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Effect of Process Parameters on Performance of EN-31 Steel using WEDM: Experimentation and Optimization

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Abstract **- EN-31 steel is a high carbon alloy steel which possess a high grade of hardness with compressive strength and abrasion resistance, good density and less corrosion resistance. Its high strength makes EN-31 steel popular and demandable in Industrial applications. The Wire Electrical Discharge Machining (WEDM) is a variant of EDM and is commonly known as wire cutting or wire-cut EDM. Generally this machining process is used in tool and die making industries, medical and surgical industries, air craft and aerospace industries, automobile industries, and used vastly in engineering applications. A metal wire with dielectric medium travels through a path and perform machining of EN-31 steel. Material of the wire is generally preferred as Tungsten, Copper, Brass, etc. In this research, Brass has been used as wire material. The main objective of this work is to identify the optimal WEDM process parameters for high material removal rate (MRR) and grater surface finish during machining. The effect of parameters, such as Pulse On time (T_{on}), Pulse Off time (T_{off}), Table feed (T.F), Wire feed (W.F), and Servo voltage (V) have been investigated to reveal their effect on MRR and surface roughness of material. The experimental plan is based on Taguchi method using these five factors each at three levels. The major application of the material is for manufacturing of cutting tools, dies, punches etc.**

Key words: WEDM, T_{on}, T_{off}, T.F, W.F, Servo Voltage, MRR, Surface Roughness

1. INTRODUCTION

Wire Electrical Discharge Machining (WEDM) is an electro thermal production process in which a thin singlestrand metal wire 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. Due to the inherent properties of the process, WEDM can easily machine complex parts and precision components out of hard conductive materials. WEDM works by creating an electrical discharge between the wire or electrode and the workpiece. As the spark jumps across the gap, material is removed from both the workpiece and the electrode. To stop the sparking process from shorting out, a nonconductive fluid or dielectric is also applied. The waste material is removed by the dielectric, and the process continues. In WEDM, a thin single-strand metal wire, usually brass, is fed through the workpiece.

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. At present, WEDM is a widespread technique used in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite, or even some ceramic materials, of any hardness. Many WEDM machines have adopted the pulse generating circuit using low power for ignition and high power for machining. However, it is not suitable for finishing process since the energy generated by the high-voltage sub-circuit is too high to obtain a desired fine surface, no matter how short the pulse-on time is assigned. As newer and more exotic materials are developed, and more complex shapes are presented, conventional machining operations will continue to reach their limitations and the increased use of WEDM in manufacturing will continue to grow at an accelerated rate. The setting is easy tuned for a straight line and become more difficult for the curve or part which is involving an angle. Ninety degree angle is the most difficult section to be cut by WEDM because of the dramatically direction changing. Wire electrical discharge machining process is a highly complex, time varying & stochastic process. The process output is affected by large no of input variables. Therefore a suitable selection of input variables for the WEDM process relies heavily on the operators technology and experience because of their numerous & diverse range. WEDM is extensively used in machining of conductive materials when precision is of prime importance. Rough cutting operation in WEDM is treated as challenging one because improvement of more than one performance measures viz. Metal removal rate (MRR), surface finish & cutting width are sought to obtain precision work as shown in Fig.1.

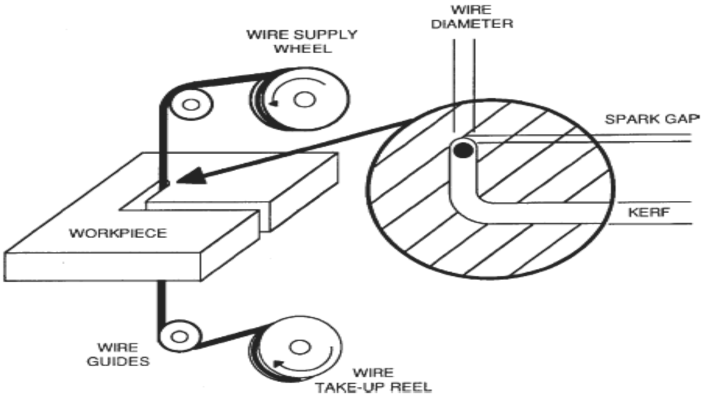

Fig.1: Schematic presentation of WEDM cutting process

2. LITERATURE REVIEW

WEDM has been widely studied by various researchers. Some prominent research papers have been referred in this thesis and described as follows:

Matz et al. [1] investigated the influence of mesostructured parameters of aluminium metal foams using Wire EDM. The influence of flushing on the EDM process is examined in this research. Patil et al. [2] experimented on WEDM for ceramic particulate reinforced aluminium matrix composite, using a plain Brass wire (CuZn37) & a copper wire coated with CuZn50 as wire electrodes. It was found that the cutting rate was greater for coated wire as compared to the plain brass wire. Galindo et al. [3] studied the surface finish & cutting speed in WEDM of poly crystalline Diamond to determine if there was a relationship between the parameters, surface finish and speed. Oliaei & Karpat [4] studied fabrication of PCD mechanical planarization tools by using µ-wire electric discharge machining. Zakaria et al. [5] observed the effect of WEDM cutting parameters for evaluating additive manufacturing of FeCuSn hybrid metal. Shivaraman et al. [6] studied on the control parameters of machining in Wire-Cut EDM for Titanium to obtain metal removal rate & surface finish using Taguchi method. Gautier et al. [7] developed a model of Wire EDM of a γ-TiAl alloy. Joshi [8] studied Wire cut EDM process limitations for EN31 steel. The optimal machining parameter setting is 24µs, pulse off 6µs, Bed speed 35µm/s etc. Kumar et al. [9] study reveals about various features of WEDM & improvements. Marigoudar et al. [10] studied on behaviour of zinc-aluminium alloy reinforced with silicon carbide particles when machined with WEDM. Kumar [11] studied about pulse on-time, pulse off-time, arch gap, duty cycle, intensity & voltage affecting MRR. Daneshmand et al. [12] used WEDM on smart NiTi60 alloys to investigate the impact of process parameters on tool wear rate, MRR & surface roughness. Sivakiran et al. [13] studied the effect of process parameters on MRR in WEDM of EN31 steel. In this paper linear regression and Taguchi's L16 orthogonal array is used. C Reddy [14] conducted experiments on WEDM based on L16 orthogonal array selecting P20 die tool steel as work material with 0.18 mm Molybdenum wire as electrode to find out higher MRR & better surface roughness. Muthu Kumar et al. [15] determined the WEDM process parameters of incoloy 800 for high material removal rate, surface roughness, kerf width based on grey-Taguchi method. Vishal Parashar et al. [16] performed experiments on stainless steel grade 304L of 10mm thickness under different cutting conditions of gap voltage, pulse on time, pulse off time, wire feed & dielectric flushing pressure for high MRR using the regression analysis and ANOVA. Rao [17] studied the effect of process parameters on MRR in WEDM, using Hot die steel (H-11) using one variable at a time approach. Kanlayasiri and Boonmung [18] investigated the effects of WEDM parameters on surface roughness of DC53, cold die steel by ANNOVA. Mahapatra & Pattanaik [19] described about parametric optimisation of WEDM process using Taguchi method, for surface roughness (Ra) & MRR. R. Ramakrushnan & Karunamoorthy [20] used Taguchi methods for L16 orthogonal arrays to measure MRR, surface roughness & wire wear ratio. BingHwa et al. [21] used WEDM for Al_2O_3/6061Al composites for machining performance, such as, cutting speed, width of slit & surface roughness. EI-Taweel et al. [22] investigated the effect of machining parameters of WEDM of inconel 601 using responsive surface methodology. Hewidy et al. [23] developed mathematical models correlating the various WEDM machining parameters with MRR, Wear ratio & surface roughness, using response surface methodology. Miller et al. [24] investigated the effects of spark on-time duration & spark on-time ratio on MRR & surface integrity of various advanced materials. Tosum et al. [25] investigated the effect of machining parameters on the kerf & MRR in WEDM, using Taguchi method. C.L. Lin et al. [26] described the grey relational analysis based on an orthogonal array & fuzzy based Taguchi method for optimising the responses. Marafona & Wykes [27] have investigated a new method of optimizing MRR using EDM with Copper-Tungsten electrodes, for improved MRR and a given wear ratio. Tarng et al. [28] optimized the cutting parameters using feed forward neural network through simulated annealing algorithm, for machining SUS 304 stainless steel of 10 & 15mm thickness.

2.1objectives

This experiment is conducted to determine good surface finish & high material removal rate of EN-31 steel by changing different machining parameters, such as Pulse on time (T_{on}), Pulse off time (T_{off}), Wire feed (W.F), Table feed (T.F) and Servo voltage (V).

3. EXPERIMENTAL WORK

The material which is taken for this experiment is EN31 steel. It is used for the manufacturing of cutting tools, dies, punches, etc. Here 3 level & 5 factors are considered to conduct the experiment. These factors are Pulse on time (T_{on}), Pulse off time (T_{off}), Table feed (T.F), Wire feed (W.F), Servo voltage (V). For each factor there are 3 levels. Then these values are put in the Taguchi method and are arranged automatically. By using the obtained values, machining operation is carried out. The machine can move 200mm in Z-axis, 350 mm in Y-axis, 250 mm in X-axis & 3° in U-V – axis. This machine consists contains upper guide, lower guide, bed, wire, and wire spool. The software used in this machine is ELCAM.

3.1 Experimental Set up

The present work focuses on MRR & Surface Roughness (Ra) of EN-31 steel in WEDM. The dimension of the steel is 306*10*6 mm. The experiment is carried out in Electronica Eco Cut Machine (Fig. 2). The wire that is used as electrode is made up of Brass. The diameter of the wire is 0.25mm. The dielectric fluid is distilled water. In this machining operation, work piece acts as anode & wire as cathode. Wire is passed between the two guiders, i.e. Upper guider & Lower guider. Lower guider is also act as Nozzle. It supplies dielectric fluid during the time of cutting operation. The function of the dielectric fluid is to cool the work piece & also act as a flushing medium. Wire is supplied continuously by the help of wire spool. The limitation is that, the wire can once be used because during the time of cutting operation it losses Electrons.

3.2 Selection of Work Piece

The work piece material used in this study is EN-31 steel. It has high resisting nature against wear and can be used for components which are subjected to severe abrasion, wear or high surface loading. The chemical & mechanical composition of EN-31 steel is given in the Table 1 and 2.

Fig. 2: Image of Wire EDM during machining (Model: Electronica Eco cut machine)

Table 1: Chemical composition of EN-31 steel

Sl. No.	Element	% of composition
1	Carbon (C)	0.90-1.10
2	Silicon (Si)	1.10-0.35
3	Manganese (Mn)	1.10 Max
4	Phosphorus (P)	0.05 Max
5	Sulfur (S)	0.05 Max
6	Chromium (Cr)	1.00-1.501

Table 2: Mechanical properties of EN-31 steel

Grade	Tensile strength (N/mm^2)	Yield strength (N/mm^2)	% of elongation	Brinell hardness	Rockwell hardness	Modulus of elasticity (N/mm^2)	Density (Kg/m^3)
EN-31	750	450	30	59	65	215000	7.85

3.3 Selection of Wire Material

In case of WEDM, various types of wires such as copper wire, brass wire, aluminium brass wire, molybdenum wire, tungsten wire & some other coated wires are used. Generally Brass wires are used in WEDM because it has good tensile strength of 490 N/mm^2. It is an alloy of Copper and Zinc. It delivers a powerful combination of low cost, reasonable conductivity, high tensile strength, & improved flush ability. Brass wire is most commonly available in the following alloys:

European: Cu63%Zn37%
Asian: Cu65%Zn35%

If a small amount of zinc is added to Copper wire drastically reduces the conductivity. Hard brass wire typically has conductivity only 20% of the Copper wire.

4. METHODOLOGIES

4.1Taguchi Method

Genichi Taguchi, a Japanese industrialist and an international consultant in the field of total quality control & assurance formulated both a philosophy and a methodology for the process of quality improvement that depends on statistical concepts, especially statistically designed experiments. The primary goals of the Taguchi methodology can be described as: i) a reduction in the variation of a product design to improve quality & lower the los imparted to the society, ii) a proper product or process implementation strategy which can further reduce the level of variation.

4.1.1 Signal – to – Noise Ratio

Traditionally a designed experiment can be used to estimate or test the significance of certain factors on the basis of a measurable response over a set of experimental conditions. Taguchi emphasized that an addition to this, the variation of the experimental data needs to be studied. In order to facilitate this study he used the concept of signal-to-noise ratio.

4.1.2 Orthogonal Arrays

Orthogonal arrays are highly fractional orthogonal designs proposed by Taguchi. These designs can not only be applicable to two level factorial experiments but also investigate main effects when factors have more than two levels. Designs are also available to investigate main effects for certain mixed level experiments where the factors included do not have the same number of levels.

4.2 Experimental Procedure

This experiment consists of 5 factors and 3 levels that are selected by Taguchi method. The factors are T_{on}, T_{off}, T.F, W.F and V shown in Table 3.

Table 3: Parameter table

Sl. No.	T_{on}	T_{off}	T.F	W.F	V
1	4	2	5	2	7
2	8	6	8	4	8
3	10	9	10	6	9

These values are taken according to the machine specification. Then these values are put in the Minitab software and then the machining parameters are arranged automatically. The experiments to be conducted are based on varying the process parameters which affect the machining process to obtain the required quality characteristics. Quality characteristics are the response values or output values expected out of the experiments. There are 64 such quality characteristics. The most commonly used are: i) Larger the better, ii) Smaller the better, iii) Nominal the best, iv) Classified attribute, and v) Signed target.

As the objective is to obtain the best surface finish & high MRR, it is concerned with obtaining the least value of surface roughness and large value for MRR. Hence the required quality characteristic is smaller the better, which states that the output must be as low as possible, tending to zero for surface roughness and larger the better, which states that the output must be as large as possible for high MRR.

4.3 Mechanism of MRR

Mechanism behind material removal rate of WEDM process is based on the conversion of electrical energy to thermal energy that categorise it to electro thermal process. During machining both the surfaces may have present smooth and irregularities cause minimum & maximum gap in between tool and work piece. At a given instant and at minimum point, suitable voltage is developed to produce electrostatic field for emission of electrons from the cathode and the electrons get accelerated towards anode. After achieving greater velocity, electrons collide with the dielectric molecules breaking them into negative and positive ions. As a result spark is generated with high temperature, causes melting and vaporisation of material from the work piece. MRR can be defined as follows:

$$\text{MRR} = \frac{Weight\ loss\ from\ the\ Work\ piece}{Density\ of\ the\ work\ piece * Machining\ time}$$

4.4 Measurement of Surface Roughness

Surface roughness is the size of the surface texture. It is expressed in μm and denoted by Ra. For higher value the surface is rough and if lowers then the surface is smooth. This value is measured by a surface roughness tester. This tester is consisted with a stylus at its top. The function of stylus is to move over the machining surface, where roughness test is to be carried out. This stylus consists with a needle at its top and this needle is moved over that surface to measure the roughness.

5. RESULT AND DISCUSSION

In this chapter, we are discussing about the effect or influence of machining parameters, i.e. T_{on}, T_{off}, V, W.F, T.F. on MRR and surface roughness (Ra) with Brass wire. In the mean time, it is to identify parameter that plays most important role during experimentation with the help of Taguchi design.

Table 4: Response table

Sl. no.	T_{on}	T_{off}	T.F	W.F	V	Initial weight	Final weight	Difference	Machining time
1	4	2	5	2	7	143.9	143.7	0.2	10.58
2	4	2	5	2	8	141.3	141.2	0.1	12.14
3	4	2	5	2	9	138.9	138.7	0.2	20.25
4	4	6	8	4	7	136.4	136.2	0.2	10.51
5	4	6	8	4	8	133.9	133.8	0.1	14.58
6	4	6	8	4	9	131.5	131.3	0.2	23.38
7	4	9	10	6	7	129.0	128.8	0.2	11.39
8	4	9	10	6	8	126.5	126.3	0.2	17.04
9	4	9	10	6	9	123.9	123.7	0.2	26.46
10	8	2	8	6	7	121.5	121.3	0.2	07.14
11	8	2	8	6	8	118.9	118.8	0.1	09.21
12	8	2	8	6	9	116.6	116.4	0.2	16.14
13	8	6	10	2	7	114.2	114.1	0.1	09.47
14	8	6	10	2	8	111.7	111.6	0.1	13.43
15	8	6	10	2	9	109.3	109.1	0.2	25.32
16	8	9	5	4	7	106.8	106.7	0.1	10.46
17	8	9	5	4	8	104.3	104.2	0.1	14.10
18	8	9	5	4	9	101.8	101.6	0.2	27.49
19	10	2	10	4	7	99.3	99.2	0.1	07.27
20	10	2	10	4	8	97.0	96.8	0.2	10.14
21	10	2	10	4	9	94.5	94.4	0.1	18.38
22	10	6	5	6	7	92.1	91.9	0.2	09.12
23	10	6	5	6	8	89.5	89.4	0.1	12.07
24	10	6	5	6	9	86.9	86.7	0.2	22.42
25	10	9	8	2	7	84.4	84.2	0.2	08.50
26	10	9	8	2	8	81.9	81.7	0.2	12.32
27	10	9	8	2	9	79.4	79.2	0.2	30.09

This table is obtained by putting all the parameters in Taguchi method. Here 27 experiments are carried out by using orthogonal array method. The results obtained are analyzed using S/N ratios, Response table and Response graphs with the help of Minitab software.

5.1 Effect of T_{on} on MRR

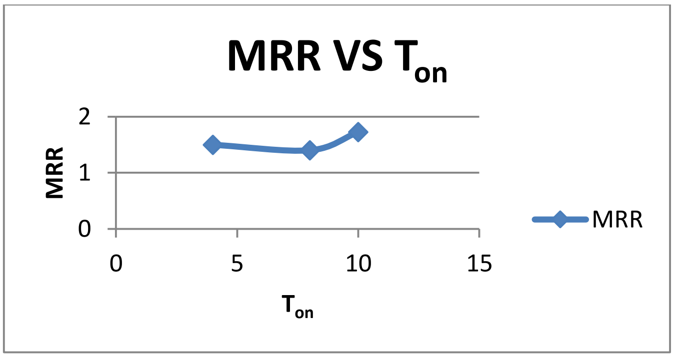

Fig 3: Relational plot between MRR & T_{on}

Relation between MRR & Ton is shown by the Fig.3. This figure shows that when Ton increases MRR is also increases.

5.2 Effect of T_{off} on MRR

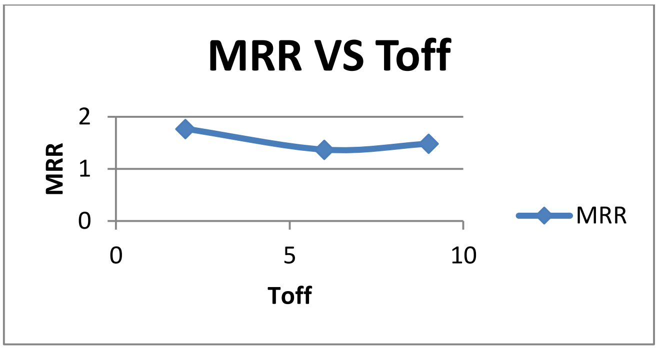

Fig.4: Relational graph between MRR & T_{off}

Fig 4 shows the relationship between T_{off} & MRR. From this figure I got that when T_{off} increases MRR decreases. That means T_{off} & MRR are inversely proportional to each other.

5.3 Effect of T.F. on MRR

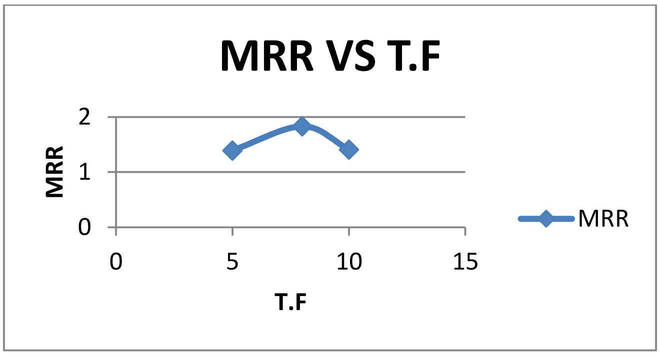

Fig.5: Relational graph between MRR & T.F

Relationship between MRR & T.F is shown by the Fig 5. This figure shows that there is no big impact of T.F on MRR. Value of T.F is more at point 8. It is due to the effect of other factors.

5.4 Effect of W.F. on MRR

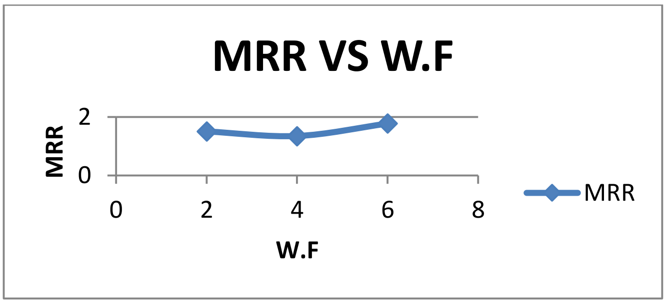

Fig.6: Relational plot between W.F & MRR

Fig 6 shows the relational between W.F & MRR. From this figure I got that when W.F increases MRR is also increases. Here W.F has a little impact over MRR.

5.5 Effect of V on MRR

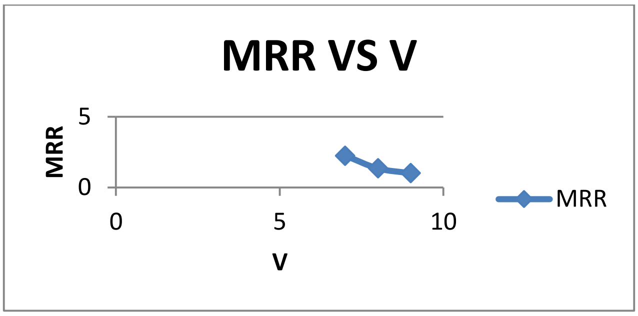

Fig.7: Relational plot between V & MRR

Relationship between V & MRR is shown by the Fig 7. From this plot it is clearly justified that when voltage increases MRR decreases. So I found that voltage has a big impact on MRR.

5.6 Effect of T_{on} on Ra

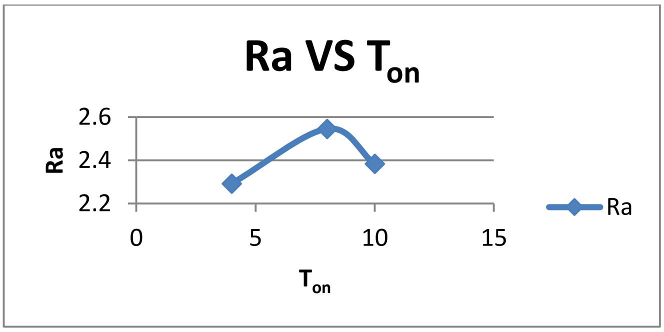

Fig.8: Relational plot between T_{on} & Ra

Fig 8 shows the relationship between T_{on} & Ra. There is no direct impact of Ton over Ra. It means Ra is not only depends upon Ton, but also is highly effected by some other parameters.

5.7 Effect of T_{off} on Ra

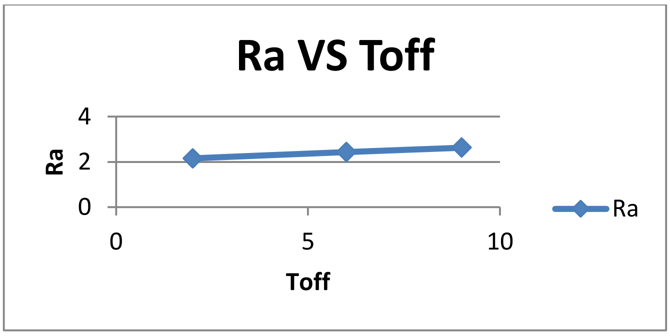

Fig.9: Relational plot between T_{off} & Ra

Fig 9 shows the relational plot between Ra & T_{off}. Here Ra increases uniformly with respect to T_{off}. To find out less surface roughness value of T_{off} should be less.

5.8 Effect of T.F. on Ra

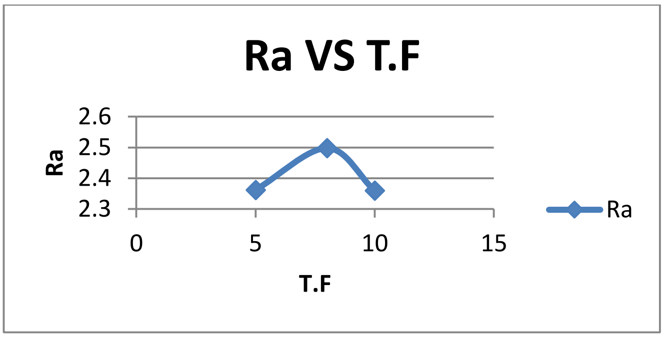

Fig. 10: Relational plot between Ra & T.F

Fig 10 shows the relationship between Ra & T.F. this figure shows T.F has less impact over Ra. That means Ra is not only depends upon T.F.

5.9 Effect of W.F. on Ra

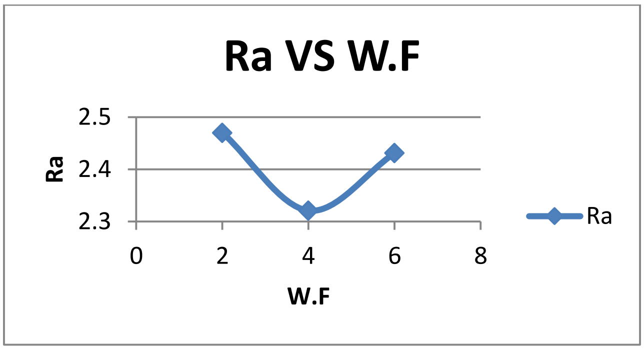

Fig.11: Relational plot between Ra & T.F

Relationship between Ra & W.F is shown by the Fig 11. This figure also shows W.F has less impact over Ra because it is depends upon some other factors highly.

5.10 Effect of V on Ra

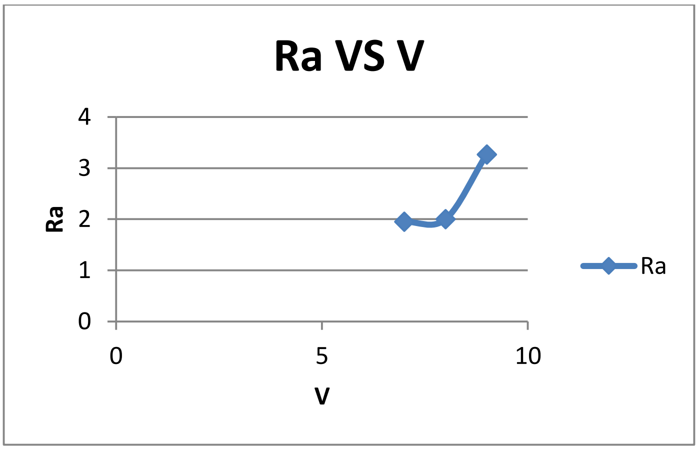

Fig 12: Relational plot between Ra & V

Fig 12 shows the relationship between Ra & V. This figure shows servo voltage has a great effect over Ra. That is when voltage increases Ra is also increases rapidly.

5.11 Main Effect Plot for input parameters

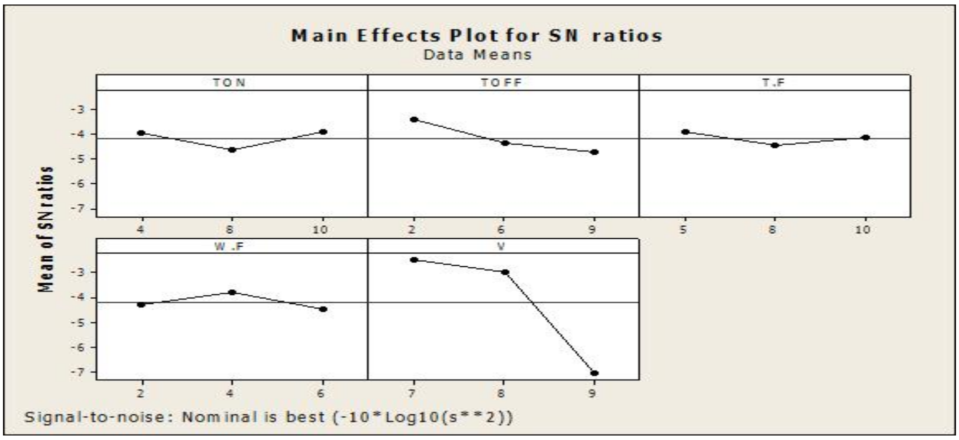

Fig 13: Effect of cutting parameters (S/N data)

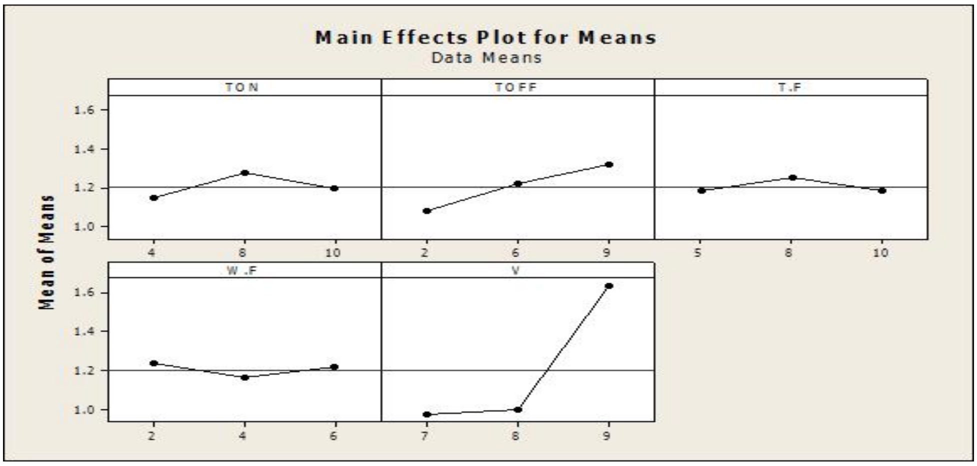

Fig.14: Main effect plot for means

The Figures 13 & 14 shows that the surface roughness increases with the increase of pulse on time & Table feed, and then it is decreases gradually. It also increases with increase in Pulse off time & Servo Voltage. It decreases by reducing of Wire Feed. It has no much influence on Surface Roughness. The discharge energy increases with the increase of Pulse on time. Larger discharge energy causes a larger crater causing a larger surface roughness value on the work piece.

5.12 Residual Plots for Means

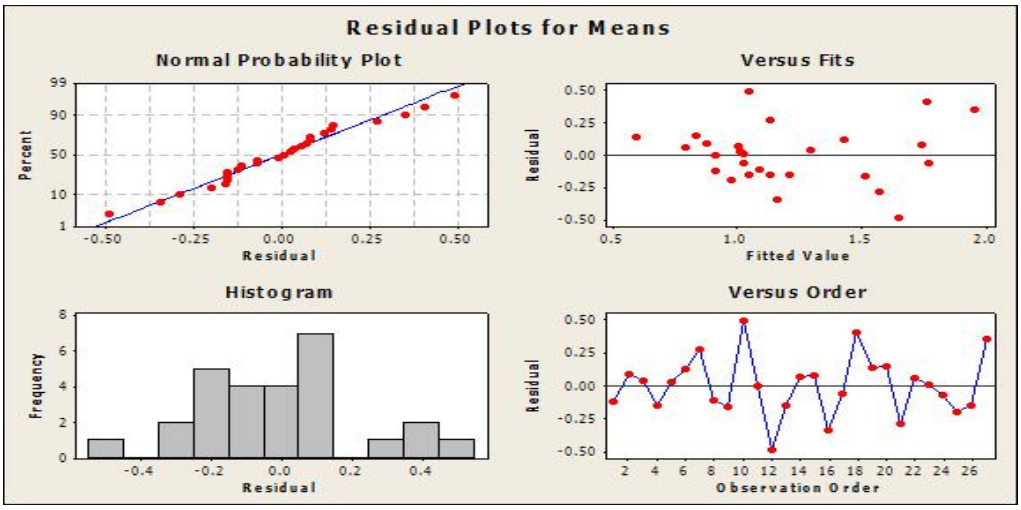

Fig.15: Residual plots for Means

Figure 15 shows the normal probability plot, versus fits, histogram & versus order plot. This is known as Residual plots for means. This layout is necessary to cheak wheather the model meets the expectation of the analysis. The interpretation of residual plots is as follows.

1. Normal probability plots indicates that the data are distributed normally. It can be seen that the standardise residue lies between -0.50 & 0.50.
2. Versus fits graph indicates the variance is constant & non linear relationship exists as well as no out liers exist in the data.
3. Histogram of the data is forms an irregular shape.
4. Versus order graph shows that there are systematic effects of the data.

5.13 Residual Plots SN Ratios

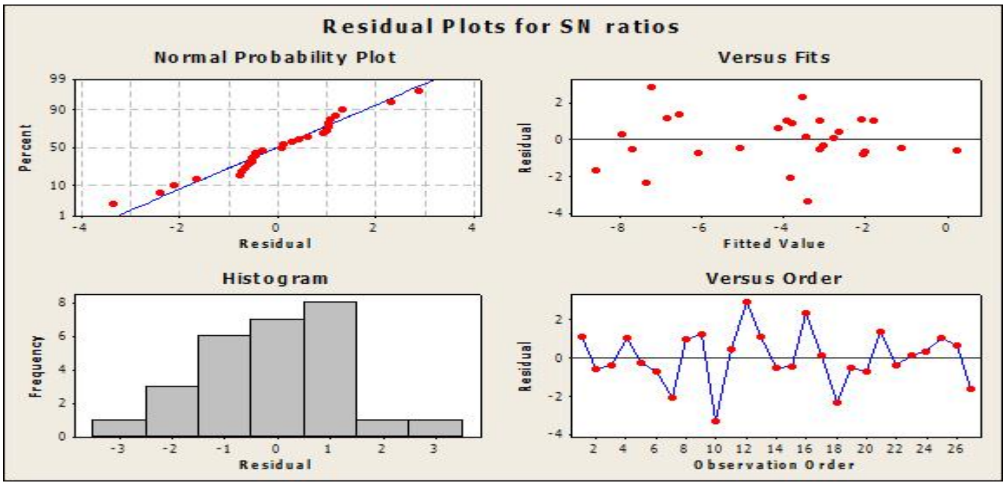

Fig 16: Residua plots for SN ratios

Fig 16 shows the relational graph between the normal probability plot, Histo gram, Versus fits & Versus order. Normal probability plot shows that all the data are lies in the limit from -4 & 4. Versus fits plot shows that all data are within the limit. Versus order plot shows that all data are arranged in a regular manner.

5.14 Interaction Plot for Means

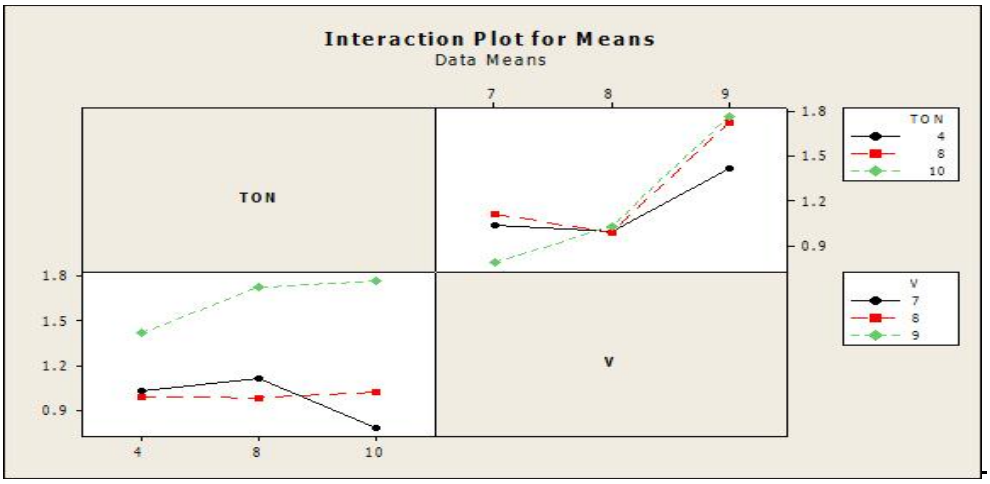

Fig 17: Interaction plots for Means

The interaction plot of MRR is shown in Fig 17. this plot shows the interaction between the two input variables taken in this experimant. The significant interaction is shown by the Right hand top most figure. It can also be confirmed from the ANNOVA table.

5.15 Interaction Plot for SN ratios

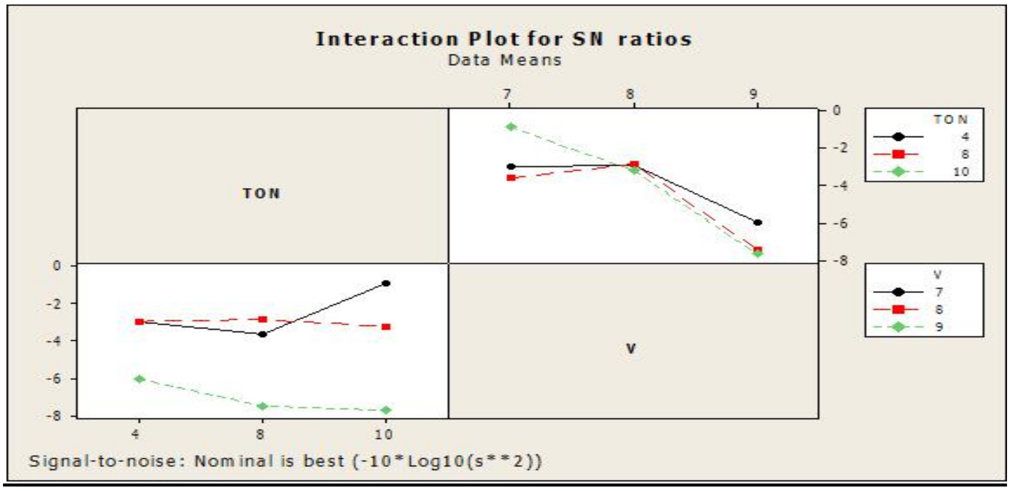

Fig 18: Interaction plots for SN ratios

Fig 18 shows the Interaction plot for SN ratios. This figure shows the Interaction between two input variables, such as T_{on} & V. The right top most figure shows that the significant relationship between T_{on} & V. The left hand side figure shows that there is no significant relationship between T_{on} & V.

5.15 Interaction Plot for St Deviations

Fig 19 shows that the Interaction plot for Ln St Deviation plot. Here also that two input variables are used, those are T_{on} & V. This figure also shows that the significant relationship between the input parameters.

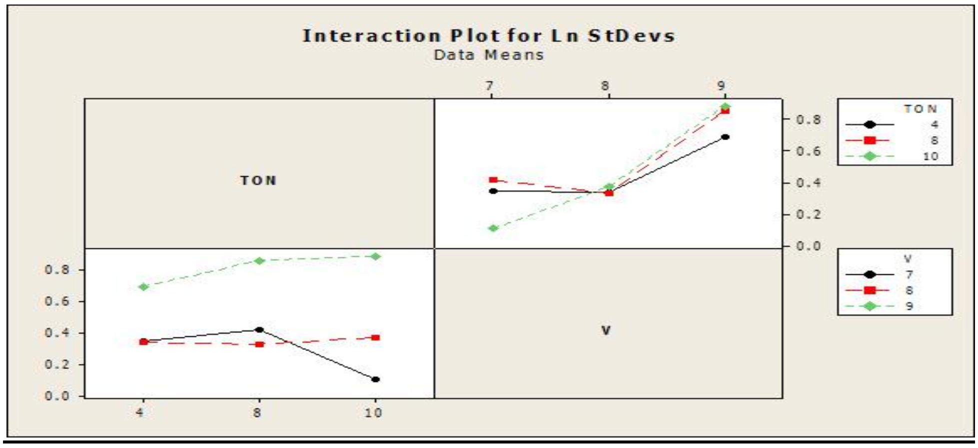

Fig 19: Interaction plots for Ln St Devs

6. CONCLUSION, LIMITATIONS AND SCOPE FOR FUTURE RESEARCH

6.1 Conclusions

This type of machining is only applicable for small size work pieces. This experiment is based upon 5 factors & 3 levels. These 5 factors are T_{on}, T_{off}, T.F, W.F, and V. The conclusions are:

i) For high MRR Larger is the better criteria is applicable. From this experiment I got that generally all the 5 factors have the major role to increase or decrease the MRR.

ii) To find out high MRR T_{on}, & W.F should increase & T_{off} & V should decrease. I got this result in experiment number 10. The value of MRR is 3.522mm^3/min. To find out this value the setup parameters are T_{on} = 8, T.F = 8, W.F = 6, T_{off} = 2, & V = 7.

iii) Similarly for Ra Lower is the better criteria is applicable. Also Ra is calculated from these 5 factors & 3 levels.

iv) To find out lower Ra value of T_{on} & T.F should increase, V & T_{off} should decrease, & W.F has no big effect for Ra. The accepted value of Ra is 1.467µm. the set value of the parameters are T_{on} = 10, T_{off} = 2, T.F = 10, V = 7 & W.F = 4.

6.2 Managerial Implications

Now a day WEDM is generally used in many applications, such as: automotive, aerospace, mould, tool and die making industries. Applications can also be found in the field of medical, optical, dental & jewellery parts processing. Owing to high process capability, it is widely used in manufacturing of cam wheels, special gear, bearing cage, various press tools, dies & similar intricate parts.

6.3 Limitations

Using WEDM, many other experiments can also be carried out by using some other parameters & levels. Here we have considered certain parameters such as T_{on}, T_{off}, T.F, W.F, and V etc. However, some other parameters like Tool Wear Rate, Dielectric Fluid Pressure, and Wire Tension etc can be taken into consideration in WEDM. At the same time, some other materials and Wires can also be used for machining purpose. It has a main limitation that it is difficult for machining of nonconductive materials.

6.4 Scope of Future Work

The following points may be suggested for future research work: i) Studying the effect of cutting other materials like Al and M.S., ii) Using other dielectric solution such as oil, iii) Using other wire materials such as Copper, Tungsten, & other coated wires, and iv) Studying the surface roughness in the current of WEDM using Scanning Electron Microscope.

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