.8820	3.230	-10.1841
13.	124	36	190	55	3.8500	11.7092	4.640	-13.3304
14.	124	44	160	40	3.5680	11.0485	4.432	-12.9320
15.	124	52	130	85	1.2935	2.2353	4.012	-12.0672
16.	124	60	100	70	0.9895	-0.0917	3.850	-11.7092

Table 5.4: Experimental Results of Wire Wear Ratio and Dimensional Deviation

Triall No.	T ON (us)	TOFF (μs)	IP (A)	SV (V)	Wire Wear Ratio	S/N Ratio (dB)	Dimensional Deviation	S/Nratio (dB)
1.	106	36	100	40	0.1250	18.0618	5.121	-14.1871
2.	106	44	130	55	0.1375	17.2339	5.102	14.1548
3.	106	52	160	70	0.1440	16.8328	5.093	14.1395
4.	106	60	190	85	0.1495	16.5072	5.054	14.0727
5.	112	36	130	70	0.2100	13.5556	5.086	14.1275
6.	112	44	100	85	0.1820	14.7986	5.088	14.1309
7.	112	52	190	40	0.2350	12.5786	5.090	-14.1344
8.	112	60	160	55	0.2275	12.8604	5.083	-14.1224
9.	118	36	160	85	0.3250	9.7623	5.072	-14.1036
10.	118	44	190	70	0.3390	9.3960	5.073	14.1053
11.	118	52	100	55	0.2850	10.9031	5.092	14.1378
12.	118	60	130	40	0.3095	10.1868	5.088	14.1309
13.	124	36	190	55	0.3840	8.3134	5.079	14.1156
14.	124	44	160	40	0.3650	8.7541	5.098	14.1480
15.	124	52	130	85	0.3300	9.6297	5.066	14.0933
16.	124	60	100	70	0.3125	10.1030	5.074	14.1070

ANALYSIS AND DISCUSSION OF RESULTS

The WEDM experiments were conducted by using the parametric approach of the Taguchi's method. The effects of individual WEDM process parameters, on the selected quality characteristics - cutting rate, surface roughness, wire wear ratio and dimensional deviation, have been discussed in this section. The average value and S/N ratio of the response characteristics for each variable at different levels were calculated from experimental data. The main effects of process variables both for raw data and S/N data were plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics. The analysis of variance (ANOVA) of raw data and S/N data is carried out to identify the significant variables and to quantify their effects on the response characteristics. The most favorable values (optimal settings) of process variables in terms of mean response characteristics are established by analyzing the response curves and the ANOVA tables.

Effect on Cutting Rate

Figure 5.1 shows the main effect plot for cutting rate (Raw Data). It is quite evident from the graph that the cutting rate increases with increase in pulse on time while it continuously decreases with increase in pulse off time and servo voltage. The cutting rate first decreases and then increases rapidly with the increase in peak current.

This is due to the fact that pulse discharge energy increases with increase in TON time and peak current leading to a faster cutting rate. As the pulse off time decreases, the number of discharges within a given period becomes more which leads to a higher cutting rate. But when pulse off time and servo voltage increase, cutting rate decreases. This is owing to the fact that time between two sparks increased with increasing pulse off time causing reduction in cutting rate.

It is also evident that cutting rate is minimum at first level of pulse on time and maximum at first level of pulse off time.

Selection of optimal levels

In order to study the significance of the process variables towards cutting rate, analysis of variance (ANOVA) was performed. From table 5.5, it is clear that pulse on time, pulse off time, peak current, servo voltage significantly affect the mean value of cutting rate. The pulse on time has the greatest effect on cutting rate with about 45% of total contribution and is followed by pulse off time, peak current and servo voltage in that order.

As cutting rate is the "higher the better" type quality characteristic, it can be seen from Figure 5.1 that the fourth level of pulse on time (A4), first level of pulse off time (B1), fourth level of peak current (C4), and first level of servo voltage (D1) provide maximum value of cutting rate. The S/N data analysis (Figure 5.2) suggests fourth level of pulse on time (A4), first level of pulse off time (B1), fourth level of peak current (C4), and first level of servo voltage (D1) as the best levels for maximum CR in WEDM process.

Table 5.6 ANOVA results for Cutting Rate (S/N ratios)

Source	DF	Seq SS	Adj MS	F	P	%age Contribution
TON	3	376.99	125.663	12.77	0.032	52.479
TOFF	3	164.79	54.931	5.58	0.096	22.940
IP	3	0.16	3.386	0.34	0.798	1.414
SV	3	136.89	45.630	4.64	0.120	19.056
Error	3	29.52				4.109
Total	15	718.35				

Effect on Surface Roughness

Figure 5.3 shows the main effect plot for surface roughness (Raw Data). It can be seen from the graph that the surface roughness increases with increase in pulse on time while it continuously decreases with increase in pulse off time. The surface roughness shows a little variation with peak current and servo voltage.

It is found experimentally that increasing the pulse on time increases the surface roughness of the specimen. This is due to the increased number of discharges per second which increase the MRR thus deteriorating the surface profile. As the pulse off time decreases, the number of discharges increases which causes poor surface accuracy. The parameter peak current was found insignificant and servo voltage had very little impact in the analysis.

Selection of Optimal Levels

In order to study the significance of the process variables towards surface roughness, analysis of variance (ANOVA) was performed. From table 5.7, it is clear that pulse on time, pulse off time, servo voltage significantly affect the mean SR values. The pulse on time has the greatest effect on surface roughness with about 80% of total contribution and is followed by pulse off time, servo voltage and peak current in that order.

As surface roughness is the "lower the better" type quality characteristic, it can be seen from Figure 5.3 that the first level of pulse on time(A1), fourth level of pulse off time(B4), fourth level of peak current (C4), and fourth level of servo voltage (D4) provide minimum value of surface roughness. The S/N data analysis (Figure 5.4) suggests the same settings of the parameters for best finish.

Table 5.7 ANOVA results for Surface Roughness (Raw Data)

Source	DF	Seq SS	Adj MS	F	P	%age Contributio n
TON	3	20.7989	6.93297	1247.30	0.000	80.338
TOFF	3	4.7998	1.59992	287.84	0.000	18.539
IP	3	0.0369	0.01231	2.21	0.265	0.142
SV	3	0.2368	0.07894	14.20	0.028	0.914
Error	3	0.0167	0.00556			0.064
Total	15	25.8891				

Table 5.8 Af WVA results for Surface Roughness (S/N Data)

Source	DF	Seq SS	Adj MS	F	P	%age Contributio n
TON	3	212.672	70.891	29.91	0.010	72.921
TOFF	3	50.774	16.925	7.14	0.070	17.441
IP	3	9.381	3.127	1.32	0.413	3.222
SV	3	11.181	3.727	1.57	0.359	3.840
Error	3	7.109	2.370			2.441
Total	15	291.117				

Effect on Wire Wear Ratio

Figure 5.5 shows the main effect plot for wire wear ratio (Raw Data). It can be seen from the graph that the wire wear ratio increases with increase in pulse on time and peak current while it shows little variation with pulse off time and servo voltage.

It is found experimentally that increasing the pulse on time increases the wire wear ratio thus significantly adding to the economic aspect of the process. This is due to the increase in the discharge energy which causes more wear of the wire. The parameter pulse off time and servo voltage had very little impact in the wire wear analysis.

3.1 Selection of Optimal Levels

In order to study the significance of the process variables towards wire wear ratio, analysis of variance (ANOVA) was performed. From tables 5.9 and 5.10, it is clear that pulse on time and peak current significantly affect both the mean and the variation in the WWR values. The parameter pulse on time has the greatest effect on wire wear ratio with about 94% of total contribution.

As wire wear ratio is the "lower the better" type quality characteristic, it can be seen from Figure that the first level of pulse on time(A1), third level of pulse off time(B3), first level of peak current (C1), and fourth level of servo voltage (D4) provide minimum value of wire wear ratio. The S/N data analysis (Figure 5.6) suggests same settings of the process parameters for minimum WWR.

Table 5.9 ANOVA results for Wire Wear Ratio (Raw Data)

Source	DF	Seq SS	Adj MS	F	P	%age Contribution
TON	3	0.109371	0.036457	3717.35	0.000	94.170
TOFF	3	0.000403	0.000134	13.68	0.030	0.346
IP	3	0.005928	0.001976	201.49	0.001	5.104
SV	3	0.000411	0.000137	13.97	0.029	0.353
Error	3	0.000029	0.000010			0.024
Total	15	0.116142				

Table 5.10 ANOVA results for Wire Wear Ratio (S/N Data)

Source	DF	Seq SS	Adj MS	F	P	%age Contribution
TON	3	157.735	52.5783	4714.68	0.000	95.443
TOFF	3	0.045	0.0150	1.34	0.407	0.027
IP	3	7.181	2.3937	214.65	0.001	4.345
SV	3	0.270	0.0901	8.08	0.060	0.163
Error	3	0.033	0.0112			0.019

Table 5.11 ANOVA results for Dimensional Deviation (Raw Data)

Source	DF	Seq SS	Adj MS	F	P	%age Contribution
TON						
TOFF	3	0.000426	0.000142	9.63	0.048	11.491
IP	3	0.000612	0.000204	13.84	0.029	16.509
SV	3	0.000800	0.000267	18.11	0.020	21.580
Error	3	0.001825	0.000608	41.31	0.006	49.231
Total	3	0.000044	0.00015			1.186
	15	0.003707				

Table 5.12 ANOVA results for Dimensional Deviation (S/N Data)

Source	DF	Seq SS	Adj MS	F	P	%age Contribution
TON	3	0.001234	0.000411	9.51	0.048	11.416
TOFF	3	0.001785	0.000595	13.76	0.029	16.514
IP	3	0.002334	0.000778	17.99	0.020	21.593
SV	3	0.005326	0.001775	41.04	0.006	49.273
Error	3	0.000130	0.000043			1.202
Total	15	0.010809				

ESTIMATION OF OPTIMUM RESPONSE CHARACTERISTICS

Cutting Rate

The optimum value of cutting rate is predicted at the optimal level of significant variables which have already been selected as the fourth level of pulse on time (A4), first level of pulse off time (Bi), fourth level of peak current (C4) and first level of servo voltage (Di).

$$Y_o = A^{\wedge} + B^{\wedge} + C4 + D1 - 3T \tag{5.1}$$

Where,

$$T = \text{overall mean cutting rate} = 1.622$$

$$A4 = \text{average cutting rate at fourth level of pulse on time} = 2.425$$

$$Bi = \text{average cutting rate at first level of pulse off time} = 2.164$$

$$C4 = \text{average cutting rate at fourth level of peak current} = 2.23$$

$$Di = \text{average cutting rate at first level of servo voltage} = 2.131$$

Substituting the values of various terms in above equation

$$\bullet K_{,,} = 2.425 + 2.164 + 2.23 + 2.131 - (3 \times 1.622) = 4.084$$

The 95 % confidence intervals of population (CIpop) are calculated using the following Equations

$$Chop = jFainJe) * \text{£} \tag{5-2}$$

Where,

V_e = variance of error

n = degree of freedom of factor

fg = degree of freedom of error term

N_{eff} = effective number of replications

Total no. of results

$eff \sim$ poF of mean (always 1)+DOF of all the factors included to estimate mean performance

$$F_{(ain, fg)} = 9.2\% \quad \hat{\mu} = 0.00740 \quad n = 3 \quad \hat{\sigma} = 1.230$$

Putting the values in above equation

$$CIPOP = \pm 0.2362$$

Therefore predicted confidence interval for population is

$$Y_g - CIPOP < \mu > \hat{\mu} \pm \hat{\sigma} \sqrt{t_{pop}}$$

$$3.8478 < 4.084 > 4.3202$$

Surface Roughness

The optimum value of surface roughness is predicted at the optimal level of significant variables which have already been selected as the first level of pulse of time (A1), fourth level of pulse off time (B4), fourth level of peak current (C4) and fourth level of servo voltage (D4).

$$K_o = \hat{\mu}_1 + \hat{\mu}_4 + \hat{\mu}_C + \hat{\mu}_D - 3T$$

Where,

T = overall mean cutting rate = 3.406

$\hat{\mu}_4$ = average cutting rate at third level of pulse on time = 1.723

$\hat{\mu}_1$ = average cutting rate at first level of pulse off

time = 2.743 $\hat{\mu}_C$ = average cutting rate at second

level of peak current = 3.350 $\hat{\mu}_D$ = average cutting

rate at first level of servo voltage = 3.205

Substituting the values of various term in above

equation

$$Y_o = 1.723 + 2.743 + 3.350 + 3.205 - (3 \times 3.406) = 0.803$$

$$CIPO = \pm 0.2048$$

(5.3)

Therefore predicted confidence interval for the population is

$$Y_f - CIPO < Y_o > Y_f + CIPO$$

$$0.5982 < 0.803 > 1.0078$$

Wire Wear ratio

The optimum value of wire wear ratio is predicted at the optimal level of significant variables which have already been selected as the first level of pulse of time (A1), third level of pulse off time (B3), first level of peak current (C1) and fourth level of servo voltage (D4).

$$Y_o = J^{\wedge} + B^{\wedge} + C1 + D^{\wedge} - 3f \tag{5.4}$$

Where,

T = overall mean cutting rate = 0.2538

A1 = average cutting rate at third level of pulse on time = 0.139

S3 = average cutting rate at first level of pulse off time = 0.248

C1 = average cutting rate at second level of peak current = 0.226

D^{\wedge} = average cutting rate at first level of servo voltage = 0.246

Substituting the values of various term in above equation

$$Y_a = 0.139 + 0.248 + 0.226 + 0.246 - (3 \times 0.2538) = 0.0976$$

$$CIPO = \pm 0.0086$$

Therefore predicted confidence interval for the population is

$$YQ - CIPO < Kp > F,, + CIPO$$

CHAPTER 6

CONCLUSIONS AND REFERENCES

CONCLUSION

1. The effects of process parameters viz. pulse on time, pulse off time, peak current and servo voltage on response characteristics viz. cutting rate, surface roughness, wire wear ratio and dimensional deviation were studied.
2. The optimal set of parameters were obtained for various performance measures using Taguchi's design of experiment methodology.
3. All the process parameters pulse on time, pulse off time, peak current and servo voltage are significant.
4. For cutting rate pulse on time (45.043), for surface roughness pulse on time (80.338), for wire wear ratio pulse on time (94.170) and for dimensional deviation servo voltage (49.231) are the most significant factors.
5. Optimal set of parameters for cutting rate is A4-B1-C4-D1, for surface roughness A1-B4-C4-D4, for wire wear ratio A1-B3-C1-D4 and for dimensional deviation A4-B4-C4-D4.

Machining Characteristics	Optimal Settings Of Parameters	Value Obtained By Taguchi Method	Confidence Interval Of The Population
Cutting Rate	A4 B1 C4 D1	4.084	±0.2362
Surface Roughness	A1 B4 C4 D4	0.803	±0.2048
Wire Wear Ratio	A1 B3 C1 D4	0.0976	±0.0086
Dimentional Deviation	A4 B4 C4 D4	5.045	±0.010

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