A PARAMETRIC OPTIMIZATION & EXPERIMENTAL ANALYSIS OF WIRE-EDM ON HASTELLOY-C22 BY TAGUCHI METHOD

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ABSTRACT

WEDM is a one of the non-conventional machining processes used for machining complex shape components and hard materials to produce intricate shapes on the wide variety of materials. With the increasing demands of high surface finish and high rate of MRR of complex shape geometries, WEDM machining process is now being replaced by non-traditional machining processes. According to this paper, optimization of wire electrical discharge machining (WEDM) process parameters such as T_{ON}*, Peak Current (Ip), Servo voltage (SV) and wire tension (WT) to yield maximum material removal rate (MRR) and minimum surface roughness (SR) of Nickel based alloy, Hastelloy C-22, a very high temperature, corrosion resistant alloy. The machining experiments were carried out according to the Taguchi parametric design (L9). Analysis of variance (ANOVA) was used to find the significance of each process parameter. Optimal results have been verified through confirmation experiments. The results indicate that* T_{on} *is the most significant factor influencing the MRR and Peak Current (Ip) is most significant factor influencing the SR followed by Servo voltage (SV) and wire tension (WT). After observing the significant factors for MRR and SR, a multiple response optimization technique (Assignment of Weights) is applied in this paper for getting optimal result for both MRR and SR.*

Keywords- Wire EDM, Hastelloy C-22, Taguchi, Anova, Assignment of weights.

I. INTRODUCTION

The Wire Electric Discharge Machining (WEDM) is a variation of EDM and is commonly known as wire-cut EDM or wire cutting. In this process, a thin metallic wire is fed on-to the work piece, which is submerged in a tank of dielectric fluid such as deionized water. This process can also cut plates as thick as 300mm and is used for making punches, tools and dies from hard metals that are difficult to machine with other methods. The wire, which is constantly fed from a spool, is held between upper and lower diamond guides. The guides are usually CNC-controlled and move in the x–y plane. In the wire-cut EDM process, water is commonly used as the dielectric fluid. Filters and de-ionizing units are used for controlling the resistivity and other electrical properties. Wires made of brass are generally preferred. The water helps in flushing away the debris from the cutting zone. The flushing also helps to determine the feed rates to be given for different thickness of the materials. The schematic of wire cut EDM is shown in Figure 1.1.1 [1].

The WEDM process requires lesser cutting forces in the material removal; hence it is generally used lower residual stress in the work pieces desired. If the energy/power per pulse is relatively low, little changes in mechanical properties of the material are expected due to these low residual stresses. The material which are not stress-relieved earlier can get distorted in the machining process. The selection of process parameters is very crucial, as in some cases the workpieces undergoes significant thermal cycles that can be severe. These thermal cycles can form recast layers and induce residual tensile stresses on the workpiece which are undesired. [2]

1.1 Mechanism of material removal in WEDM- In the WEDM process, the motion of wire is slow. It fed the programmed path and material is removed from the workpiece accordingly. Electrically conductive materials are cut by the WEDM process by the electro-thermal mechanisms. Material removal takes place by a series of discrete discharge between the wire electrode and workpiece in the presence of a di-electric fluid. The dielectric fluid gets ionised in between the tool-electrode gap thereby creating a path for each discharge. The area wherein discharge takes place gets heated to very high temperatures such that the surface gets melted and removed. The cut particles (debris) get flushed away by the continuously flowing dielectric fluid.

1.2 Applications of Wire-Cut EDM -Wire EDM is used for cutting aluminium, brass, copper, carbides, graphite, steels, nickel alloy, and titanium. The wire material varies with the application requirements. Example: for quicker cutting action, zinc-coated brass wires are used while for more accurate applications, molybdenum wires are used.

- Aerospace, Medical, Electronics and Semiconductor applications
- Tool & Die making industries.
- For cutting the hard Extrusion Dies
- In making Fixtures, Gauges & Cams
- Cutting of Gears, Strippers, Punches and Dies
- Manufacturing hard Electrodes.
- Manufacturing micro-tooling for Micro-EDM, Micro-USM and such other micromachining applications.

1.3 Process parameters in WEDM- The process parameters that can affect the quality of machining or cutting are as follows:

- Electrical parameters: Peak current, pulse on time, pulse off time and supply voltage and polarity.
- Non- electrical parameters: Wire speed; work feed rate, machining time, gain and rate of flushing.
- Electrode based parameters: Material and diameter of the wire.

1.4 Taguchi methodology- Taguchi techniques are statistical methods developed by Genichi Taguchi to improve the Quality of manufacturing goods. Basically, classical experimental design methods are to complex and not easy to use. A large number of experiments have to be carried out when the number of the process parameter increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments like, L9, L27, L81 etc. of which a suitable array can be selected for a particular design [3].

1.4.1 Steps in Taguchi methodology- Taguchi proposed a standard 8-step procedure for applying his method for optimizing any process:

Step-l: Identify the main function, side effects, and failure mode.

Step-2: Identify the noise factors, testing the conditions, and quality characteristics.

Step-3: Identify the objective function to be optimized.

Step-4: Identify the control factors and their levels.

Step-5: Select the orthogonal array matrix experiment.

Step-6: Conduct the matrix experiment.

Step-7: Analyze the data; predict the optimum levels and the performance.

Step-8: Perform the verification experiment and plan the future action.

1.5 Analysis Of Variance (ANOVA) -Taguchi suggests two different routes to carry out complete analysis of the experimental data. In the first approach, results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis of the raw data. The second approach, which Taguchi strongly recommends, is to use Signal-to-Noise (S/N) ratios for the same steps of the analysis. The S/N ratio is generally represented by η and is a concurrent quality metric linked to the loss function. By maximizing the S/N ratio, the loss associated with the process can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. [4]

1.6 Multiple response optimization technique (Assignment of Weights)- In assignment of weights method, the multi-response problem is converted into a single response problem. Suppose we have two responses in a problem. Let $W1$ be the weight assigned to, say the first response $R1$ and $W2$ be the weight assigned to the second response $R2$. The sum of the weighted response (W) will be the single response, where

$$W = W1R1 + W2R2$$

This (W) is termed Multi Response Performance Index (MRPI). Using this MRPI, the problem is solved as a single response problem. In the multi-response problem, each response can be the original observed data or its transformation such as S/N ratio. In this approach, the major issue is the method of determining the weights. Literature review indicates that several approaches have been used to obtain MRPI.

$$(\text{MRPI})i = W1Y11 + W2Y12 + \ldots + WjYij$$

(MRPI)i = MRPI of the ith trial/experiment

Wj = Weight of the jth response/dependant variable

Yij = Observed data of ith trial/experiment under jth response

2- Literature Review- Here reviews signifies the formulation of the best possible output within a given set of elements or conditions. However it involves various methods such as Taguchi's method which can be applied to find optimum process parameters, ANOVA (analysis of variance) to study performance characteristics, Regression analysis for estimating predicted values of the parameters.

Y.S. Liao, et al. proposed an effective and precise way of determining the appropriate machining parameters based on Taguchi design method and ANOVA which was time effective and cost saving as well. The objective was to achieve shortest machining time whilst at the same time, satisfying the requirements of accuracy and surface roughness. They found that the table feed and Pulse on time have a significant influence on material removal rate, gap voltage and total discharge frequency however, gap width and surface roughness are mainly influenced by pulse on time. Hence larger table feed and a smaller Ton will result in higher value of surface roughness. [5]

Pujari Srinivasa Rao, et al. besides presenting optimal combination of parameters for surface roughness and material removal rate for Aluminum 2014 T6 alloy also developed mathematical models which predicted the SR and MRR with high Regression coefficient value with the help of Optimization of performance measures by hybrid genetic algorithm its results clearly showed that a sacrifice in cutting efficiency is essential for production of Quality Surfaces and vice versa. White layer thickness measurements were made for suggested the combination of parameters whose magnitude or value is relatively high when compared to heavy and other light metals. [6]

Shivkant Tilekar, et al. included effect on kerf width along with surface roughness of Aluminum and mild steel using single objective Taguchi method. both the parameters were measured by surface profilometer and optical microscope respectively. Both kerf width and surface roughness were minimized successfully and process parameters word stated ANOVA showed that in case of kerf width wire feed rate and Spark on times have significant effect on Aluminum and mild steel respectively.[7]

3- Methodology- Taguchi technique is a powerful statistical technique used for analyzing and optimizing the process parameters. The Taguchi analysis uses orthogonal arrays from design of experiments theory to study the influence of a large number of variables on responses with a small number of experiments. In this method, the experimental results are transformed into a signal-to-Noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values [8]. Taguchi classified the quality characteristics into three categories such as Lower the better, Higher the better and Normal the better. The formula used for calculating S/N ratio is as follows.

Lower the better: S/N ratio $(\dot{\eta}) = -10\, log_{10} \frac{1}{n} \sum_{i=1}^{n} y_i^2$

Where y_i = observed response value, n= number of replication.

Normal the better: It is used where the nominal or target value and variation about that value is minimized.

Nominal the better: S/N ratio $(\dot{\eta}) = -10\, log_{10} \frac{\mu^2}{\sigma^2}$

Where μ =mean and σ = variance

Higher the better: It is used where the larger value is desired.

Higher the better: S/N ratio $(\dot{\eta}) = -10 log_{10} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}$

Where y_i = observed response value, n= number of replication.

3.1-Selection of Process Parameters- In this investigation, WEDM parameters such as T_{ON} , Peak Current (I_P), Servo voltage (SV) and Wire tension (WT) were considered. According to Taguchi's design of experiments, for four parameters and three levels L9 Taguchi orthogonal array was selected. The number of factors and their corresponding levels are shown in the Table 3.1.1 and the basic Taguchi L9 (3^4) orthogonal array used for this work.

CODE	VARIABLE	LEVEL 1	LEVEL 2	LEVEL 3
1	Pulse on time (T_{ON}) in μs	110	115	120
2	Peak Current(I_P) in amp	90	120	150
3	Servo Voltage (SV) in volt	25	30	35
4	Wire Tension (WT) in N/mm^2	6	10	14

3.2-Material removal rate (MRR) calculation- The material removal rate has been calculated by using the formula as shown below.

$$MRR = \frac{LBH}{T}$$

Where, L= length of slot (mm), B= Kerf width (mm), H= Height of slot (mm), T= time taken to cut the slot (min). In this experiment L=5mm, H=24mm, kerf width B measured by Tool maker microscope after machining experiment, and T estimated at the time of machining of HastelloyC22.

4- Experimentation- All Experiments were carried out on ELECTRONICA ECO Cut Wire EDM machine, with the work piece as HastelloyC22. The wire used was Zinc Coated Bras wire of diameter 0.25mm. Die-electric fluid used is ionized water. The present work is focused to study the effect of Pulse on time, Peak Current, Servo voltage, wire tension and discharge time on Material removal rate and Surface roughness using design of experiments, Taguchi method and ANOVA analysis is carried out for finding the individual effect of parameters. The dimensions of the work material are of mm after forging. The material was grinded before carrying out experiments on WEDM, to ensure that there are no irregularities on the sheet. After grinding, the dimensions measured are 30×30×24 mm. The Composition of HastelloyC22 is given below.

4.1-Experimental values of Material Removal Rate (MRR) and Surface Roughness- After the calculation of MRR and Surface roughness (measured by SR profilometer), table has been given below:

Table 4.1.1 Experimental values of MRR and SR

Exp. no	Material removal rate (MRR) in mm^3/min	Surface roughness (SR) in µm
1	0.962	0.90
2	1.346	1.35
3	1.522	1.83
4	1.564	1.14
5	1.920	1.54
6	2.641	2.35
7	1.980	1.46
8	3.020	2.12
9	3.241	2.63

5-Result and Discussion-Software MINITAB 15 was used for the design and analysis of experiments to perform the Taguchi and ANOVA analysis. The optimization of process parameters using Taguchi method provides the evaluation of the effect of individual independent parameters on the identified quality characteristics. The statistical analysis of variance (ANOVA) was carried out. Based on the ANOVA, the contribution of each parameter in influencing the variation in quality characteristic was evaluated. The ANOVA also provides an indication of which process parameters are statistically significant.

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5.1- Influence of Process Parameters on MRR-In this investigation, the S/N ratio was chosen according to the criterion, the "larger-the-better" in order to maximize MRR. The S/N ratio for the "larger-the-better" target for all the responses was calculated.

Table 5.1.1 Response Table for Signal to Noise Ratios Larger is better

SN	Parameters	Level 1	Level 2	Level 3
A	T_{ON}	1.964	5.995	**8.582**
B	I_P	3.161	5.949	**7.432**
C	SV	**5.900**	5.56	5.083
D	WT	5.181	5.650	**5.711**

In the present study, MRR of WEDM was analyzed to determine the effect of WEDM process parameters on MRR. The experimental results were transformed into a signal-to-noise (S/N) ratio using the Minitab statistical software. Main effects at all the levels of the chosen parameters are calculated and listed in Table 5.1.1. The main effect for S/N ratio is plotted in Figure 5.1.2. It is observed from Figure 5.1.2 that the MRR is highest at the level 3 of T_{ON}, Highest at the level 3 of $I_{P,}$ Highest at the level 1 of SV and Highest at the level 3 of WT. It is clear that the highest S/N ratio is the optimal level of each process parameter is A3 B3 C1 D3. Therefore, both i.e. T_{ON} at 120, I_P at 150, SV at 25 and WT at 14.

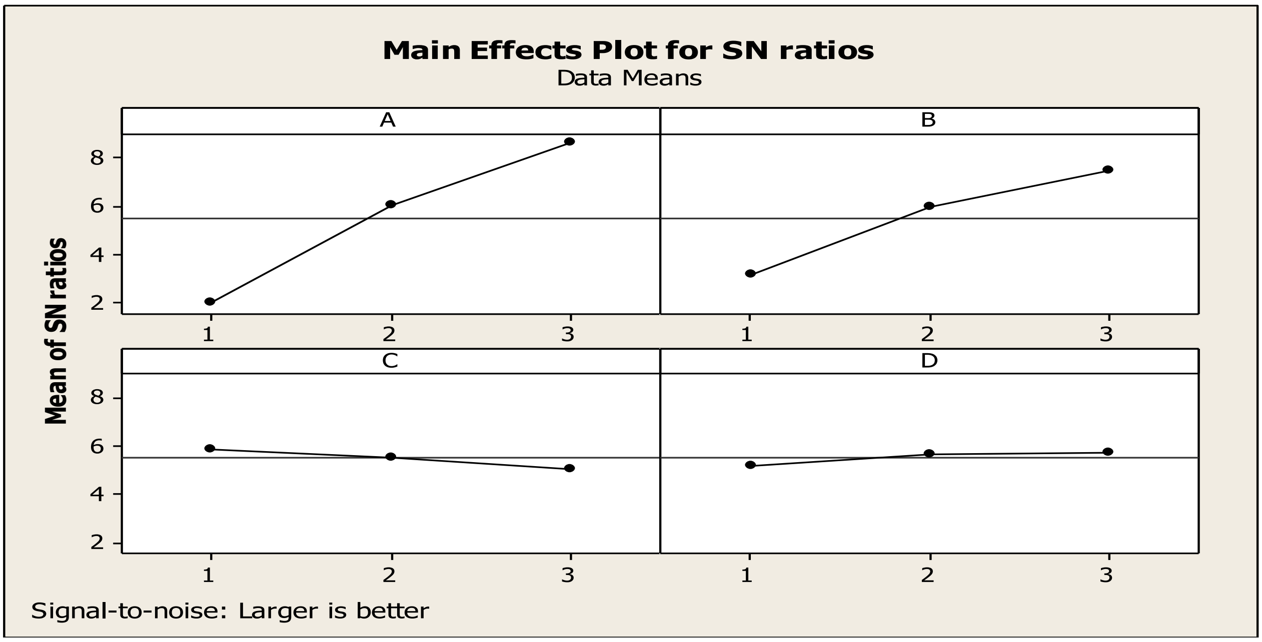

Figure 5.1. Main effects plots for S/N ratio of MRR.

The analysis of variances of the factors is shown in Table 5.1.2 which clearly shows that the SV and WT are not important factors that influences MRR. T_{ON} (68.88%) is the most influencing factor for MRR followed by Ip (28.96%).

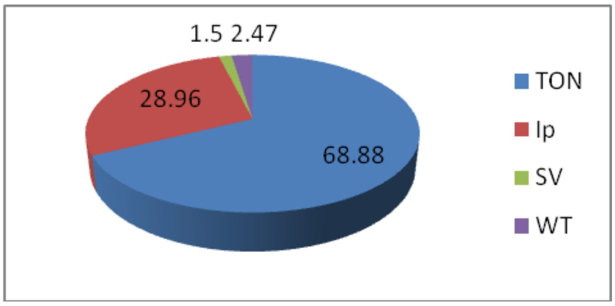

Table 5.1.2. Analysis of Variance for S/N ratios for MRR

FACTORS	DOF	SUM OF SQR	MEAN SQR	F_{RATIO}	CONTRIBUTION
T_{ON}	2	66.443	33.22	127.76	**68.88 %**
I_P	2	27.94	13.97	53.73	**28.96 %**
SV	2	0.780	0.39	1.5	1.54 %
WT	2	0.239	0.119	0.45	2.47 %
ERROR	4	1.068	0.26		

5.2- Influence of Process Parameters on Surface Roughness- In this investigation, the S/N ratio was chosen according to the criterion, the "smaller-the-better" in order to minimize surface roughness.

Table 5.2.1 Response Table for Signal to Noise Ratios smaller is better

SN	Parameters	Level 1	Level 2	Level 3
A	T_{ON}	**-2.314**	-4.103	-6.071
B	I_P	**-1.170**	-4.295	-7.023
C	SV	-4.344	**-4.048**	-4.095
D	WT	**-3.745**	-4.438	-4.305

In the present study, surface roughness of WEDM was analyzed to determine the effect of WEDM process parameters. Main effects at all the levels of the chosen parameters are calculated and listed in Table 5.2.1. The main effect for mean and S/N ratio is plotted in Figure 5.2.

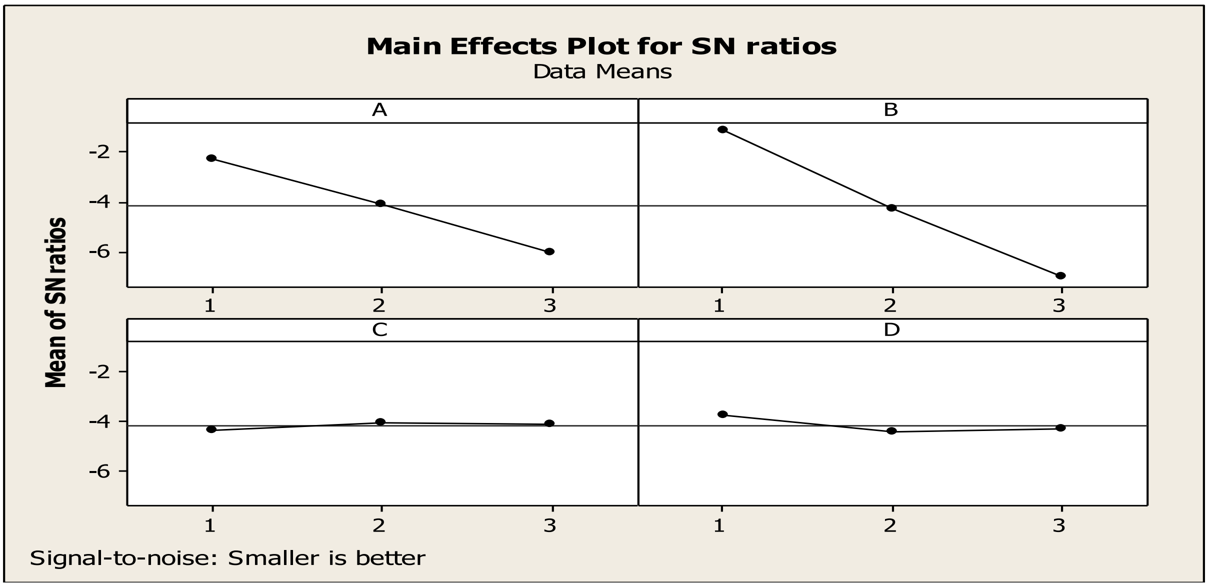

Figure 5.2. Main effects plots for S/N ratio of SR

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It is observed from Figure 5.2 that the surface roughness is lowest at the level 1 of T_{ON}, at the level 1 of I_P, at the level 2 of SV and at the level 1 of the WT. It is clear that the highest S/N ratio is the optimal level of each process parameter. Therefore the S/N ratio values indicate that the surface roughness is at minimum when T_{ON} at level 1, Ip at level 1, SV at level 2 and WT at level 1, i.e. Ton at 110, Ip at 90, SV at 30 and WT at 6. It is clear that the highest S/N ratio is the optimal level of each process parameter is A1 B1 C2 D1.

The analysis of variances of the factors is shown in Table 5.2.2 which clearly indicates that I_P (73.99%) and T_{ON} (28.77) is the major factor affecting SR of followed by SV (0.168%) and WT (1.36 %).

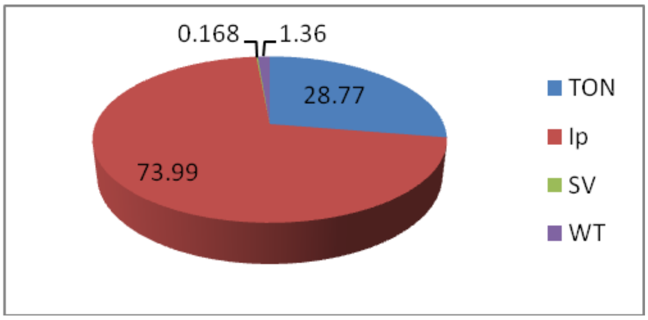

Table 5.2.2. Analysis of Variance for S/N ratios for SR

FACTORS	DOF	SUM OF SQR	MEAN SQR	F_{RATIO}	CONTRIBUTION
T_{ON}	2	21.18	10.59	37.55	**28.77 %**
I_P	2	54.46	26.23	93.014	**73.99%**
SV	2	0.1237	0.061	0.2163	0.168 %
WT	2	1.005	0.5025	1.781	1.36 %
ERROR	4	1.1287	0.282		

5.3- Validation- Confirmation experiments were carried out at the optimum process condition to validate the optimum results estimated by the statistical analysis. The comparison of predicted MRR and SR with experimental results at optimal levels is presented in Table 5.3.1 and Table 5.3.2 respectively.

Table 5.3.1 Result of the Confirmation Experiment for MRR

	Initial cutting parameters	**Optimal cutting parameters**	
		Prediction	**Experiment**
Level	A3 B3 C2 D1	**A3 B3 C1 D3**	A3 B3 C1 D3
MRR mm^3/min	3.241	**3.580**	3.452
S/N ratio (db)	10.2136	**11.086**	
Improvement in S/N ratio		**0.8724**	

Table 5.3.2 Result of the Confirmation Experiment for SR

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	A1 B1 C1 D1	**A1 B1 C2 D1**	A1 B1 C2 D1
SR in µm	0.90	**0.86**	0.85
S/N ratio (db)	0.915	**1.209**	
Improvement in S/N ratio		**0.294**	

5.4 Optimization of Multiple Responses- There are two responses. One is the material removal rate (MRR) and the second is the Surface Roughness (SR). Also note that MRR is larger—the better type of quality characteristic and SR is smaller—the better type of quality characteristic.

The weights are determined as follows. For MRR (larger—the better characteristic), the individual response (data) is divided by the total response value ($\sum MRR$). In the case of SR (smaller—the better characteristic), reverse normalization procedure is used. That is, for each response data, 1/SR is obtained and then *W*SR is computed. From Table 5.4.1, $\sum MRR$ = 18.196 and $\sum 1/SR$ =5.884

Now calculated the weights of responses from Formula given below:

$$W_{MRRi} = \frac{MRRi}{\sum MRR}, \quad W_{SRi} = \frac{1/_{SRi}}{\sum 1/_{SR}}$$

Table 5.4.1Weights and MRPI values for illustration

S.N.	MRR	W_{MRR}	SR	1/SR	W_{SR}	MRPI
1	0.962	0.052	0.90	1.11	0.188	0.219
2	1.346	0.0739	1.35	0.74	0.125	0.268
3	1.522	0.0836	1.83	0.546	0.092	0.529
4	1.564	0.0859	1.14	0.877	0.149	0.304
5	1.920	0.1055	1.54	0.649	0.110	0.371
6	2.641	0.145	2.34	0.427	0.072	0.325
7	1.980	0.108	1.46	0.684	0.116	0.383
8	3.02	0.165	2.12	0.471	0.080	0.246
9	3.241	0.178	2.63	0.380	0.064	0.562

Now, we consider MRPI as a single response of the original problem and obtain solution using Taguchi method (Larger the better). Since MRPI is a weighted score, optimal levels are identified based on maximum MRPI values.

Table 5.4.2 Response Table for Signal to Noise Ratios Larger is better

SN	Parameters	Level 1	Level 2	Level 3
A	T_{ON}	-10.053	-9.572	**-8.508**
B	I_P	-10.623	-10.744	**-6.766**
C	SV	**-11.712**	-8.928	-7.493
D	WT	-8.936	-9.845	**-9.352**

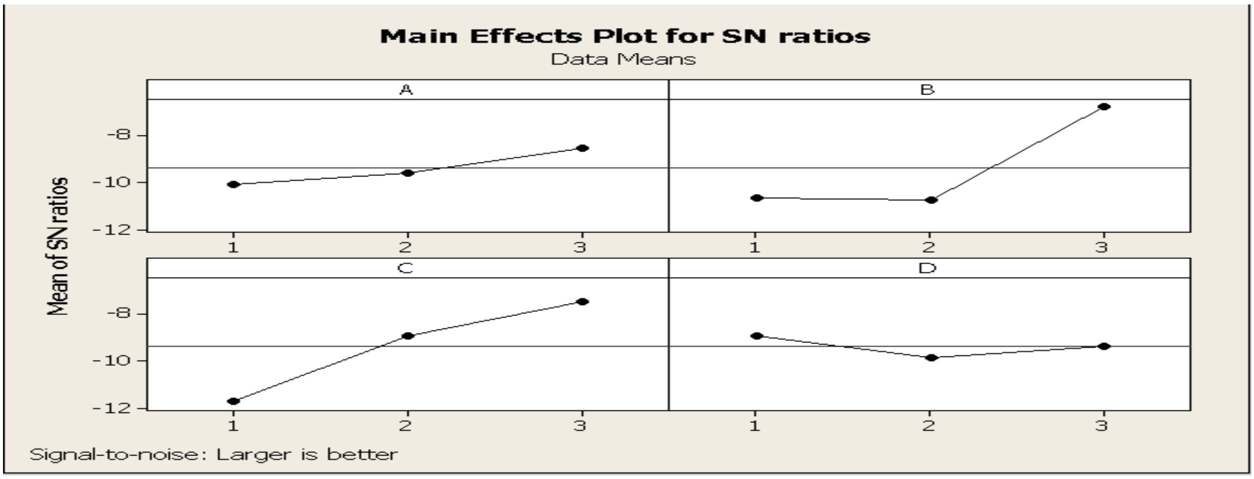

Figure 5.4.1. Main effects plots for S/N ratio of Multiple Responses.

The optimal levels are selected based on maximum MRPI are A_3, B_3, C_3 and D_1

IV. CONCLUSION

In the present study, the effect of WEDM process parameters like pulse on time (T_{ON}), Peak Current (I_P), Servo voltage (SV) and wire tension (WT) on machining responses MRR and SR of Hastelloyc-22 has been investigated using Taguchi Technique.

- The optimum process parameters for maximization of MRR are T_{ON} at level 3 (120), Ip at level 3 (12), SV at level 1 (25) and WT at level 3 (14).
- Similarly, the factors T_{ON} at level 1 (110), Ip at level 1 (8), SV at level 2 (30) and WT at level 1(6) is recommended for minimization SR.
- The ANOVA results indicate that T_{ON} is the major factor affecting MRR (68.88%) and Peak Current (I_P) is the major affecting SR (73.99%).
- After applying the Multi responses optimization method, it's clear that Optimal process Parameters is A3B3C3D1. If we consider only for Surface roughness, then the optimal result is A1B1C2D1. But if consider MRR then the optimal result is A3B3C1D3.

7- Future Scope- The following are the suggestions which may improve to be usefull for the future:

1. Some parameters like type of dielectric used, flushing pressure, duty cycle, electrode material can be varied, and as a result , their effects can be studied.
2. The effects of machining parameters on recast layer thickness should be used.

3. Cryogenic treatment to the wire electrode may be used as one of the prosess.
4. A lot of research work still needs to be carried out in the field of Wire EDM by machining Super alloys such as Hastelloy materials, Different grades of Hastelloy utilizing other process parameters and using deferent Techniques

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