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Optimization of Material Removal Rate in Wire EDM Using Design of Experiment

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Abstract: Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the conventional machining processes. WEDM utilizes a continuously travelling wire electrode made of Cu, brass or tungsten of diameter 0.05 -0.30mm, capable of achieving very small corner radii. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the work piece and the wire electrode, eliminating the mechanical stresses during machining. The effects of various process parameters of WEDM pulse on time (Ton), pulse off time (Toff), gap voltage (SV), peak current (IP), have been investigated to reveal their impact on material removal rate. The experimental plan is performed by a standard RSM design called central composite design. The experimental studies were performed on WEDM machine in the ABRS Impex Pvt. Ltd, Delhi. It is concluded from the study that the material removal rate (MRR) increases with increase in pulse on time (Ton) and peak current (IP) while if decreases with increase in pulse off time (Toff) and servo voltage (SV).

Keywords: WEDM, Process parameters, pulse on time, pulse off time, gap voltage, peak current etc.

1. INTRODUCTION

Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the main stream machining processes. The development of new advanced engineering materials and the need to meet demand for precise and flexible prototype and low-volume production of components have made wire electrical discharge machining (WEDM) an important manufacturing process. WEDM is a process of repetitive sparking cycles. A series of electrical pulses generated by pulse generator unit is applied between the work-piece and travelling wire electrode during spark discharge, there is flow of current across the wire electrode-work piece gap. Energy contained in tiny spark discharge removes a fraction of work material. Duration of each spark is very short. Large number of such time spaced tiny discharges between the work piece and wire electrode cause the electro-erosion of work piece material. The entire cycle time is usually few micro-seconds. The frequency of sparking is as high as thousands of sparks per second. The area over which a spark is effective is also very small. However, temperature of the area under the spark is very high. As a result, the spark energy is capable of partly melting and partly vaporizing material from localized area on both the electrodes, i.e. work piece and tool. The material is removed in form of craters which spread over the entire surface of the work piece. Particles eroded from the electrode are known as debris. Figure 1.1 illustrates the various terminologies of WEDM cycle.

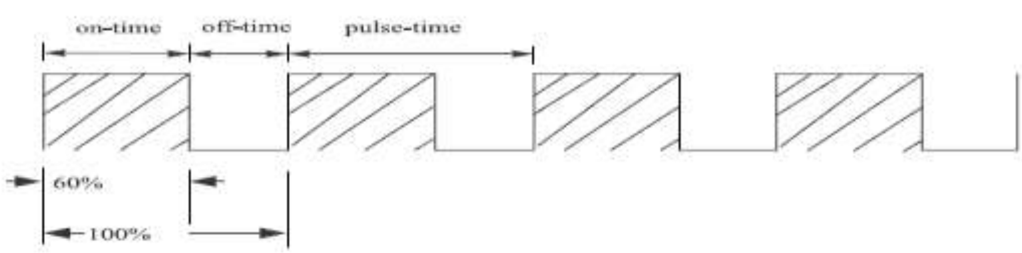

Fig. 1.1: An illustration of on-time, off-time, pulse-time and duty cycle.

In this process a pulsed DC power supply is applied between work-piece and wire electrode. It results in the intense electrical field at the location where surface irregularity provides the narrowest gap. Negatively charged particles (electrons) break from the cathode surface and move towards the anode surface under the influence of electric field forces. During this movement in inter-electrode gap, the electrons collide with the neutral molecules of dielectric, which is injected from a nozzle in the machining area. In this process, electrons are also detached from these neutral molecules of the dielectric resulting in still more ionization. The ionization soon becomes so intense that a very narrow channel of continuous conductivity is established. In this channel, there is a continuous flow of considerable number of electrons towards the anode and that of ions towards the cathode.

Their kinetic energy is converted into heat energy, resulting in heating of anode due to the bombardment of electrons and heating of cathode due to the bombardment of ions. Thus, it ends up in a momentary current impulse resulting in a discharge which may be an arc or a spark. The spark energy raises the localized temperature of the wire electrode and work piece to such a high value that it results either in melting, or melting as well as vaporization of small amount of material from the surface of both electrodes at the point of spark contact. In fact, due to evaporation of dielectric the pressure in the plasma channel rises to a very high value (say, 200 atm.) and it prevents the evaporation of superheated metal. As soon as the off- time of pulse starts, the pressure drops instantaneously allowing the superheated metal to evaporate. The amount of metal eroded from the work piece and wire electrode will depend upon the contributions of electrons and ions respectively

2. LITERATURE REVIEW

In recent years an extensive research has been carried out on WEDM relating to improving performance measures, optimizing the process variables, monitoring and controlling the sparking process, simplifying the wire design and manufacture, improving spark efficiency by various researchers. Pandey P.C and Shan HS [1] wrote a book on MMP in which working procedure and detail construction of WEDM described. Some of the work related to the present study is discussed in the following paragraphs. In the past, various methods were employed to quantify the impact of control parameters on part surface quality. According to Trezise ([2], the fundamental limitations on machining accuracy are dimensional consistency of the wire and positional accuracy of the work table in WEDM process. Most of the uncertainties arise due to unsupported section of the wire. Mazuzawa et al., [3] to manufacture micro-parts there is often need to compensate the wear by replicating electrodes.

To address this requirement, a technique for on-the machine electrode generation was developed, that utilized a technology called micro-Wire Electrode Discharge Grinding. Scott et al [4] have presented a formulation and solution of a multi objective optimization problem for the selection of the best parameter settings on a WEDM machine. The measures of performance for the model were MRR and surface quality. In that study, a factorial design model has been used to predict the measures of performance as a function of a variety of machining parameters. They used a factorial design method, to determine the optimal combination of control parameters in WEDM considering the measures of machining performance as metal removal rate and the surface finish. The study concluded that control factors are discharge current, the pulse duration and the pulse frequency. Williams and Rajurkar [5] described that the main goals of WEDM manufacturers and users are to achieve a better stability and high productivity of the process i.e. higher machining rate with desired accuracy and minimal surface damage.

Surface roughness profiles were studied with stochastic modeling and analysis methodology to better understand the process mechanism. Scanning electron microscopic examination highlighted important features of machined surfaces in WEDM.Dauw and Albert [6] reported an analysis of the six contributing factors. Attention is given in particular to one of these factors, the wire tool itself. Tine several types of wire are compared from their metallurgical aspect. Their physical composition and relative performance are analyzed and a cost to performance ratio is given for a series of wires considered. As a conclusion, it is shown that the wire tool, although often considered as an evident EDM accessory has influenced very substantially the EDM wire cutting performance. Since the commercial introduction of wire EDM on the market, end 1969 begins 1970, the overall performance of the wire EDM has undergone a tremendous evolution. Six major contributing factors have been responsible for this important change. One of these, the wire tool electrode has been improving substantially yielding an enormous increase of the overall performance (cutting speed, cutting accuracy, precision, cost etc).

Prasad and Mishra [7] determined the temperature distribution in the material of the wire in order to predict failure due to thermal load. In the present work, a simple computational model is developed which will give the temperature values for varying magnitudes of parameters, viz., input power, pulse-on time, wire velocity and wire diameter. It is reported that the optimum control of these parameters will help in preventing thermal failure, thus obtaining better utilization of the process. A finite-difference thermal model to predict the temperature distribution along the wire for the WEDM process in the zone of the discharge channel is proposed[8]. The power is presumed to be dissipated in a single spark through a volumetric heat source present within the wire over the discharge channel width, which, in turn, is calculated from the available literature. The temperature distributions are calculated by varying the values of different pertinent parameters: input power (50–300 W), pulse-on time (10–200 μs), wire velocity (0.5–10 m/min) and wire diameter (0.1–0.3 mm)[9]. Luo [10] analyzed the technical requirements of fast-cutting WEDM.

Based on a synthesis of experimental results and pulse energy analysis, an energy-distribution diagram concerning the correlation between cutting speed and comprehensive machining conditions has been established to determine a suitable parameter combination for a stable fast-cutting process. High power density and high pulse density are found to be two basic requirements for a constant high cutting speed. Harmful energy loss has to be reduced, otherwise the wire temperature becomes too high due to the dissipated heat. According to the energy-distribution diagram, machining conditions such as cutting width, wire diameter and wire travelling speed are also considered in increasing the cutting speed. After an optimization of the energy distribution in fast-cutting WEDM, a 4-fold improvement in cutting speed has been achieved whilst the wire service life remains almost unchanged. The achievements described have practical significance in enhancing die productivity as well as in transferring WEDM into a general cutting alternative. Spedding and Wang [11] made an attempt at modeling the process through Response Surface Methodology and Artificial Neural Networks.

Wire electrical discharge machining (WEDM) technology has been used widely in production, aerospace/aircraft, medical and virtually all areas of conductive material machining. Its complexity and stochastic nature have stimulated numerous attempts to model it accurately. A response surface model based on a central composite rotatable experimental design, and a 4-16-3 size back-propagation neural network has been developed. The pulse-width, the time between two pulses, the wire mechanical tension and the injection set-point are selected as the factors (input parameters); whilst the cutting speed, the surface roughness and the surface waviness are the responses (output parameters). The two models are compared for goodness of fit. Verification experiments have been carried out to check the validity of the developed models. It is concluded that both models provide accurate results for the process. Magara et al [12] carried out an investigation on the dynamic wire vibration mechanism and a mathematical model was derived. This model is compared with experimental results.

The measured displacement of a wire electrode in machining a thin plate is analyzed with impulsive force measured through impulse response by a single discharge. The force acting on the wire depends on the direction of the wire movement in vibration. In WEDM, it is very important to restrain the vibration of the wire electrode for the improvement of machining accuracy. A 3rd order system equation for the WEDM system is derived considering material removal and vibrational features of the system. As the discharge circuit suddenly changes according to gap condition, this vibration system is essentially nonlinear. Simulation of WEDM is performed with the modelled system. Huang et al [13] made an attempt to unveil the influence of the machining parameters (pulse-on time, pulse-off time, table feed-rate, flushing pressure, distance between wire periphery and work piece surface) on the machining performance of WEDM in finish cutting operations. The gap width, the surface roughness and the white layer depth of the machined work piece surface are measured and evaluated.

Based on the Taguchi quality design method and numerical analysis, it is found that the pulse-on time and the distance between the wire periphery and the work piece surface are two significant factors affecting the machining performance. Mathematical models relating machining parameters and performance are established by regression and non-linear programming using the Feasible-direction algorithm to obtain the optimal machining parameters. A strategy of optimal multi-cut WEDM process planning from rough to finish cutting operations, including the number of machining operations and their corresponding machining-parameters setting for each operation, has been proposed. Experimental results show that the proposed approach can achieve better performance than that achieved by a well-skilled operator.

A better surface quality and dimensional accuracy value can be obtained in less machining time.[14] Puri and Bhattacharya [16] carried out an extensive study of wire lag phenomenon in WEDM and established the trend of variation of geometrical inaccuracy caused due to wire lag with various machine control parameters. In this research study, all the machine control parameters are considered simultaneously for machining operation which comprised a rough cut followed by a trim cut. The objective of study was to carry out an experimental investigation based on the Taguchi method involving thirteen control factors for given machining criteria, such as average cutting speed, surface finish characteristics and geometrical inaccuracy caused due to wire lag. Guo et al [17] adopted a method of computer simulation to study the vibration of the wire electrode under the action of successive discharges, by which the effect of wire fluctuation on the distribution of the discharge points is also analyzed. In wire electric discharge machining, the vibration of the wire electrode has a significant influence on the performance and stability of the machining process.

The results show that the discharge points can be distributed much more evenly along the span of the wire when an optimum condition is reached between discharge energy, discharge frequency, wire tension and wire span. Under such a condition, it is possible that the hazard of wire breaking can be avoided. Simao et al [15] Electrical discharge machining (EDM) is a widely used process in the mould / die and aerospace industries. Following a brief summary of the process, the paper reviews published work on the deliberate surface alloying of various work piece materials using EDM. Details are given of operations involving powder metallurgy (PM) tool electrodes and the use of powders suspended in the dielectric fluid, typically aluminium, nickel, titanium, etc. Following this, experimental results are presented on the surface alloying of AISI H13 hot work tool steel during a die sink operation using partially sintered WC / Co electrodes operating in a hydrocarbon oil dielectric. An L8 fractional factorial Taguchi experiment was used to identify the effect of key operating factors on output measures (electrode wear, work piece surface hardness, etc.). With respect to micro hardness, the percentage contribution ratios (PCR) for peak current, electrode polarity and pulse on time were ~24, 20 and 19%, respectively.

Typically, changes in surface metallurgy were measured up to a depth of ~30 μm (with a higher than normal voltage of ~270 V).Cogun and Tosun [20] carried out an investigation on the effect and optimization of machining parameters on the kerf (cutting width) and material removal rate (MRR) in WEDM operations. The experimental studies were conducted under varying pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. The settings of machining parameters were determined by using Taguchi experimental design method. The level of importance of the machining parameters on the cutting kerf and MRR is determined by using analysis of variance (ANOVA). The optimum machining parameter combination was obtained by using the analysis of signal-to-noise (S/N) ratio. The variation of kerf and MRR with machining parameters is mathematically modeled by using regression analysis method. The optimal search for machining parameters for the objective of minimum kerf together with maximum MRR is performed by using the established mathematical models. Ahmet and Çayda[18] adopted an experimental investigation of the machining characteristics of AISI D5 tool steel in wire electrical discharge machining process.

During experiments, parameters such as open circuit voltage, pulse duration, wire speed and dielectric fluid pressure were changed to explore their effect on the surface roughness and metallurgical structure. Optical and scanning electron microscopy, surface roughness and micro hardness tests were used to study the characteristics of the machined specimens. Taking into consideration the experimental results, it is found that the intensity of the process energy does affect the amount of recast and surface roughness as well as micro cracking, the wire speed and dielectric fluid pressure not seeming to have much of an influence. Leao and Pashby [19] they presented a literature survey on the use of dielectric fluids that provide an alternative to hydrocarbon oil. It has been reported that water-based dielectrics may replace oil-based fluids in die sink applications. Gaseous dielectrics such as oxygen may also be the alternative. Nonetheless, these need further research in order to be commercially viable. Electrical discharge machining became a commercial process after the discovery of the importance of the dielectric fluid, which affects factors such as productivity and quality.

Health, safety and environment are also important factors, particularly when oil-based fluids are used. Hewidyet al [21] highlighted the development of mathematical models for correlating various WEDM machining parameters of Inconel 601 material such as: peak current, duty factor, wire tension and water pressure with the metal removal rate, wear ratio and surface roughness. This work has been established based on the response surface methodology (RSM). Using WEDM technology, complicated cuts can be made through difficult-to-machine electrically conductive components. The high degree of the obtainable accuracy and the fine surface quality make WEDM valuable. The right selection of the machining conditions is the most important aspect to take into consideration in processes related to the WEDM of Inconel 601 material. Inconel is one of the recent materials that is developed to be hard, strong and temperature resistant. Kuriakose and Shunmugam [22] developed a multiple regression model to represent relationship between input and output variables and a multi-objective optimization method based on a Non-Dominated Sorting Genetic Algorithm (NSGA) was used to optimize WEDM process.

WEDM is one of the important non-traditional machining processes, which is used for machining of difficult-to-machine materials and intricate profiles. Being a complex process, it is very difficult to determine optimal parameters for improving cutting performance. Cutting velocity and surface finish are most important output parameters, which decide the cutting performance. There is no single optimal combination of cutting parameters, as their influences on the cutting velocity and the surface finish are opposite in nature. A non-dominated solution set has been obtained and reported. S. S. Mahapatra et al.[24], studied Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method. Wire electrical discharge machining (WEDM) is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in WEDM is treated as a challenging one because improvement of more than one machining performance measures viz. metal removal rate (MRR), surface finish (SF) and cutting width (KERF) are sought to obtain a precision work. Using Taguchi's parameter design, significant machining parameters affecting the performance measures are identified as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow.

It has been observed that a combination of factors for optimization of each performance measure is different. In this study, the relationship between control factors and responses like MRR, SF and KERF are established by means of nonlinear regression analysis, resulting in a valid mathematical model. Finally, genetic algorithm, a popular revolutionary approach, is employed to optimize the wire electrical discharge machining process with multiple objectives. He described the development of a model and its application to optimize WEDM machining parameters. This paper outlines the development of a model and its application to optimize WEDM machining parameters. Experiments are conducted to test the model and satisfactory results are obtained. The methodology described here is expected to be highly beneficial to manufacturing industries, and also other areas such as aerospace, automobile and tool making industries.Sanchez et al [23] presented a new approach to the prediction of angular error in wire-EDM taper-cutting. A systematic analysis of the influence of process parameters on angular error is carried out using Design of Experiments (DOE) techniques.

A quadratic equation for the prediction of angular error that takes into account electrical parameters and part geometry is derived. Validation results reveal a dominant influence of the mechanical behaviour of the wire, rather than that of EDM regime. Following this assertion an original finite element model (FEM) to describe the mechanical behaviour of soft wires, typically used in taper-cutting operations, has been developed taking into account non-linear phenomena such as contact mechanics, plastic behaviour, stress-stiffening and large displacements. Both the results of DOE techniques and FEM simulation have been validated through experimental tests in industrial conditions. Kanlayasiri and Boonmung [25] presented an investigation of the effects of machining variables on the surface roughness of WEDMed DC53 die steel. In this study, the machining variables investigated were pulse-peak current, pulse-on time, pulse-off time, and wire tension. Analysis of variance (ANOVA) technique was used to find out the variables affecting the surface roughness. Assumptions of ANOVA were discussed and carefully examined using analysis of residuals. Quantitative testing methods on residual analysis were used in place of the typical qualitative testing techniques. Results from the analysis show that pulse-on time and pulse-peak current are significant variables to the surface roughness of WEDMed DC53 die steel. The surface roughness of the test specimen increases when these two parameters increase.

Bhaskar Reddy et.al, [16] have investigated for best parameter selection to obtain maximum Metal removal rate (MRR) and better surface roughness (Ra) by conducting the experimentation on CONCORD DK7720C four axes CNC Wire Electrical Discharge Machining of P20 die tool steel with molybdenum wire of 0.18mm diameter as electrode. From the literature several researchers have been applied the Taguchi method is used to optimize the performance parameters in WEDM process.

3 EXPERIMENTATION WORK

3.1 PROCESS PARAMETERS

There are various process parameters of WEDM affecting the machining characteristics. On the basis of literature review and some pilot investigations (not reported here), the following process parameters have been selected for study in the range shown in table 3.1

Table 3.1 Process parameters with their ranges.

Symbol	Input Parameters	Range
A	Peak current (IP)	50-150 Amps
B	Pulse on time (Ton)	100-125 machine units
C	Pulse off time (Toff)	20-50 machine units
D	Servo voltage (SV)	18-47 Volts

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3.2 MACHINE TOOL USED WITH OPERATIONAL DETAILS

The machine performs multiplicity of operations in one setup.

Fig. 3.1 CNC Wire EDM MACHINE.

Technical Specifications of Machine Tool

• Design	Fixed column, moving table
• Table size	400 x 650 mm
• Max.work piece height	250 mm
• Max. work piece weight	500 kg
• Main table traverse (X, Y)	300, 400 mm
• Auxiliary table traverse (u, v)	80, 80 mm
• Max. taper cutting angle	±30°/50 mm
• Max. wire spool capacity	10 kg
• Wire electrode diameter	0.25 mm (Std.) ,0.15, 0.20 mm (Optional)
• Dielectric	Deionised water

3.3 WORK PIECE MATERIAL

The work piece material is a high carbon high chromium (HCHCr) die steel with excellent wear resistance, hot toughness and good thermal shock resistance. The chemical composition of the material is shown in table 3.2

Table 3.2 Composition of work material.

S.NO.	MATERIAL	PERCENTAGE
1.	CARBON	2.02
2.	SILICON	0.33
3.	MAGANESE	0.37
4.	SULPHUR	0.027
5.	PHOSPHORUS	0.026
6.	NICKEL	0.062
7.	CHROMIUM	11.55
8.	MOLYBDENUM	0.023
9.	COPPER	0.009
10.	IRON	Rest

3.4 EXPERIMENTAL DATA

The experimental work is carried out as per the central composite design using RSM methodology. The design is prepared with the help of Design expert software version 6.0.8 which is used to create experimental designs. The design is shown in table 3.3

Table 3.3 Experimental Design

			Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	Run	Block	A:IP	B:TON	C:TOFF	D:SV	Response 1
		(UNIT)	AMP	M U	MU	VOLTS	MRR
7	1	Block 1	50.00	125.00	50.00	18.00	1.5
8	2	Block 1	150.00	125.00	50.00	18.00	1.4
18	3	Block 1	200.00	112.50	35.00	32.50	0.8
30	4	Block 1	100.00	112.50	35.00	32.50	1.2
29	5	Block 1	100.00	112.50	35.00	32.50	1.1
10	6	Block 1	150.00	100.00	20.00	47.00	3.1
21	7	Block 1	100.00	112.50	5.00	32.50	2.1
28	8	Block 1	100.00	112.50	35.00	32.50	1
23	9	Block 1	100.00	112.50	35.00	3.50	0.47
15	10	Block 1	50.00	125.00	50.00	47.00	2.7
17	11	Block 1	0.00	112.50	35.00	32.50	2.5
5	12	Block 1	50.00	100.00	50.00	18.00	0.8
9	13	Block 1	50.00	100.00	20.00	47.00	1.9
26	14	Block 1	100.00	112.50	35.00	32.50	2.1
13	15	Block 1	50.00	100.00	50.00	47.00	2.2
24	16	Block 1	100.00	112.50	35.00	61.50	3.19
25	17	Block 1	100.00	112.50	35.00	32.50	1.8
11	18	Block 1	50.00	125.00	20.00	47.00	2.2
27	19	Block 1	100.00	112.50	35.00	32.50	1.9
20	20	Block 1	100.00	137.50	35.00	32.50	1.85
12	21	Block 1	150.00	125.00	20.00	47.00	2.4
4	22	Block 1	150.00	125.00	20.00	18.00	0.8
22	23	Block 1	100.00	112.50	65.00	32.50	2.1
14	24	Block 1	150.00	100.00	50.00	47.00	2.2
1	25	Block 1	50.00	100.00	20.00	18.00	0.7
2	26	Block 1	150.00	100.00	20.00	18.00	0.8
16	27	Block 1	150.00	125.00	50.00	47.00	2.5
6	28	Block 1	150.00	100.00	50.00	18.00	0.7
3	29	Block 1	50.00	125.00	20.00	18.00	0.8
19	30	Block 1	100.00	87.50	35.00	32.50	1.8

4. ANALYSIS OF EXPERIMENTAL RESULTS

4.1 DESCRIPTION OF EXPERIMENT WITH RESULTS

The influence of the input parameters on response in WEDM process has been examined. The input parameters are Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) and peak current (IP). The experiments have been performed on high chromium high carbon steel with a wire of diameter 0.25 mm and the obtained data has been analyzed with the help of RSM using design expert software. The result of experiment shows that Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) and peak current (IP) influence material removal rate (MRR).

4.2 DISCUSSION OF RESULTS

The experimentation was carried out according to the CCD design and the analysis was accomplished using design expert software version 6.0.8. The analysis of variance for MRR using software is given in table 4.1

Table 4.1 Sequential sum of squares

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	
Mean vs Total	81.741013	1	81.741013			
Linear vs Mean	11.0653	4	2.766325	94.751868	< 0.0001	
2FI vs Linear	0.426375	6	0.0710625	4.4485522	0.0057	Suggested
Quadratic vs 2FI	0.0831783	4	0.0207946	1.4156675	0.2766	
Cubic vs Quadratic	0.17625	8	0.0220313	3.4983459	0.0581	Aliased
Residual	0.0440833	7	0.0062976			
Total	93.5362	30	3.1178733			

Table 4.2 ANOVA for Response Surface ANOVA for Response Surface 2FI Model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	**11.49168**	**10**	**1.149168**	**71.93853**	**< 0.0001**	significant
A-A	**0.459267**	**1**	**0.459267**	**28.75035**	**< 0.0001**	
B-B	**7.820417**	**1**	**7.820417**	**489.5625**	**< 0.0001**	
C-C	**2.112267**	**1**	**2.112267**	**132.2291**	**< 0.0001**	
D-D	**0.67335**	**1**	**0.67335**	**42.15209**	**< 0.0001**	
AB	**0.133225**	**1**	**0.133225**	**8.339959**	**0.0094**	
AC	**0.005625**	**1**	**0.005625**	**0.352128**	**0.5599**	
AD	**0.01**	**1**	**0.01**	**0.626006**	**0.4386**	
BC	**0.255025**	**1**	**0.255025**	**15.96471**	**0.0008**	
BD	**0.0081**	**1**	**0.0081**	**0.507065**	**0.4851**	
CD	**0.0144**	**1**	**0.0144**	**0.901448**	**0.3543**	
Residual	**0.303512**	**19**	**0.015974**			

The Model F-value of 71.93 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this much magnitude could occur due to noise. p- values less than 0.0500 indicate model terms are significant. In this case A,B,C,D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve our model.

Figure 4.1 shows the normal probability distribution which shows that no problem with the results.

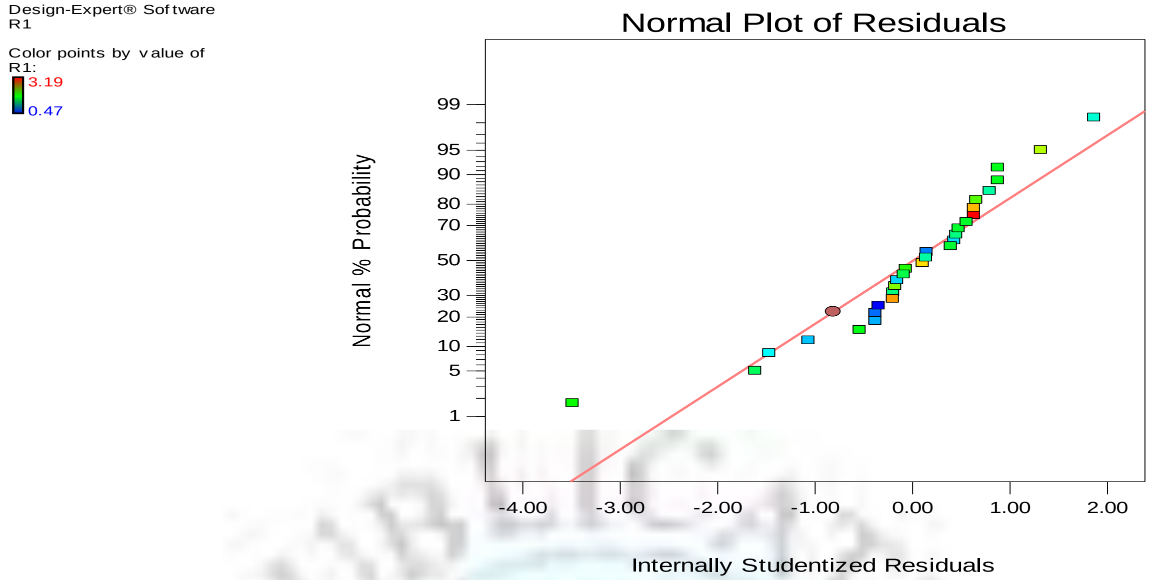

Fig. 4.1 Normal probability plot

4.2.1 Effect of Pulse on time on MRR

It can be seen from fig.4.1 that machining speed increases with increase in the pulse on-time. It means that the number of sparks in unit time increases which increase in discharge energy. As a result machining speed becomes faster with increase in pulse on time. So the pulse on time can be adjusted to get the desired material removal rate.

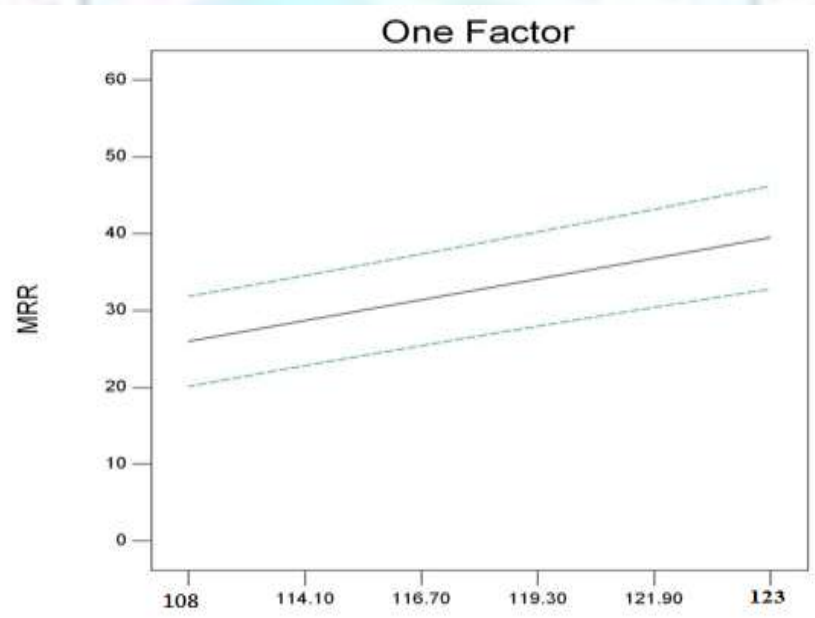

Fig 4.2 Effect of Ton on MRR.

CONCLUSIONS

The following conclusions are drawn from the experimental study:

1. When pulse on time is increased the material removal rate increases.
2. When pulse off time is increased the material removal rate decreases.
3. When servo voltage is increased the material removal rate decreases.

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