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Optimization of Machining Parameters on quality characteristics in Wire-EDM process

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Abstract

l (HSS) on material removal rate (MRR) in Wire-EDM process. The investigated machining parameters are pulse peak current, pulse-ON time, Pulse-OFF time, wire feed, wire tension (WT) and flushing pressure. Analysis of variance (ANOVA) is used to analyze the machining variables affecting the MRR. The results show that pulse peak current, pulse- ON time and flushing pressure are the significant parameters to maximize the MRR. After analysis, the predicted optimal value of MRR is 0.0249 g/min. The surface morphology of M-2 HSS is also examined by scanning electron microscope (SEM) which explores the necessity to optimize the MRR in order to get better surface texture after the machining.

1. Introduction

Wire-cut electrical discharge machine (WEDM) is an indispensable process for machining and shaping hard, fragile and difficult-cutting in the tool and die industry process, which has a thin wire as an electrode transforms electrical energy into thermal energy for removing work material [1]. The movement of the wire is controlled by CNC technology. WEDM is growing at highly accelerated rate owing to its capability of achieving great dimensional accuracy, surface finish and contour generation features. WEDM provides the best alternative, sometimes the only alternative, for machining conductive, exotic and hard to machine material with the scope of generating intricate shapes and profile. Due to its widespread applicability in industry, manufacturing engineers require a reliable model for the prediction of output performance of this process [2].

2. Literature Survey

Wire-EDM process is described by various models in the literature. The research on WEDM involves the optimization of the process parameters surveying the influence of the various factors which affect the machining performance and productivity. In the WEDM, the rough cutting operation is a challenging one because improvement of more than one machining performance measures viz. MRR, surface finish, and cutting width (kerf) are sought to obtain a precision work [3]. Mustafa Ilhan Gookler and Alp Mithat Ozanozgii [4] performed an experiment in order to investigate the effects of cutting parameters on surface roughness for 1040, 2379, and 2738 steel materials in the WEDM process. A semi-empirical modal of the MRR on the work and tool for various materials have been established by employing dimensional analysis based upon pertinent process parameters such as pulse peak current, pulse duration, electric polarity and the properties of materials and then verified by making use of the standard Taguchi method in the WEDM process [5]. Ko-Ta Chiang and Fu-Ping Chang [6] presented an effective approach for the optimization of the WEDM process of Al_2O_3 particle reinforced material (6061 alloy) with multiple performance characteristics such as MRR and surface roughness (SR) with considering the machining parameters namely the cutting radius of work piece, on-time of discharge, off-time of discharge, arc on time of discharge, arc off time of discharge, servo voltage, wire feed and water flow based on the grey relational analysis. K. Kanlayasiri and S. Boonmung [7] investigated the effects of machining variables on the SR of newly developed cold die steel DC53 using WEDM process. Analysis of variance (ANOVA) technique was used to find out optimum machining variables affecting the SR and results show that pulse-on time and pulse peak current are significant variables. The application of the fuzzy logic analysis coupled with Taguchi method is used to optimize the precision and accuracy of the high-speed

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electrical discharge machining process and analysis of variance (ANOVA) is also employed to identify factor (pulse time, duty cycle and peak value of discharge current) as the most important parameters and factors powder concentration in dielectric fluid and powder size are found to have relatively weaker impact on the process design of the high-speed EDM [8]. To enhance the speed and stability of EDM process, larger discharge current is applied and aluminium (Al) powder is added into the working fluid throughout the experiment and Taguchi dynamic approach coupled with proposed ideal function model is used to optimize a high-speed EDM process for high machining precision and accuracy. ANOVA is used to account the experimental error and also revealed that the powder related factors contribute slightly to the functional variation in the high-speed EDM process [9]. Jin yuan et al. [1] discussed the development of reliable multi-objective optimization based on Gaussian Process Regression (GPR) to optimize the high-speed wire-cut electrical discharge machining (WEDM-HS) process, considering mean current, on-time and off-tome of input features and MRR and SR as output responses. S. Sarkar et al. [2] discussed the trim cutting operation of γ-titanium aluminide material by WEDM and developed a second order modal of surface roughness, dimensional shift and cutting speed using response surface methodology (RSM). The trim machining condition cutting operation has been optimized for a given machining conditions by desirability function approach and Pareto optimization algorithm and observed that performance of the developed Pareto optimization algorithm is superior to desirability function approach.

In many machining processes, material removal rate is the important machining characteristics that play a very critical role in determining the quality of the engineering components. It becomes more desirable to produce higher material removal rate during the machining.

The objective of this paper is to study the main influencing factors among the controllable parameters on material removal rate of the material. The name of chosen control parameters are pulse peak current, pulse ON time, pulse OFF time, wire feed, wire tension and flushing pressure of dielectric fluid. To optimize the machining parameters for MRR, the experiment is planned according to Taguchi's L27 orthogonal array. M2-HSS is selected as work material for experiment on 4-axes sprint cut CNC WEDM machine. The selection of HSS as a work material is worthwhile due to versatilities of its uses such as manufacturing of various cutting tool: taps, drills, milling cutter, tool bits, gear cutter, saw blades etc., though usage of punches and dies is increasing. High speed steel is used to make fine hand tools where relatively good toughness at high hardness is coupled with high abrasion resistance. It is also suitable for low speed applications requiring a durable sharp edge such as files, chisels, and hand plane blades

3. Selection of levels of machining parameters

There are several stages during the machining such as a rough cut, a rough cut with finishing and a finishing stage in the WEDM. In the rough cut with finishing stage, the MRR is primary important and is the most challenging process. Optimum levels of machining parameter are required to achieve desired results during this machining process. The machining parameters chosen for the experiment were pulse peak current, pulse duration (T_{ON}), pulse-off time (T_{OFF}), wire feed, wire tension and flushing pressure. The levels of selection of machining parameters were chosen based on conducting the pilot tests on the WEDM. A pilot experimentation using one-factor-at-a-time approach was conducted to identify feasible ranges of process parameters. On the basis of pilot experimentation, the ranges and subsequently the levels of machining parameters were chosen as shown in Table 1.

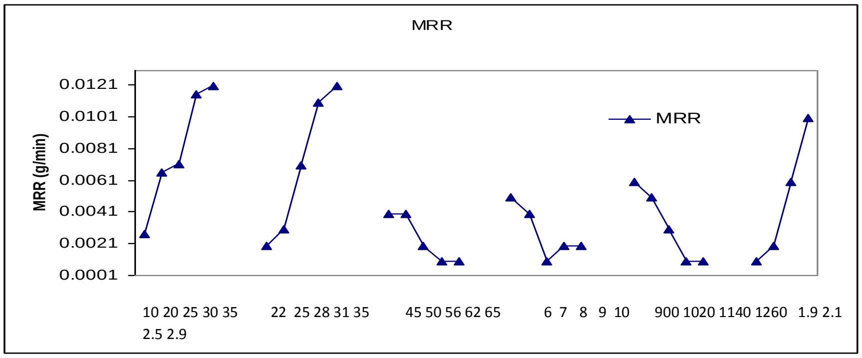

Fig: 1. Pilot test for

Table: 1. Selection of machining parameters

Control factors	Symbols	Level			Unit
		I	II	III	
Pulse peak current	A	10	20	30	Amp
Pulse-on time(T_{ON})	B	25	28	31	µs
Pulse-off time (T_{OFF})	C	50	56	62	µs
Wire Feed (WF)	D	7	8	9	m/min
Wire Tension (WT)	E	1020	1140	1260	G
Flushing pressure	F	2.1	2.5	2.9	Kg/cm^2

Table: 2. Fixed Parameters of WEDM

1	Wire	Zinc –coated copper wire of 0.25mm
2	Shape of work piece	Rectangular piece of 230x25x12 mm^3
3	Location of work piece on working table	At the centre of the table
4	Angle of cut	Vertical
5	Pulse peak voltage (VP)	12 volt
6	Spark gap voltage (SV)	20 volt
7	Servo Feed (SF)	15 mm/min
8	Cutting Speed (CS %)	100%
9	Temperature of dielectric	28º C
10	Conductivity of dielectric fluid	20 mho

4. Optimization Technique

In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly and at low cost. The Taguchi method uses a special design of orthogonal arrays to study the entire process parameter space with a small number of experiments only. A loss function is then defined to calculate the deviation between the experimental value and the desired value. Taguchi recommends the use of loss function to measure the performance characteristics deviating from the desired value. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio.

The loss function (L) for objective of HB (higher the better) is defined as:

$$L_{HB} = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{MRR}^{2}} \qquad (1)\ \ [3]$$

Where, y_{MRR} indicates the response of metal removal rate and 'n' indicates the number of trials in each experiment.

The S/N ratio as a logarithmic transformation of the loss function can be calculated as:

$$S/N \text{ ratio for MRR} = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{MRR}^{2}} \right)$$

(2) [3]

ANOVA is a statistically based, objective decision-making tool for detecting any differences in average performance of groups of items tested [10]. It is elaborated in [8] that ANOVA is performed to identify the process parameters of wire-EDM that significantly affect the multiple performance characteristics. An ANOVA table consists of sums of squares, corresponding degree of freedom, the F-ratio corresponding to the ratios of two mean squares, and the contribution proportions from each of the control factors. These contribution proportions can be used to assess the importance of each factor for the interested multiple performance characteristics (MPCs). The total sum of squares, SS_T, in the ANOVA is:

$$SS_T = \sum_{i=1}^{n} \left(MPCI_i - \overline{MPCI} \right)^2 \qquad (4)$$

Where $MPCI_i$ is the interested MPCIs (multiple performance characteristics indices) response of the ith trial, $\overline{MPCI}$ is the overall average of the interested MPCIs responses, and n is the number of trials. SS_K, the sum of squares of the tested control factors k, where k = A, B ... F, can be calculated as:

$$SS_k = m_k \left[\sum_{j=1}^{m_k} \left(MPCI_{k_j} - \overline{MPCI} \right)^2 \right] \qquad (5)$$

Where $MPCI_{k_j}$ is the average response for the jth level of factor k. The estimated variance of factor k, MS_K, is the ratio of SS_K to its degree of freedom (DOF), and the estimated variance of random error is the so-called mean squared error, or MS_E, which is the ratio of SS_E (sum of squares of error) to its degree of freedom. Then, the F-ratio is simply the ratio of MS_K

to MS_E, the contribution proportion of factor ‘P’, in percentage, is:

Contribution percentage of factor (6)

$$p = \left[\frac{SS_k - (DOF \times SS_E)}{SS_T} \right] \times 100\,\%$$

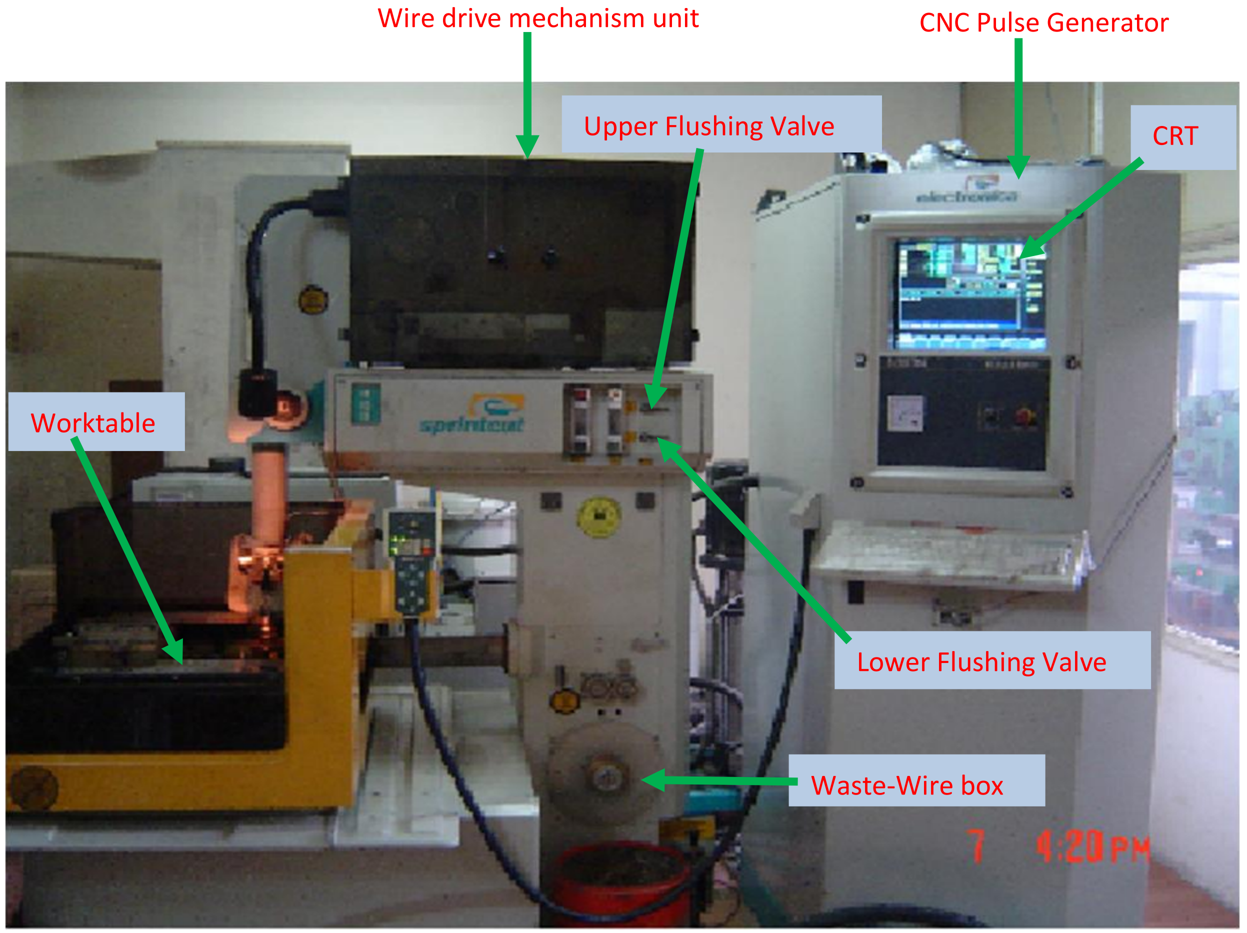

Fig: 2. Experimental Set-up

In this experiment, both the allocation of the experimental material (work-piece) and the order in which the individual trials of the experiment performed are to be randomly determined because the observations or errors are to be independently distributed random variables in ANOVA. Randomization usually makes this assumption valid. By properly randomizing the experiment, the effect of extraneous factors or confounding variables that may be present are averaged out. Confidence level of 95% (α = 0.05) is used throughout analysis of the experiment. Only main effects and second-order interactions are included in the analysis while high order interactions are neglected.

5. Experimental Set-up

The experiment was performed on sprint cut high precision 4-axes CNC Wire-EDM and M2-HSS (composition C-0.8%, Si-0.40%, Mn-0.40%, Cr-4.30%, W-6.5%, V-2.00%, Mo-5.00% and balance Fe) was used as work material. The pulse power supply was used a transistor controlled RC circuit. ELPULS-40 ADLX pulse generator and EMT 100W-% CNC controller was used in the WEDM. The machine tool comprised a main work table (called as X-Y table), an auxiliary table (called as U-V table) and a wire drive mechanism. The work-piece was mounted and clamped on the main work table. A zinc coated brass wire of 0.25 mm diameter was used as a tool electrode. A travelling wire continuously was fed from wire feed spool for travelling through the work-piece and went finally to the waste-wire box. Along its travelling path, the wire was supported under tension between a pair of wire guides which were disposed on both sides of the work-piece.

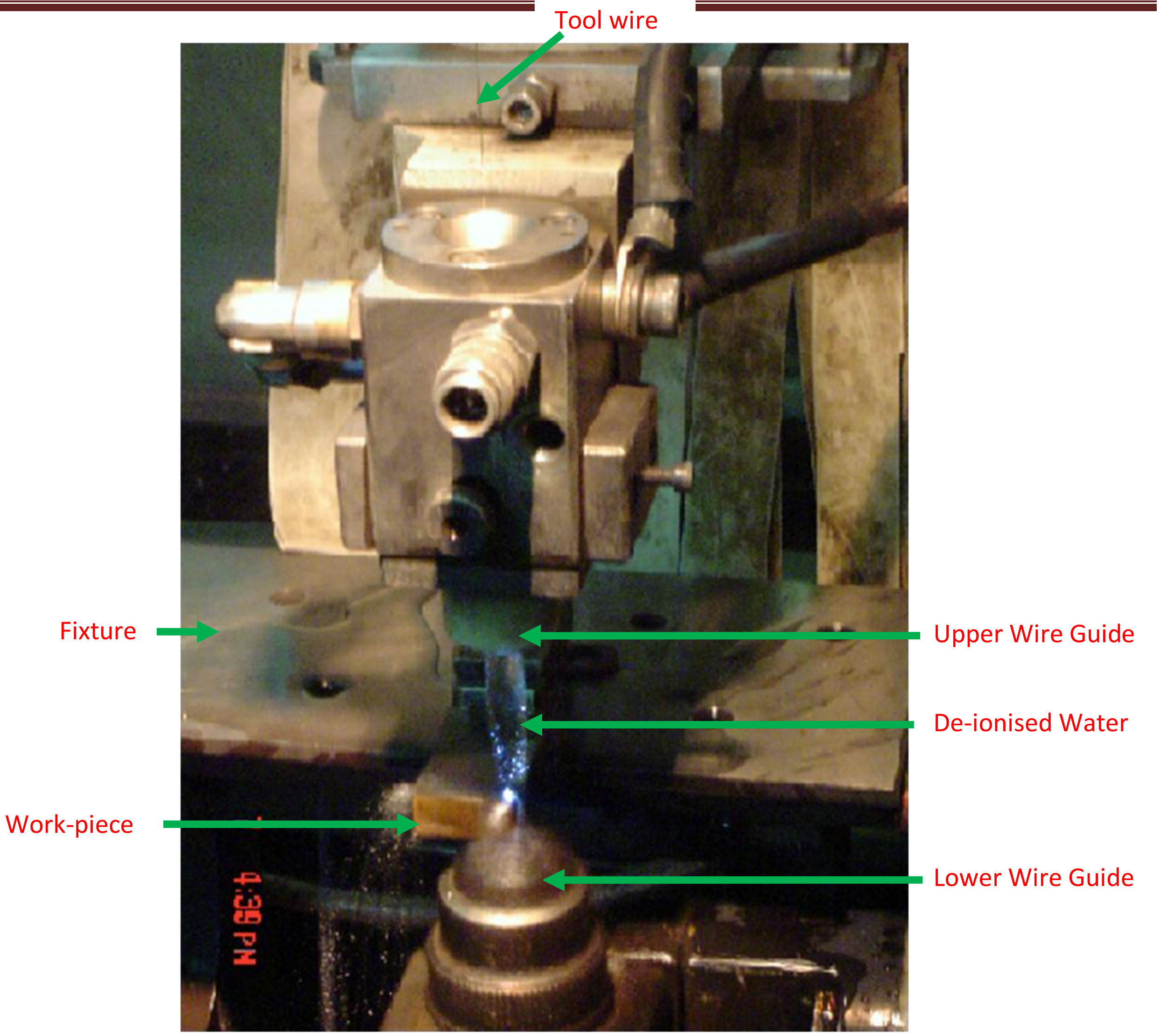

Fig: 3. Machine Tool of WEDM

Lower wire guide was stationary whereas the upper wire guide was supported by the U-V table. As the machining proceeds, the work table carrying the work-piece was displaced transversely along a predetermined path which was stored in the controller. Figure 2 and 3 indicate the experimental set-up and Machine tool of WEDM.

6. Experimentation

The design of experiment was based on Taguchi's L27(3^{13}) orthogonal array in which twenty seven rows corresponding to the number of experiments with 13 columns for the control parameters at three levels, as shown in table 3. The influence of six control parameters A, B, C, D, E and F with the interaction effects of AxB, AxC and AxF was considered on the behaviour of MRR of the material. The experimental results obtained using L27 orthogonal array were further transformed into a signal-to-noise ratio (S/N ratio). The experiments were conducted for each combination of rows as per selected in L_{27} orthogonal array and number of experiments for each observation are three, i.e. the number of replication are three.

The material removal rate (g/min) was calculated by weight difference of the specimen before and after machining using a type E-12005 sartorius precision scale (precision= 0.1mg). In this machining, the height of the work piece was chosen to be 25mm so that cross-section of the cut made was 12 mm x 25 mm for each experiment.

Table 3 L27 orthogonal array

	A	B	(AxB)1	(AxB)2	C	(AxC)1	(AxC)2	F	(AxF)1	(AxF)2	D	E	
Trial no	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

7. Results and discussion

The MRR of WEDM process mainly depends on the electrical conductivity and melting temperature of the work material while melting temperature basically depends on the energy content of a single spark discharge. The energy content of a single discharge can be expressed as a product of pulse peak current and pulse on time. The higher value of discharge energy causes wire breakage resulting intermittency in the machining that is not favourable. Therefore, to improve the overall cutting efficiency, the balanced values of T_{OFF} and T_{ON} should be chosen. Because if value of T_{OFF} is less than the defined current time, the value of T_{ON} will be higher due to which more number of discharges occurred during the machining resulting very high cutting rate and finally breakage of tool wire. In this study, a minimum value of pulse peak current was selected 10 Amp to achieve a remarkable value of MRR during machining. The maximum value of pulse peak current was selected 30 Amp that was the maximum limit of WEDM for super finishing operation. However, very high value of T_{OFF} lowers the pulse duty factor and also reduces the average gap current. The travelling wire becomes thin and brittle due to continuous spark erosion. Therefore, it is always desirable to set the maximum value of wire feed rate but practically it should be in optimum limit due to having higher cost of brass wire pool. The deflection in the wire is caused due to spark induced reaction forces and water pressure. Therefore, it is a need of tension in the wire which is a gram equivalent load with which the continuous fed wire is kept under tension so that it remains straight between the wire guides. The value of tension in the wire increases with increasing the thickness of the work piece. To obtain the continuous machining with higher value of cutting speed, the optimum value of flushing pressure is also required with consideration of thickness of work piece. The de-ionised water is used as a dielectric medium for flushing because it permits widening of spark gap to minimize short circuit resulting high cutting speed. Water gives more benefits as compare to other fluids in terms of good cooling effect, non-flammable and non-toxicity.

After conducting all experiments, decision must be made concerning which parameter affects the performance of the WEDM. These decisions were made with the assistance of an analytical technique analysis of variance (ANOVA). The results are obtained from the experiments as shown in table 4.

Using these experimental results, the effect of each machining parameter on MRR can be analysed in fig. 4. These figures illustrate the average values of the performance characteristics for each parameter at different levels. The average values of main effects and S/N ratios effect for MRR were obtained and reported in tables 6 and10. The figure 4 refers to concentrate highly on parameters A, B and F for indicating large variation. Therefore, parameters A, B and F are playing vital roll to optimize the MRR. The parameter values at levels A_3, B_3 and F_3 for MRR are the best choice in terms of both mean response and variation.

Table: 4. Experimental results of MRR at super finishing mode of machine using L_{27} orthogonal array

Exp No	A	B	C	D	E	F	Mean of MRR(g/min)	S/N ratio(db)
1	1	1	1	1	1	1	0.005657	-44.9483
2	1	1	2	2	2	2	0.004296	-47.3387
3	1	1	3	3	3	3	0.003641	-48.7756
4	1	2	1	3	3	2	0.006115	-44.2721
5	1	2	2	1	1	3	0.005106	-45.8384
6	1	2	3	2	2	1	0.003801	-48.402
7	1	3	1	2	2	3	0.006794	-43.3575
8	1	3	2	3	3	1	0.004579	-46.7846
9	1	3	3	1	1	2	0.003827	-48.3428
10	2	1	1	1	3	1	0.011808	-38.5565
11	2	1	2	2	1	2	0.01216	-38.3013
12	2	1	3	3	2	3	0.012127	-38.3249
13	2	2	1	3	2	2	0.025234	-31.9603
14	2	2	2	1	3	3	0.01503	-36.4608
15	2	2	3	2	1	1	0.012142	-38.3142
16	2	3	1	2	1	3	0.022471	-32.9676
17	2	3	2	3	2	1	0.016878	-35.4536
18	2	3	3	1	3	2	0.01225	-38.2373
19	3	1	1	1	2	1	0.020721	-33.6718
20	3	1	2	2	3	2	0.013831	-37.1829
21	3	1	3	3	1	3	0.010432	-39.6326
22	3	2	1	3	1	2	0.022044	-33.1342
23	3	2	2	1	2	3	0.017128	-35.3259
24	3	2	3	2	3	1	0.013749	-37.2346
25	3	3	1	2	3	3	0.023033	-32.753
26	3	3	2	3	1	1	0.015018	-36.4678
27	3	3	3	1	2	2	0.013675	-37.2815

ANOVA was performed on raw data as well as S/N data. ANOVA of raw data and S/N data for MRR is shown in Table 5 and Table 8 which describe that pulse peak current and pulse-on time have produced higher impact on MRR. ANOVA of raw data indicates that the selected process parameters A3, B3, F3 for MRR significantly affect the mean values of MRR. Table 7 and Table 9 indicate pooled ANOVA of raw data and S/N data at 95% confidence level for MRR.

The percentage (%) contribution of parameters affecting mean values of MRR, i.e. pulse-peak current (53.91%), pulse-on time (20.58%) and flushing pressure (16.3%), indicates the influence of pulse-peak current is more than the other parameters. ANOVA of S/N ratio also suggests the same inference to select the process parameters for MRR. Jin Yuan et al.[1], S.S. Mahapatra et al.[3] and Ko-Ta Chiang et al. [6] also verified that the pulse peak current, pulse-on-time and flushing pressure are the main influencing factors during the WEDM.

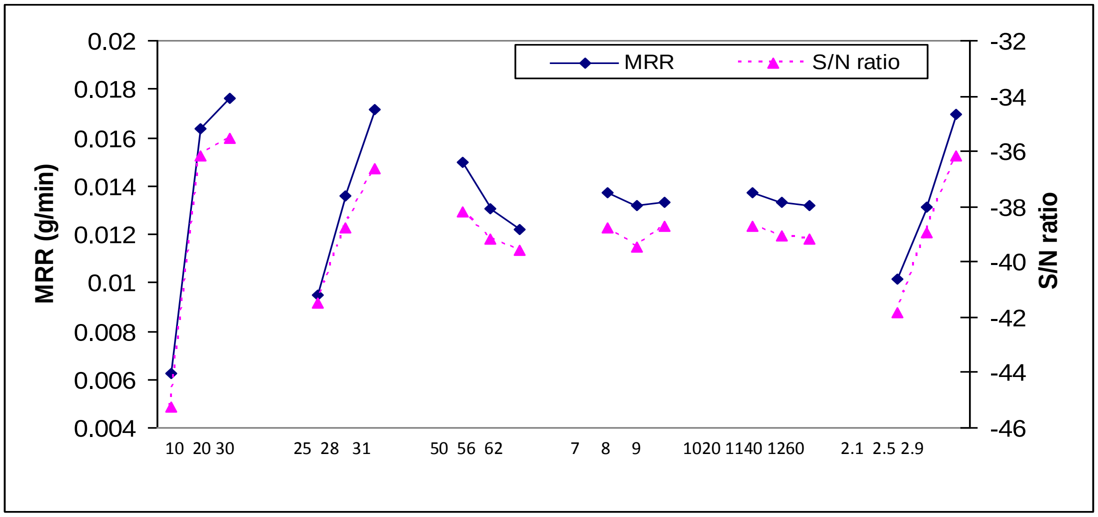

Fig: 4 Effect of control factors on MRR

Table: 5. AVOVA for MRR (Main Effect)

	Factors	DOF	Sum of squares	Variance	F-Ratio	Percent
1	Pulse Current	2	0.000695	0.000348	63.18182	53.14
2	TON	2	0.000266	0.000133	24.18182	19.81
3	TOFF	2	0.000037	1.85E-05	3.363636	2.02
4	Wire Feed	2	0.000001	5E-07	0.090909	0
5	Wire Tension	2	0.000001	5E-07	0.090909	0
6	Flushing Pressure	2	0.000211	0.000106	19.18182	15.54
7	(AxB)1	2	0.000028	0.000014	2.545455	1.32
8	(AxB)2	2	0.000023	1.15E-05	2.090909	0.93
9	(AxC)1	2	0.0000004	2E-07	0.036364	0
10	(AxC)2	2	0.00001	0.000005	0.909091	0
11	(AxF)1	2	0.000003	1.5E-06	0.272727	0
12	(AxF)2	2	0.0000001	5E-08	0.009091	0
	Other/Error	2	0.000011	5.5E-06		7.24
	Total	26	0.001287			100

Table: 6. Main Effect for MRR

	Factors	Level 1	Level 2	Level 3
1	Pulse Current	0.00628	0.016344	0.017626
2	TON	0.009486	0.013594	0.017169
3	TOFF	0.014986	0.013081	0.012183
4	Wire Feed	0.013689	0.01322	0.013341
5	Wire Tension	0.013716	0.013353	0.013181
6	Flushing Pressure	0.01015	0.013126	0.016974
7	(AxB)1	0.014534	0.013649	0.012065
8	(AxB)2	0.014714	0.012734	0.012802
9	(AxC)1	0.013562	0.01345	0.013237
10	(AxC)2	0.012943	0.013	0.014307
11	(AxC)1	0.013357	0.013039	0.013853
12	(AxC)2	0.013475	0.01345	0.013324

Table: 7. Pooled ANOVA 95% for MRR (Main Effect)

	Factors	DOF	Sum of squares	Variance	F-Ratio	Percent
1	Pulse Current	2	0.000695	0.000348	631.8182	53.91
2	TON	2	0.000266	0.000133	241.8182	20.58
3	TOFF	(2)	(0.000037)		Pooled	0
4	Wire Feed	(2)	(0.000001)		Pooled	0
5	Wire Tension	(2)	(0.000001)		Pooled	0
6	Flushing Pressure	2	0.000211	0.000106	191.8182	16.3
7	(AxB)1	(2)	(0.000028)		Pooled	0
8	(AxB)2	(2)	(0.000023)		Pooled	0
9	(AxC)1	(2)	(0.0000004)		Pooled	0
10	(AxC)2	(2)	(0.00001)		Pooled	0
11	(AxF)1	(2)	(0.000003)		Pooled	0
12	(AxF)2	(2)	(0.0000001)		Pooled	0
	Other/Error	20	0.000011	5.5E-07		9.21
	Total	26	0.001287			100

Table: 8. ANOVA for MRR (S/N ratio)

	Factors	DOF	Sum of squares	Variance	F-Ratio	Percent
1	Pulse Current	2	536.613	268.3065	205.44	61.88
2	TON	2	106.77	53.385	40.8767	12.07
3	TOFF	2	8.898	4.449	3.4065	0.72
4	Wire Feed	2	3.008	1.504	1.15	0.04
5	Wire Tension	2	0.939	0.4695	0.35	0
6	Flushing Pressure	2	147.428	73.714	56.44	16.78
7	(AxB)1	2	1.632	0.816	0.6248	0
8	(AxB)2	2	1.654	0.827	0.6332	0
9	(AxC)1	2	0.657	0.3285	0.2515	0
10	(AxC)2	2	2.711	1.3555	1.03	0.01
11	(AxF)1	2	27.0175	13.50875	10.34	2.82
12	(AxF)2	2	22.885	11.4425	8.76	2.34
	Other/Error	2	2.612	1.306		3.34
	Total	26	862.826			100

Table: 9. Pooled ANOVA 95% for MRR (S/N ratio)

	Factors	DOF	Sum of squares	Variance	F-Ratio	Percent
1	Pulse Current	2	536.613	268.3065	2054.41	62.16
2	TON	2	106.77	53.385	408.76	12.34
3	TOFF	(2)	(8.898)		Pooled	0
4	Wire Feed	(2)	(3.008)		Pooled	0
5	Wire Tension	(2)	(0.939)		Pooled	0
6	Flushing Pressure	2	147.428	73.714	564.42	17.05
7	(AxB)1	(2)	(1.632)		Pooled	0
8	(AxB)2	(2)	(1.654)		Pooled	0
9	(AxC)1	(2)	(0.657)		Pooled	0
10	(AxC)2	(2)	(2.711)		Pooled	0
11	(AxF)1	(2)	(27.0175)		Pooled	0
12	(AxF)2	(2)	(22.885)		Pooled	0

	Other/Error	20	2.612	0.1306		8.45
	Total	26	862.826			100

Table: 10. S/N ratio Effect for MRR

	Factors	**Level 1**	**Level 2**	**Level 3**
1	Pulse Current	-45.27	-36.16	-35.5
2	TON	-41.49	-38.79	-36.63
3	TOFF	-38.19	-39.18	-39.55
4	Wire Feed	-38.79	-39.44	-38.69
5	Wire Tension	-38.72	-39.03	-39.17
6	Flushing Pressure	-41.86	-38.92	-36.14
7	(AxB)1	-38.69	-38.93	-39.29
8	(AxB)2	-38.73	-39.31	-38.87
9	(AxC)1	-38.75	-39.04	-39.12
10	(AxC)2	-39.04	-39.32	-38.56
11	(AxF)1	-40.09	-39.15	-37.67
12	(AxF)2	-40.19	-38.76	-37.97

In Tables 9 the error percent (%) contribution of MRR 8.45% is very small (less than 15%). Therefore, it is proved that no important factors are omitted during the experiment and there is no opportunity for the further improvement [10].

4.1 Estimation of optimum quality characteristics [10]

After analysis, the selected significant factors for MRR are A3, B3, and F3.The optimum value of MRR can be evaluated as:

$$\mu_{MRR} = \bar{A}_3 + \bar{B}_3 + \bar{F}_3 - 2\bar{T}_{MRR} \quad (7)$$

Where μ_{MRR} is mean values of MRR. $\bar{T}_{MRR}$ is the grand average value of MRR=0.0134 g/min. $\bar{A}_2, \bar{A}_3, \bar{B}_3, \bar{C}_1, \bar{D}_1, \bar{F}_1, \bar{F}_3$ are average values of MRR at selected levels.

$$\mu_{MRR} = 0.0249$$

The confidence interval (CI) for the predicted result can be calculated this given equation

$$CI = \sqrt{F_\alpha(1, f_e) V_e \left[\frac{1}{\eta_{eff}} + \frac{1}{R}\right]} \quad (9)$$

Where

$F_\alpha(1, f_e) =$ The F-ratio at a confidence level of (1-α) against DOF=1 and error DOF (f_e)

$V_e =$ Error variance

R= sample size for confirmation experiment = 3

η_{eff} is the effective number of replications:

$$\eta_{eff} = \frac{N}{1+[Total\ DOF \text{ in the estimation of mean}]}$$

(10)

N= Total number of results= 27*3=81

Using following values for MRR:

Total degree of freedom in the estimation of mean = 6

η_{eff} =11.51, $F_{0.05}$ (1, 20) = 4.35 (tabulated)

The confidence interval = CI = ± 0.001.

For 95% confidence interval, the predicted optimum MRR is 0.0239 < μ_{MRR} < 0.0259 g/min.

8. Confirmation Experiment

The confirmation experiment is the final step to validate the conclusion drawn from the analysis phase of Taguchi's parameter design approach. The optimum conditions are set for the significant factors and a selected number of tests are conducted under these specifically selected conditions. The average of results of the confirmation experiment is compared with the anticipated average of selected factors under selected levels. Three confirmation experiments were conducted at the optimum levels of the process parameters recommended by the analysis phase. The average values of MRR at the optimal setting of process parameters of WEDM process was found to be 0.0217g/min shown in table 11. These results were within 95% confidence interval of the predicted optima of quality characteristics. Hence, the optimal settings of the process parameters, as predicted for MRR in the analysis, can be implemented.

Table 11 Result of the confirmation experiment for MRR

	Optimal machining parameters	
	Prediction	Experimental
Levels	$A_3B_3C_1D_1E_1F_3$	$A_3B_3C_1D_1E_1F_3$
MRR(g/min)	0.0249	0.0217

9. Surface Morphology

To observe the surface characteristics and type of material removal mechanism of the machined work-pieces, there was a need of SEM micrographs. Having seen these SEM micrographs, it is obvious that the machined surfaces are covered with re-solidified layer formation films. The topography of the machined surfaces concludes that there are many droplets on the wire-EDMed surface, which indicates that the material removal mechanism (MRM) is most probably melting and evaporating. SEM micrographs show that a foamy and porous layer is formed after machining. The basic cause of foamy structure is the generation of many gas bubbles during machining; the generations of bubbles are clearly visible. The oxidation and decomposition of HSS induced by the thermal energy (temperature10, 000ºC-12, 000ºC during sparking) is the main cause to form such types of foamy and porous structure on the machined surface in the WEDM process. However, the oxidation and decomposition reactions may increase the material removal rate of HSS by WEDM process in de-ionized water and generate a large amount of gas responsible for the porous structure of the machined surface.

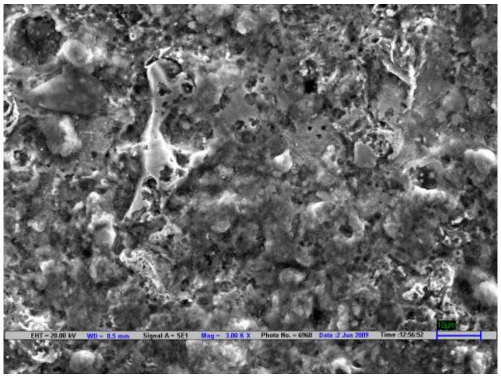

Fig: 5. Experiment No.13
Maximum MRR=0.0252 g/min at pulse current 20Amp, pulse-on time 28µs, Flushing pressure 2.5 Kg/cm^2

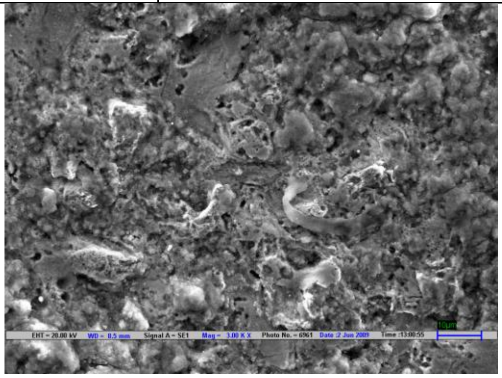

Fig: 6. Confirmation Experiment
MRR= 0.0217 g/min at pulse current 30Amp, pulse-on time 31µs, Flushing pressure 2.9 Kg/cm^2

In experiment number 13, the higher value of the product of pulse-peak current and pulse-on time (20 Amp*28µs) was taken by which maximum MMR (=0.0252g/min) was obtained. The SEM micrographs of machined surface obtained in experiment 13 and confirmation experiment are shown in fig 5 and fig 6.

10. Conclusion

It is observed that the S/N ratio with Taguchi's parameter design is a simple, systematic, reliable and more efficient tool for optimizing multiple performance characteristics of WEDM process parameters. The main conclusions of this study may be summarized as follows:

1. Pulse peak current and Pulse-on time (T_{ON}) and flushing pressure have been found to play significant role in rough cutting operations for maximization of MRR.
2. The fluctuation in electrical parameters (Pulse-peak current and pulse-on time) beyond and below the optimal setting are responsible to decrease the MRR.
3. The statistical influence of pulse-peak current on MRR is more than the effect of other parameters.
4. The predicted optimal range of MRR at 95% confidence level was:
   $0.0239 < \mu_{MRR} < 0.0259$ g/min.
5. The study of SEM micrographs conclude that besides the WEDM material removal mechanism such as melting or evaporation, other mechanism can also occur such as the oxidation and decomposition of the base material M-2 HSS.

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