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RESEARCH ARTICLE

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AN EXPERIMENTAL INVESTIGATION OF SURFACE ROUGHNESS FOR VIBRATION ASSISTED WORKPIECE IN WEDM USING TAGUCHI METHOD

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ABSTRACT

In WEDM some of the input parameters affect Surface Roughness (S.R) more than other like pulse on time (Ton). As the pulse on time increases the output measure i.e. surface roughness goes on increasing. As the cutting speed low due to improper removal of debris from cutting zone the surface roughness goes on increasing. In order to solve this problem, the vibration assisted workpiece used in WEDM which remove the debris fast and increasing the cutting speed and the high speed of cutting speed responsible for decreasing the surface roughness. In this study, the effect of workpiece vibration which produced by vibration unit with other electrical parameters of WEDM such as pulse on time (Ton), pulse off time (Toff) and servo-voltage (S.V) on surface roughness of WEDM was investigated. In this experiment the special purpose key of bright mild steel 1045 chosen as a workpiece. Investigation of surface roughness done with respect to the workpiece vibrated at frequency 25Hz, 70Hz & 115Hz. Taguchi method is used to formulate the experimental layout, to analyses the effect of each parameter on the surface roughness and to predict the optimal choice for each WEDM parameter. The experimental result showed that combination of vibration at different frequency & other electrical parameters of WEDM, assured continuous machining process & significant reduction in surface roughness achieved because combination of vibration, dielectric pressure and high speed compare to WEDM without vibration assisted responsible for the decreasing surface roughness.

Keywords: WEDM, Taguchi Method, Pulse on time, Frequency of vibration, Surface Roughness, Bright Mild Steel 1045

1. INTRODUCTION

The surface character has significant effect on the serviceability and thus can't be neglected in design. It is the designer's responsibility to specify the natures of the surface on the machined components. Currently more than 20 mathematical parameters are applied to the characterization of a surface, but most commonly specified parameter is the surface roughness, waviness and lays.

1.1 Definition of Surface Roughness Average: Roughness averages (R_a) is defined as the arithmetical average of the departures of the profile above and below the reference line (Center or electrical mean line) throughout the prescribed length.

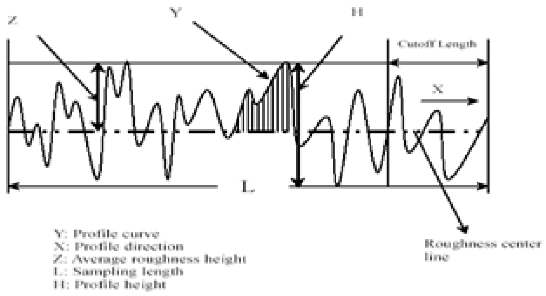

Figure: 1 The sampling length

A mathematical expression for this is give below; Figure 1 shows the sample length of specimen over which R_a value is to be measure. Where

$$R_a = \frac{1}{L}\int_0^L |Y(x)|dx \qquad (1)$$

R_a = the arithmetic average deviation from the mean line (µin & µm)

L= the sampling length in (mm & inch)

Y= the ordinate of the profile curve in (mm & Inch)

Surface values are normally assessed as the mean results of the several sampling length taken consecutively along the surface. As shown in Figure 1.

1.2 Methods of Measuring Surface Roughness: Many parameters have been proposed to characterize surface roughness. The commonly used parameters, together with standard measurement methods, are defined in national and international standards, which are broadly equivalent but differ somewhat in detail. The American national standard is ASME; a series of ISO and DIN standards cover the same subjects, the most relevant in the current context being ISO 4288:1996, 150 4287:1997, and DIN 4768:1990. These standards define the parameters most often used for inspection and tolerance of machined surfaces: the arithmetic average roughness Ra, maximum peak height Rp, maximum valley depth Rv , peak-to-valley height Rt , ten-point height R_z , and bearing ratio t_p, The parameters Ra, Rp, Rv and Rt are all defined with respect to a centerline of a filtered stylus trace. Filtering is performed to remove the slope and waviness components of the trace.

Surface roughness of a machined product could affect several of the product's functional attributes, such as contact causing surface friction, wearing, light reflection, heat transmission, ability of distributing and holding a lubricant, coating, and resisting fatigue. Therefore, surface roughness becomes one of the important quality aspects in turning operation products. The parameter Ra is used in this study. The average roughness (Ra) is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length (Figure 1). Therefore, the Ra & Rq is specified by the following equation 1 & 2 respectively as mentioned above:

$$R_q = \sqrt{\frac{\sum_{n=1}^{N} y_n^2}{N}} \qquad (2)$$

1.3 Surface Roughness Measurement Technique: There are a number of useful techniques for measuring surface roughness,

1. Observation and touch - the human finger is very perceptive to surface roughness
2. Stylus based equipment - very common
3. Interferometer-uses light wave interference patterns

The total surface profile which is the net of surface roughness and waviness is usually measured with the profilometre device that electronically measures the surface texture with stylus not unlike a phonograph needle. In this work the surface roughness was measured by Mitutoyo surftest SJ-210.

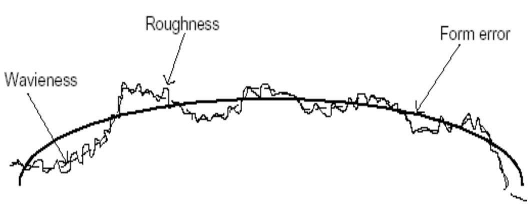

Figure: 2 Geometric errors of surface

1.4 Surface Roughness Errors: A surface which is nominally smooth and flat will always exhibit some roughness. Which may vary from fine to coarse, depending on the finishing operation used. It may also exhibit some waviness, and may also be curved, thus - Machining of products, regardless of the use of high precision tool, shows some irregularities on the surface. The irregularities are categorized, according to its wavy like properties (frequency, amplitude), into three main groups. These are surface roughness, waviness, and form error. The figure 3 shows the surface roughness, waviness and form error on the surface.

The component of surface texture which are:

Roughness: Surface roughness is the true air- metal boundary on the surface. It is generally defined, as the magnitude of wavelength per amplitude that is less than 10 of the surface waves. The only irregularity that does not change the general dimension of the product even if it is high is surface roughness. That is the irregularities in the surface texture which are inherent in the production process, but excluding waviness and errors of form.

Waviness: Waviness errors are irregularities of longer wavelength on the surface. The magnitude of wavelength per amplitude is range 10 to 100 of the surface waves.

Form error: If the surface irregularities wavelength per amplitude is in the order of 1000, then these errors are called form error.

1.5 Importance of Surface Quality: Surface Quality can be important when dealing with,

- Lubrication - small indentations can hold lubricant
- Resistant to wear - smoother surfaces wear less
- Tool life - rough surfaces will correlate to shorter tool life
- Fatigue/stress raisers
- Corrosion - smoother surfaces easier to clean, less surface area to erode
- Noise reduction - smooth surfaces make less noise when rubbing, for example meshing gears.
- Fit - pressure seals could leak through pits

1.6 Basic Principle of WEDM Process: The mechanism of material removal in WEDM is similar to conventional machining process in which erosion effect produced by the series of electrical sparks produced between the work piece & the wire electrode surrounded by stream of dielectric fluid continuously flowing in the machining Zone [1]. A temperature range of 8000°C–12,000°C exist between cathode and anode in the form of thermal energy after applying voltage pulses between the work–piece and the wire electrode during WEDM process.

When the pulsating DC power supply occurring between 20,000 and 30,000 Hz is turned off, the plasma channels breaks down. As a result of breaking of plasma channel a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten particles from the machining zone in the form of microscopic debris [2]. The typical cutting rates in case of WEDM are 300 mm^2/min. for a 50 mm thick D2 tool steel and 750 mm^2/ min. for 150 mm thick aluminium [3], and surface finish is as fine as 0.04–0.25μRa. WEDM makes use of deionised water instead of hydrocarbon oil as dielectric fluid flowing within the sparking zone. Though the deionised water is not suitable for conventional EDM as it causes rapid electrode wear, but it is ideal for WEDM because of its low viscosity and fast cooling rate [4].

2. LITERATURE REVIEW

In the literature review some research papers are related to effect of vibration which is given to either workpiece or tool electrode in Die Sinking Electric Discharge Machining & Wire Electric Discharge Machining on Material Removal Rate (MRR), Surface Roughness (S.R) and some research papers are related to effect of input process parameters of WEDM such as pulse on time (Ton), pulse off time (Toff), Wire feed rate (W.F), Servo-voltage (S.V) on Performance characteristics of WEDM such as, Surface roughness (S.R) & Cutting Speed (C.S).

By the application of vibration onto the micro-EDM process, the machining time can be reduced significantly. Process time decreases with increase vibration frequency and constant amplitude. The total duration of arcing events is reduced by the application of vibration and decreases with increasing frequency [3]. FEM model has been developed using homogenous Helmholtz equation. Galerkin's method has been used for the model development. The results of ultrasonic assisted EDM are compared with pure EDM. During the upward motion of the work piece, the dielectric in the working zone between the tool and work piece is pumped out which is similar to the pumping action of reciprocating pump. Due to this pumping action of the work piece, the dielectric containing debris is pushed out, thus resulting in reduced adhesion of the debris particles with the tool and work piece. When the workpiece is moving in the downward direction dielectric is sucked inside which in turns helps in the inclusion of fresh dielectric in the working zone. As compared to no-vibration, the pressure is maximum under the tool tip during the work piece is moving upward and exerting force on the dielectric. During the downward motion a low pressure area is created under the tool tip resulting in the suction of fresh dielectric. Ultrasonic vibration assisted EDM has better flushing as compared to the pure EDM. The up and down movement of work piece at ultrasonic frequency enhance the flushing. The better flushing subsequently improve material removal rate [4]. Work presents an attempt to use a low-frequency vibration on workpiece of stainless steel (SS 304) during EDM process. The workpiece was vibrated with variations of low-frequency and low-amplitude. The results show that the application of low-frequency vibration in EDM process can be used to increase the material removal rate, and decrease the surface roughness and tool wear rate [5]. The results of experimental studies carried out to conduct a comprehensive investigation on the influence of ultrasonic vibration of workpiece on the characteristics of Electrical Discharge Machining (EDM) process of FW4Welding Metal in comparison with the conventional EDM process. The studied process characteristics included the material removal rate (MRR), tool wear ratio (TWR), and surface roughness (Ra and Rmax) of the workpiece after the EDM and ultrasonic assisted EDM (US-EDM) processes. In the case of short pulse on-times, material removal rate in the US-EDM process is approximately quadruple that of the EDM process. On the contrary, in the long pulse on-times, ultrasonic vibration of workpiece leads to the reduction of the MRR. In the short pulse on-times, the TWR in the US-EDM process is lower than that of in the EDM process, and this condition reverses with increase in pulse on-time. The surface roughness of the workpiece machined by the US-EDM process is slightly larger than that of applied to the EDM process [6]. The effect of vibration frequency and amplitude for three different settings of aspect ratios has been studied experimentally. The machining performance improves as MRR increases and EWR decreases significantly after applying workpiece vibration (Kv > 1) in micro-EDM. For the setting of Kv > 1, the machining performance and microhole quality improves with increasing vibration frequency and amplitude up to certain optimum values. However, very high frequency and amplitude are found to be unsuitable from the perspective of micro-hole surface quality and accuracy. Kv is the ratio of maximum acceleration of the vibrating plate in gravitational direction to gravitational acceleration 'g' [7].To enhance the flushing of debris particles, an attempt is made to give continuous and discontinuous ultrasonic vibrations to work-piece in EDM process. The effects are explored using high Carbon high Chromium steel as work-piece and Copper as tool electrode. In this work L18 orthogonal array based on Taguchi design is used to conduct a series of experiments and the experimental data is statistically evaluated by Analysis of Variance (ANOVA). Discontinuous ultrasonic vibrations improve the MRR by improving the dielectric flushing to a greater extent. The average length, width and number of micro-cracks increase with the peak current and pulse duration. The micro-cracks seem to reduce when the peak current and pulse duration are set at very low levels [8]. Effects of rotary magnetic field and also ultrasonic vibration of workpiece were studied on dry EDM process performance. Magnetic field can expel the debris from machining gap and improve the process stability; subsequently, the MRR increased and lead to smoother surface. Ultrasonic vibration of workpiece acts as a pump at gap space and can remove the debris away. Also, it can improve the process stability and increases the number of normal discharge and confines the ARC probability [9]. In µ-EDM processes, the addition of nano graphite powder to a dielectric fluid significantly reduced machining time and improved surface quality. In addition, introduction of workpiece vibration augmented this effect to further increase the machining efficiency. The graphite powders contributed significant reduction of the machining time. When the nano-graphite powders were added into the dielectric fluid, the fastest machining time was 3.52 min at a powder concentration of 10 g/l, which was 20 times faster than that machined in the pure dielectric fluid. By combining the workpiece vibration and powder suspension, the fastest machining time of 2.95 min was achieved when the workpiece vibration was applied along with the introduction of graphite powders at a concentration of 20 g/l [10]. The design and utilization of a unit composed of piezoelectric actuators for machining seal slots in turbine components was considered. This aims the optimization of the flushing mechanisms through vertical vibration of the tool electrodes while manufacturing high aspect ratios cavities and therewith the optimization and/or reduction of both process time and electrode wear. The relative tool electrode wear could be reduced by 21%. The material removal rate was improved by 11 %. High vibration frequencies and low amplitudes increase the machining efficiency. These improvements lie on the improved flushing conditions, which lead to the improvement of process stability [11]. To facilitate high precision machining, vibration is introduced in any of workpiece, tool and working medium, which is called Vibration Assisted Machining (VAM). VAM is found to be effective in advanced machining techniques in improving the process stability and quality of the products. VAM can be applied to almost all the precision machining techniques. Although proper mechanics of the machining process supporting the improvements in machining have to be developed [12]. In general, the material of wire (electrode) is taken as brass/copper in WEDM. But in this work, Molybdenum wire is used. The main goal of this research work was to investigate the effect of various process parameters on material removal rate (MRR) while machining Ti6AL4V work piece on WEDM using Molybdenum wire. Pulse on time (Ton) is the most significant influencing machining parameter having direct effect on metal removal rate (MRR) in the machining of Ti alloy and maximum MRR was obtained at Ton 120 µsec. Pulse off Time (Toff) is the second most significant influencing machining parameter and optimal value of Toff was found at 55 µsec for maximum MRR. It was also concluded that for rough and high-speed cutting (for higher MRR), the optimal wire feed rate of Molybdenum wire was 15 m/min for Ti alloy work-piece. And the optimal wire tension was found 1300 gms. It was concluded that for rough and high-speed machining, the optimal value of servo voltage is 80 volts [13]. The effects of certain process parameters such as peak current (I_p), pulse on time (T_{on}), pulse off time (T_{off}), and servo reference voltage (SV) on MRR and R_a investigated. Based on the investigation performed the most significant parameters on both MRR and Ra were found to be peak current and pulse on time, whereas pulse off time and servo voltage were less effective factors. Both MRR and Ra increase or decrease simultaneously. In other words high MRR can be obtained at cost of surface finish [14].An investigation has been made to combine ultrasonic vibration and wire electrical discharge turning. The ultrasonic system consists of an ultrasonic generator, a transducer, and a wire holder. When the wire is being driven, the transducer together with the wire holder vibrates under the resonance condition. Experimental results indicate that ultrasonic vibration and power are the most significant influencing parameters on MRR. Rotational speed and pulse off time are the next in ranking [15]. Wire electric discharge machining (WEDM) of Titanium alloy (Ti-4.5Al-2V) is studied by author, in WEDM the prime objective in cutting operation is to achieve the highest possible cutting speed along with desirable surface finish without sacrificing productivity. The material removal rate (MRR) is mostly affected by the peak current, pulse-on time, pulse off-time, and taper angle. The surface roughness values (SR) are influenced mostly by peak current, taper angle, pulse-on time, pulse off-time, and dielectric flow rate [16].

3. EXPERIMENTAL SET-UP AND SELECTION OF PROCESS PARAMETERS

The pulse generator capacity of the machine is 40A. The pulse generator supplies the electrical energy to the spark gap in the form of pulses. The machine tool unit comprises of a main worktable (called X-Y table) by which the fixture is clamped on auxiliary table (called U-V table) and wire drive mechanism. The vibration actuator use for giving vibration to workpiece fixed in the fixture. Then workpiece fixed on the fixture. Figure 3 shows the experiments are carried out on CNC sprint cut wire EDM of Electronica Machine tool ltd.

Figure 3: Electronica Sprintcut WEDM Use in Experiment

A line diagram of vibration unit used for giving the vibration to workpiece in this experiment shown in Figure 4

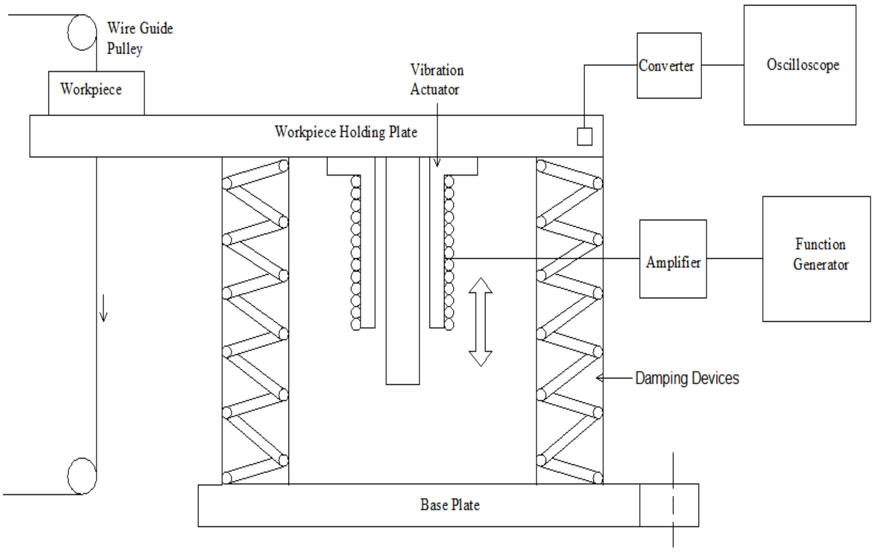

Figure 4: Line Diagram of Vibration Unit Use in this Experiment

3.1 Workpiece Electrode: The work piece material used in this investigation was bright mild steel 1045 special purpose keys. The specimen prepared from bright mild steel 1045 keys by the help of Angel grinder in the size of 75×5×5 mm.

Table I: Chemical composition of workpiece

Constituent	Carbon (C)	Manganese (Mn)	Silicon (Si)	Sulphur (S)	Phosphorous (P)
% Composition	0.45	0.76	0.26	0.03	0.04

Table II: Mechanical properties of workpiece

Tensile Strength	Yield Strength	Elongation in 50 mm	Hardness
690 Mpa	460 Mpa	11.5%	210 HB

3.2 Tool Electrode: Uncoated brass wire having diameter of 0.25 mm is used in the present investigation as the electrode. Tool electrode which is brass wire act as a cathode in the present experiment and workpiece which is mild steel specimen act as an anode. The main advantage of using brass is that it is easily available. Brass Wire was the successor to Copper wire and is still the most commonly used wire today. Brass, which is an alloy of Copper and Zinc, delivers a powerful combination of low cost, reasonable conductivity, high tensile strength, and improved flushability. (It should be noted that even a small amount of Zinc added to Copper wire drastically reduces the conductivity. Hard Brass wire typically has conductivity only 20% of Copper wire. Brass wire is most commonly available in the following alloys: Cu 63%, Zn 37% & Cu 65%, Zn 35%.

Since it is the Zinc that gives Brass Wire its improved flushability, some manufacturers now offer a "high zinc" brass which is Cu60%Zn40%. This increase in Zinc content can increase cutting speed up to 5% in some optimized applications.

3.3 Selection of Process Parameters and their Ranges: In order to obtain high cutting speed the optimal level of WEDM process parameters with frequency of vibration need to be determined. Based on the critical review of literature, process variables of the WEDM are selected according to transient state.

The process parameters selected for this study are as following:

a. Frequency (F)
b. Pulse on Time (Ton)
c. Pulse off Time (Toff)
d. Servo voltage

The frequency level of vibration choosen in this experiment was 25-115 (Hz) which gave to workpiece with the help of vibration unit.

In Sprint-cut WEDM, the value of Pulse-ON time ranges 100 to 131(machine unit), Pulse-Off time ranges 00 to 63 (machine unit), Servo voltage ranges 00 to 99 (volt). Other constant parameters use in experiment shown in Table III.

Table III: Other constant parameters in experiment

Peak current (Ip)	Gap voltage (VP)	Water pressure (WP)	Wire feed rate (WF)	Wire Tension (WT)	Servo Feed (SF)
230 Amp	2 (machine unit)	1 (machine unit)	3 (machine unit)	8 (machine unit)	2150 (machine unit)

4. DESIGN OF EXPERIMENTS

4.1 Taguchi 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 [Roy (1990)].

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives [Ross (1996)]:

- 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.

4.2 Signal to Noise Ratio: Classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out as the number of the process parameters increases. To solve this important task, the Taguchi method uses a special design of orthogonal array to study the entire parameter space with only a small number of experiments. The experimental results are then transformed into a signal-to-noise (S/N) ratio. The S/N ratio can be used to measure the deviation of the performance characteristics from the desired values. The categories of performance characteristics in the analysis of the S/N ratio depend upon output parameters to be controlled. We have selected only one category which is:

• The lower-the-better for Surface Roughness (S.R)

4.3 L9 Orthogonal Array: In L9 (3^4) array 9 rows represent the 9 experiment to be conducted with 3 columns at, 3 levels of the corresponding factor. The matrix form of these arrays is shown in Table 4, where 1, 2, 3 in the table represents the level of each parameters.

Input Factors:-

1) Frequency
2) Pulse- On Time (Ton),
3) Pulse- Off Time (Toff),
4) Servo Voltage (SV).
Responses measured: Surface Roughness (S.R)

Table IV: Taguchi L9 Orthogonal array Design Matrix

Exp. No	Factor 1	Factor 2	Factor 3	Factor 4
E1	1	1	1	1
E2	1	2	2	2
E3	1	3	3	3
E4	2	1	2	3
E5	2	2	3	1
E6	2	3	1	2
E7	3	1	3	2
E8	3	2	1	3
E9	3	3	2	1

Table V: Levels for various control factors Use in Experiment

Sr. No	Factors	Levels		
		1	2	3
1	Frequency (Hz)	25	70	115
2	Ton (machine unit)	102	110	118
3	Toff (machine unit)	20	40	60
4	S.V (Volts)	40	60	80

5. RESULT & DISCUSSION

Firstly the experiment (E1- E9) performed without vibration i.e. the frequency of vibration was zero and other three variable factors used as table IV for experiment E1 to E9.Constant parameters used from Table III.

Table VI: Surface Roughness for experiment (E1-E9) at frequency = 0

Experiment no	E1	E2	E3	E4	E5	E6	E7	E8	E9
Surface Roughness (µm)	4.53	4.87	4.76	4.29	4.46	5.31	3.94	4.14	4.39
Mean S.R for (E1-E3) = 4.72				Mean S.R for (E4-E6) = 4.69			Mean S.R for (E7-E9) = 4.16		

In order to see the effect of process parameters on the surface roughness, experiments were conducted using L_9 OA (Table IV). The mean values of surface roughness for each parameter at levels 1, 2 and 3 for experimental data and S/N ratio are shown in table VII.

Table VII: Calculations of Signal to Noise ratio for Surface Roughness

Expt. No.	Repet. 1 for S.R	Repet. 2 for S.R	Repet. 3 for S.R	Mean	Variance	Sum of Squares of reciprocals	S/N Ratio (Lower-the-better)	S/N Ratio (Mean)
E1	4.385	4.247	4.352	4.328	0.0052	18.74	-12.73	12.73
E2	4.660	4.700	4.740	4.70	0.0016	22.09	-13.44	13.44
E3	4.741	4.602	4.640	4.661	0.0052	21.73	-13.37	13.37
E4	3.930	4.040	4.210	4.060	0.020	16.50	-12.17	12.17
E5	4.250	4.160	4.280	4.23	0.0039	17.90	-12.53	12.53
E6	5.010	5.130	5.20	5.113	0.0092	26.15	-14.18	14.17
E7	3.780	3.698	4.018	3.832	0.0276	14.70	-11.67	11.67
E8	3.840	3.960	3.920	3.907	0.0037	15.26	-11.84	11.84
E9	4.030	4.160	4.201	4.130	0.0080	17.06	-12.32	12.32
Sum	38.626	38.697	39.561				-114.25	
Total Sum	116.884							
Avg.	4.329							

The response table for signal to noise ratio for surface roughness is shown in Table VIII and Response table for % improvement in S.R shown in Table IX and the corresponding ANOVA table is shown in Table X & XI. For S.R, the calculation of S/N ratio follows "Lower the Better" model.

Table VIII: Response Table for Signal to Noise Ratios for S.R

Level	Frequency	Pulse on Time	Pulse off Time	Servo voltage
L1	-13.18	-12.19	-12.91	-12.53
L2	-12.96	-12.60	-12.65	-13.10
L3	-11.94	-13.29	-12.52	-12.460
Delta	1.24	0.69	0.39	0.64
Rank	1	2	4	3

Table IX: Response table for % Improvement in S.R

Level	Frequency	Pulse on Time	Pulse off Time	Servo voltage
L1	4.56	4.07	4.45	4.23
L2	4.47	4.28	4.30	4.55
L3	3.96	4.63	4.24	4.21
Delta	0.61	0.56	0.21	0.34
Rank	1	2	4	3

Table X: Anova S/N

Source	SS	DOF	V	P	F-Ratio
Frequency	2.61	2	1.30	48.04	10.97
Pulse on Time	1.84	2	0.92	33.10	7.77
Pulse off Time	0.24	*	*	*	*
Servo Voltage	0.74	2	0.37	13.58	3.10
Error	0.24	2	0.12	4.38	
Total	5.41	8		100	

Where, SS - sum of squares, DOF - degrees of freedom, V - Variance, P - determines % contribution of each source, F- ratio of variance of a source to variance of error.

Table XI: Anova Raw Data

Source	SS	DOF	V	P	F-Ratio
Frequency	1.92	2	0.96	43.56	102.26
Pulse on Time	1.45	2	0.73	33.03	77.54
Pulse off Time	0.21	2	0.10	4.76	11.17
Servo Voltage	0.65	2	0.33	14.82	34.78

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Error	0.17	18	0.0093	3.83	
Total	4.40	26	*	100	

Where, SS - sum of squares, DOF - degrees of freedom, V - Variance, P - determines % contribution of each source, F- ratio of variance of a source to variance of error.

The average values of surface roughness for each parameter at levels 1, 2 and 3 for experimental data and S/N ratio are plotted simultaneously in Figures 5 (a, b, c, d). For surface roughness S/N ratio is (lower - the- better).

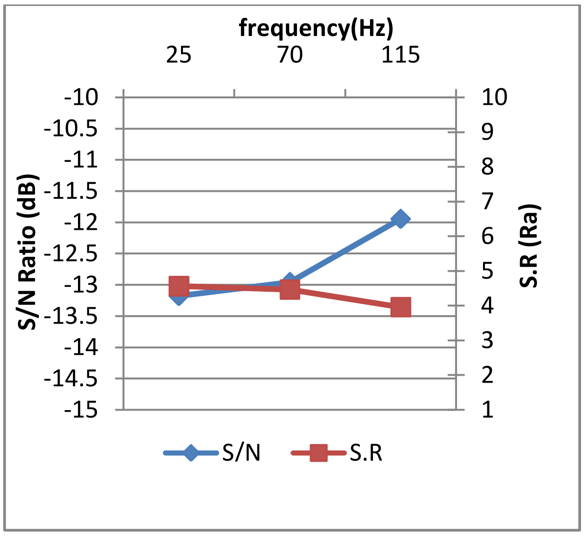

Figure 5: (a)

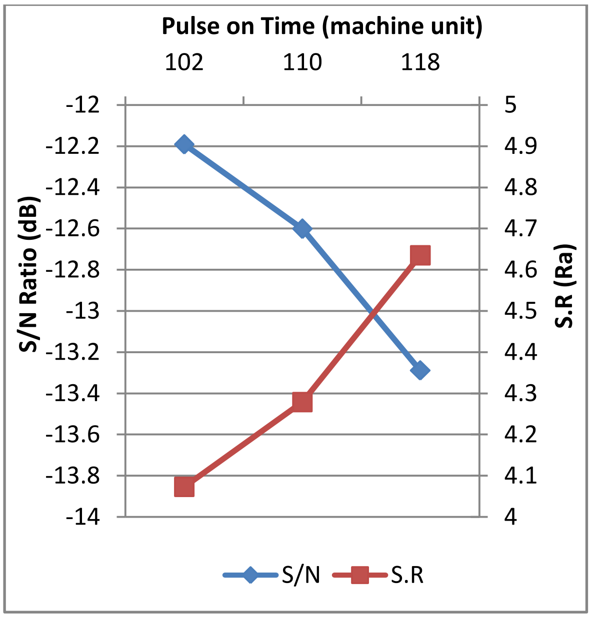

Figure 5: (b)

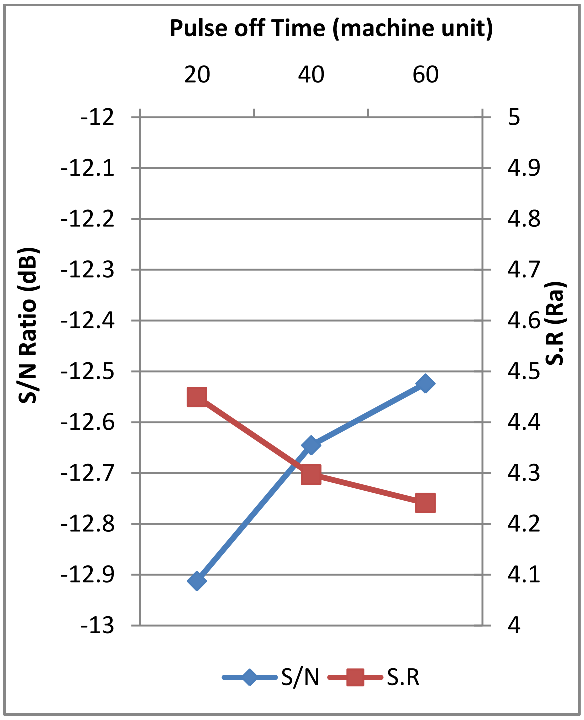

Figure 5: (c)

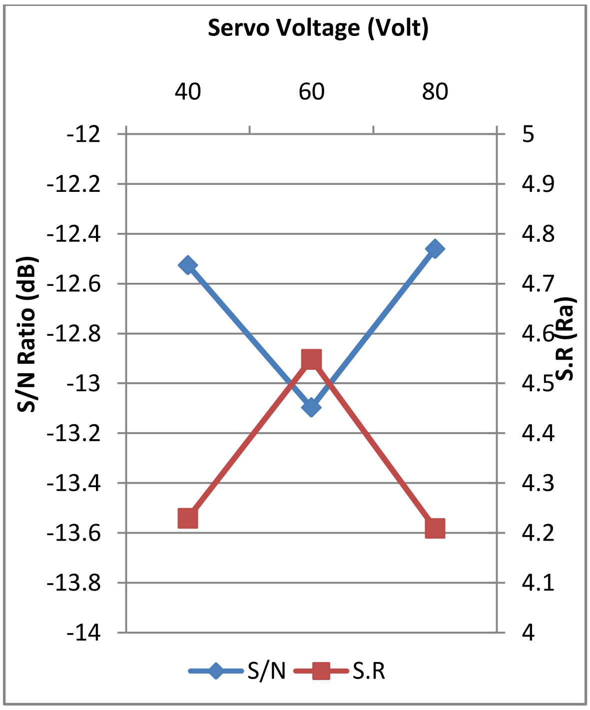

Figure 5: (d)

Figure 5 (a, b, c, d) S/N ratio & S.R curves for different parameters

Figure 5 (a) shows that the surface roughness decreases with the increase of frequency of vibration. This is because increasing in vibration increase cutting speed and higher cutting speed produce smooth surface.

Figure 5 (b) shows that surface roughness increases with the increase of pulse on time (Ton). The discharge energy increases with the pulse on time and larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece.

Figure 5 (c) shows that surface roughness decreases when pulse off time increases. As the pulse off time decreases, the number of discharges increases which causes poor surface accuracy.

Figure 5 (d) shows that surface roughness increases when servo voltage increase in the range of 40-60 (volt) and after that it decrease from 60-80 (volt). With increase in servo voltage the average discharge gap gets widened resulting into better surface accuracy due to stable machining.

5.1 Selection of optimal levels for Surface Roughness: From tables X & XI, it is clear that frequency, pulse on time, pulse off time, servo voltage significantly affect both the mean and the variation in the S.R values. The response tables (Tables VIII and IX) show the average of each response characteristic (S/N data, means) for each level of each factor. The tables include ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. The ranks and the delta values show that pulse on time have the greatest effect on cutting speed and is followed by pulse off time , frequency of vibration, and servo voltage in that order. As surface roughness is the "lower the better" type quality characteristic, it can be seen from Figure 5(a, b, c, d) that the third level of frequency i.e. (115 Hz), first level of pulse on time i.e. (102 machine unit), third level of pulse off time i.e. (60 machine unit) and third level of servo voltage i.e. (60 volt) provide minimum value of surface roughness. The S/N data analysis from Figure 5 (a, b, c, d) also suggests the same levels of the variables frequency of vibration, pulse on time, pulse off time and servo voltage i.e. (115, 102, 60, and 80) are the best levels for minimum Surface Roughness in WEDM process.

5.2 Experimental Verification: After performing the statistical analysis on the experimental data, it has been observed that there is one particular level for each factor for which the response is minimum in case of S.R. So for finding the optimum parameter setting for each response factors, the additive model of Taguchi method is used. S/N ratio is calculated based on the formula containing negative of logarithmic value, which is a monotonic decreasing function. So S/N ratio should be always kept at minimum value. Therefore in finding the optimum parameter setting, the levels of input factors are chosen in such a way that the S/N ratios for those levels have minimum values (for each input factor). There is one optimum parameter settings corresponding to the four response factors. The combination of input factor levels, for which optimum settings will be obtained, is given in Table XII.

Table XII: Optimal Parameter Setting of Input Factors

Physical Requirement	**Optimal Combination**			
	Frequency	**Pulse on time**	**Pulse off time**	**Servo voltage**
Minimum Surface Roughness	115	102	60	80

Using this optimum parameter settings, three verification experiments has been carried out and the experimental results for surface roughness (Avg.) are shown in Table XIII.

Table XIII: Verification Experimental Results & Calculation of Response Factor S.R

Verification Experiment For	**Surface Roughness (S.R)**
Minimum Surface Roughness	3.28 (μm)

6. CONCLUSION:

The important conclusions from the present experiment work are –

Surface Roughness: It is clear from Figure 5 (a) that Surface roughness decreases with the increase of frequency of vibration. Frequency of vibration has largest effect on surface roughness compare to other input parameters in terms of decreasing surface roughness. This is because increasing in vibration increase cutting speed and higher cutting speed produce smooth surface. Response table for S/N for surface roughness (Table VIII) shows that the effectiveness rank of frequency of vibration on surface roughness is 1st & Anova for raw data (Table XI) shows that the percentage contribution of frequency is 43.56 which is maximum in all four input factors.

- Surface roughness increases with the increase of pulse on time (Ton) as shown in Figure 5 (b). The discharge energy increases with the pulse on time and larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece. Response table for S/N for surface roughness (Table VIII) shows that the effectiveness rank of pulse on time on surface roughness is 2nd & Anova for raw data (Table XI) shows that the percentage contribution of pulse on time is 33.03 which is lower only from frequency source.
- Figure 5 (c) shows that Surface roughness decreases when increases pulse off time (Toff). As the pulse off time decreases, the number of discharges increases which causes poor surface accuracy. Response table for S/N for surface roughness (Table VIII) shows that the effectiveness rank of pulse off time on surface roughness is 4th & Anova for raw data (Table XI) shows that the percentage contribution of pulse off time is 4.76 which is minimum in all four sources.
- Surface roughness increases when servo voltage increase in the range of 40-60 (volt) and after that it decrease from 60-80 (volt) and its shown in Figure 5 (d). With increase in servo voltage the average discharge gap gets widened resulting into better surface accuracy due to stable machining. Response table for S/N for surface roughness (Table VIII) shows that the effectiveness rank of servo voltage on surface roughness is 3rd & Anova for raw data (Table XI) shows that the percentage contribution of servo voltage is 14.82 which is lower from frequency and pulse on time but higher than pulse off time.
- Figure 6 (a, b, c, d) shows the Surface Roughness variation at different input parameters and this one also shows the same level of input factors as shown in table XII at which minimum surface roughness obtained i.e. (115, 102, 60, 80).

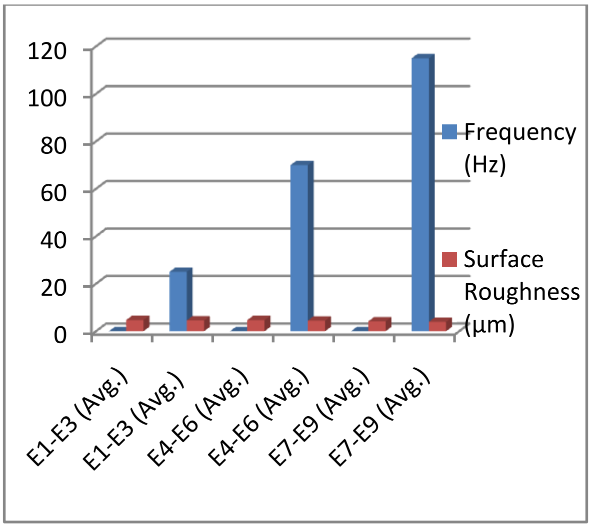

Figure 6: (a)

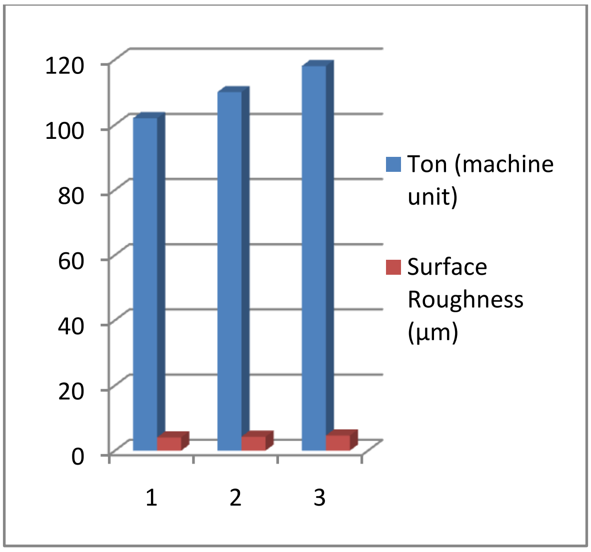

Figure 6: (b)

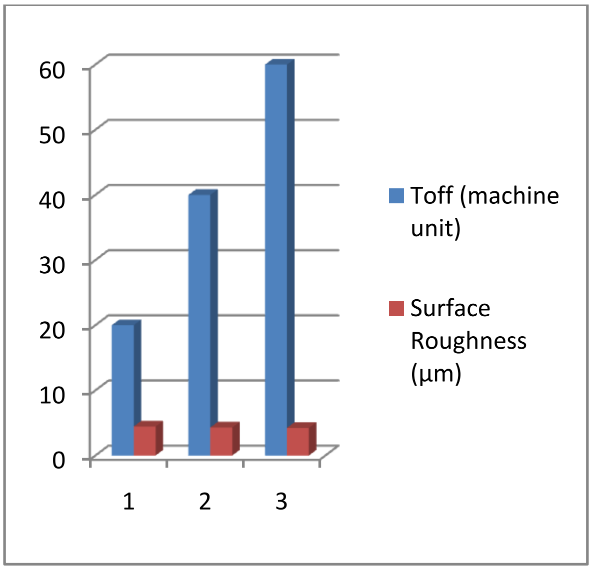

Figure 6: (c)

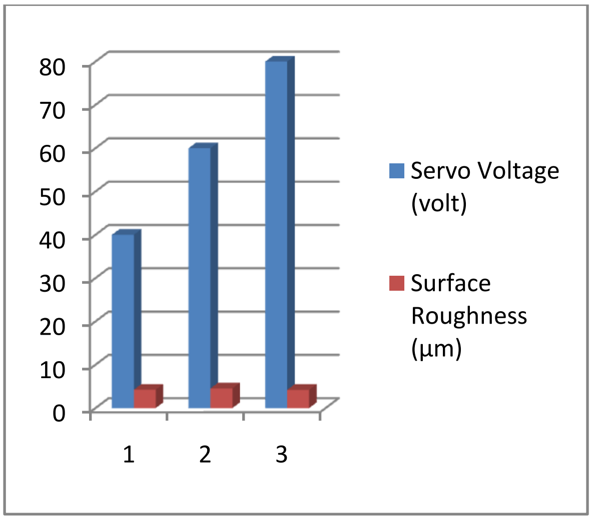

Figure 6: (d)

Figure 6: (a, b, c, d) Surface roughness variation at different input parameters

It is clear from table (VIII & IX) that effectiveness rank of frequency of vibration on Surface roughness is 1st. It means that its affects surface roughness more than pulse on time, servo-voltage and pulse off time respectively. The present experiment aim is to achieve the minimum surface roughness on Wire EDM. Table XIII shows that the minimum surface roughness i.e. 3.28 µm achieved at parameters (frequency of vibration= 115 Hz, pulse on time= 102 machine unit, pulse off time= 60 machine unit and servo voltage= 80 volt).

So Optimum parameters for which surface roughness is optimize for bright mild steel 1045 given as follows;

Frequency of vibration (F) : 115 Hz
Pulse on Time (Ton) : 102 machine unit
Pulse off Time (Toff) : 60 machine unit
Servo Voltage (SV) : 80 volt

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