OPTIMIZATION OF MICRO-WIRE EDM OPERATION USING GREY TAGUCHI METHOD

A thesis submitted in partial requirements for the degree

Of

Bachelor of Technology

In

Mechanical Engineering

By

Nand Lal Gupta

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Department of Mechanical Engineering

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Under the guidance of
Prof. K.P. Maity

Department of Mechanical Engineering

National Institute of Technology, Rourkela

May, 2011

National Institute of Technology
Rourkela

CERTIFICATE

This is to certify that this report entitled, "**OPTIMIZATION OF MICRO-WIRE EDM OPERATION USING TAGUCHI METHOD**" submitted by Nand Lal Gupta in partial fulfillment for the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this report has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Place: NIT Rourkela

Date:

Prof. K.P.Maity
Dept. of Mechanical Engineering
National Institute of Technology
Rourkela – 769008, Orissa Date:

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CONTENTS

Abstract

Micro-wire EDM is an emerging technology in the field of Micro-machining to fabricate very complex micro products. Micro wire EDM is a very complex process involving the different process parameters. In the present investigation an optimization of micro wire EDM has been carried out using Grey Taguchi method. The parameters involved are voltage, capacitance, feed rate and wire speed. MRR and kerf width are taken as the response criteria. Experimental investigation has been carried out in multi-process Micro-EDM machine.

Wire electrical discharge machining process is a highly complex, time varying & stochastic process. This is used in the fields of dies, molds; precision manufacturing and contour cutting etc. any complex shape can be generated with high grade of accuracy and surface finish using CNC WEDM. The output of the process is affected by large no of input variables. Hence a suitable selection of input variables for the wire electrical discharge machining (WEDM) process depends heavily on the operator's technology & experience. WEDM is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in wire EDM is very challenging one because improvement of more than one performance measures viz. Metal removal rate (MRR), surface finish & cutting width (kerf) are of prime importance. This paper proposes optimal parameter setting. Using taguchi's parameter design, significant machining parameters affecting the performance measures are identified as pulse peak current, pulse on time, and duty factor. The effect of each control factor on the performance measure is studied individually using the plots of signal to noise ratio. The study demonstrates that the WEDM process parameters can be adjusted so as to achieve better metal removal rate, surface finish, electrode wear rate.

CHAPTER-1

Introduction

Electrical discharge machining (EDM) is one of the must extensively used non-conventional, thermo-electric metal removal process which encodes material from the work place by a series of discrete spark between a work and a tool electrode immersed in a liquid dielectric medium. Electrical energy is used directly to cut the material in final shape. Melting and vaporization takes place by theses electrical discharges. The minute a mounts of the work material is then ejected and flushed away by the dielectric medium. The sparks occur at high frequency which continuously and effectively removes the work prices material by melting and evaporation. To initiate the machine process electrode and work piece are separated by a small gap known as 'spark gap' which results into a pulsed discharge causing the removal of material. The dielectric acts as a deionizing medium between two electrodes and its flow helps in vacating the resoliclified debris to assure optimal conditions for spark generation. In micro-wire EDM operation the work piece metal is cut with a special metal wire electrode that is programmed to travel along a definite path. Spark discharges and generated between a small wire electrode and a work piece to produce complex two dimensional and three-dimensional shapes according to a NC path. A very thin wire in the range of 0.02 to 0.3 mm in diameter as an electrode is used in the wire-cut EDM. It machines a work piece with electrical discharge like a bands haw by moving either the work piece or the wire. The mechanism of metal removal is same as in connectional EDM. The most prominent feature of a moving wire is that a complicated cutout can be early machined without using a forming electrode.

The CNC system of wire EDM has the duty to provide the function of geometry trajectory, sequential control, pulse generator control, wire feed and wire tension control and machining process control. The wire transport system of a wire EDM guarantees a smooth wire transport and constant tension of wire.

The machine consists of a work piece contour movement control unit, work piece mounting table and wire driven part which ensures accurate movement of the wire oat constant tension. The purpose of WEDM is to achieve better stability and higher productivity, higher machining rate with accuracy. A large number of variables are involved in the process; also the nature of the process is stochastic. Hence even a highly skilled operator is unable to perform the optimal performance. Although WEDM machines available today have some kind of process control, still selection is very tough to ensure optimal setting.

1.1 IMPORTANT FEATURES OF MICRO-WIRE EDM

1. Electrode wear is negligible.
2. Forming electrode to produce shape is not required.
3. Machined surface are very smooth.
4. Dimensional and Geometrical Tolerances are very tight.
5. Straight hole production is possible with higher precision.
6. Relative tolerance between punch and die is much higher and die life is extended.
7. The machine can be operated unattended for long time at high rate.
8. No special skills are required to run the machine.
9. Any electrically conductive material can be machined irrespective of its hardness.
10. This process allows the shaping and machining of complex structure with high machining accuracy in the order of micron. The surface roughness achievable is R_z = 0μm.

1.2 OBJECTIVE

There are a lot of parameters which affect the wire EDM machine performance. It is very though to derive exact and real mathematical models between machining performance and machining parameters. The reason is very complex mechanism involved in the process. The main objective is as follows:-

1. To determine significant parameters affecting the performance of machining.
2. To discuss the cause effect relationship of machining parameters and the performance in WEDM.
3. Achieving the shortest machining time, satisfying the accuracy and surface roughness requirements.
4. To establish the mathematical model to relate machining parameters and machining performance by regression and correlation analysis.
5. To find out important parameters affecting the performance of machining.
6. The optimal machining parameters are obtained under constraint and requirants.

1.3 PROCESS PARAMETERS OF MICRO-WIRE EDM PROCESS.

S.No.	**Parameters**	**Range**
1.	Frequency	0-200KH_z
2.	Pulse width	1-10 μs
3.	Gap% of Voltage	60-100%
4.	Gain	0-100
5.	Pulse peak currant	40A
6.	Output Voltage	60-250V
7.	Dwell time	0.205
8.	Polarity	+/-
9.	Hole diameter	0.05-1mm
10.	Spindle speed	100-1000 ___

Machine Parameters:

1. Table feed.
2. Pulse on time.
3. Pulse off time.
4. Flushing

Wire Parameters:

1. Material of wire.
2. Diameter of wire.
3. Wire speed.
4. Wire tension.

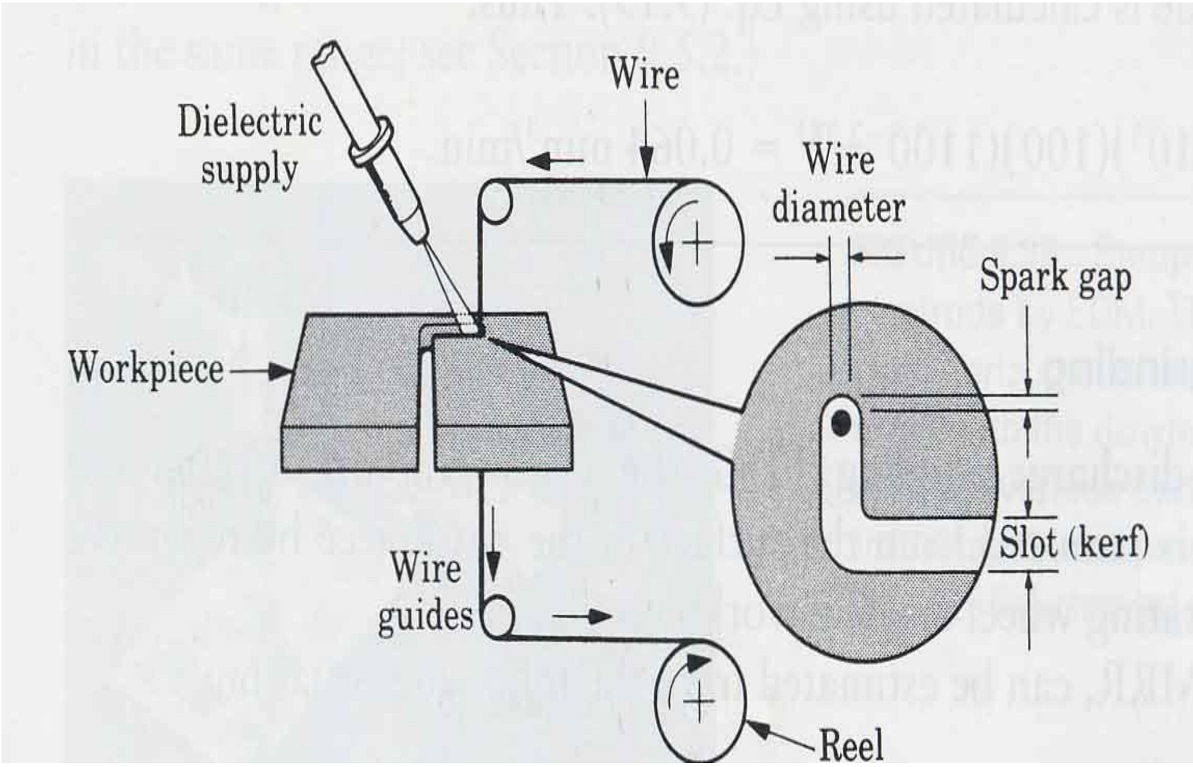


Fig. 1. Principle of WEDM

CHAPTER 2

Literature Review

Effect of process parameters on material removal rate in wire EDM [H.singh, R.Garg]

The effect of various process parameters of WEDM like pulse on time (T_{on}),pulse off time(T_{off}),gap voltage(SV),peak current (IP),wire feed (WF) ,wire tension (WT) have beem investigated.The paper reveals there influence on the MRR of hot die steel(H-11).one variable at a time approach is used .the experiments were carried out on Electronica Sprint cut WEDM.

Nihat Tosun et.al [8] investigated on the effects and optimization of machining parameters on the (cutting width) and material removal rate (MRR) in wire EDM operation .the experiments were conducted under various wire speed ,open circuit voltage ,pulse duration and dielectic flushing pressure .the design of experiment was done using Taguchi Method.

A mathematical model was developed correlating the various wire EDM parameters like peak current, duty factor, wire tension and water present by Hewidy et al. [9].the variation of above parameters were correlated with MRR.

Experimental methodology:

ELECTRONICA SPRINTCUT WEDM machine was used to perform the experiments. The effects of the various inputs parameters, pulse on time (Ton), pulse off time (T_{off}), wire tension(WF) and wire feed (WF) are studies on MRR.

CuZn37 Master Brass wire with 0.25 diameter (900N/mm^2,tensile strength) was used in the experiment.The work piece material ,H-11 hot die steel with 125mm×100mm×24mm was used.During the experiment 5mm×5mm square was cut to obtain a rectangular punch of 5mm×5mm×24mm.

Conclusions/Findings:

The material removal rate directly increases with increase in T_{on} and peak current IP whereas decreases with increase in T_{off} and servo voltage.

state of art electrical discharge machining EDM

K.H, HO,S.T.NEWMAN.

This paper review the current research work relating to the improvement of performance measure ,optimizing the process variables,monitoring and control sparking.

Optimizing the process variables:

The EDM process involves complicated discharge mechanism ,that is why it is very stochastic in nature.various process variables are correlated with performance measures to maximize the MRR,whereas to minimize the tool wear rate(TWR) and yielding the desired surface roughness.S/N ratio coupled with the analysis of variance (ANOVA) technique are used to measure the amount of deviation from the desired performance measure.The process variables include electrical and non-electrical parameters both . an objective function under the multi-constraint conditions is formulated which is based on the mathematical model developed. The optimization problem is solved by the feasible direction method to obtain the the optimal machining parameters . Experimental results demonstrate that the machining models are appropriate and the derived machining parameters satisfy the actual requirements in practice.

A study on machining parameter optimization:

A proper selection of machining parameters is a must for the wire electrical discharge machining .the selection depends mainly on the operators technology and experience because the range of parameters is quite diverse .Based on the Taguchi quality design method and ANOVA,an approach to determine parameter setting is proposed in the paper.The important factors affecting the machining parameters like MRR,gap width,surface roughness,sparking frequency,average gap voltage and normal ratio are determined.Mathematical models are established using regression analysis.Objective function under the multi constrain condition is formulated based on the mathematical model developed.

Experimental equipment and design of experiment:

A WEDM machine, developed by ITRI (Industrial Technology Research Institute) and CHMER company Taiwan, was used for the experiment.

The work material specification , electrode and the other machining conditions were taken as follows:

(1) work piece (anode) :SICDI 1 alloy steels;

(2) electrode (cathode): 00.25 mm brass wire;

(3) work piece height: 30 mm;

(4) cutting length: 20 mm;

(5) open voltage: 95 V;

(6) servo reference voltage:10 V ,and

(7) specific resistance of fluid : 1-3 mA

Design of experiments:

L18 mixed arrays table was chosen for the experiment.six controlling factors having three levels(small,medium and large)were selected as controlling factors:

1. Pulse on time
2. Pulse off time
3. Table feed
4. Wire tension
5. Wire speed
6. Flushing pressure

Conclusions:

It is inferred from the experiment that the table feed and pulse-on time have asignificant influence on the metal removal rate, the gapvoltage and the total discharge frequency, whereas the pulse on time has a significant influence on the gap width and the surface roughness Therefore, adjusting the table feed and T is an appropriate strategy to control the discharging frequency to prevent the breakage of wire. A larger table feed & a smaller ton are recommended as longer ton will result in higher value of Ra..

Monitoring and control of micro-wire EDM:

In this paper presented by Mu-Tian Yan description about the development of anew monitoring and control system has been given.it contains a new pulse discriminating and control system has been given.it contains a new pulse discriminating and control system which identifies four major gap states categorized as –

- Open circuit
- Normal spark
- Arc discharge
- Short circuit

Observing the characteristics of gap voltage waveform investigations were made to study the influence of machining feed rate ,pulse interval and thickness of the work piece on the variation of proportion of normal discharge ,arc discharge and short circuit(also known as normal ratio arc ratio and short ratio respectively).observations reflects that high machining feed rate or increase of work piece height results in increase of short ratio .Also it is observed that long pulse interval causes an increase in the short ratio under a constant feed rate .A control strategy is devised to achieve the stability of the machining operation. It is done by regulating the pulse interval of each spark in real time based on identified gap states.

Following conclusions were drawn from the observations:

1. Discharge pulse can be classified into four pulse types by combination of some of the time periods and gap voltage characteristics .The proportion of short circuit and sparking frequency can be used to monitor and evaluation of the gap condition.
2. If we set the long pulse interval and high table feed ,it causes the gap to become smaller which results an increase in short ratio.
3. The increase of work piece thickness equivalent to MRR result in the formation of much debris in the spark gap leading to the increase of short ratio.
4. A pulse interval control strategy has been proposed according to the classification of discharge pulse to improve the abnormal machining conditions.

CHAPTER 3

Optimization Techniques

Taguchi method: Taguchi's method is an efficient tool for the design of high quality manufacturing system.Dr.Genichi Taguchi,a Japanese engineer has developed a method based on orthogonal arrays (OA).In this method quality is measured by the deviation of a characteristic from its target value.A loss function is developed from this deviation.uncontrollable factors which are also known as noise cause such deviation and result into loss.taguchi method seeks to minimize the noise because the elimination of noise factor is impractical.this method provides much reduced variance for the experiment with optimum setting of process control parameters.So taguchi philosophy is based on integration of design of experiments(DOE) with parametric optimization of processes to get the desired results

A three stage design operation is done in taguchi's method to determine the target value and tolerances for relevant parameters in the product.the three stage designs are-

1. System design
2. Parameter design
3. Tolerance design

System design: a prototype of the product is created using scientific and engineering principle and experience.This is done having an eye on the functional requirement .

Parameter design:Taguchi defines a performance measure known as the signal to noise ratio(S/N).The target of the parameter design is to find the optimal setting of the product and the process parameters so that the performance variability is minimized.Selection of parameters is done to maximize the S/N ratio.Signal represents the square of the mean value of the quality characteristic while noise is the measure of the variability of the characteristics.

Tolerance Design: After the system design and the parameter design tolerance design is done in the third stage.in this step we set tolerances in the range of admissible values around the target value of the control parameters.

Taguchi's signal to noise ratio are the logarithmic functions of desired output.It is taken as the objective function for optimization.Orthogonal array provides a set of well balanced experiments.S/N ratio is the ratio of the mean to standard deviation.Here mean refers to signal and standard deviation refers to noise.the ratio depends on the quality characteristic of the product/process to be optimized.the standard S/N ratios are as follows-

- Nominal is the best
- Lower the better
- Higher the better

Gray Based Taguchi Method

to solve the multiple performance characteristics problems,the taguchi method is coupled with grey relational analysis.Grey based Taguchi is widely used in different field of engineering to solve multi response optimization problem.

- Grey Relational Analysis: In grey relational analysis experimental datas are first normalized in the range of 0 to 1.This process is known as grey relational generation.Grey relational co-efficient are calculated to represent the correlation between ideal and the actual normalized data.

Grey Relational Generation: According to the normalization three types of data normalization are done-

I. Lower the better (LB)
II. Higher the better (HB)
III. Nominal is the best (NB)

For LB criteria:

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \quad (1)$$

For higher the better (HB) criteria,

$$x_i(k) = \frac{y_i\ (k) - \min\ y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \quad (2)$$

where x_i (k) is the value after the Grey relational generation, min y_i (k) is the smallest value of y_i (k) for the k^{th} response, and max y_i (k) is the largest value of y_i (k) for the k^{th} response.

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}} \quad (3)$$

An ideal sequence is $x_0(k)$ (k= 1, 2, 3......, 25) for the responses. The definition of Grey relational grade in the course of Grey relational analysis is to reveal the degree of relation between the 25 sequences [$x_0(k)$ and $x_i(k)$, i=1, 2, 3.......,]

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (4)$$

where n = number of process responses.

For calculating the S/N ratio, having criteria larger the better eq. 5 can be used.

$$-10\log\left[\frac{1}{n}\sum\nolimits_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (5)$$

CHAPTER- 4

Experimental Details

1. According to the taguchi design method L_9 Orthogonal array was chosen for the optimization of the process.
2. Four control factors were chosen at three levels-
   I. Voltage (A)
   II. Capacitance(B)
   III. Wire feed(C)
   IV. Wire speed(D)
3. Two response parameters measured were-
   I. Kerf
   II. MRR

MRR can be calculated by, MRR = K×H×FR×ρ

Where K=Kerf width, FR=wire feed, H=sheet thickness (=.5mm), ρ =density of stainless steel (= 8000 kg/m^3)

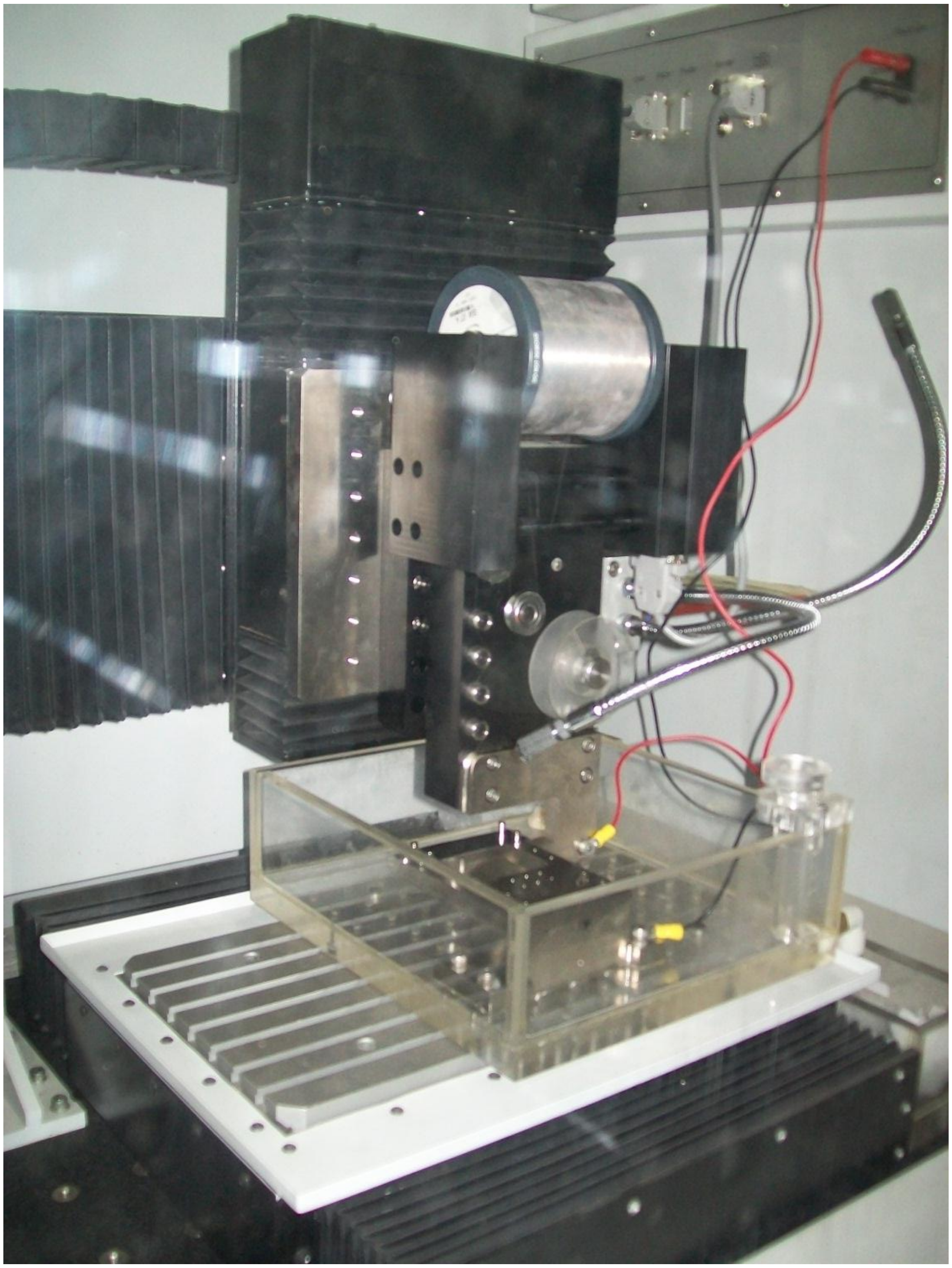


Fig. 2. Experimental Setup

Table 1. Specification of Mikrotool DT110

Travel	X-Axis Y-Axis Z-Axis	200mm 100mm 100mm
Table	Table working surface T-slot configuration	350 x 200mm 6mm x 7 (Qty) x 25mm
Spindle Head	Spindle	Power (Speed range)
	Spindle AC Servo	100W (1 to 5000 rpm) (1 to 140,000 rpm)
	Optional High Speed Spindles:	
	Without tool change function:	20,000 rpm to 60,000 rpm
	With tool change function:	60,000 rpm
Power Requirement	Electrical power supply Pneumatic supply	230v, 50/60Hz 6 to 7 kg/sq.cm
Machine Size	Height	1900mm (2700mm with open door)
	Machine Space	1.5m x 1.1m
Machine Accuracy	Resolution	100 nm
	Accuracy	+/- 1 micron / 100 mm
	Repeatability	1 micron for all axes
Standard Accessories	• Tanks for different machining processes	
Optional Accessories	• Wire EDM attachment • Wire EDG attachment • Integrated CCD based camera for on-machine inspection • Integrated Touch Probe	

Fig. 3. Mikrotool DT-110

Table 2. Machining parameters and their levels

SYMBOL	PARAMETER	UNIT	LEVEL-1	LEVEL-2	LEVEL-3
A	Voltage	Volts	90	110	120
B	Capacitance	Micro farad	0.00001	0.001	0.1
C	Wire Feed	Micron/sec	e 6.0	e 8.0	e 10.0
D	Wire speed		10%	15%	20%

Table 3. Experimental Results

Run order	Kerf	MRR
1	0.60	0.108
2	0.70	0.168
3	0.65	0.105
4	0.55	0.132
5	0.80	0.240
6	0.82	0.148
7	0.62	0.186
8	0.70	0.126
9	0.72	0.173

CHAPTER 5

RESULTS AND DISCUSSIONS

DATA ANALYSIS:

Table 4. Grey Relational Generation

Run order	Kerf	MRR
Ideal Sequence	1	1
1	0.815	0
2	0.444	0.454
3	0.629	0.659
4	1	0.181
5	0.074	1
6	0	0.303
7	0.740	0.591
8	0.444	0.136
9	0.370	0492

Step3 Calculation of Grey relation Coefficient

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(k) + \psi\Delta_{\max}}$$

Run Order	Kerf	MRR
Ideal Sequence	1	1
1	0.185	1
2	0.556	0.546
3	0.371	0.341
4	0	0.819
5	0.926	0
6	1	0.697
7	0.260	0.409
8	0.556	0.864
9	0.630	0.508

Calculation of grey relational grade:

Run order	Kerf	MRR
Ideal Sequence	1	1
1	0.729	0.333
2	0.473	0.478
3	0.574	0.594
4	1	0.379
5	0.350	1
6	0.333	0.417
7	0.658	0.550
8	0.473	0.366
9	0.442	0.496

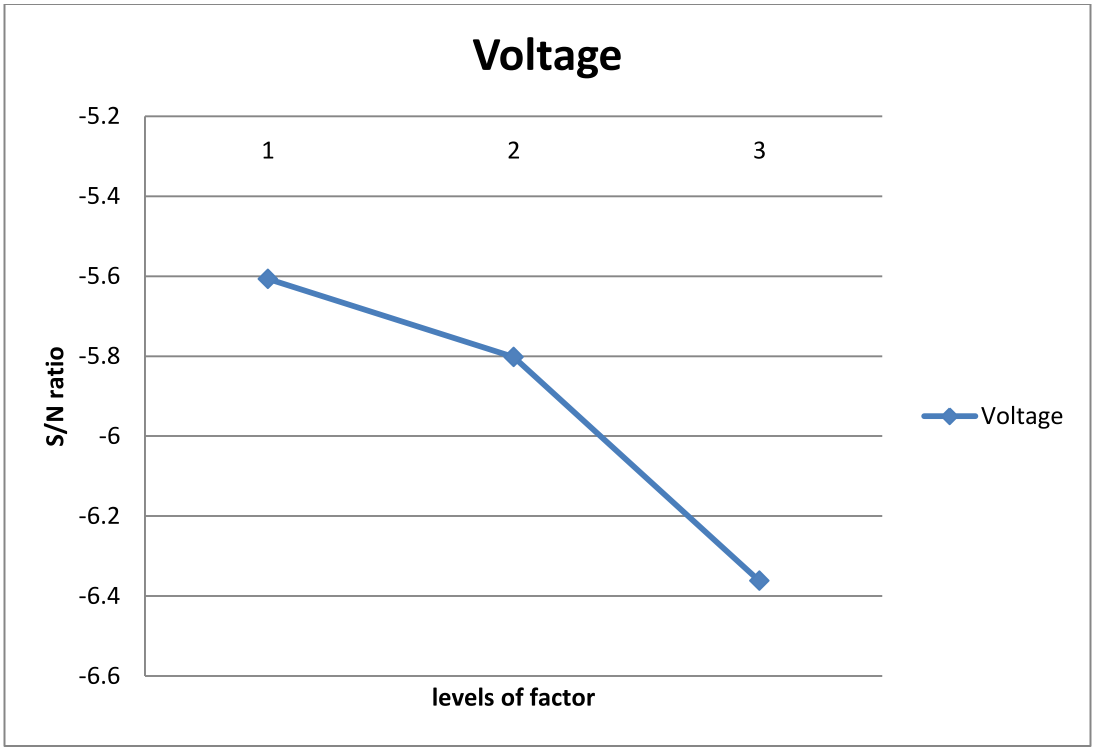
Grey Relational Grade:

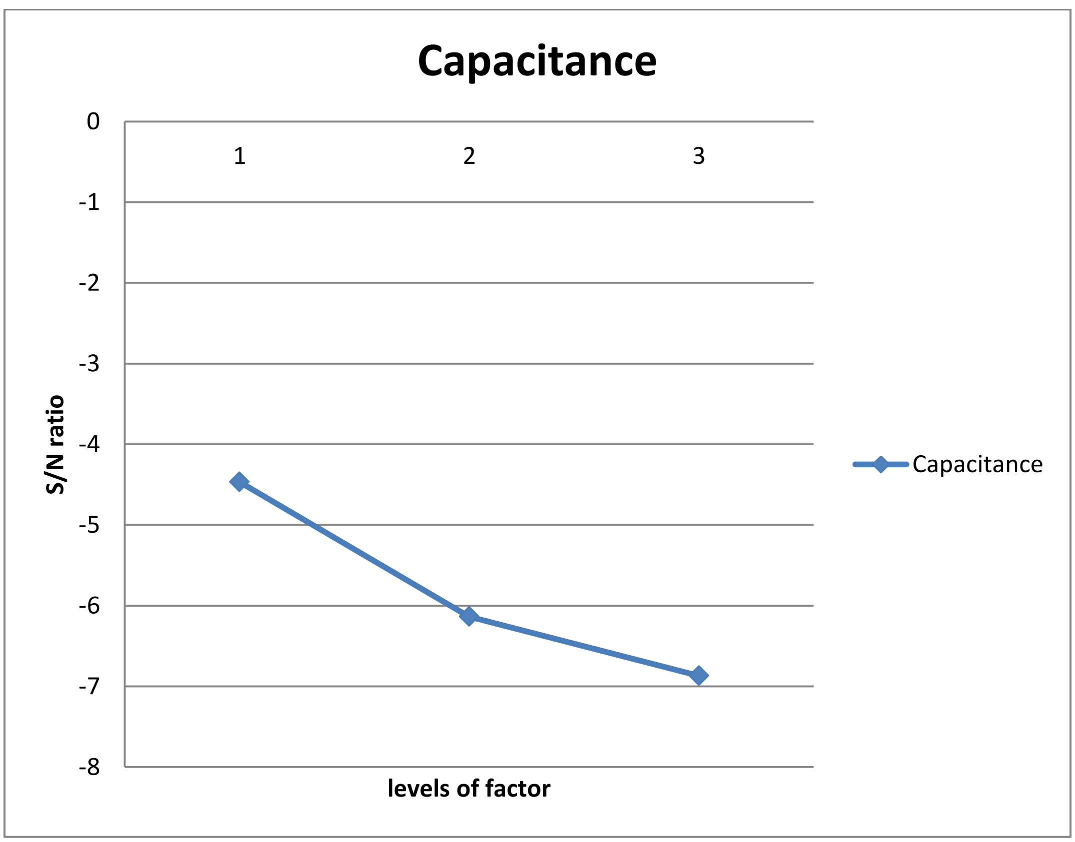
Run Order	Grey Relational
1	0531
2	0.475
3	0.584
4	0.689
5	0.675
6	0.375
7	0.604
8	0.419
9	0.469

	Grey Relational Grade		
Factor	**Level l**	**Level 2**	**Level 3**
Voltage	**0.530**	**0.579**	**0.497**
Capacitance	**0.608**	**0.523**	**0.476**
Wire Feed	**0.441**	**0.544**	**0.621**
Wire Speed	**0558**	**0.484**	**0.564**

$$\eta_{ij} = -10\log\left(\frac{1}{r}\sum_{k=1}^{r}\frac{1}{v_{ijk}^{2}}\right)$$

	Mean Grey Relational Grade		
Factor	**Level l**	**Level 2**	**Level 3**
Voltage	**-5.607**	**-5.802**	**-6.362**
Capacitance	**-4.468**	**-6.136**	**-6.869**
Wire Feed	**-7.365**	**-5.676**	**-4.187**
Wire Speed	**-5.351**	**-6.777**	**-5.536**


Voltage
-5.2
-5.4
-5.6
-5.8
-6
-6.2
-6.4
-6.6
1
2
3
S/N ratio
levels of factor
Voltage


Capacitance
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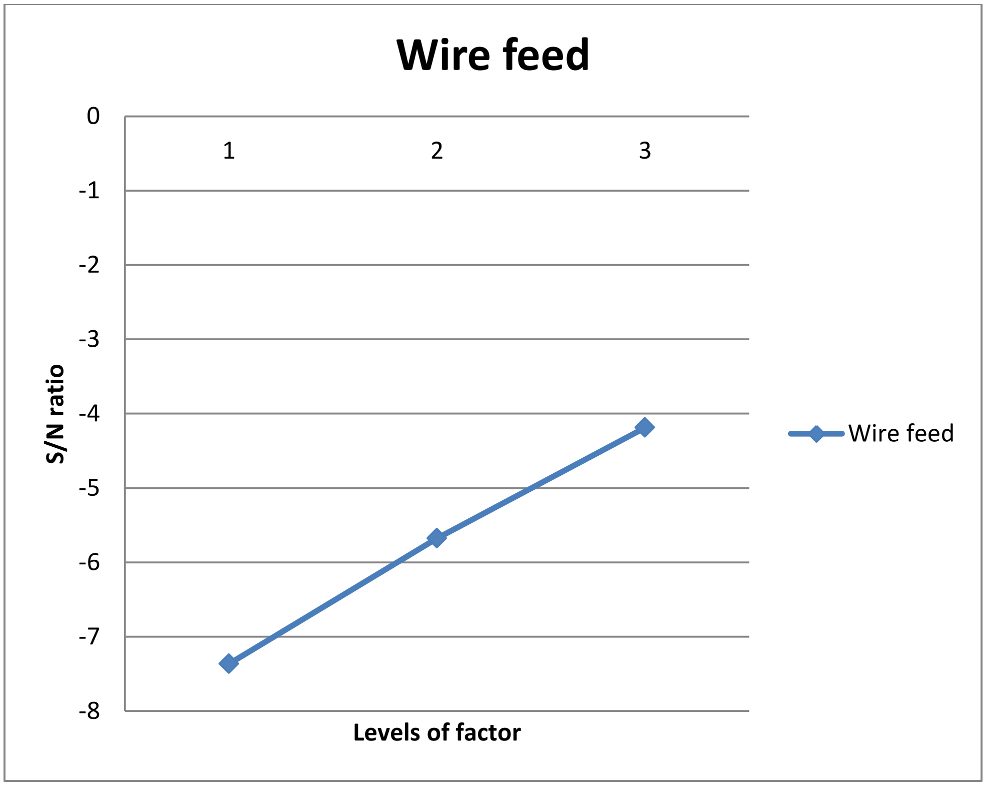
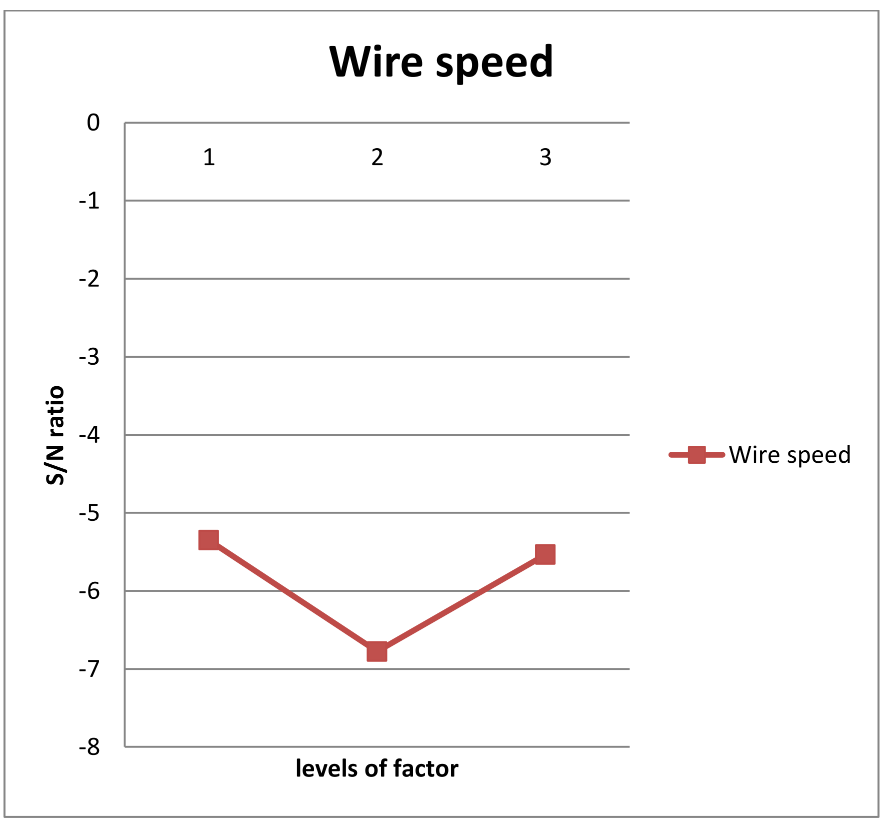
-1
-2
-3
-4
-5
-6
-7
-8
1
2
3
S/N ratio
levels of factor
Capacitance



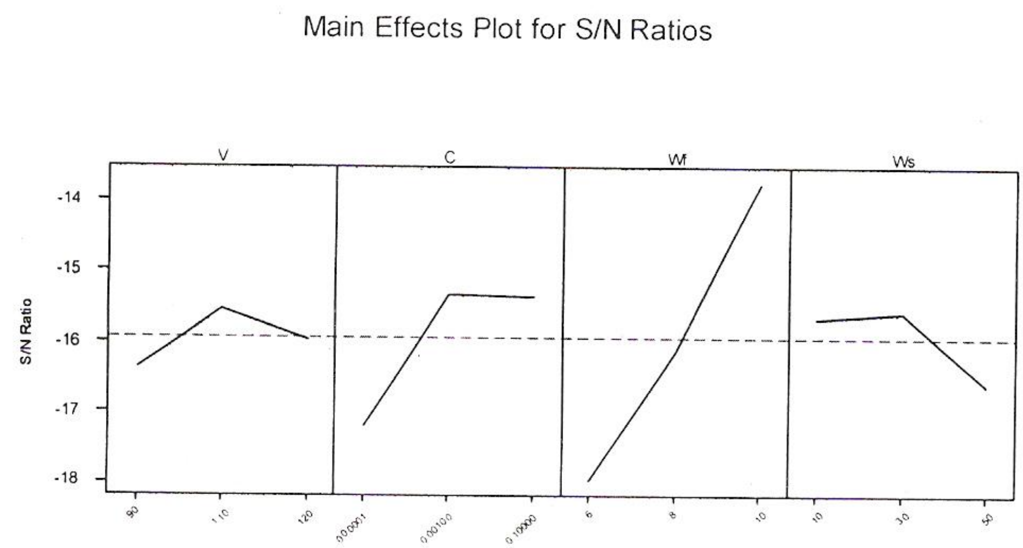
Wire feed
0
-1
-2
-3
-4
-5
-6
-7
-8
1
2
3
S/N ratio
Levels of factor
Wire feed



Wire speed
0
-1
-2
-3
-4
-5
-6
-7
-8
1
2
3
S/N ratio
levels of factor
Wire speed

ANALYSIS BY MINITAB

PLOT OF S/N RATIO VS DIFFERENT LEVELS OF INPUT PARAMETERS



Optimal Setting for maximizing MRR

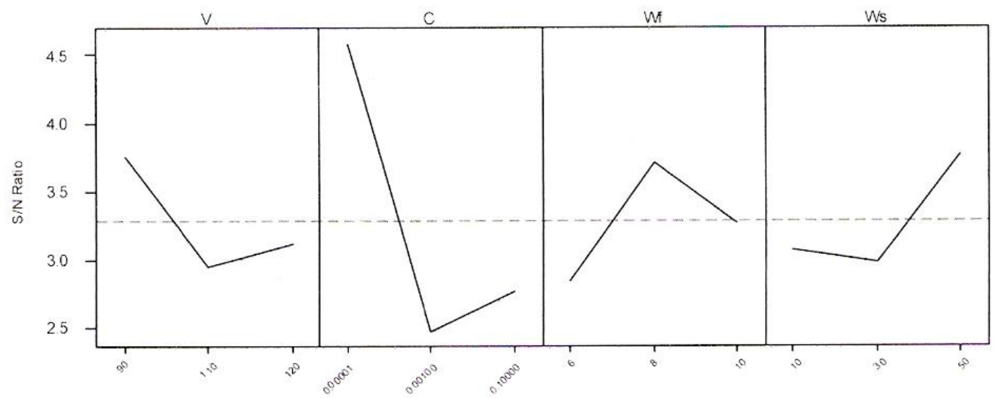
Response Table for Signal to Noise Ratios

Larger is better

Level	V	C	Wf	Ws
1	-16.3415	-17.1766	-17.9730	-15.6555
2	-15.5264	-15.2941	-16.1071	-15.5661
3	-15.9471	-15.3444	-13.7349	-16.5935
Delta	0.8152	1.8825	4.2380	1.0274
Rank	4	2	1	3

V	C	Wf	Ws	Kerf	MRR
90	0.00001	6	10	0.60	0.108
90	0.00100	8	30	0.70	0.168
90	0.10000	10	50	0.65	0.195
110	0.00001	8	50	0.55	0.132
110	0.00100	10	10	0.80	0.240
110	0.10000	6	30	0.82	0.148
120	0.00001	10	30	0.62	0.186
120	0.00100	6	50	0.76	0.126
120	0.10000	8	10	0.72	0.173

Main Effects Plot for S/N Ratios



Optimal Setting for minimizing Kerf

Response Table for Signal to Noise Ratios

Smaller is better

Level	V	C	Wf	Ws
1	3.75892	4.59396	2.84814	3.07618
2	2.95156	2.47332	3.71471	2.99131
3	3.12975	2.77294	3.27737	3.77274
Delta	0.80736	2.12064	0.86657	0.78143
Rank	3	1	2	4

CHAPTER - 6

Conclusions:

Optimization of micro wire EDM process on stainless steel using Taguchi method-based Grey analysis was studied in this thesis.

- Wire EDM is a complex process having many numbers of factors affecting the process, but for current study the main factors considered are: Voltage, capacitance, wire feed and wire speed.
- The effects of these factors on kerf and MRR have been studied.
- For optimizing the process variables Grey-based Taguchi method has been applied.
- **Optimum parameter settings obtain from S/N ratio plot are voltage = 90V, capacitance = 0.00001μF, wire feed 10μm/s, wire speed 10%.**
- Confirmatory experiment has been performed and found a good agreement between predicted and experimental value.
- According to MINITAB analysis, optimal condition for minimizing kerf is V = 90 volts, C = 0.00001 μF, WF = 8 μm/s, and WS = 50%.
- Optimal conditions for maximizing MRR is V = 110 volts, C = 0.001 μF, WF = 10 μm/s, and WS = 30%.

References:

[1] Yan ,Mu-Tian & Chiang,Tsung-Liang , Design and experimental study of a power supply for micro-wire EDM, Int J Adv Manuf Technol (2009) 40.

[2] Norliana Mohd Abbas, Darius G. Solomon, Md. Fuad Bahari, A review on current research trends in electrical discharge machining (EDM), International Journal of Machine Tools & Manufacture 47 (2007) .

[3] K.H. Ho, S.T. Newman, State of the art electrical discharge machining (EDM), International Journal of Machine Tools & Manufacture 43 (2003).

[4] D.T Pham, S.S Dimov,Bigot.S, A.Irvanov, K.Popov, Micro-EDM-recent developments and research issues., International Journal of Machine Tools & Manufacture 149(2004).

[5] Y.S. Liao,: Y.Y. Chu and M.T. Yan: Study Of Wire Breaking Process And Monitoring Of WEDM, Int. J. Mach. Tools Manufact. Vol. 37, No. 4, pp. 555-567, 1997

[6] R. E. Williams and K. P. Rajurkar, Study of wire electrical discharged machine surface characteristics, Journal of Materials Processing Technology,28(1991) pp. 127-138

[7]. S.S Mohapatra, Amar pattnaik,Optimization of WEDM process parameters using Taguchi method, International Journal of Advanced manufacturing Technology (2006)

[8]. P.J Ross. Taguchi Techniques For Quality Engineering. New York, McGraw-Hill ,1984

[9] Y.S Liao , J.T.Huang, A study on the machining parameter optimization of WEDM, Journal of Material Processing Technology,71(1997) pp. 487-493

[10] Mohd Amri Lajis , H.C.D. Mohd Radzi, The Implementation of Taguchi Method on EDM Process ofTungsten Carbide, European Journal of Scientific Research ISSN 1450-216X Vol.26 No.4 (2009), pp.609-617

[11] C.L.Lin, J.L.lin & T.C.Ko ,Optimization of the EDM process based on the Orthogonal Array with Fuzzy Logic and Grey Relational Analysis Method, International Journal of Advanced manufacturing Technology,19(2002) pp. 271-277

[12] Mu-Tian Yan , Hsing – Tsung Chien,Monitoring & Control of the micro wire –EDM process, International Journal of Machine Tools & Manufacture ,47(2007)pp.148-157.

[13] . S.H.Lee, X.P Li ,Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide,Journals ofMaterial Processing Technology 115 (2001) pp.344-358.

[14] www.sciencedirect.com

[15] www.wikipedia.com

[16] Fundamentals of Quality Control and Improvement by Amitava Mitra.

[17] H.Singh, R.Garg Effects of process parameters on material removal rate in WEDM,Journals of achievements in materials and manufacturing engg.Vol. 32,issue 1,jan 2009 .

[18] Saurav Dutta, A.Bandyopadhyay, P.K Pal, grey based taguchi Method for optimization of bead geometry, Int J Adv Manuf Technol (2008) 39..