“PARAMETRIC OPTIMIZATION OF WIRE ELECTRIC DISCHARGE MACHINING ON D2 DIE STEEL USING TAGUCHI’S METHODOLOGY”

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A MAJOR THESIS

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STUDENT'S DECLEARATION

I, hereby declare that the dissertation entitled "PARAMETRIC OPTIMIZATION OF WIRE ELECTRIC DISCHARGE MACHINING ON D2 DIE STEEL USING TAGUCHI'S METHODOLOGY" being presented here in the partial fulfillment for the award of the Degree of master of Engineering (production Engineering), is an authentic record of own work carried out by me under the guidance and supervision of Mr. R.K. Singh and Mr. M.S. Niranjan , Department of Mechanical Engineering, Delhi College of Engineering Delhi.

I, further declare the the dissertation has not been submitted to any other Institute/ university for the award of any degree or diploma or any other purpose whatsoever.

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CERTIFICATE

This is to certify that the major report entitled ***"parametric optimization of wire electric discharge machining on D2 die steel using taguchi's methodology"*** which is being submitted by Mr. Ritesh Mehra to the Mechanical Engineering (Production engineering) Department of the Delhi College of Engineering, Delhi for the award of the degree of Master of Engineering (Production Engineering) is a record of bonafide research work carried out by him. He has worked under my guidance and supervision.

The results contained in this thesis, have not been submitted in part or full to any other university for the award of any degree or diploma.

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ABSTRACT

The aim of this project is to optimize the WEDM combination parameters in order to get the optimum material removal rate (MRR) and surface roughness (SR) on material of D2 Die Steel. This project begins with a preliminary design that proposes on the design factors which have possibility to affect the responses. In this project we are concentrating on only five parameters for experiment which are called control parameter. That are peak current (IP), time on (T ON), time off (T OFF), wire feed (WF) and wire tension (WT). Remaining all parameters which are called fixed parameter and their optimum values are taken constant throughout the experiments. It starts with application of Design of Experiment (DOE) on Taguchi Method that applying L-18 (6^1,3^4) from the Orthogonal Array (OA). Results which have been obtained from the 18 trials of experiments are analyzed to get the optimum condition and predicted value. Also an analysis is done on multi-quality by MINITAB 15 software to get a best combination factors for all combination of the responses.

The optimal values obtained using the multi-quality optimization model has been validated by confirmation experiments. This dissertation work present an investigation on the effect and optimization of the machining parameter for material removal rate and surface roughness, in wire electric discharge machining (WEDM) of D2 die steel.

Key words: ANNOVA, WEDM, SR, MRR

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NOMENCLATURE AND ACRONYMS

Symbol	Notation	Units
MRR	Material Removal Rate (in cross sectional area)	mm^2/min
SR	Surface roughness	μm
T-ON	Pulse on time.	μs
T-OFF	Pulse off time.	μs
S/N ratio	Signal to noise ratio.	dB
ANOVA	Analysis of Variance	
WEDM	Wire Electric Discharge Machine/ Machining	
EDM	Electric Discharge Machine/ Machining	
NCM	Non-conventional machining.	
DOE	Design of experiment	
OA	Orthogonal array	

Chapter 1

INTRODUCTION

EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive. WEDM is a type of EDM process. In recent years, the technology of wire electrical discharge machining (WEDM) has been improved significantly to meet the requirements in various manufacturing fields, especially in the precision die industry. WEDM is a thermo electrical process in which material is eroded from the work piece by a series of discrete sparks between the work piece and the wire electrode (tool) separated by a thin film of dielectric fluid (deionized water) that is continuously fed to the machining zone to flush away the eroded particles. The movement of wire is controlled numerically to achieve the desired three-dimensional shape and accuracy of the work piece. The mechanism of WEDM is shown in Fig. 1.1.

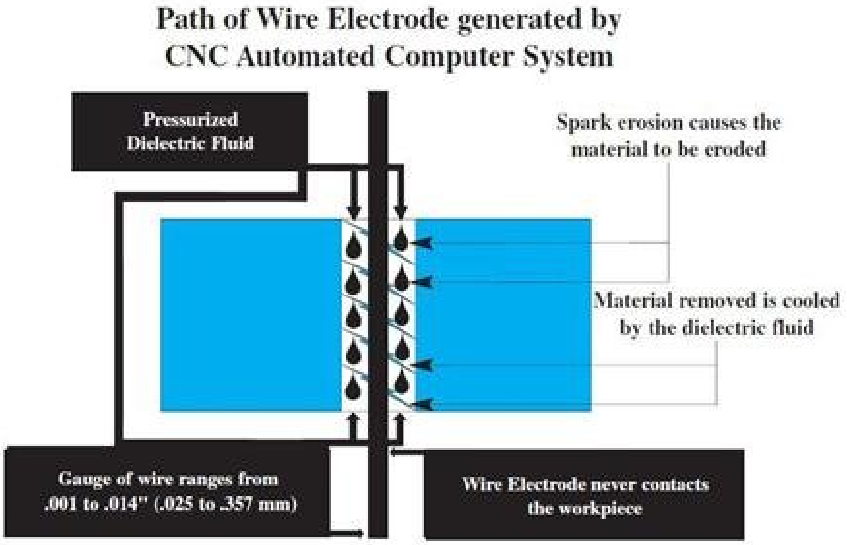


Fig 1.1 Mechanism of WEDM

The history of EDM Machining Techniques goes as far back as the 1770s when it was discovered by an English Scientist. However, Electrical Discharge Machining was not fully taken advantage of until 1943 when Russian scientists learned how the erosive effects of the technique could be controlled and used for machining purposes.

When it was originally observed by Joseph Priestly in 1770, EDM Machining was very imprecise and riddled with failures. Commercially developed in the mid 1970s, wire EDM began to be a viable technique that helped shape the metal working industry we see today. In the mid 1980s.The EDM techniques were transferred to a machine tool. This migration made EDM more widely available and appealing over traditional machining processes.

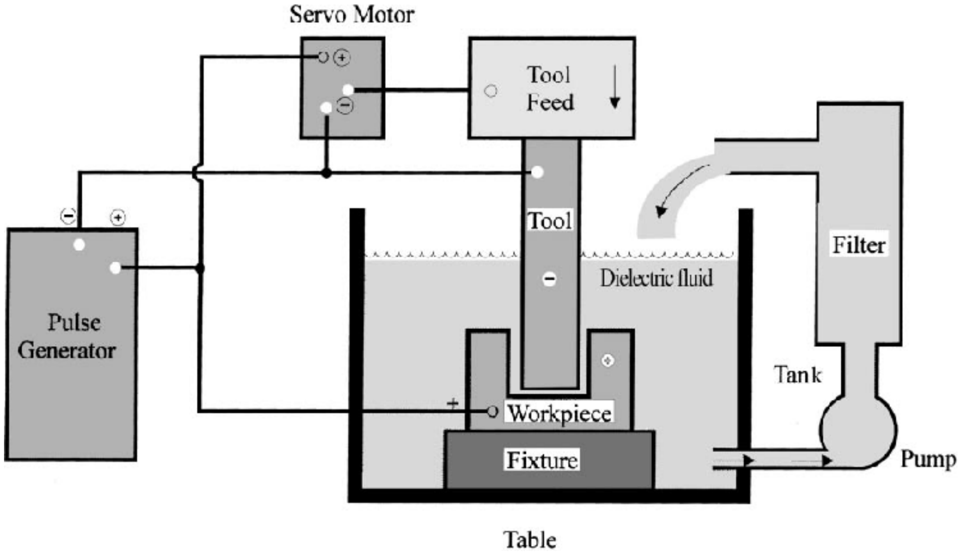
The new concept of manufacturing uses non-conventional energy sources like sound, light, mechanical, chemical, electrical, electrons and ions. With the industrial and technological growth, development of harder and difficult to machine materials, which find wide application in aerospace, nuclear engineering and other industries owing to their high strength to weight ratio, hardness and heat resistance qualities has been witnessed. New developments in the field of material science have led to new engineering metallic materials, composite materials and high tech ceramics having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion. Non-traditional machining has grown out of the need to machine these exotic materials. The machining processes are non-traditional in the sense that they do not employ traditional tools for metal removal and instead they directly use other forms of energy. The problems of high complexity in shape, size and higher demand for product accuracy and surface finish can be solved through non-traditional methods. Currently, non-traditional processes possess virtually unlimited capabilities except for volumetric material removal rates, for which great advances have been made in the past few years to increase the material removal rates. As removal rate increases, the cost effectiveness of operations also increase, stimulating ever greater uses of nontraditional process. The Electrical Discharge Machining process is employed widely for making tools, dies and other precision parts.

EDM has been replacing drilling, milling, grinding and other traditional machining operations and is now a well established machining option in many manufacturing industries throughout the world. And is capable of machining geometrically complex or hard material components, that are precise and difficult-to-machine such as heat treated tool steels, composites, super alloys, ceramics, carbides, heat resistant steels etc. being widely used in die and mold making industries, aerospace, aeronautics and nuclear industries. Electric Discharge Machining has also made its presence felt in the new fields such as sports, medical and surgical, instruments, optical, including automotive R&D areas.

1.1. Principle of EDM

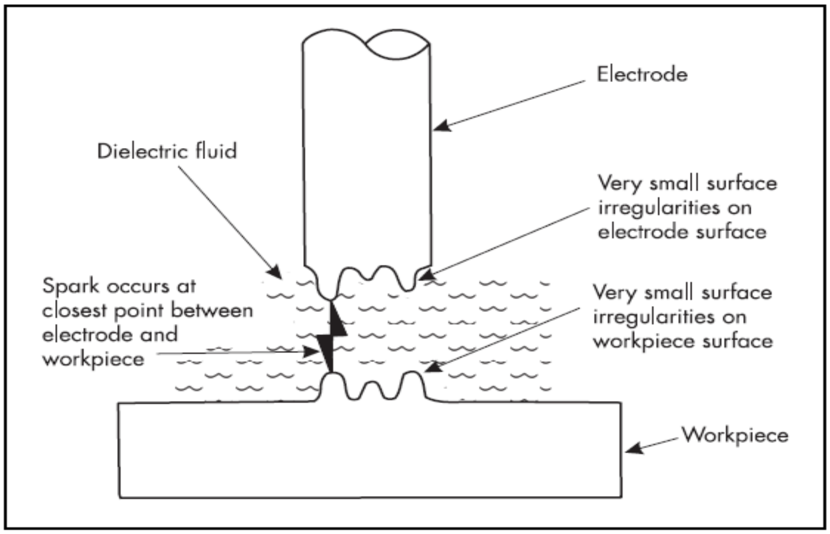
The electro sparking method of metal working involves an electro erosion effect which connotes the breakdown of electrode material accompanying any from electric discharge. (The discharge is usually through a gas, liquid or in some cases solids.) A necessary condition for producing a discharge is the ionization of the dielectric that is splitting up if its molecules in to ions and electrons.

Consider the case of a discharge between two electrodes (tool cathode and work anode) through a gaseous or liquid medium. As soon as suitable voltage is applied across the electrodes, the potential intensity of the electric field between them build up until at some predetermined value, the individual electron break loose from the surface of the cathode and are impelled towards the anode under the influence the field forces. While moving in the inter-electrode space, the electrons collide with the neutral molecules of the dielectric detaching electrons from them and causing ionization. At some time or the other, the ionization becomes such that a narrow channel of continuous conductivity is formed. When this happens, there is a considerable flow of electrons along the channel to the anode, resulting in a momentary current impulse or discharge. The liberation of energy accompanying the discharge leads to the generation of extremely high temperature, between 8000 C and 12000 C, causing fusion or partial vaporization of the metal and dielectric fluid at the point of discharge. The metal in the form of liquid drop is dispersed in to the space surrounding the electrodes by the explosive pressure of the gaseous products in the discharge. This results in the formation of a tiny crater at the point of discharge in the work piece.

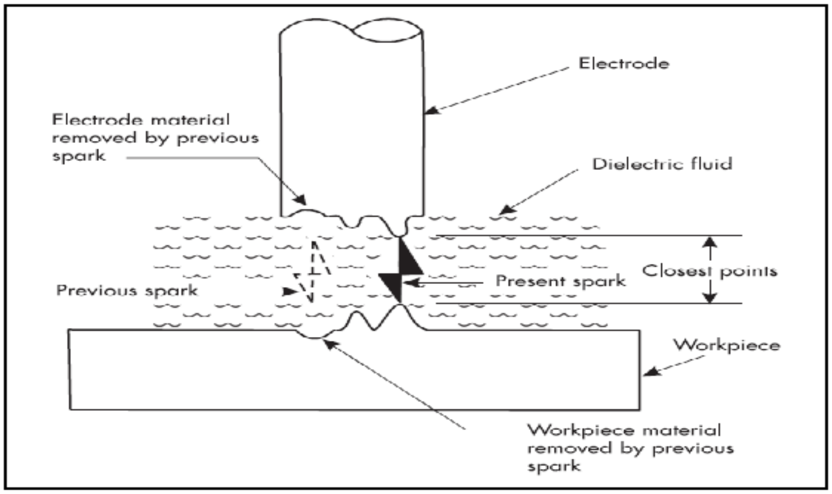


1.2. Schematic diagram of EDM

Fig.1.2 is shown the electric setup of the Electric discharge machining. The tool is made cathode and work piece is anode. When the voltage across the gap becomes sufficiently high it discharges through the gap in the form of the spark in interval of from 10 of micro seconds. And positive ions and electrons are accelerated, producing a discharge channel that becomes conductive. It is just at this point when the spark jumps causing collisions between ions and electrons and creating a channel of plasma. Fig 1.3 & fig 1.4 shows the spark generates between the closest point of the electrode and work piece.



1.3. Sparking occurs at closest point between the electrode and work



1.4. Next spark occurs at closest points between electrode and work piece

1.2. Types of EDM –

Basically there are two types of EDM

1. Die-sinking EDM
2. Wire-cut EDM

1.2.1. Die-sinking EDM-

In the Sinker EDM Machining process, two metal parts submerged in an insulating liquid are connected to a source of current which is switched on and off automatically depending on the parameters set on the controller. When the current is switched on, an electric tension is created between the two metal parts. If the two parts are brought together to within a fraction of an inch, the electrical tension is discharged and a spark jumps across. Where it strikes, the metal is heated up so much that it melts. Sinker EDM, also called cavity type EDM or volume EDM consists of an electrode and work piece submerged in an insulating liquid such as, more typically, oil or, less frequently, other dielectric fluids. The electrode and work piece are connected to a suitable power supply. The power supply generates an electrical potential between the two parts. As the electrode approaches the work piece, dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.

These sparks usually strike one at a time because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the work piece. As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters. Schematic diagram of Die sinking EDM is shown in the fig. 1.5.

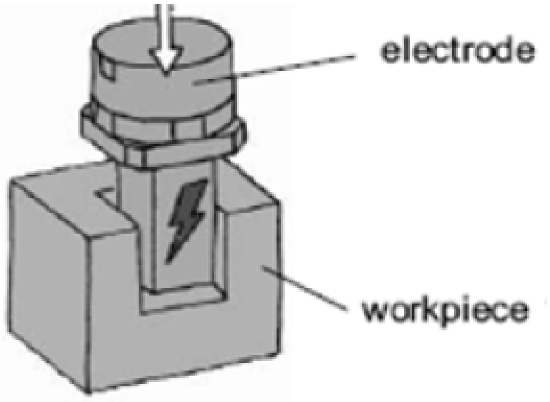


Fig. 1.5 Die sinking EDM

1.2.2. Wire-cut EDM –

Wire EDM Machining (also known as Spark EDM) is an electro thermal production process in which a thin single-strand metal wire (usually brass) in conjunction with de-ionized water (used to conduct electricity) allows the wire to cut through metal by the use of heat from electrical sparks. A thin single-strand metal wire, usually brass, is fed through the work piece, submerged in a tank of dielectric fluid, typically de-ionized water. Wire-cut EDM is typically used to cut plates as thick as 300mm and to make punches, tools, and dies from hard metals that are difficult to machine with other methods.

Wire-cut EDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. If the energy/power per pulse is relatively low (as in finishing operations), little change in the mechanical properties of a material is expected due to these low residual stresses, although material that hasn't been stress-relieved can distort in the machining process. Due to the inherent properties of the process, wire EDM can easily machine complex parts and precision components out of hard conductive materials. Schematic diagram of WEDM is shown in fig 1.6.

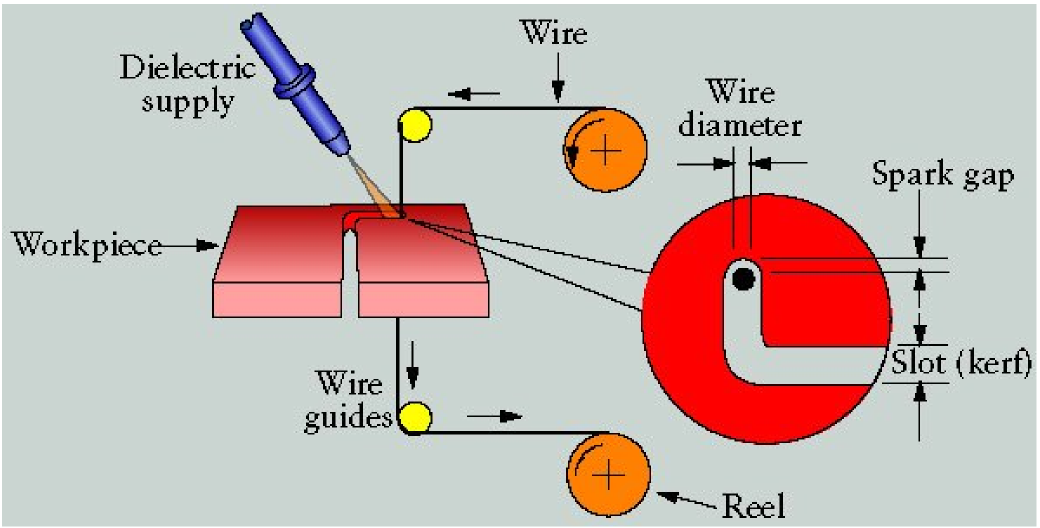


Fig 1.6 Schematic diagram of WEDM

1.3 Machining parameters of Wire EDM process

Different parameters controlling the energy and machining conditions are given below with their setting formats

1. TON: Pulse ON Time

During this period the voltage (VP) is applied across the electrodes

Range: 000-031 (in step of 1) N-pulse (normal pulse)

100-131 (in step of 1) e-pulse (equi-energy pulse)

Higher the TON setting larger is the pulse on period.

The single pulse discharge energy increases with increasing TON period, resulting in higher cutting rate. With higher value of TON, however, surface roughness tends to be higher. The higher value of discharge energy may also cause wire breakage.

2. TOFF: Pulse OFF Time

Voltage for the gap is absent during this period.

Range: 00-63 (in step 1)

Higher the TOFF setting larger is the pulse off period.

With a lower value of TOFF, there is more number of discharges in a given time, resulting in increase in the sparking efficiency. As a result, the cutting rate also increases.

Using very low values of TOFF period, however, may cause wire breakage which in turn reduces the cutting efficiency.

As and when the discharge condition becomes unstable, one can increase the TOFF period. This will allow lower pulse duty factor and will reduce the average gap current.

3. Peak current (A)

Range: 010-230 (in step 1)

Higher the IP setting larger is the peak current value.

Increase in the IP value will increase the pulse discharge energy which in turn can improve the cutting rate further.

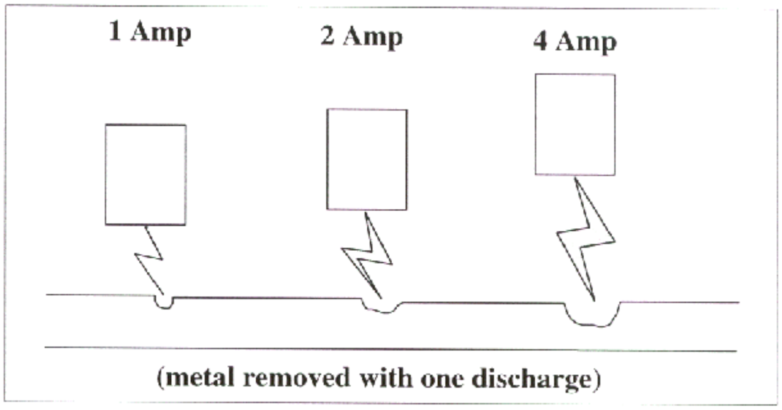


Fig 1.7 Effect of Current on the MRR and SR

4. Duty factor

Duty factor is a percentage of the pulse duration relative to the total cycle time. Generally, a higher duty factor means increased cutting efficiency. It is calculated in percentage by dividing pulse duration by the total cycle time (on-time + off-time).

Duty Factor (%) = (Pulse duration /Total cycle time) × 100

5. Pulse frequency

Pulse frequency is the number of cycles produced across the gap in one second. The higher the frequency, finer is the surface finish that can be obtained. With an increase of number of cycles per second, the length of the on-time decreases. Short on-times remove very little material and create smaller craters. This produces a smoother surface finish with less thermal damage to the work piece. Pulse frequency is calculated by dividing 1000 by the total cycle time (on-time + off-time) in microseconds.

Pulse Frequency (kHz) = 1000/Total cycle time

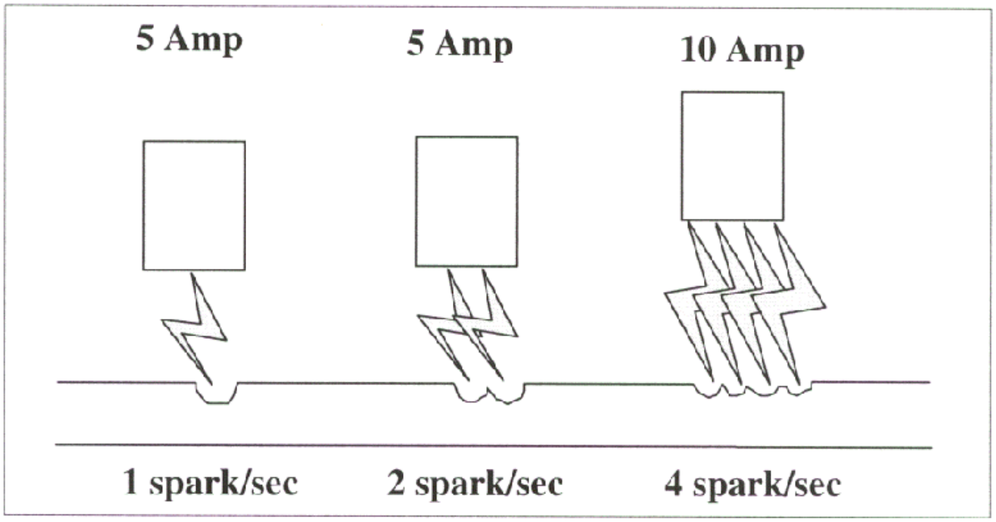


Fig 1.8 Effect of the discharge frequency on the MRR and SR

6. **VP: pulse peak voltage**

   This is for selection of open gap voltage.

   Range 1 or 2

Increase in the VP value will increase the pulse discharge energy which in turn can improve the cutting rate. Normally it is always ‘2’. For latest machines only setting ‘2’ is available.

7. **WP: flushing pressure of water dielectric**

   This is for selection of flushing input pressure.

   Range: 0 to 15 (for 16 step programmable flushing)

   0 or 1 (0- low pressure, 1-high pressure)

High input pressure of water dielectric is necessary for cutting with higher values of pulse power and also while cutting the jobs of higher thickness. Low input pressure is used for thin jobs and in trim cuts.

8. WF: wire feed rate

This is a feed rate at which the fresh wire is fed continuously for sparking.

Range: 01-15 (in step of 1)

Higher values of wire feed rate (above 6) are required for working with higher pulse power (where the job cutting rates are higher).

9. WT: wire Tension setting

This is a gram-equivalent load with which the continuously fed wire is kept under tension so that it remains straight between the wire guides.

Range: 01-15 (in step of 1)

While wire is being fed continuously, appropriate wire tension avoids the unintentional wire deflection from its straight path (between the wire guides). The wire deflection is caused due to spark induced reaction forces and water pressure.

10. SV: spark gap set voltage

This is a reference voltage for the actual gap voltage.

Range: 00-99 (in step of 1) volt.

11. SF: servo feed setting

This parameter decides the servo speed; the servo speed, at the set of value of SF, can vary in proportion with the gap voltage (normal feed mode) or can be held constant while machining (with constant feed mode).

Range: 0000-0990 for normal feed

1000-1999 for constant feed

2000-2999 for constant voltage

In constant feed mode, the 3 least significant digits of SF define the feed rate in tenths of mm/min. 1050 will give 5.0 mm/min constant speed.

In constant voltage mode, the feed is adjusted by the controller to maintain the gap voltage close to SV setting.

Here SF can be varied from

1000 to 990 in normal mode

000 to 999 in constant feed mode and

000 to 990 in constant feed mode by pressing up or down arrow keys or by page up or down. Whereas selection of first digit i.e. 0, 1 or 2 can be done by pressing numeric key 0, 1 or 2

12. Threshold setting (in percent of SV-set voltage) for corrective action in abnormal discharge condition.
Range: 0-99 (%).

13. CC: Corner Control factor used in rough cut (1st cut). If CC=3, cutting speed and power is reduced to 30 (%) at corner.

14. CRK: Radius compensation factor

CRK is the amount of corner correction in microns for 1 mm corner radius. From this value corner correction of other corner radii is automatically done by controller.

CRK value depends on job material, job thickness and cutting speed.

This parameter is set in E-code table only. To find value please refer operating manual.

15. CS%: Cutting Speed Over-ride %

This on-line parameter is provided to reduce the cutting speed to set CS% value without modifying the set machining condition parameter or the E-code. This parameter is effective for rough machining conditions where TON is set to 16µsec or higher value. It is automatically discarded in trim cuts where TON is less than16µsec.This parameter is mainly used to reduce the cutting speed in order to avoid wire breakage in the following rough machining conditions.

- If the wire electrode type or brand is different the one specified in the technology guidelines and if it is not suitable for high speed machining (e.g. plain brass wire electrode- for bravocut wire CS% is approximately 75.).
- If the wire electrode is of inferior quality.
- If wire vibration is excessive due to bad wire spool winding quality or wear-out / defects in the wire drive system elements.
- If the work piece material has defects.
- In difficult machining conditions where one or both of the flushing nozzles are far away from the work piece surface.
- For job profiles having very sharp corners.
- For taper cut machining with large taper angles.
- For complex profiles machining with different top bottom profiles.
- For unattended machining operation to avoid any risk of wire breakage.
- In any other unstable machining condition.

CS% = 100 = normal cutting speed as per selected machining condition.

16. **C DWELL**: this parameter is used to provide Dwell (delay) in second at corner for achieving sharp corners, it is active for linear – linear motion and if CC% is greater than zero.
Range: 0 to 99 sec.

During installation default value will be set to 2 sec.

C dwell of 2 sec is recommended in all cuts.

Table 1.1 Advantages and Disadvantages of WEDM Process [Tech. Commentary EPRI (1986)]

Advantages	**Limitations**
WEDM can cut any material that conducts electricity	Work piece must be conductive
Can create intricate and unusual shapes	Slower material removal rate
No tool force on machine, electrode, or work piece	Electrode wear can produce inaccuracies
Easily automated	Cavities may be slightly tapered
Great precision and repeatability	Undesirable recast layer may need to be removed
Can create solid dies eliminating sectionalizing and grinding	Leaves a very shallow, highly stressed surface layer
May eliminate secondary (surface finish) operations	Equipment is expensive

In the present work taguchi's L_{18} orthogonal array is used to conduct the experiment to optimize the different quality characteristics during machining of work piece (for making die). Peak current, pulse on time, pulse off time, wire feed, wire tension are taken as controlled process parameter. Remaining all process parameters are fixed at their optimum value. The responses of the project are material removal rate and surface roughness. The objective of the present work is to find out the proper set of parameter for machining. Significant parameters which affect the machining performance are finding by the analysis of variance. For achieving the maximum material removal rate and minimum surface roughness find the optimum value of each parameter separately. At the last optimize the both MRR and SR simultaneously by using utility concept. Entire work is performed on the sprint-cut wire EDM (elpulse-40). High carbon and high chrome (D2) die steel has been used as a work piece material and zinc-coated cu wire as cutting tool.

Chapter 2

LITERATURE REVIEW

The WEDM process is economical if it is used to cut complex work pieces and difficult-to-machine materials. In manufacturing die and mold components like sheet metal press dies, extrusion dies, etc., prototype and special form inserts manufacturing, WEDM is commonly used In other word, WEDM is widely used in precise manufacturing system that emphasize on the quality and high precision production.

Accompanying the development of mechanical industry, the demands for alloy materials having high hardness, toughness and impact resistance are increasing. Nevertheless, those materials are difficult to be machined by traditional machining methods.

In practice, it makes very difficult to utilize the optimal functions of a machine owing to there being too many adjustable machining parameters. The Taguchi method, a powerful experimental design tool, uses simple, effective, and systematic approach for deriving of the optimal machining parameters. . The machining parameters can be set for optimum machining with the knowledge of the effect of the machining parameters on performance measures, as a result of the experimental study.

2. Research work in Wire Electrical Discharge Machining (WEDM)

WEDM is a well-known machine among manufacturers and users because they know the capability of the machine on difficult-machined materials and to produce intricate shapes. Using the machine, they emphasized on achievement of higher machining productivity with a desired accuracy and surface finish. So, many researchers are aware and tried to explore and create something to raise the effectiveness and efficiency of WEDM.

2.1. **Cabanes, E.Portillo, M.Marcos, J.A. Sanchez (2006)et al** have proposes an on-line supervision system that monitors and diagnoses in advance degraded cutting regimes in WEDM. In this respect, the supervision system will allow to increase the process performance by readjusting the machining parameters depending on different levels of alarm. Four types of wire breaking phenomena have been identified. The distribution of the anticipation time before wire breakage has been also studied. The results have shown that the detection strategy provides an anticipation time longer than 50 ms in approximately 80% of the total wire breakage cases. The system has been successfully validated through a considerable number of experimental tests. WEDM machine operating under different conditions that may cause degraded operation for different work piece thickness. The efficiency of the supervision system has been quantified through an efficiency rate ratio defined in this. The results have been successful showing an average system efficiency of 82%. [1]

2.2. **J. Wang and B. Ravani (2002),** have develop a computational method for numerical control (NC) of travelling wire electric discharge machining (EDM) operation from geometric representation of a desired cut profile in terms of its contours. Normalized arc length parameterization of the contour curves is used to represent the cut profile and a subdivision algorithm is developed together with kinematic analysis to generate the required motions of the machine tool axes. In generating the tool motions for cutting sections with high curvatures such as corners with small radii, a geometric path lifting method is presented that increases the machining gap and prevents gauging or wire breakage.[2]

2.3. **G.W.Qin, K.Oikawa, G.D.W.Smith, S.M.Hao (2003)** et al they found that, Wire electric discharge machining (Wire-EDM) induced a new phase in Ti–46Al–2Cr (in at.%) intermetallic alloy has been identified by using X-ray diffraction technique. The new phase is found to be neither TiO2 nor Al2O3, but well consistent with FCC structure titanium hydride with the lattice parameter of 4.49–4.50 A ˚. The new phase exists in the wire-EDM cut alloy surface layer limiting to about 70 mm thick, much deeper than the wire-EDM induced recast layer thickness of 2–3µm. One processing, vacuum annealing at 400–600^{0}C, has been proposed to remove this hydride induced by wire-EDM. In addition, the wire-EDM induced micro cracks extensively happen on the EDM-cut surface and penetrate into matrix up to 10–30μm [3].

2.4. **W.J. Hsue, Y.S. Liao, S.S. Lu (1997) et al,** they studied that Fundamental geometry properties of wire electrical discharge machining (WEDM) process in corner cutting. The concept of discharge-angle is introduced, and its mathematical expression is derived by analytical geometry. A model to estimate the metal removal rate (MRR) in geometrical cutting is developed by considering wire deflection with transformed exponential trajectory of wire centre. The computed MRR is compared with measured sparking frequency of the process since they are equivalent to each other for an iso-energy type machine. A very good agreement is obtained. Both of the discharge angle and MRR drop drastically to a minimum value depending on the corner angle being cut as the guides arrive at the corner apex, and then recover to the same level of straight-path cutting sluggishly. Hence the observed phenomenon of increased gap-voltage and decreased sparking frequency in corner cutting can be physically interpreted. In addition, the variation of the machining load caused by the change of MRR, which was taken as unknown disturbance in the past, can be predicted and used for control purpose [4].

2.5. **Z.N. Guo, T.C. Lee, T.M. Yue and W. S. Lau (1997) et al,** they found that combined technology of ultrasonic and wire electrical discharge machining (W-EDM). The theory to describe the vibration modes of the wire under the action of ultrasonic has been established. Experimental results show that wire vibration induced by ultrasonic action has a significant effect on the overall performance of the W-EDM process. It was found that there exists an optimum relationship between the vibration amplitude of the wire and the discharge energy, by which the highest cutting rate and the best machined surface quality, can be obtained. In addition, ultrasonic vibration reduced the residual tensile stress of the machined surface [5].

2.6. **Jerzy Kozak, Kamlakar P. Rajurkar, Niraj Chandarana (2003), et al,** they studied on the effect of clamping position on the WEDM performance. The improvement in process performance due to silver coating application on the work piece is also described.

- WEDM machining characteristics of Si3N4 composite with a conductivity of 0.01s/cm was investigated for different clamping positions. It was observed that there was a significant change in cutting velocity depending upon the clamp position. It corresponds with changes of electric resistance of work piece during machining. As the cut approaches the clamp, there was an increase in MRR. A reduction in MRR occurs when the wire moves away from the clamp. Hence, it was found that actual MRR depends on the individual machining geometry and relative position of wire electrode with respect to clamping.
- To reduce the energy loss due to of drop voltage in the work piece, the machining of Si3N4 was carried out with conductive silver paint applied over the work piece. A significant increase in MRR was observed due to silver coating [6].

2.7. **S.Sarkar, S.Mitra, B.Bhattacharyya (2004), et al** investigates on wire electrical discharge machining of γ-titanium aluminide alloy. Aim is to select the optimum cutting condition with an appropriate wire offset setting in order to get the desired surface finish and dimensional accuracy. The process has been modelled using additive model in order to predict the response parameters i.e. cutting speed, surface finish and dimensional deviation as function of different control parameters and the main influencing factors are determined for each given machining criteria. Finally, the optimum parametric setting for different machining situation arising out of customer requirements have been synthesized and reported [7].

2.8. **T.A. Spedding and Z.Q. Wang (1997), et al** they attempt the optimization of the process parametric combinations by modeling the process using artificial neural networks (ANN) and characterize the WEDMed surface through time techniques. A feed forward back- propagation neural network based on a central composite rotatable experimental design is developed to model the machining process. The periodic component of the surface texture is identified and an autoregressive AR (3) model is used to describe its stochastic component [8].

2.9. **H. S. YAN, R. S. LEE and Y. C. YANG (1994)**, **et al they** proposes a CAD/ CAM mathematical foundation to design ruled surfaces for wire-cut electrical discharge machining. This method combines the boundary planes concept the plucker coordinate representation on lines, control lines and design function to generate free from ruled surfaces. The tool motion and offset surface can also be generated simply by the same approach for computer numerical control (CNC) wire-cut EDM. The algorithm being different from conventional methods can present a surface or tool path concisely and uniquely [9].

2.10. **Y.S. Liao, Y.P. Yu (2004), et al** they found that, the relationship between machining parameters and machining characteristics of different materials in WEDM is difficult to obtain because a large number of experiments must be conducted repeatedly. A new concept attempting to solve this problem is presented in this paper. The specific discharge energy (SDE) defining as the real energy required removing a unit volume of material is proposed. The SDE is constant for a specific material. Experimental results reveal that the relative relationship of SDE between different materials is invariant as long as all materials are machined under the same machining conditions. It is also found that the materials having close value of SDE demonstrate very similar machining characteristics such as machining speed, discharge frequency, groove width and surface finish of the machined surface under the same machining conditions. This result can be applied for the determination of the settings of machining parameters of different materials. Furthermore, by dimensional analysis of SDE, a quantitative relationship between machining characteristics such as the material removal rate and the efficiency of material removal and machining parameters is derived [10].

2.11. **Y.S. Liao, J.T. Huang, Y.H. Chen (2003), et al** they found that, To obtain good surface roughness, the traditional circuit using low power for ignition is modified for machining as well. With the assistance of Taguchi quality design, ANOVA and *F*-test, machining voltage, current-limiting resistance, type of pulse-generating circuit and capacitance are identified as the significant parameters affecting the surface roughness in finishing process. A dc pulse-generating circuit of positive polarity (wire electrode is set as anode) can achieve a better surface roughness in finishing operation. In addition, it is found that a low conductivity of dielectric should be incorporated for the discharge spark to take place.

After analyzing the effect of each relevant factor on surface roughness, appropriate values of all parameter are chosen and a fine surface of roughness Ra = 0.22 μm is achieved. The improvement is limited because finishing process becomes more difficult due to the occurrence of short circuit attributed to wire deflection and vibration when the energy is gradually lowered [11].

2.12. **X. Cheng, K. Nakamoto, M. Sugai, S. Matsumoto, Z.G. Wang, K. Yamazaki (2008), et al** they developed the ultra high precision machine tool for productive nano machining of sophisticated 3D geometry products made of hard materials and the following are conclusions:

- ➢ A unique counter motion linear motor system has been developed such that stable machining can be performed at up to 0.5 g acceleration/deceleration.
- ➢ For the custom tool fabrication, the unique 6-axis wire EDM machine has been developed with the CAM system, which can automatically generate NC programs through the user-friendly GUIs to define the tool geometry and machine system parameters.
- ➢ Custom-designed micro-PCD cutters (1 mm and 200 μm in diameter) have successfully been made by the developed tool fabrication system.
- ➢ Using the fabricated tools, the miniature sophisticated 3D geometry work piece made of tungsten carbide has successfully been machined in the ‘‘ductile’’ mode achieving the machined surface roughness, Ra, of less than 10 nm and peak to

valley, Ry, of less than 30 nm, thus verifying the excellent capability of designed machine tool and tool fabrication system [12].

2.13. **Mu-Tian Yan, Yi-Peng Lai (2007), et al they** developed and apply of a new fine-finish power supply in wire-EDM. The transistor-controlled power supply composed of a full-bridge circuit, two snubber circuits and a pulse control circuit was designed to provide the functions of anti electrolysis, high frequency and very-low-energy pulse control. Test results indicated that the pulse duration of discharge current can be shortened through the adjustment of capacitance in parallel with the sparking gap. High value of capacitance contributes to longer discharge duration. A high current-limiting resistance results in the decrease of discharge current. Peak current increases with the increase of pulse on-time and thus contributes to an increase in thickness of recast layer. Experimental results not only verify the usefulness of the developed fine-finish power supply in eliminating titanium's bluing and rusting effect and reducing micro-cracking in tungsten carbide caused by electrolysis and oxidation, but also demonstrate that the developed system can achieve a fine surface finish as low as 0.22 μm Ra [13].

2.14. **Albert W.-J. Hsue, M.-T. Yan, S.-H. Ke (2007),et al** they differentiate the performance between driven by linear synchronous motors (LSM) and conventional rotary motors associated with ball-screw on the WEDM . Mathematical models of both drive types are derived and their parameters are identified through standard procedures. Then some theoretical characteristics are revealed, and the models are verified through conducted experiments. Since both drives are equipped with optical linear scales of sub-micrometer resolution, the measurements are compared on the same level. Specific phenomena such as wear and transmission stiffness of ball-screw driven table and cogging force of direct LSM driven table are discussed. Then the machining errors occurred in corners and arcs cutting, and meso-scaled parts are compared in the Wire-EDM processes. Experimental results showed that the accuracy and deviation outcomes with direct drive are much better than those with conventional drive, especially in high feed rate and around points where feed direction was changed [14].

2.15. **Fuzhu Han, Jun Jiang, Dingwen Yu (2006), et al they** studied the differences in surface morphology under various pulse durations, thermo-analysis was carried out to investigate the mechanism of erosion of the work piece material using the finite element method. Additionally, related single discharge experiments under different pulse energies were performed. Under the same discharge energy, the comparison of analytical and experimental results shows that a discharge current with a short-duration pulse and a high peak value removes the work piece material mainly by gasifying, while a discharge current with a long-duration pulse and low peak value removes the work piece material mainly by melting. It was also found that surfaces machined by a discharge current with a short- and long-duration pulses would have similar roughness values when the pulse energies were almost the same and were high enough; however, the surface morphologies would be totally different. A discharge current with a long pulse duration and a low peak value could not produce craters on the work piece surface when the pulse energy was reduced to a certain value. However, a discharge current with a short pulse duration and a high peak value could produce clear craters on the work piece surface. This indicates that a discharge current with a short pulse duration and a high peak value can generate better surface roughness, which cannot be achieved with a current with long pulse duration and a low peak value [15].

2.16. **Masanori Kunieda and Chika Furudate (2005), et al** they described the development of a new dry wire electrical discharge machining (dry-WEDM) method, which is conducted in a gas atmosphere without using dielectric liquid to improve the accuracy of finish cutting. In dry-WEDM, the vibration of the wire electrode is minute due to the negligibly small process reaction force. In addition, as the gap distance is narrower than that in conventional WEDM using dielectric liquid, and there is no corrosion of the work piece, high accuracy in finish cutting can be realized in dry-WEDM. However, some drawbacks of dry-WEDM include lower material removal rate compared to conventional WEDM and streaks are more likely to be generated over the finished surface. Increasing the wire winding speed and decreasing the actual depth of cut is effective to resolve these drawbacks [16].

2.17. Mu-Tian Yan, Yau-Jung Shiu (2007), et al they described a combined two-degree-of-freedom controller and disturbance observer design for a direct drive motion control system actuated by permanent-magnet linear synchronous motors (PMLSM). A feedback controller based on pole-placement design method is proposed to achieve desired tracking performance as well as stabilize the closed-loop system. A newly designed feed forward controller is proposed to reduce tracking errors based on an inverse model of the direct drive system. A digital disturbance observer is implemented to be included in the proposed feedback–feed forward control structure to compensate for nonlinear friction, cogging effects, and external load disturbance. Furthermore, the proposed control scheme has been verified as being internally stable. Experimental results indicate that the proposed controller can achieve a high contouring accuracy of ±0.3 µm as well as provide disturbance rejection and robustness. The maximum contour error of circular trajectory was reduced from 8.5 to 3.2 µm in comparison with proportional-integral-derivative (PID) controller [17].

2.18. K.K. Choi, W.J. Nam, Y.S. Lee (2007), et al they studied on the effects of heat treatment on the surface machined by W-EDM, specimens of die steel STD11 are prepared by four different manufacturing methods—type A: milling and then grinding, type B: wire-cut electric discharge machining only, and type C: low temperature heat treatment or type D high temperature heat treatment afterW-EDM. As a consequence, the following conclusion can be drawn:

- As for the surface roughness, type A results in a better surface than any others (types B–D). However, the heat treated surfaces afterW-EDM (types C and D) improve the surface roughness slightly.
- From EDS inspections, a small amount of Cu is observed in the surfaces by types B–D which arise from the brass electrode used in W-EDM, with the large amount of Cu being reduced with the high temperature tempering.
- Microstructures of the top surface and side cross section of type A specimen are completely different from those of the others (types B–D) which were subjected to the rapid heating and cooling during W-EDM.

Type D, following the high temperature tempering after W-EDM, could remove the heat affected zone completely.

- Finally, the on-line experiments for the service life of a press die for a chain product have shown that the quality of a press die by type D could be as good as those by type A [18]

2.19. **K.H.Ho, S.T.Newman, S. Rahimfard, R.D. Allen (2004), et al** they review the vast array of research work carried out from the spin-off from the EDM process to the development of the WEDM. It reports on the WEDM research work involving the optimization of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. They also highlight the adaptive monitoring and control of the process investigating the feasibility of the different control strategies of obtaining the optimal machining conditions. A wide range of WEDM industrial applications and future research work is reported [19].

2.20. **Indrajit Mukherjee, Pradip Kumar Ray (2006),** they described the different optimization technique, their advantages and drawbacks. In this paper, the application potential of several modeling and optimization techniques in metal cutting process, classified under several criteria, has been critically appraised, and a general framework for parameter optimization in metal cutting processes is suggested for the benefits of selection of an appropriate approach [20].

2.21. **A.B. Puri, B.Bhattacharyya (2002),** they present the study of geometrical inaccuracy caused due to wire lag with various machine control parameters. In this study authors considered all the machine control parameters simultaneously for a rough cut followed by a trim cut. They carried out an experimental investigation based on the Taguchi method involving thirteen control factors with three levels for an orthogonal arrayL_{27} (3^{13}). They described the influence of each control parameter on every response [21].

2.22. **Hari Singh, Pradeep Kumar (2005),** they describe the Taguchi's approach and utility concept to optimize the multi-machining characteristics simultaneously. They discussed a case study on En24 steel turned parts using titanium carbide coated tungsten carbide inserts. They had chosen the three process parameters as, cutting speed, feed and depth of cut. After optimization they found a single optimal condition to get near optimal value of all the response characteristics simultaneously. The response characteristics optimizes were MRR, tool wear rate, power consumption and surface finish [22].

2.23. **S. S. Mahapatra, Amar Patnaik (2006),** they determine that the important machining parameters for performance measures like MRR, SF, and kerf separately in the WEDM process. Factors like discharge current, pulse duration, and dielectric flow rate and their interactions have been found to play a significant role in rough cutting operations for maximizations of MRR, minimization of surface roughness and minimization of cutting width. Taguchi's L_{27} experimental design method is used to obtain optimum parameter combination for maximization of MRR, SF as well as minimization of kerf. Interestingly, the optimal levels of the factors for all the objectives differ widely. In order to optimize for all the three objectives, mathematical models are developed using the non-linear regression method. The confirmation experiment shows that the errors associated with MRR, SF, and kerf are 3.14, 1.95, and 3.72%, respectively. The optimum search of machining parameter values for the objective of maximizing of MRR and SF and minimization of kerf are formulated as a multi-objective, multivariable, non-linear optimization problem. This study also evaluates the performance measures with equal importance to weighting factors since higher MRR, SF and low kerf are equally important objectives in WEDM application [23].

Chapter 3

PROBLEM FORMULATION

Metal cutting is the one of the most important processes carried out in an industry. The study of metal cutting focuses on the features of tools, input work materials and machine parameter settings which affects the process efficiency and output quality characteristics (or response). It is very essential to optimize the every parameter which affects the response (or output). A significant improvement in process efficiency may be obtained by process parameter optimization that identifies and determines the regions of critical process control factors leading to desired outputs or responses with acceptable variations ensuring a lower cost of manufacturing. Various parameters which are affecting the wire EDM process is shown in fig 3.1.

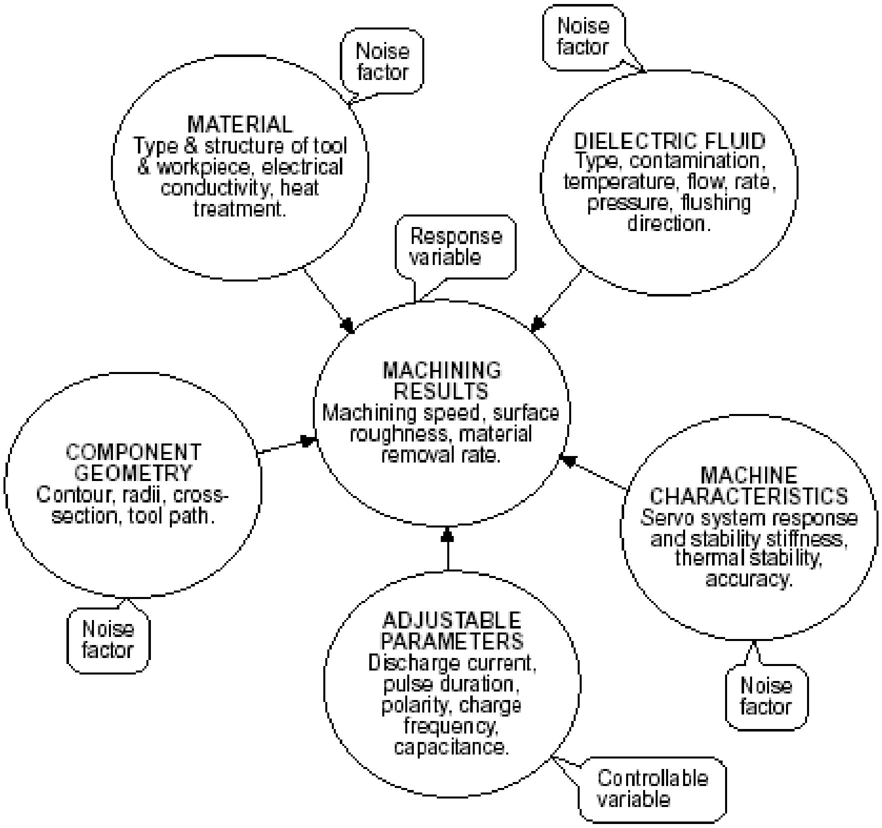


Fig. 3.1 Factor affecting WEDM

Now a days the technology of metal cutting improving day by day for achieving common goal ,maximum MRR & minimum SR. It is very necessary to find out the optimum parameter for machining.

3.1. Preview of the Present Investigation

It is very difficult to make a complex shape in machining by the conventional processes. Now a days in every industry most of the metal cutting work is performed with unconventional machining methods. If we want to make a die, it should be high strength so we can't use other manufacturing methods for making the die. Die materials are widely used in unconventional machining processes viz. Moreover quality of machined product depends on the quality of work piece. Die making industry is very important to downstream industries such as deep drawing, cold forging, plastic injection molding and powder metallurgy etc. Any technological changes in die-making industry surely affect those in downstream manufacturing. In powder metallurgy industry, powdered material is pressed in a cavity (i.e. die) with a high pressure so that different constituents of powder adhere with each other. This pressed material is ejected out of the die and move through the controlled atmosphere at high temperature. This is called sintering, in which heat is used to turn the powdered substances into solids without actually melting the material. Die surface should be smooth so that ejection of pressed powder (compact) becomes easy and no detriment effect on the surface of inserts. Taper should be avoided in die for the easy ejection of compact and smooth movement of punch.

It is well established fact that a high material removal rate and good surface finish can never be achieved simultaneously in WEDM. This is an age old problem and continuous efforts are being made by different researchers all over the world to fulfill such an objective. A rough cut (first cut) followed by one or two trim cuts is considered as a probable solution to the above problem depending upon customer requirements. From accuracy point of view wire offset is absolutely essential for achieving close dimensional tolerance. The purpose of trim cutting operation is to improve surface finish and to reduce the inaccuracies produced by minor job deformations after first cut. Trim cut improves the die life by reducing the thickness of thermally affected layer formed, in the first cut, on the machined surface.

To reduce the total manufacturing time and to avoid the prediction of wire offset for number of trim cuts, we have divided die cutting operation in two steps; a rough cut followed by single trim cut.

It is obvious that the surface produced by rough cutting operation is totally removed by finish cutting operation. In case of multi-pass cutting the prime objective in the first cut is to achieve the highest possible cutting speed. In case of trim cutting the prime objective is to achieve desired surface finish and dimensional accuracy. But if during rough cut appropriate wire offset is not chosen then it may cause dimensional inaccuracies resulting in increased number of trim cuts.

In the research work, Taguchi's L_{18} orthogonal array is used to conduct the experiments to optimize the different quality characteristic during machining of dies. Experimental work is performed on sprint-cut wire EDM (elpulse-40). High carbon & high chrome (D2) die steel has been used as a work piece material and Zinc- coated copper wire as a cutting tool (cathode). Process parameters are peak current, pulse-on time, pulse-off time, wire speed and wire tension. Response parameters are material removal rate (MRR) and surface roughness (SR).

The WEDM process consists of three operations, a roughing operation, cutting operation and a surface finishing operation. In this dissertation work roughing and finishing is combined. Thus, the main thrust of this investigation is the multiple response optimizations with regard to material removal rate and surface roughness in wire electric discharge machining of D2 steel during rough cut to enhance the machining efficiency of the process.

3.2 Objective of Present Investigation.

There are many machining parameters affecting the wire EDM machine performance and the real mathematical models between machining performance and machining parameters are not easy to be derived because of the complex machining mechanism. The objectives are as follows:-

1. To find out the proper set of parameter by using taguchi method (MINITAB15) software.
2. To determine significant parameters affecting the machining performance
3. To find out the optimum value of each parameter for achieving the highest MRR & lowest SR separately.
4. Simultaneous optimization of multi-quality characteristics using Taguchi's approach and utility concept.

Chapter 4

EXPERIMENTAL DESIGN AND ANALYSIS

There is no machine in this world which has 100% efficiency. The responses of every machine are not constant. It varies continuously due to environmental effect, due to friction and due to human error. We have to provide some tolerances. For increasing the accuracy of machine we have to optimize the parameter. There are many methods for optimization. In the traditional one-variable-at-a-time approach, only one variable at a time is evaluated keeping remaining variables constant during a test run. This type of experimentation reveals the effect of the chosen variable on the response under certain set of conditions. The major disadvantage of this approach is that it does not show what would happen if the other variables are also changing simultaneously. This method does not allow studying the effect of the interaction between the variables on the response characteristic. The Taguchi method provides a solution to this problem.

4.1 Taguchi's Philosophy

Taguchi's comprehensive system of quality engineering is one of the great engineering achievements of the 20th century. The methods focus on the effective application of engineering strategies rather than advanced statistical techniques. It includes both upstream and shop-floor quality engineering. Upstream methods efficiently use small-scale experiments to reduce variability and remain cost-effective, and robust designs for large-scale production and marketplace. Shop-floor techniques provide cost-based, real time methods for monitoring and maintaining quality in production. The farther upstream a quality method is applied, the greater leverages it produces on the improvement, and the more it reduces the cost and time. Taguchi's philosophy is founded on the following three very simple and fundamental concepts:

- Quality should be designed into the product and not inspect into it.

- Quality is the 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's proposes an "off-line" strategy for quality improvement as an alternative to an attempt to inspect quality into a product on the production line. 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. In the present work Taguchi's parameter design approach is used to study the effect of process parameters on the cutting speed, die width and surface roughness in die cutting during rough cut.

4.1.1 Loss Function and S/N Ratio

The heart of Taguchi method is his definition of 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 characteristics. Taguchi defines quality loss via his 'loss-function'. He unites the financial loss with the functional specification through a quadratic relationship that comes from Taylor series expansion.

$$L(y) = k(y - m)^2$$

Where, L = loss in monetary unit

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 traditional and the Taguchi loss function concept have been illustrated in Figure 4.1(a) and Figure 4.1(b). The following two observations can be made from Figure 4.1 (a, b).

- The further the product's characteristic varies from the target value, the greater is the loss. The loss is zero when the quality characteristic of the product meets its target value.
- The loss is a continuous function and not a sudden step as in the case of traditional approach (Figure 4.1b).

This consequence of the continuous loss function illustrates the point that merely making a product within the specification limits does not necessarily mean that product is of good quality.

In a mass production process the average loss per unit is expressed as:

$$L(y) = \left\{ k(y_1 - m)^2 + k(y_2 - m)^2 + \dots\dots + k(y_n - m)^2 \right\} \quad (4.1)$$

Where, $y_1, y_2, \dots\dots y_n$ = values of characteristics for units 1, 2…n respectively

n = number of units in a given sample

k = constant depending upon the magnitude of characteristic and the monitory unit involved

m = Target value at which characteristic should be set.

Equation (4.1) can be written as:

$$L(y) = k(\text{MSD})$$

Where MSD denotes mean square deviation, which presents the average of squares of all deviations from the target value rather than around the average value.

Taguchi transformed the loss function into a concurrent statistic called S/N ratio, which combines both the mean level of the quality characteristic and variance around this mean into a single metric [Ross (1996), and Barker (1986)]. The S/N ratio consolidates several repetitions (at least two data points are required) into one value. A high value of S/N ratio indicates optimum value of quality with minimum variation. Depending upon the type of response, the following three types of S/N ratio are employed in practice [Byrne and Taguchi (1987)].

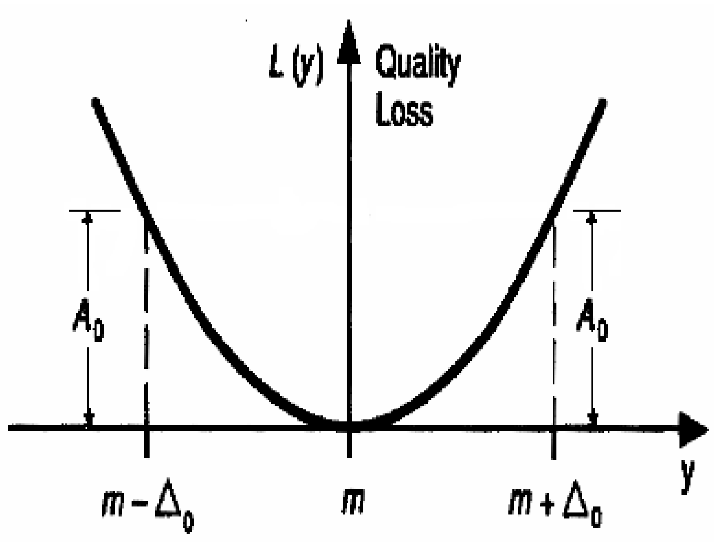


Figure 4.1 (a) Taguchi Loss Function

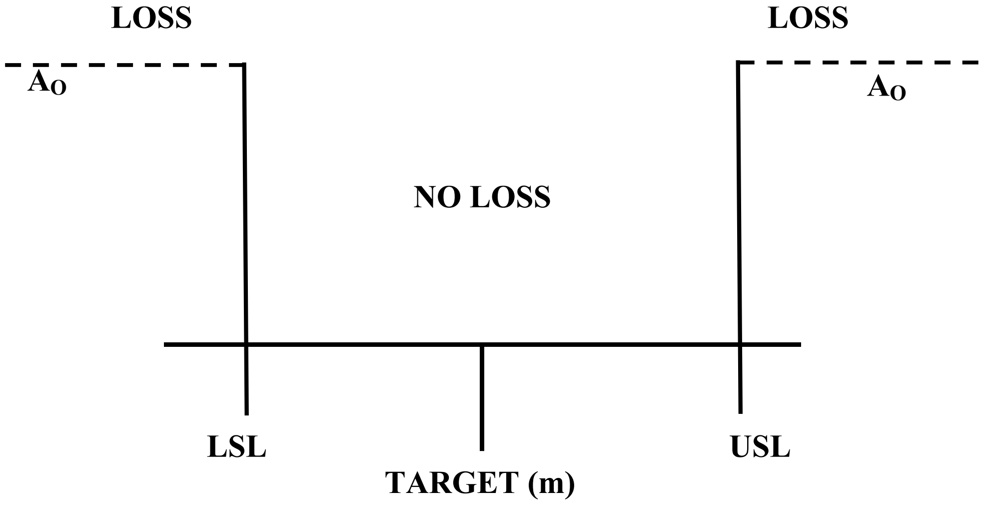


Figure 4.1 (b) Traditional

Figure 4.1Tthe Taguchi Loss-Function and the Traditional Quality Philosophy Approach

1. Larger the better:

$$\left(S/N\right)_{HB} = -10\ \log\left(MSD_{HB}\right) \tag{4.2}$$

where

$$MSD_{HB} = \frac{1}{R} \sum_{j=1}^{R} \left(1/y_j^2\right)$$

2. Lower the better:

$$\left(S/N\right)_{LB} = -10\ \log\left(MSD_{LB}\right) \tag{4.3}$$

where

$$MSD_{LB} = \frac{1}{R} \sum_{j=1}^{R} \left(y_j^2\right)$$

3. Nominal the best:

$$\left(S/N\right)_{NB} = -\log\left(MSD_{NB}\right) \tag{4.4}$$

where

$$MSD_{NB} = \frac{1}{R} \sum_{j=1}^{R} \left(y_j - y_o\right)^2$$

R = Number of repetitions

t is to be mentioned that for nominal the best type of characteristic, the standard definition of MSD has been used. For smaller the better type the target value is zero. For larger the better type, the inverse of each large value becomes a small value and again the target value is zero. Therefore, for all the three expressions the smallest magnitude of MSD is being sought. The constant 10 has been purposely used to magnify S/N number for each analysis and negative sign is used to set S/N ratio of larger the better relative to the square deviation of smaller the better.

4.1.2 Experimental Design Strategy

Taguchi recommends orthogonal arrays (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.

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives:

- To estimate 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 trend 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. Taguchi suggests two different routes to carry out the complete analysis of the experiments. First the standard approach, where the results of a single run or the average of the 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 (S/N) ratio for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function. 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 parameter (transform of raw data) of the experiment.

Taguchi recommends the use of outer OA to force the noise variation into the experiment i.e. the noise is intentionally introduced into the experiment. Generally, processes are subjected 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 controllable parameters and analyze them using an appropriate S/N ratio. In the present investigation, both the analysis: the raw data analysis and S/N data analysis have been performed. The effects of the selected EDM 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 have been establish through S/N data analysis. No outer array has been used.

4.1.3 Taguchi Procedure for Experimental Design and Analysis

Figure 4.2 illustrates the stepwise procedure for Taguchi experimental design and analysis. It is described in the following paragraphs.

4.1.3.1 Selection of OA

In selecting an appropriate OA, the following prerequisites are required:

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

Several methods are suggested by Taguchi for determining which parameters to include in an experiment. These are:

a. Brainstorming
b. Flow charting
c. Cause-effect diagrams

The total degrees of freedom (DOF) of an experiment are a direct function of total number of trials. If the number of levels of a parameter increases, the DOF of the parameter also increase 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. 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.

The standard two-level and three-level arrays are:

a) Two-level arrays: L_4, L_8, L_{12}, L_{16}, L_{32}

b) Three-level arrays: L_9, L_{18}, L_{27}

The number as subscript in the array designation indicates the number of trials in that array. The degree of freedom (DOF) available in an OA is:

$$f_{L_N} = N - 1$$

Where f_{L_N} = total degrees of freedom of an OA

L_N =OA designation

N = number of trials

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

$f_{L_N} \geq$ Total DOF required for parameters and interactions.

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

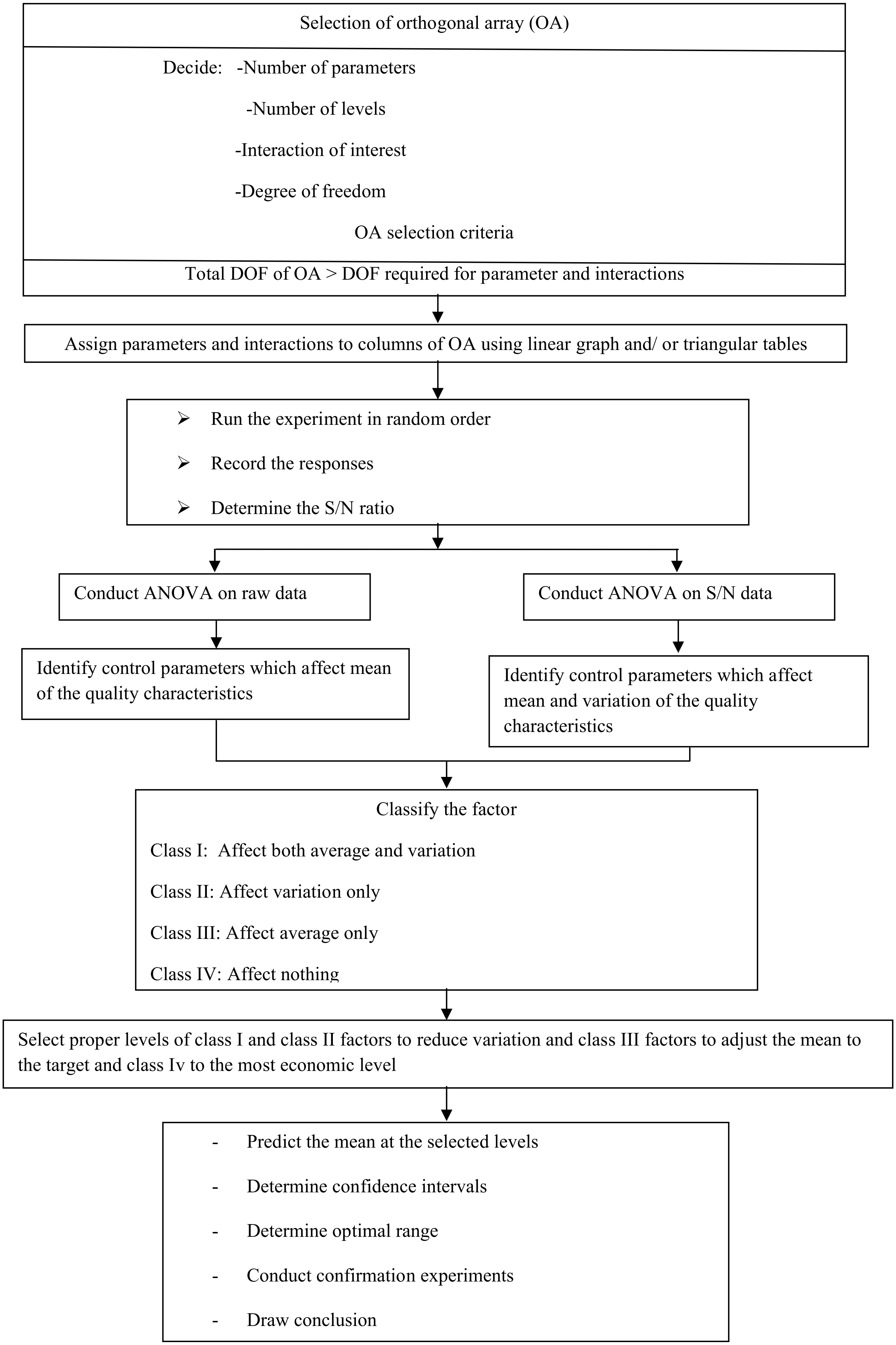


Fig 4.2 Taguchi Experimental Design and Analysis Flow Diagram

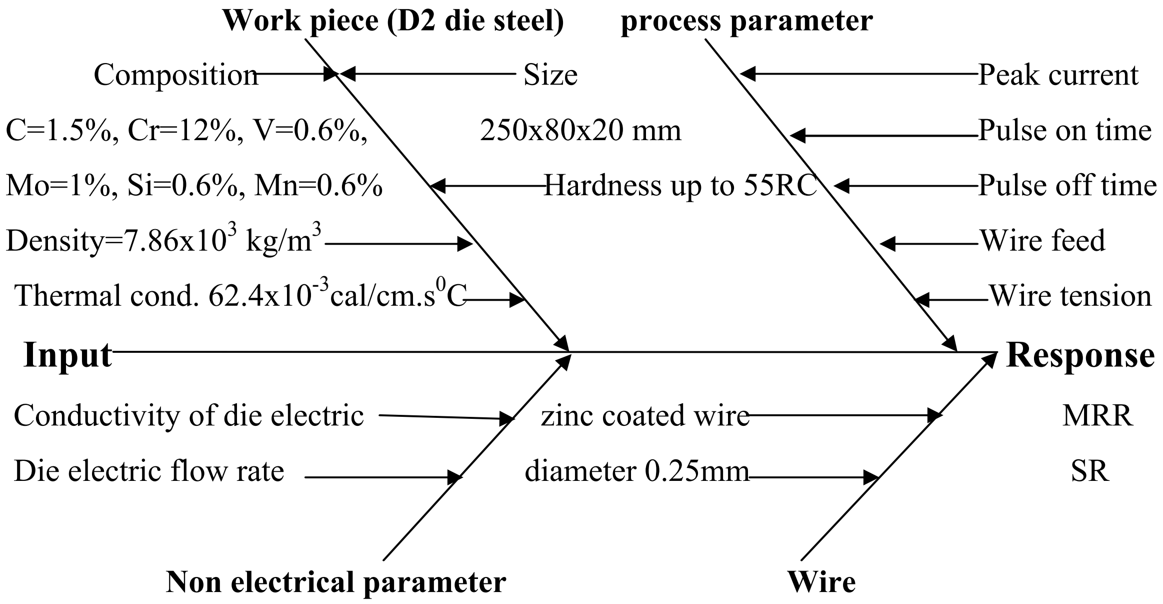


Fig4.3 cause and effect diagram for wire EDM process

4.1.3.2 Assignment of Parameters and Interactions to OA

An ‘OA’ has several columns to which various parameters and their interactions are assigned. Linear graphs and Triangular tables are two tools, which are useful for deciding the possible interactions between the parameters and their assignment in the columns of ‘OA’. Each ‘OA’ has its particular liner graphs and interaction tables.

4.1.3.3 Selection of Outer Array

Taguchi separates factors (parameters) into two main groups:

- Controllable factors
- Noise factors;

Controllable factors are factors that can easily be controlled. Noise factors, on the other hand, are nuisance variables that are difficult, impossible, or expensive to control. The noise factors are responsible for the performance variation of a process. Taguchi recommends the use of outer array for noise factors and inner array for the controllable factors. If an outer array is used the noise variation is forced into the experiment.

However, experiments against the trial condition of the inner array may be repeated and in this case the noise variation in unforced in the experiment. The outer array, if used will have the same assignment considerations.

4.1.4 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 for to reduce bias in the experiment.

4.1.4.1 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 ratio ANOVA, plot of average responses, interaction graphs, etc. In the present investigation, following methods are used.

1. Plot of average response curves
2. ANOVA for raw data
3. ANOVA for S/N data

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of a parameter on the response. Typically, ANOVA for OA's are conducted in the same manner as other structured experiments. The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. A standard ANOVA is conducted on S/N ratio, which identified the significant parameters.

4.1.4.2 Parameter Classification and Selection of Optimal Levels

ANOVA of raw data and S/N ratio identifies the control factors, which affect the average response and the variation in the response respectively. The control factors are classified into four groups:

Group I : Parameters, which affect both average and variation

Group II : Parameters, which affect variation only

Group III : Parameters, which affect average only

Group IV : Parameters, which affect nothing

The parameter design strategy is to select the suitable levels of group I and II parameters to reduce variation and group III parameters to adjust the average values to the target value. The group IV parameters may be set at the most economical levels.

4.1.4.3 Prediction of Mean

After determination of the optimum condition, the mean of the response (μ) at the optimum condition is predicted. This mean is estimated only from the significant parameters. The ANOVA identifies the significant parameters. Suppose, parameters A and B are significant and A_2B_2 (second level of both A and B) is the optimal treatment condition. Then, the mean at the optimal condition (optimal value of the response characteristic) is estimated as:

$$\begin{aligned}\mu &= \overline{T} + \left(\overline{A}_2 - \overline{T}\right) + \left(\overline{B}_2 - \overline{T}\right) \\ &= \overline{A}_2 + \overline{B}_2 - \overline{T}\end{aligned}$$

$\overline{T}$ = overall mean of the response

$\overline{A}_2, \overline{B}_2$ = average values of response at the second levels of parameters A and B respectively

It may sometimes be possible that the predicated combination of parameter levels (optimal treatment condition) is identical to one of those in the experiment. If this situation exits, then the most direct way to estimate the mean for that treatment condition is to average out all the results for the trials which are set at those particular levels.

4.1.5 Determination of Confidence Intervals

The estimate of the mean (μ) is only a point estimate based on the average of results obtained from the experiment. It is a statistical requirement that the value of a parameter should be predicted along with a range within which it is likely to fall for a given level of confidence. This range is called confidence interval (CI). Taguchi suggests two types of confidence intervals for estimated mean of optimal treatment conditions.

1. CI_{CE} – Confidence Interval (when confirmation experiments (CE)) around the estimated average of a treatment condition used in confirmation experiment to verify predictions. CI_{CE} is for only a small group made under specified conditions.
2. CI_{POP} – Confidence Interval of population; around the estimated average of a treatment condition predicted from the experiment. This is for the entire population i.e. all parts made under the specified conditions.

The confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{POP}) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_{\alpha}\,(1, f_e)\, V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{4.5}$$

$$CI_{POP} = \sqrt{\frac{F_{\alpha}\,(1, f_e)\, V_e}{n_{eff}}} \tag{4.6}$$

Where,

$F_{\alpha}(1, f_e)$ = The F-ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e., f_e = error DOF, N = Total number of result, R = Sample size for confirmation experiments, V_e = Error variance,

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean responce}]}$$

4.1.6 Confirmation Experiment

The confirmation experiment is the final step in verifying the conclusions from the previous round of experimentation. The optimum conditions are set for the significant parameters (the insignificant parameters are set at economic levels) and a selected number of tests are run under specified conditions. The average values of the responses obtained from confirmation experiments are compared with the predicted values. The average values of the response characteristic obtained through the confirmation experiments should be within the 95% confidence interval, CI_{CE}. However, these may or may not be within 95% confidence interval, CI_{POP}. The confirmation experiment is a crucial step and is highly recommended to verify the experimental conclusions.

4.2 Optimizing Multi-quality Characteristics.

In this study, a simplified methodology based on Taguchi's approach and utility concept has been used for determining optimal setting of the process parameters for multi-characteristic product. In fact, the methodology is an extension of Byrne and Taguchi (1987).

4.2.1 The Utility Concept.

The utility of a product on a particular characteristic measures the usefulness of that particular characteristic of the product. In this study it is assumed that overall utility of a product is the sum of utilities of each of the quality characteristics. If Xi is the measure of effectiveness of an attribute (characteristic) i and there are n attributes evaluating the outcome space, then the joint utility function can be express as (Derk, 1982):

$$U(X_1, X_2, \ldots\ldots, X_n) = f[U_1(X_1), U_2(X_2), \ldots\ldots U_n(X_n)]$$

Where $U_i(X_i)$ is the utility of the ith attribute. Assuming that the attributes are independent and have no interactions between themselves, and the overall utility function is a linear sum of individual utilities, the function becomes:

$$U(X_1, X_2, \ldots X_n) = \sum_{i=1}^{n} Ui(Xi)$$

The attributes may be given priorities as per customer's requirements and corresponding weights for the individual utility index. The overall utility function can then be written as

$$U(X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} WiUi(Xi)$$

Where Wi is the weight assigned to attribute i and the sum of the weights for all attributes is equal to 1. The utility function is of "higher the better" type. If the composite measure (the overall utility) is maximized, the quality characteristics considered for the evaluation of utility will be optimized (maximized or minimized).

4.2.1.1 Determination of Utility Value.

To determine the utility value for a number of quality characteristics, a preference scale for each quality characteristic is constructed. Later these scales are weighted to obtain a composite number (overall utility). If a log scale is chosen, the preference number (Pi) is given by Gupta and Murthy (1980).

$P_i = A \log (X_i / X_i')$, where X_i is the value of quality characteristic or attribute i, X_i' is the minimum acceptable value of the quality characteristic i and A is a constant Arbitrarily, we choose A such that $P_i = 9$ at $X_i = X^*$, where X^* is the optimum value of Xi assuming such a number exists. So, $A = \dfrac{9}{\log(X^* / Xi)}$. The next step is to assign weights or relative importance to the quality characteristic. The weight should be assigned such that the total sum of all the weights should be unity.

The overall utility can be calculated as: $U = \sum_{i=1}^{n} WiPi$

4.2.2 The Multi-quality Characteristic Optimization Algorithm

1. Find optimal values of the selected quality characteristics separately using Taguchi experimental design and analysis.

2. Using the optimal values and the minimum quality levels for the characteristics from the experimental data, construct preference scale for each quality characteristic.
3. Assign weights Wi, i= 1,2, . . . , n based on experience and end use of the product
4. Find utility values for each product against each trial condition of the experiment using equation given above.
5. Use these values as a response of the trial conditions of the selected experimental plan.
6. Analyze results using the procedure suggested by.
7. Find the optimal settings of the process parameters for optimum utility (mean and minimum deviation around the mean) based on the analysis in step 6.
8. Predict the individual characteristic values considering the optimal significant parameters determined in step 7.
9. Conduct confirmation experiment at the optimal setting and compare the Predicted optimal values of the quality characteristics with the actual ones.

Chapter 5

METHODOLOGY

In the present work Taguchi's DOE approach along with Utility concept is used to find out the optimal setting of the process parameters. Taguchi's L_{18}, a mixed type of Orthogonal array (OA) is used to conduct the experiments. In L_{18} OA, one parameter having six levels and rest of the parameters are set on three levels each. The method adopted is given in following sub sections:

5.1 Experimental Procedure.

A series of experiments were conducted to study the effects of various machining parameters on WEDM process. Studies have been undertaken to investigate the effects of important parameters viz., Discharge current, pulse on time, pulse off time, wire speed and wire tension on cutting speed, surface roughness and die width. Taguchi's DOE approach is used to optimize the process parameters. Experiments were carried out on D2 tool steel as work piece electrode and zinc coated copper wire as a tool electrode. Distilled water has been used as dielectric fluid throughout the tests.

The experiments were carried out in CNC sprint cut wire EDM of Electronica Machine tool ltd. The pulse generator supplies the electrical energy to the spark gap in the form of pulses. The ELEKTRA Wire cut electrical discharge machine comprises of Machine Tool, a power supply Unit (ELPULS), and a Dielectric unit and a chiller unit. The machine tool unit comprises of a main worktable (called X-Y table) on which the work piece is clamped an auxiliary table (called U-V table) and wire drive mechanism. The main table moving along X and Y axes, in the steps of 1 micrometer by means of D.C. servomotor. The U& V axes which parallel to X & Y axes respectively are driven by the same motor which drives the table. The traveling wire which is continuously fed from wire feed spool which moves through the work piece and is supported under tension between a pair of wire guides which are located at the opposite sides of the work piece.

The lower wire guide is stationary whereas the upper wire guide which is supported by the U-V table can be displaced transversely, along U and V axes, with respect to the lower wire guide. The upper wire guide can also be positioned vertically along Z axis by moving the quill. A series of electrical pulses generated by the pulse generator unit are applied between the work piece and the traveling wire electrode, to cause the erosion of the work piece material. As the material removal or machining proceeds, the worktable carrying the work piece is displaced transversely by the X-Y controller and the driver along a predetermined path programmed in the controller. The path specifications can be supplied to the controller via a program which is stored on floppy disk or directly the controller (MDI made).

5.2 Work piece Electrode

The work piece material used in this investigation is D2 tool steel. Composition of D2 steel is C= 1.5%, Cr= 12%, V= 0.6%, Mo= 1%, Si=0.6%, Mn= 0.6% and balance is Fe. A D2 tool steel plate of size $250\times 80\times 20$ mm is heat treated to raise its hardness up to 55 RC. All the six faces of tool steel plate are grinded to remove the burrs and rusts so that wire moves smoothly throughout the work piece.

Table 5.1 Physical Properties of D2 Steel.

Density (×1000 kg/m^3)	7.86
Co-efficient of thermal expansion(per ^oC from 0^oC)	11.6×10^{-6}
Thermal conductivity (cal/cm.s^oC)	62.4×10^{-3}
Specific heat (cal/g^oC)	0.110

Fig.5.1 Sprint-cut WEDM

D2 steel is also characterized by its high dimensional stability after hardening and tempering, high compressive strength. The success of a metal forming tool depends on optimizing all the factors affecting its performance. Usually, operating conditions (applied loads, abrasive environments, impacts, and other factors) determine how well a tool holds up. Most tool failures are related to such mechanical causes. However, with a variety of tool steels available for manufacturing metal forming tools, it is often possible to choose a tool steel with a favorable combination of properties for particular applications. By comparing the levels of metallurgical properties offered by different steels, tool users can determine which tool steels are best suited for fixing or resisting performance problems, or for enhancing tool performance. Tool steels can be categorized and compared by those properties which have a direct influence on tool performance: hardness, toughness (impact resistance), and wear resistance. Table 5.1 shows the physical properties of D2 steel at 25^0 C.

5.3 Tool Electrode

Wire is used as an electrode and the electrode material used in this investigation is Zinc coated copper wire. Wire electrode having diameter 0.25mm is used. Zinc coated copper wire electrode can conduct high current as compare to simple copper wire.

5.4 Selection of Process Parameters and their Ranges

In order to obtain high material removal rate and better quality of surface produced by WEDM process, the optimal level of WEDM process parameters need to be determined. Based on the critical review of literature, process variables of the WEDM were selected according to transient state.

The following process parameters were selected for this study as follows:

a. Peak Current.
b. Pulse- ON time.
c. Pulse-OFF time.

d. Wire feed
e. Wire Tension

In Sprint-cut wire EDM the value of peak current ranges b/w 010 to 230A, Pulse-ON time b/w 100 to 131, Pulse-OFF varies b/w 0-63, Wire feed 1-15m/min and Wire tension ranges between 1 to 15N.

5.5 Response Characteristics

The effect of selected process parameters were studied on the following response characteristics of EDM process:

1. Material Removal Rate(MRR)
2. Surface Roughness (Ra)

5.5.1 Material Removal Rate (MRR)

The material removal rate signifies the rate at which the material is cut away from a specimen in unit time. Material removal rate is calculated from the cutting speed which is displayed on the computer screen of the MCU of Sprint-cut Wire Electric Discharge Machine. Depending upon the hardness of specimen material removal rate will differ for a given setting of parameters.

5.5.2 Surface Roughness

Surface roughness is a key factor in dies and rolling contact devices. Dies for sintered carbide tools require high surface finish for the easy ejection of powder material (compact) and also for long die life. In the present study surface roughness was measured with the digital surface tester of Mitutoyo SJ-201P. It gives the Ra value of surface in micrometer.

5.6 Scheme of Experiments

Taguchi parametric design methodology is adopted in this experiment. The experiments were conducted by using Taguchi's L18 OA array. Five controllable factors are selected. Parameters of the setting are given in table 5.2 and 5.3.

5.6.1 Selection of Orthogonal Array (OA) and Parameter Assignment

Before selecting a particular OA to be used as a matrix for conducting the experiments, the following two points were first considered as suggested by Ross (1996), and Roy (1990):

1. The number of parameters and interactions of interest
2. The number of levels for the parameters of interest

The non-linear behavior, if exists, among the process parameters can only be studied if more than two levels of the parameters are used. Therefore, each parameter was analyzed at minimum three levels. In this study mixed type of array is chosen in which one parameter is set at six levels and rest are set at three levels. The selected number of process parameters and their levels are given table 5.3. Degree of freedom (DOF) associated with each factor is equal to (no. of level -1). Therefore total degree of freedom For the five factors is $(5\times2+2\times4) = 13$. As per Taguchi's method the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So an L18 OA (a standard Mixed-level OA) having 17 (=18-1) degree of freedom was selected for the present analysis. The experiments were conducted at each trial conditions as given in table 5.4.

Table 5.2 Fixed and control parameters

Control Factors	**Symbols**	**Fixed Parameters**	
Discharge Current	A	Wire Type	Zinc coated brass,
Pulse-ON	B		Diameter 0.25mm
Pulse-OFF	C	Angle of cut	Vertical
Wire Speed	D	Work piece Thickness	20mm
Wire Tension	E	Wire Compensation	0.14
		Work piece hardness	55 RC
		Corner cutting factor	5
		Dielectric pressure	15 k_g/cm^2
		Conductivity of Dielectric	20 S
		Peak Voltage	110 volt DC
		Gap between work surface & upper guide nozzle	1 mm.

Table 5.3 Levels for various control factors

Sr. No.	Level	Control Factors				
		A	B	C	D	E
1	**1**	40	106	30	7	8
2	**2**	70	116	40	8	9
3	**3**	100	126	50	9	10
4	**4**	130	--	--	--	--
5	**5**	160	--	--	--	--
6	**6**	190	--	--	--	--

5.7 Experimentation

While performing various experiments, the following precautionary measures were taken:

1. Each set of experiments was performed at room temperature in a narrow range $(26 \pm 2^0 C)$.
2. With continuous usage of wire electrode, there was problem of deposition of wire material on work surface which reduces the surface quality of specimen. To minimize this problem, high pressure flushing was used.

In this phase, five process parameters viz. peak current, pulse on time; pulse off time, wire speed and wire tension were selected as given in table 5.3. Experiments were conducted according to the test conditions specified by the L_{18} OA (Table 5.4).

Table 5.4 Parametric trial conditions using L_{18} OA

Sr. No	**Parametric Trial conditions**				
	A (IP)	**B (T ON)**	**C (T OFF)**	**D (WF)**	**E (WT)**
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	2	1	1	2	2
5	2	2	2	3	3
6	2	3	3	1	1
7	3	1	2	1	3
8	3	2	3	2	1
9	3	3	1	3	2
10	4	1	3	3	2
11	4	2	1	1	3
12	4	3	2	2	1
13	5	1	2	3	1
14	5	2	3	1	2
15	5	3	1	2	3
16	6	1	3	2	3
17	6	2	1	3	1
18	6	3	2	1	2

Table 5.5 Parametric trial conditions using L_{18} OA with their values

Sr. No	Parametric Trial conditions				
	A (IP)	B (T ON)	C (T OFF)	D (WF)	E (WT)
1	40	106	30	7	8
2	40	116	40	8	9
3	40	126	50	9	10
4	70	106	30	8	9
5	70	116	40	9	10
6	70	126	50	7	8
7	100	106	40	7	10
8	100	116	50	8	8
9	100	126	30	9	9
10	130	106	50	9	9
11	130	116	30	7	10
12	130	126	40	8	8
13	160	106	40	9	8
14	160	116	50	7	9
15	160	126	30	8	10
16	190	106	50	8	10
17	190	116	30	9	8
18	190	126	40	7	9

Chapter 6

RESULTS AND DISCUSSION

This chapter contains the analysis and discussion of the results of experiments presented in table 6.1. In this chapter, the result of the analysis from the collected data in the experiment is determined. During the experiment, the data is collected without making replication on experiment. So, none variance index called as signal to noise ratio (S/N) will be calculated is of no mean. On the analysis stage, the first step is to calculate the main effects of factors. From the main effects of factors, the optimum conditions for each factor can be traced. That means the required optimum characteristic either for minimize or maximize on specific performance measures (material removal rate and surface roughness) can be applied using the main effects of factors in order to determine the optimum level of each factor.

After the optimization, the second step is applying formula of Analysis Of Variance (ANOVA) to analyze the partial factorial experiment data that implemented before. Actually, ANOVA is not directly analyze the data but rather determines the variability (variance) of the data. ANOVA is a standard statistical technique that confidently can be used on analysis fractional experiment from Taguchi's design which specially developed by Orthogonal Arrays (OA). In this research, the number of experiment is reduced from 4374 sets to L_{18} orthogonal arrays that obviously saving time and cost.

6.1 Analysis of Result for Single Response Optimization.

The experiments were planned by using the parametric approach of the Taguchi's method. The standard procedure to analyze the data, as suggested by Taguchi, is employed. The average values and S/N ratio of the quality/response characteristics for each parameter at different levels are calculated from experimental data. The main effects of process parameters both for raw data and S/N data are plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics. The analysis of variance (ANNOVA) of raw data and S/N data is performed to identify the significant parameters and to quantify their effect on the response characteristics. The most favorable conditions (optimal settings) of process parameters in terms of mean response characteristic are established by analyzing response curves and the ANNOVA Tables.

The analysis of response data is done by well known software "MINITAB 15" specifically used for the design of experiment applications. In this section, the effect of independent WEDM process parameters (peak current, pulse on time, pulse off time, current, wire speed and wire tension) on the selected response characteristics (material removal rate and surface roughness) will be discussed. The average values of response characteristics and S/N ratio (dB) for each parameter at all levels are calculated.

Table 6.1 Experimental Results of Various Response Characteristics

EXP. NO.	Material Removal Rate (mm^2/min)	Surface roughness (μm)
1	18.20	0.914
2	38.54	1.644
3	44.83	1.875
4	41.13	1.308
5	50.54	2.718
6	47.87	2.802
7	53.92	1.656
8	58.81	2.724
9	64.29	3.218
10	36.09	1.186
11	55.58	2.855
12	60.23	3.412
13	39.16	1.479
14	48.10	2.774
15	66.18	3.301
16	31.94	1.513
17	48.52	2.824
18	60.21	3.176
	Avg. value= 48.00778	2.29558

6.1.1 Effect on Material Removal rate (MRR).

The average values of material removal rate and the S/N ratio for each set of parameter at different levels are calculated using MINITAB15 and given in Table 6.2. The response tables for mean & S/N ratio are given in table 6.3 and 6.4.

Table 6.2 Raw data for material removal rate.

S. NO.	MRR (mm^2/min)	SNRA1 (dB)	MEAN1
1	18.20	25.2014	18.20
2	38.54	31.7182	38.54
3	44.83	33.0314	44.83
4	41.13	32.2832	41.13
5	50.54	34.0727	50.54
6	47.87	33.6013	47.87
7	53.92	34.6350	53.92
8	58.81	35.3890	58.81
9	64.29	36.1629	64.29
10	36.09	31.1477	36.09
11	55.58	34.8984	55.58
12	60.23	35.5963	60.23
13	39.16	31.8569	39.16
14	48.10	33.6429	48.10
15	66.18	36.4145	66.18
16	31.94	30.0867	31.94
17	48.52	33.7184	48.52
18	60.21	35.5934	60.21
	Avg. value= 48.00778		

Table 6.3.Response table for S/N Ratios (larger is better) (MRR)

Level No.	**peak Current A**	**Pulse-ON B**	**Pulse-OFF C**	**Wire feed D**	**Wire Tension E**
1	29.98	33.87	33.11	32.93	32.56
2	33.32	33.91	33.91	33.58	33.42
3	35.40	35.07	32.82	33.33	33.86
4	33.88				
5	33.97				
6	33.13				
Delta	5.41	4.20	1.10	0.65	1.30
Ranks	1	2	4	5	3

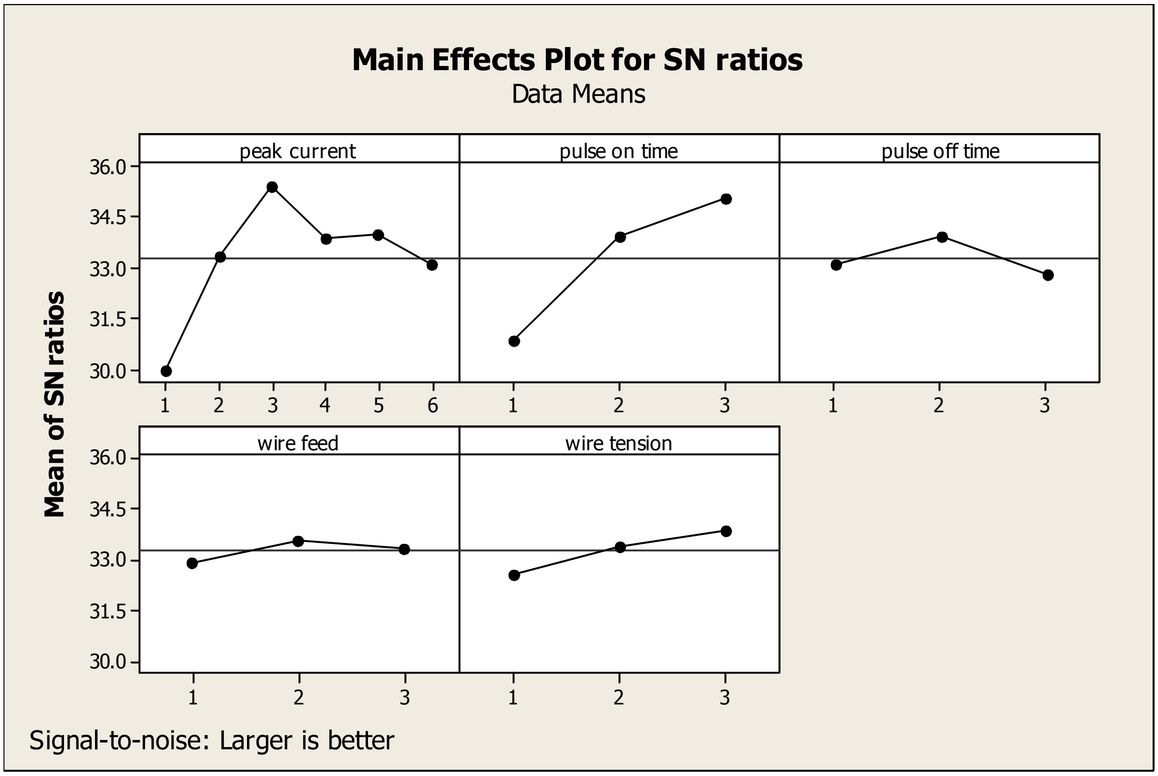


Fig 6.1 Main effect plots for S/N ratio (MRR)

Table 6.4.Response table for Mean (MRR)

Level No.	peak Current A	Pulse-ON B	Pulse-OFF C	Wire feed D	Wire Tension E
1	33.86	36.74	48.98	47.31	45.47
2	46.51	50.02	50.43	49.47	48.06
3	59.01	57.27	44.61	47.24	50.50
4	50.63				
5	51.15				
6	46.89				
Delta	25.15	20.53	5.83	2.23	5.03
Rank	1	2	3	5	4

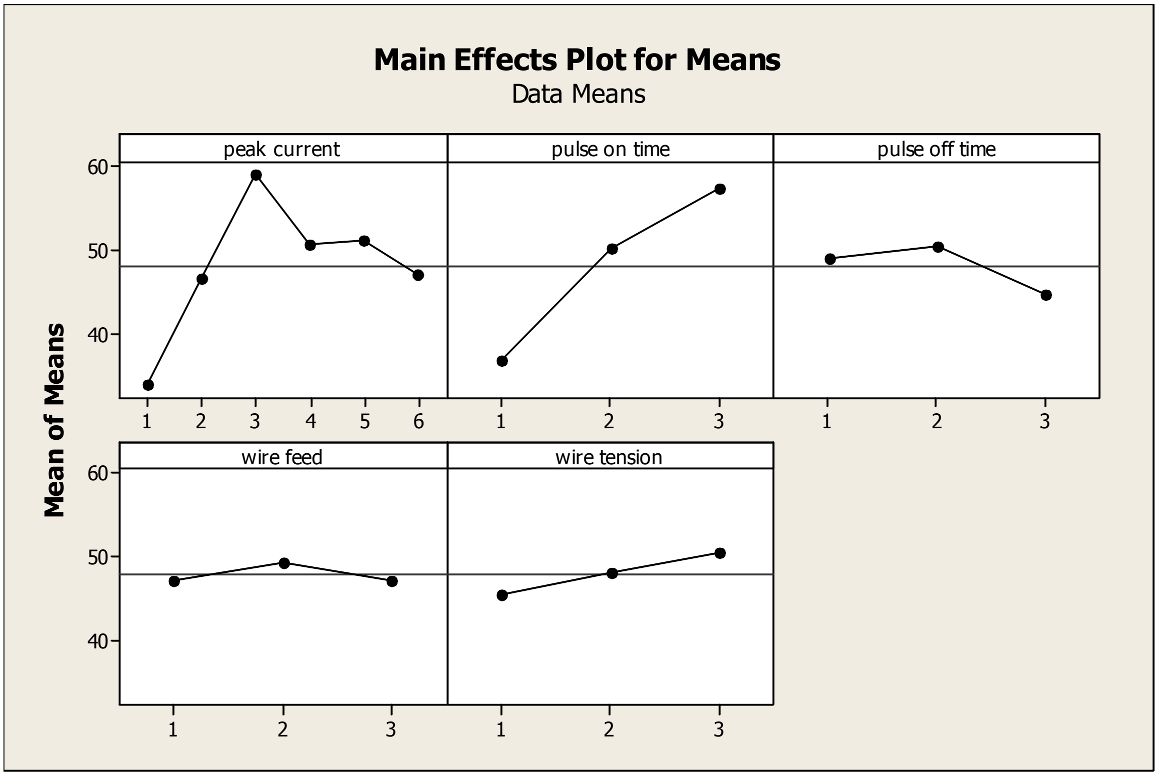


Fig 6.2 Main effect plots for Mean (MRR)

Average value of Material removal rate, calculated from raw data is 48.00778**mm^2/min**. It is clear from S/N plots the max. S/N ratio occurs correspond to A3, B3, C2, D2, and E3. Therefore the predicted mean (optimum) Value will be corresponds to these factors but the only significant factors would be chosen. The significant factors are chosen from ANOVA table.

Table 6.5 ANOVA for S/N data (MRR)

Source	**DOF**	**Seq. SS**	**Adj SS**	**Adj MS**	**F**	**P**
Peak current A	5	48.611	48.611	9.722	4.35	0.039
Pulse on time B	2	56.400	56.400	28.200	12.61	0.019
Pulse off time C	2	3.853	3.853	1.927	0.86	0.489
Wire speed D	2	1.301	1.301	0.651	0.29	0.762
Wire tension E	2	5.225	5.225	2.613	1.17	0.399
Error	4	8.946	8.946	2.237		
Total	17	124.339				

Seq SS= Sum of squares, DOF= degree of freedom, Adj SS= adjusted SS, Adj MS= adjusted mean square or variance.

S = 1.49561 R-Sq = 92.80% R-Sq(adj) = 69.42%

Table 6.6 ANOVA for Mean (Raw data) (MRR)

Source	**DOF**	**Seq. SS**	**Adj SS**	**Adj MS**	**F**	**P**
Peak current A	5	1024.38	1024.38	204.88	8.84	0.028
Pulse on time B	2	1300.50	1300.50	650.25	28.05	0.004
Pulse off time C	2	110.42	110.42	55.21	2.38	0.208
Wire speed D	2	19.30	19.30	9.65	0.42	0.685
Wire tension E	2	76.03	76.03	38.01	1.64	0.302
Error	4	92.71	92.71	23.18		
Total	17	2623.33				

Seq SS= Sum of squares, DOF= degree of freedom, Adj SS= adjusted SS, Adj MS= adjusted mean square or variance.

S = 4.81442 R-Sq = 96.47% R-Sq(adj) = 84.98%

** Significant at 95% confidence level.

6.1.1.1 Selection of Optimum Level

In order to study the significance of process parameters toward the material removal rate, analysis of variance (ANOVA) is performed. The ANOVA of the raw data and S/N data are given in table 6.5 and 6.6. For 95 % confidence level value of P should be less than 0.05. Therefore, from above tables, it is clear that the only two parameters A and B significantly affect both the mean and variation in the values of material removal rate. Material removal rate is the "**higher the better**" type of quality characteristics. Therefore higher value of material removal rate is considered to be optimal.

Predicted mean or optimal value of material removal rate = $\{(\overline{A}_3 + \overline{B}_3) - (T_{avg})\}$ =

(59.01+57.27) - 48.00778 = 68.2722 mm^2/min.

6.1.2 Effect on Surface Roughness

The Raw data and S/N data for the surface roughness is given in table 6.7. In die making surface roughness is a key factor and it depends upon the energy drop across the electrodes. In rough cut, weightage to surface finish is less as compared to other response. High pulse energy creates very rough surface and chance of deep recast layer is more. Therefore, to eliminate the recast layer and to reduce number of trim cuts, die should be machined at adequate cutting speed so that low surface roughness can be achieved. Surface roughness is a "smaller is better" type characteristic. Main effects of each parameter are calculated from response table 6.8 & 6.9. These effects are plotted using MINITAB 15.

Average value of Surface Roughness, calculated from raw data is **2.29558 (µm).** It is clear from S/N plots the max. S/N ratio occurs correspond to A1, B1, C3, D3, and E2. Therefore the predicted mean (optimum) Value will be corresponds to these factors but the only significant factors would be chosen. The significant factors are chosen from ANOVA table.

Table 6.7 Raw data for Surface finish.

S. NO.	**S R (µm)**	**SNRA2 (dB)**	**MEAN2**
1	0.914	0.7811	0.914
2	1.644	-4.3180	1.644
3	1.875	-5.4600	1.875
4	1.308	-2.3322	1.308
5	2.718	-8.6850	2.718
6	2.802	-8.9494	2.802
7	1.656	-4.3812	1.656
8	2.724	-8.7041	2.724
9	3.218	-10.1517	3.218
10	1.186	-1.4817	1.186
11	2.855	-9.1121	2.855
12	3.412	-10.6602	3.412
13	1.479	-3.3994	1.479
14	2.774	-8.8621	2.774
15	3.301	-10.3729	3.301
16	1.513	-3.5968	1.513
17	2.824	-9.0173	2.824
18	3.176	-10.0376	3.176
	Avg value =2.29558		

Table 6.8 Response table for S/N ration (Smaller is better) (SR)

Level No.	**Peak Current** **A**	**Pulse-ON** **B**	**Pulse-OFF** **C**	**Wire feed** **D**	**Wire Tension** **E**
1	-2.999	-2.402	-6.701	-6.760	-6.658
2	-6.656	-8.116	-6.914	-6.664	-6.197
3	-7.746	-9.272	-6.176	-6.366	-6.935
4	-7.085				
5	-7.545				
6	-7.551				
Delta	4.747	6.870	0.738	0.394	0.737
Rank	2	1	3	5	4

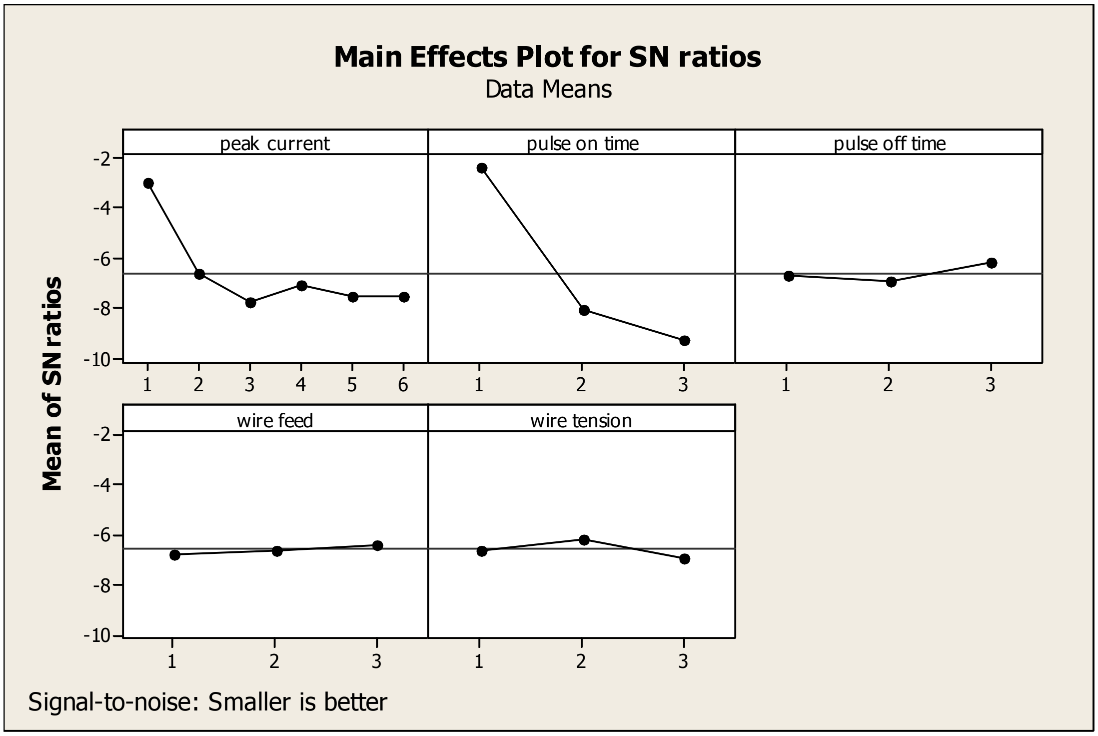


Fig.6.3 Main effect Plots for S/N ratio (SR)

Table 6.9 Response table for Mean (SR)

Level No.	**Peak Current** **A**	**Pulse-ON** **B**	**Pulse-OFF** **C**	**Wire feed** **D**	**Wire Tension** **E**
1	1.478	1.343	2.403	2.363	2.359
2	2.276	2.590	2.348	2.317	2.218
3	2.533	2.964	2.146	2.217	2.320
4	2.484				
5	2.518				
6	2.504				
Delta	1.055	1.621	0.258	0.146	0.142
Rank	2	1	3	4	5

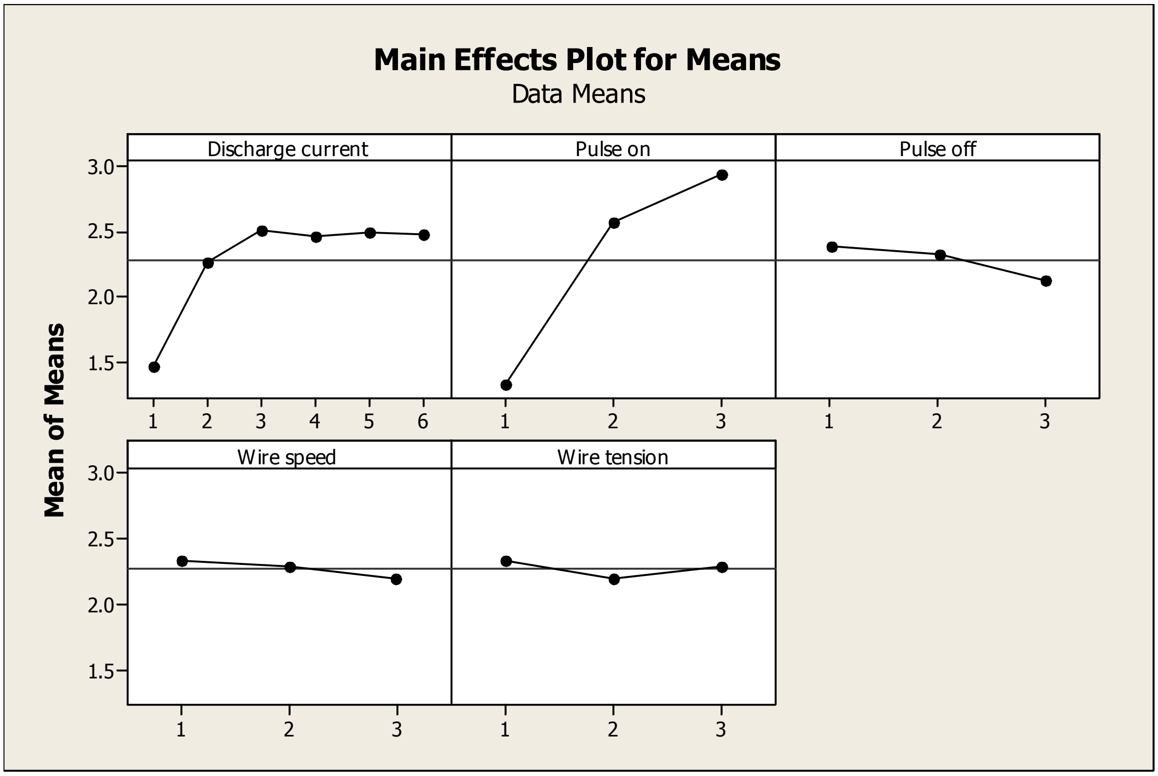


Fig.6.4 Main effect Plots for Mean (SR)

In order to study the significance of process parameters toward the Surface Roughness, analysis of variance (ANOVA) is performed. The ANOVA of the raw data and S/N data are given in table 6.10 and 6.11.

Table 6.10 ANOVA for S/N Data (SR)

Source	**DOF**	**Seq. SS**	**Adj SS**	**Adj MS**	**F**	**P**
peak current A	5	48.942	48.942	9.788	36.69	0.002
Pulse on time B	2	162.389	162.389	81.195	304.30	0.000
Pulse off time C	2	1.731	1.731	0.866	3.24	0.145
Wire feed D	2	0.507	0.507	0.254	0.95	0.459
Wire tension E	2	1.666	1.666	0.833	3.12	0.153
Error	4	1.067	1.067	0.267		
Total	17	216.302				
Seq SS= Sum of squares, DOF= degree of freedom, Adj SS= adjusted SS, Adj MS= adjusted mean square or variance. S = 0.516547 R-Sq = 99.51% R-Sq(adj) = 97.90%						

Table 6.11 ANOVA for Mean Data (SR)

Source	DOF	Seq. SS	Adj SS	Adj MS	F	P
peak current A	5	2.56257	2.56257	0.56257	12.41	0.015
Pulse on time B	2	8.64829	8.64829	4.32415	104.72	0.000
Pulse off time C	2	0.22049	0.22049	0.11025	2.67	0.183
Wire feed D	2	0.06706	0.06706	0.03353	0.81	0.506
Wire tension E	2	0.06397	0.06397	0.03199	0.77	0.520
Error	4	0.16517	0.16517	0.04129		
Total	17	11.72756				
Seq SS= Sum of squares, DOF= degree of freedom, Adj SS= adjusted SS, Adj MS= adjusted mean square or variance. S = 0.203208 R-Sq = 98.59% R-Sq(adj) = 94.01%						

** Significant at 95% confidence level.

6.1.2.1 Selection of Optimum Level

From these tables, it is clear that the only one parameter two parameters A and B significantly affect (taking factors which have values of P close to 0.05) both the mean and variation in the values of surface roughness. Surface roughness is the "smaller the better" type of quality characteristics. Therefore lower value of surface roughness is considered to be optimal.

Predicted mean or optimal value of surface finish is = ($\bar{A}_1$+$\bar{B}_1$-T_{avg}) = (1.478+1.343-2.298558) = 0.52542 (μm)

6.1.3 Confirmation Experiment:

Confirmation experiments were conducted for the material removal rate and surface roughness. The experimental values obtained at the optimal setting of parameters are **MRR = 63.9872 mm^2/min** and **SR=0.908µm** Therefore, confirmation experiment shows that the error associated with material removal rate and surface roughness.

The summary results are given in table 6.12. Table displays the optimal values of the selected characteristics and corresponding optimal setting of process parameters.

Table 6.12 Summary of results for single response optimization.

Quality characteristic	**Optimal setting of process parameters**	**Significant process parameters (at 95% confidence level)**	**Predicted optimal value of quality characteristic**	**Confirmation experimental value**
Material Removal Rate	A_3 B_3 C_2 D_2 E_3	A, B	68.2722 mm^2/min.	63.9872 mm^2/min
Surface Roughness	A_1 B_1 C_3 D_3 E_2	A, B	0.52542 µm	0.908µm

The effect of process parameters on individual response characteristics is evaluated. But there is contradiction in some output response. If we optimize one characteristic, it may affect the other. As in case of both output responses, if we optimize material removal rate it will increase the surface roughness.

Therefore to optimize these output response simultaneously for better performance, we have to implement another technique. In this study I have used the Utility concept along with Taguchi technique for simultaneous optimization of the two output responses.

6.2 Optimizing Multi-quality Characteristics

In this study, a simplified methodology based on Taguchi's approach and utility concept has been used for determining optimal setting of the process parameters for multi-characteristic product. In fact, the methodology is an extension of Byrne and Taguchi (1987).

The raw data for both machining characteristics is given in table 6.13 on next page.

6.2.1 Preference Scale Construction.

1. Material Removal rate.

X^* = optimum value of material removal rate (MRR) = 68.2722 mm^2/min.

X' = Minimum acceptable value of material removal rate = 30 mm^2/min

[MRR varies from 18 to 66.18 mm^2/min but 30 mm^2/min is chosen for good MRR.]

Using these values, the preference scale for CS was constructed as

$$P_{MRR} = 25.2 \log \left(\frac{X_i}{30} \right)$$

2. Surface Roughness

X^* = optimum value of Surface roughness (SR), R_a= 0.52542μm

X' = Minimum acceptable value of SR= 3μm

[SR varies between 0.914 to 3.412 μm**,** greater value of SR produces deep recast layer. Therefore, we rejected 3.412 μm

Using these values, the preference scale for SR was constructed as

$$P_{SR} = -11.89 \log\left(\frac{X_i}{3} \right)$$

Table 6.13 Raw data for MRR and SR

EXP. NO.	Material Removal Rate (mm^2/min)	Surface roughness (μm)
1	18.2	0.914
2	38.54	1.644
3	44.83	1.875
4	41.13	1.308
5	50.54	2.718
6	47.87	2.802
7	53.92	1.656
8	58.81	2.724
9	64.29	3.218
10	36.09	1.186
11	55.58	2.855
12	60.23	3.412
13	39.16	1.479
14	48.1	2.774
15	66.18	3.301
16	31.94	1.513
17	48.52	2.824
18	60.21	3.176
	Average value = 48.00778	Average value = 2.29558

6.2.2 Weights of Quality Characteristics

The weights to the selected quality characteristics were assigned as given below.

W_{MRR} = weight assigned to material removal rate (MRR) = 0.50

W_{SR} = weight assigned to Surface roughness (SR) = 0.50

6.2.3 Utility Value Calculation

The utility value of each die piece was calculated using the following relation (overall utility function):

$$U(n, R) = P_{SR}(n, R) \times W_{SR} + P_{MRR}(n, R) \times W_{CS}$$

Where, n= trial number, n = 1, 2, 3……, 18; R = replication number, R= 1, 2, 3

The utility values thus calculated are reported in table 6.14

Here n= 18 and R= 1

6.2.4 Analysis of Utility Data

The data were analyzed both for mean response and signal-to-noise (S/N) ratio. Since utility is a "higher the better" (HB) type of characteristic, $(S/N)_{HB}$ has been used:

The mean responses and main effects in terms of utility values are calculated and reported in table 6.15 and 6.16. These effects are plotted using MINITAB 15.

Table 6.14 Utility Data

Sr. No.	**UTILITY DATA**	**S/N ratio (dB)**	**Mean**
1	0.33512	9.3206	0.168996
2	2.92436	10.6603	2.58040
3	3.41204	11.7561	3.02826
4	3.87083	9.8526	3.59612
5	3.10906	8.7342	2.61280
6	2.73343	13.5213	2.22796
7	4.74314	11.8937	4.39698
8	3.93264	12.0188	3.43572
9	3.98969	10.6510	3.44228
10	3.40841	10.8868	3.16337
11	3.50221	10.8354	2.99105
12	3.48152	10.3304	2.91638
13	3.28488	8.8984	2.97296
14	2.78560	12.2184	2.28317
15	4.08246	6.4897	3.52734
16	2.11098	8.9028	1.79217
17	2.78704	11.2811	2.27919
18	3.66484	9.3206	3.12141
	Avg. value=**3.231014**		

Table 6.15 Response table for S/N ratio (Larger is better) (UTILITY)

Level No.	**Peak Current** **A**	**Pulse-ON** **B**	**Pulse-OFF** **C**	**Wire Speed** **D**	**Wire Tension** **E**
1	3.495	7.209	7.715	7.304	6.867
2	10.114	9.959	10.857	10.419	10.654
3	12.478	10.958	9.555	10.403	10.605
4	10.791				
5	10.782				
6	8.891				
Delta	8.983	3.749	4.0634	3.115	3.788
Rank	1	3	4	5	2

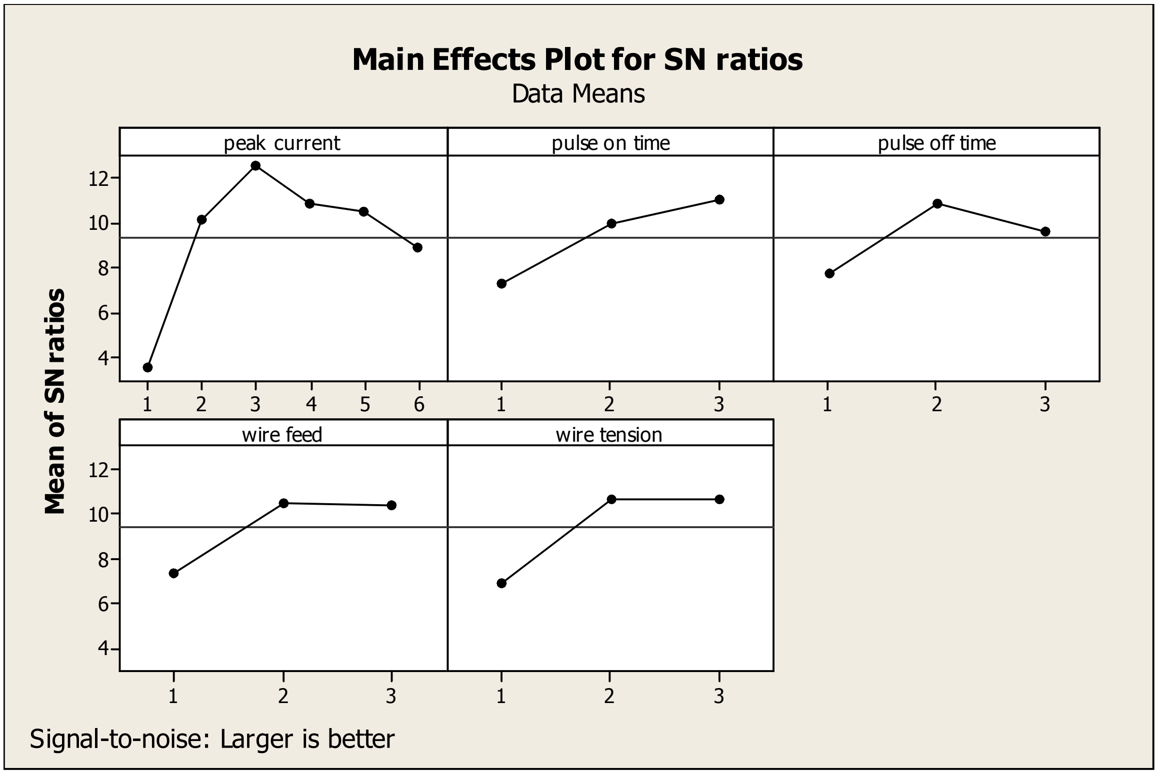


Fig.6.5 Main effect Plots for S/N ratio for utility

Table 6.16 Response table for Mean (UTILITY)

Level No.	**Peak Current** **A**	**Pulse-ON** **B**	**Pulse-OFF** **C**	**Wire Speed** **D**	**Wire Tension** **E**
1	2.224	2.959	3.095	2.961	2.759
2	3.238	3.173	3.535	3.400	3.441
3	4.222	3.561	2.064	3.332	3.493
4	3.464				
5	3.384				
6	2.854				
Delta	1.998	0.602	0.471	0.550	0.734
Rank	1	3	4	5	2

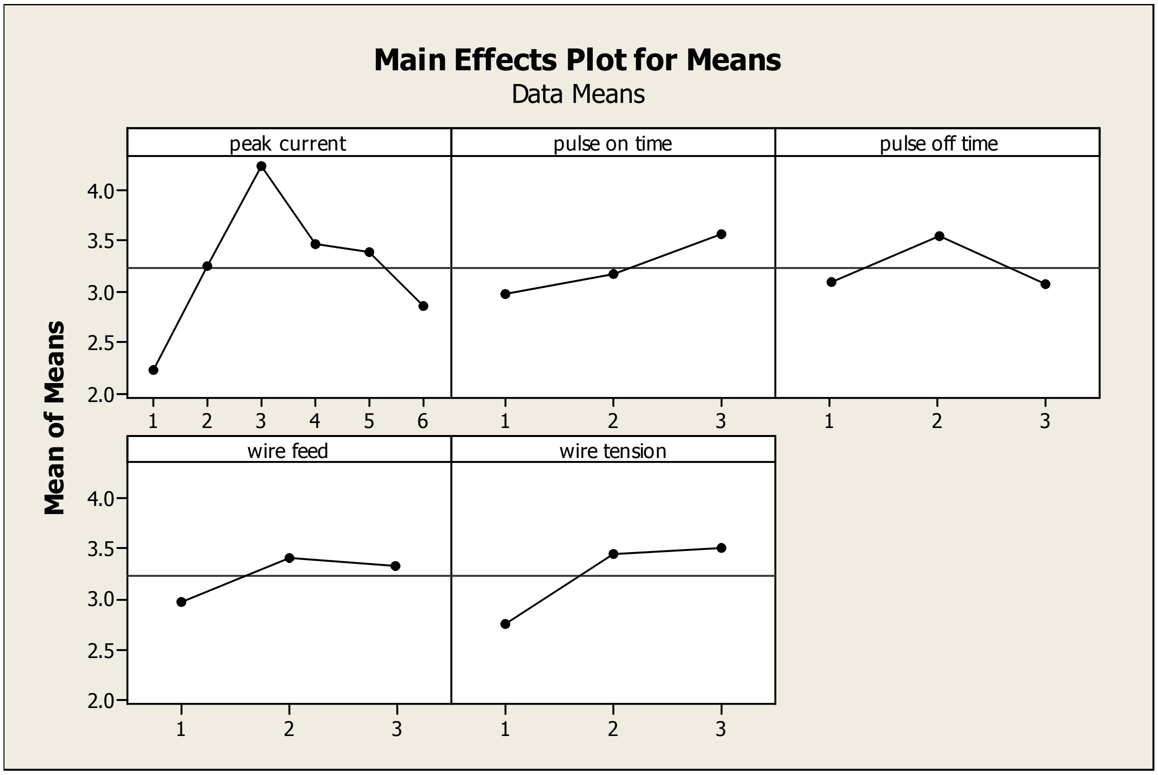


Fig.6.6 Main effect Plots for mean for utility

It is clear from the main plots (fig. 6.5) that parameter settings correspond to A_3 B_3 C_2 D_2, E_3, would yield the best performance in terms of utility value and S/N ratio within the selected rang of parameters.

Table 6.17 ANOVA for S/N ratio (UTILITY)

Source	**DOF**	**Seq. SS**	**Adj SS**	**Adj MS**	**F**	**P**
peak current A	5	144.64	144.64	28.93	1.08	0.0483
Pulse on time B	2	45.24	45.24	22.62	0.85	0.0428
Pulse off time C	2	29.91	29.91	14.96	0.56	0.061
Wire feed D	2	30.60	30.60	19.30	0.72	0.0540
Wire tension E	2	56.64	56.64	28.32	1.06	0.053
Error	4	107.01	107.01	26.75		
Total	17	422.05				
Seq SS= Sum of squares, DOF= degree of freedom, Adj SS= adjusted SS, Adj MS= adjusted mean square or variance. S = 5.17232 R-Sq = 74.64% R-Sq(adj) = 0.00%						

Table 6.18 ANOVA for Mean Data (UTILITY)

Source	**DOF**	**Seq. SS**	**Adj SS**	**Adj MS**	**F**	**P**
peak current A	5	6.647	6.647	1.3295	1.33	0.0402
Pulse on time B	2	1.1162	1.1162	0.5581	0.56	0.044
Pulse off time C	2	0.8325	0.8325	0.4162	0.42	0.0685
Wire feed D	2	0.6716	0.6716	0.3358	0.34	0.073
Wire tension E	2	2.0126	2.0126	1.0063	1.01	0.061
Error	4	3.995	3.995	0.998		
Total	17	15.2730				

Seq SS= Sum of squares, DOF= degree of freedom, Adj SS= adjusted SS, Adj MS= adjusted mean square or variance.

S = 0.999063   R-Sq = 73.86%   R-Sq(adj) = 0.00%

Predicted mean or optimal value of utility = {($\bar{A}_3$ +$\bar{B}_3$)-(T_{avg})} = 4.552

$\bar{A}_3$=4.222 from table 6.16

$\bar{B}_3$=3.561 from table 6.16

T_{avg}=3.231014 from table 6.14

Therefore,

$$CI_{CE} = \sqrt{f_{\alpha(1,f_e)} V_e (\frac{1}{n_{eff}} + \frac{1}{R})}$$

$$\eta_{eff} = \frac{N}{1 + \text{DOF [associated in estimate of mean response]}}$$

R= 1

$\eta_{eff} = 18/[1 + 13]$ = 3.85

$V_e = 0.998$ (From table 18)

$f_e = 4$ (From table 18)

$f_{0.05\ (1,4)} = 7.7087$ (Tabulated F value; Roy, 1990)

$CI_{pop} = \pm 3.113$

Therefore utility ranges are mean $\mu_{MRR,SR}$- CI_{CE}< $\mu_{MRR,SR}$ < $\mu_{MRR,SR}$+ CI_{CE}

$$\mathbf{1.409 < \mu_{MRR,SR} < 7.635}$$

The optimal setting of the process parameters for the multi-characteristics optimization (MRR and SR) are given in table 6.19 below.

Table 6.19 Optimal Parameter Setting

Peak current (A_3, third level)	100
Pulse-ON time (B_3, third level)	126
Pulse-OFF time (C_2, second level)	40
Wire speed (D_2, Second level)	8
Wire tension (E_2, Second level)	9

6.2.5 Confirmation experiments

Three confirmation experiments have been conducted at the optimum settings of the process parameters. The following average values have been found for the quality characteristics considered:

(a) Average cutting rate = 61.526 mm/min

(b) Average surface roughness = 2.87µm

The utility value of the machined part has been calculated using the following relation:

$$U = P_{MRR} * W_{MRR} + P_{SR} * W_{SR}$$

$= 7.8608*0.5 + 0.2288*0.5$

$= 3.816$

This experimentally obtained utility value is lying within the 95% CI_{CE} of the optimal range of the utility calculated for utility function (UMRR, SR).

6.3 Summary of Results and Comparison with Single Characteristic Optimization

The summary results and comparison with single characteristic optimization are reported in table 6.20.

Table 6.20 Summary and comparison of results

Method	Characteristic	Optimal condition	Predicted values	Confirmed experimental value
Single characteristic optimization	MRR	A_3 B_3 C_2 D_2 E_3	MRR=68.2722 mm^2/min.	63.9872 mm^2/min
	SR	A_1 B_1 C_3 D_3 E_2	SR=0.52542 (μm)	SR=0.908µm(μm)
Multi-characteristic optimization	MRR, SR	A_3 B_3 C_2 D2 E_2	$1.409 < \mu_{MRR,SR} < 7.635$	61.526 mm^2/min 2.87 (μm) $\mu_{MRR,SR} = 3.816$

Chapter 7

CONCLUSIONS AND SCOPE OF FUTURE WORK

The Taguchi methodology is employed to find out the main parameters that affect the different machining criteria, such as average Material Removal Rate and Surface Roughness in the present set of study. Five control factors have been studied simultaneously to establish the trend of variation of a few important machining criteria with these control factors. A rough cut has been considered as a machining operation. Our target was to optimize the cutting parameters with D2 die steel having good material removal rate and adequate surface finish during rough cut.

7.1 Conclusions

Base on the constraints of the present set of experimentation, the following conclusions are drawn

1. The average material removal rate (MRR) is mostly affected by the pulse-on time and peak current during rough cut. Optimum setting for MRR is A_3, B_3, C_2, D_2 and E_3.
2. The surface roughness values (SR) are influenced mostly by pulse-on and peak current only during rough cut. The optimal setting of process parameters found as A_1, B_1, C_3, D_3 and E_2.
3. A single set of parametric combination can never produce the highest productivity (within the possible range) with the best surface finish at high material removal rate and least geometrical inaccuracy. A proper trade-off becomes inevitable to satisfy all the above-mentioned machining criteria simultaneously.
4. The optimal values obtained using the multi-characteristic optimization model has been validated by confirmation experiments. The optimal setting of process parameters is A3 =100, B3 =126, C2 =40, D2=8, E2 =9. Correspond to this setting experimental value are SR=2.87(μm) and MRR=61.526mm^2/min.

5. The weight assigned to the selected quality characteristics was different for different characteristics. However with a different set of weights, a different set of optimal parameters for the quality characteristics will results. The optimal set predicted will be closer to the set predicted for the single characteristic which is having the largest weight.
6. The model can be extended to any number of quality characteristics provided proper utility scales for the characteristics are available from the realistic data.

7.2 Scope for Future Work

1. L_{18} orthogonal array does not provide interaction between different parameters. Therefore higher order orthogonal arrays (OA) can be considered to incorporate all the possible interactions of the process parameters.

2. The study can be extended using different work materials, and hybrid optimization techniques.

3. Further research might attempt to take more factors, such as wire, work piece material, work piece height and dielectric flow rate into account as process inputs.

4. Other performance criteria, such as, the skewness, waviness and white layer depth of the wire electro-discharge machined job surface, might be investigated using the same approach presented here.

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