Optimization of Wire Electro Discharge Machining of HCHCr Material using Taguchi Methodology

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Abstract: In this paper, the cutting of High Carbon High Chromium (HCHCr) material using Wire electro discharge machining (WEDM) with a brass wire by using Taguchi methodology has been reported. The Taguchi method is used to formulate the experimental layout, to analyze the effect of each parameter on the machining characteristics, and to predict the optimal choice for each WEDM parameter such as Pulse on time, Pulse off time, feed, Sensitivity. It is found that these parameters have a significant influence on machining characteristic such as material removal rate (MRR), Overcut (OC) and Surface Roughness (Ra). The analysis using Taguchi method reveals that, in general the feed and sensitivity significantly affects the MRR and Pulse on time and Pulse off time has the favorable effect on the Ra.

Keywords: WEDM, Taguchi method, HCHCr, material removal rate, Overcut and Surface roughness.

I. INTRODUCTION

Wire Electrical Discharge Machining or WEDM is a machining method primarily used for hard metals or those that would be impossible to machine with traditional techniques. The non-contact machining technique has been continuously evolving from a mere tool and dies making process to a micro-scale application machining alternative attracting a significant amount of research interests.

One critical limitation, however, is that WEDM only works with materials that are electrically conductive. WEDM is especially well-suited for cutting intricate contours or delicate cavities that would be difficult to produce with a grinder, an end mill or other cutting tools. Metals that can be machined with WEDM include hardened tool-steel, titanium and carbide etc.

II. NEED FOR WIRE ELECTRIC DISCHARGE MACHINING (WEDM)

Among all the non-traditional machining processes, WEDM has some advantages that make its acceptability over other machining options.

Advantages

- It has ability to create complex and intricate parts with a high degree of accuracy.
- This process is able to machine hard materials that other machining processes would have difficulties.
- Another advantage of WEDM is its ability to machine parts on an extremely small scale.
- While using this process, the workpiece is not deformed from impact because there is no direct contact between the electrode and the material.
- The work piece is burr-free after completion and saved from heat damage because very little is actually generated during the procedure that would harm the material.

Disadvantages
- WEDM is low Material Removal Rate.
- Limited to electrical conductive materials only.

III. WORKING PRINCIPLE OF WEDM

In wire EDM a very thin wire serves as the electrode. Special brass wires are typically used; the wire is slowly fed through the material and the electrical discharges actually cut the workpiece. Wire EDM is usually performed in a bath of water. The wire itself does not actually touch the metal to be cut; the electrical discharges actually remove small amounts of material and allow the wire to be moved through the workpiece. When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric (at least in some point), which breaks,

allowing current to flow between the two electrodes. This phenomenon is the same as the breakdown of a capacitor (condenser). As a result, material is removed from both the electrodes.

IV. EXPERIMENTAL PROCESS OF WEDM

1. The basic processes of WEDM
Voltage and amperage control spark between wire electrodes

- Demonized dielectric fluid surrounds wire electrode and work piece.
- Dielectric fluid acts as resistor until enough voltage is applied then fluid ionizes and spark melts and vaporizes the material.
- Once sparking process is completed workpiece material is cooled by dielectric fluid.
- Melted work piece material forms in WEDM chips. A filter then removes chips and dielectric fluid is reused.
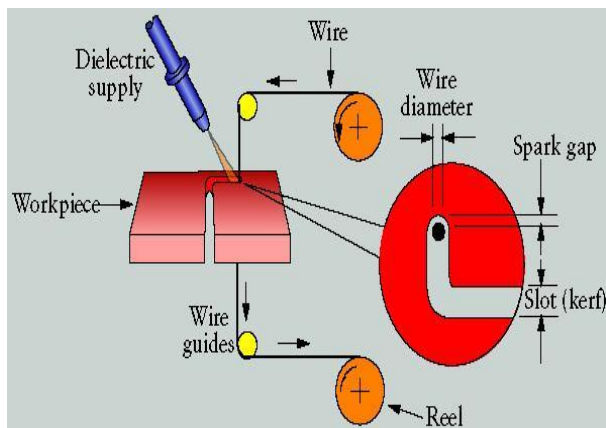

Figure 1: Experimental Setup

EDM oil was used as a dielectric fluid in this experiment. Diameter of electrode and thickness of work piece is measured by digimatic micrometer. (Make: Mitutoyo, Least count: 0.001 mm). Weight of work piece is measured by Precisa-make weighing machine (Accuracy: 0.1mg).

2. Principle of WEDM
Wire electric discharge machining is a controlled metal removing technique whereby an electric spark is used to cut the work piece, which takes a shape according to the path given by software. The electrode (Wire) is made from electrically conductive material (used Brass Wire). The work piece and wire are both in continuous flow of a dielectric fluid. Dielectric fluid should be nonconductor of electricity. A servo mechanism maintains a gap of about 0.01 to 0.02 mm between the electrode & the work piece, preventing them from coming into contact with each other. A direct current of low voltage & high amperage is delivered to the electrode. These electrical energy impulses vaporize the oil at this point. This

permits the spark to jump the gap between the electrode and the work piece through the dielectric fluid. Intense heat is created in the localized area of the spark impact, the metal melts and a small particle of molten metal is expelled from the surface of the workpiece. The dielectric fluid which is constantly being circulated carries away the eroded particles of metal during the off cycle of the pulse and also assists in dissipating the heat caused by the spark.

3. Work piece Material
HCHCr material is used as work piece material in this research work.

Table 1: Material Properties of HCHCr

Sr. No.	Parameter	Value
01	Ultimate Tensile Strength (Psi)	1,35,000
02	Hardness Rockwell	60
03	Elongation (%)	45
04	Density (Kg/cu m)	8220
05	Melting Range (^{0}F)	2200 to 2450

Input Factors
1) Pulse on time (Ton)
2) Pulse off time (Toff)
3) Feed (f)
4) Sensitivity (Sen)

Responses Measured
1) Material Removal Rate (MRR)
2) Overcut (OC)
3) Surface roughness (Ra)

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V. DESIGN OF EXPERIMENTS

Taguchi Method
Taguchi methods are the most recent additions to the toolkit of design, process and manufacturing engineers, and quality assurance experts. In contrast to statistical process control, which attempts to control the factors that adversely affect the quality of production, Taguchi methods focus on design – the development of superior performance designs (of products and manufacturing processes) to deliver quality.
An experimental design scheme of statistical experiments that uses orthogonal arrays however entails the following considerations and consequences

1) The orthogonal array leads only to a main effect design. Use of an orthogonal array forces the investigator

to assume that the response one observe can be approximated by an additive function, separable into the effects of the individual (main) control factors under study. One assumes no other effects, in particular no interactions, to be present. A verification experiment can later verify whether this approximation is satisfactory and a valid one.

2) The columns of the orthogonal arrays are pair-wise orthogonal. In every pair of columns, all combinations of the levels of each (independent) factor under study occur and they do so equal number of times.

3) It follows from no. 2 that the main effect estimates of all factors and their associated sum of squares are independent under the assumption of normality and equality of observation variance. Hence the significance test (ANOVA) for these factors is independent.

4) When orthogonal array guides the experiments, one computes the main factor effect. These computed effect may be then used to predict the response for any combination of factor treatments, because one assumes that these effects are separable and additive. The variance of the prediction error (caused by factors not controlled in the experiments and the exclusion of interactions) is the same for all such treatment combinations.

5) Factors which are studied may be discrete or continuous. For continuous factors it is possible to break down main effects of three level factors into linear and quadratic terms.

A non-linear effect may sometimes be useful in fine tuning and improving the initial design.

6) In the initial stages of optimization, one may limit the investigation to the study of main effect. Later on, it is possible to run larger orthogonally designed experiments to study interaction effects also, if necessary. Taguchi aimed at making the design robust first, followed by an adjustment to put performance at desired target. The task begins by recognizing the different factors influencing performance belong to two distinct categories

- Design parameter: It is the distinct and intrinsic features of the process or the product that influence and determine its performance.
- Noise factor: It is the factor that is either too hard or uneconomical to control, even though this may cause unwanted variation in performance.

If one seeks to maximize a performance aspect or minimize it, variations to the loss function form are available. If the performance characteristic y happens to be such that the smaller it is the better, then the loss can be expressed by the expression

$$L(y) = k.y^2$$

On the other hand if the performance characteristic is such that the larger it is better, then:

$$L(y) = k.(1/y^2)$$

- **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. Usually, there are three categories of performance characteristics in the analysis of the S/N ratio

- lower-the-better,
- higher-the-better,
- nominal-the-better

VI. DESIGN OF EXPERIMENT FOR WEDM OF HCHCR MATERIAL

The design of experiment (D.O.E.) chosen for the electric discharge machining of HCHCr was a Taguchi L9 orthogonal array, by carrying out a total number of 9 experiments along with 4 verification experiments (optional).

- L9 Orthogonal Array

L9 (In 3^4) array 9 rows represent the 9 experiment to be conducted with 4 columns at, 3 levels of the corresponding factor. The matrix form of these arrays is shown in table 3.1, where 1, 2, 3 in the table represents the level of each parameter.

Table 3: Level of each parameter

Sr. No.	Factors	Levels		
		1	**2**	**3**
1	Ton (µs)	31	32	33
2	Toff (µs)	6	7	8
3	Feed (mm/min)	80	90	100
4	Sensitivity	8	9	10

Based on the Taguchi L9 orthogonal array, the values of input factors are placed in the design matrix and it is shown in Table 4

Table 4: L9 Design Matrix

Experiment No.	T_{on} (sec)	T_{off} (sec)	Feed (mm/min)	Sensitivity
E1	31	6	80	8
E2	31	7	90	9
E3	31	8	100	10
E4	32	6	90	10
E5	32	7	100	8
E6	32	8	80	9
E7	33	6	100	9
E8	33	7	80	10
E9	33	8	90	8

Table 5: Experimental Results & Calculation of Various Response Factors based on Taguchi L9 Orthogonal Array

Experiment No	MRR (gm/min)	OC (mm)	Ra (µ)
E1	1.4	0.436	3.27
E2	1.27	0.431	3.5
E3	1.22	0.431	3.74
E4	1.56	0.414	3.32
E5	1.38	0.441	3.58
E6	1.25	0.42	3.61
E7	1.6	0.414	3.49
E8	1.38	0.417	3.57
E9	1.21	0.49	4.02

Where MRR= Weight/time, OC= Size of slot- Size of removed part.

• Analysis on Experimental Data

After the experimental procedure, different response factors like material removal rate (MRR), Overcut (OC), Surface roughness (Ra) of cut section were calculated from the observed data. Then a statistical analysis was performed on the calculated values and the signal to noise ratio values of four response factors are tabulated in Table 5.1 shown in next page.

• Effect of Input Factors on Material Removal Rate (MRR)

The response table for signal to noise ratio for material removal rate (MRR) is shown in Table 7 and the corresponding analysis of variance (ANOVA) table is shown in Table 8 for material removal rate (MRR), the calculation of S/N ratio follows "**Larger the Better**" model.

• Effect of Input Factors on Surface Roughness

The response table for signal to noise ratio for Surface roughness (Ra) is shown in Table 11 and the corresponding analysis of variance (ANOVA) table is shown in Table 12. For radial overcut (ROC), the calculation of S/N ratio follows "**Smaller the Better**" model. So Pulse-off time (T_{off}) & Pulse-on time (T_{on}) has the maximum effect on radial overcut. Feed (f) and Sensitivity (Sen) has less effect on Surface Roughness (Ra).

Table 6: Calculation of Signal to Noise ratio for Various Response Factors

Experiment No.	S/N Ratio for MRR	S/N Ratio for OC	S/N Ratio for Ra
E1	2.92	7.21	-10.29
E2	2.73	7.31	-10.88
E3	2.14	7.31	-11.46
E4	3.86	7.66	-10.42
E5	2.79	7.11	-11.08
E6	1.94	7.54	-11.15
E7	4.08	7.66	-10.86
E8	2.79	7.6	-11.05
E9	1.65	6.2	-12.08

Table 7: Response Table for Signal to Noise Ratios for MRR

Level	Pulse-on Time T_{on}	Pulse-off Time T_{off}	Feed f	Sensitivity Sen
1	2.597	3.62	2.550	2.453
2	2.863	2.77	2.747	2.917
3	2.840	1.91	3.000	2.930
Delta	0.266	1.71	0.450	0.477
Rank	4	1	3	2

Table 8: Analysis Of Variance (ANOVA) for MRR

Sources	D.O.F	Sum of differences of squares	Mean square	% contribution
T_{on}	2	0.1303	0.065	2.47
T_{off}	2	4.3862	2.1931	83.32
f	2	0.3053	0.1526	5.77
Sen	2	0.4430	0.2215	8.44
Total	8	5.2648	-	-

So Pulse-off time (T_{off}) and Sensitivity (Sen) have the maximum effect on material removal rate whereas pulse-on time (T_{on}) and Feed (f) have less effect.

• Effect of Input Factors on Overcut

The response table for signal to noise ratio for Overcut is shown in Table 9 and the corresponding analysis of variance (ANOVA) table is shown in Table 10. For Overcut, the calculation of S/N ratio follows "**Smaller the Better**" model.

So Sensitivity (Sen) has the maximum effect on overcut and Pulse-off time (T_{off}) also has some influence on it whereas Feed (f) and Pulse-on time (T_{on}) have much less effect on overcut.

Table 9: Response Table for Signal to Noise Ratios for OC

Level	Pulse-on Time T_{on}	Pulse-off Time T_{off}	Feed f	Sensitivity Sen
1.	7.277	7.510	7.450	6.840
2.	7.440	7.340	7.060	7.503
3.	7.153	7.020	7.360	7.523
Delta	0.284	0.490	0.390	0.683
Rank	4	2	3	1

● Verification experiment

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 responses are either maximum (in case of MRR) or minimum (in case of OC and Ra). The signal to noise ratio (S/N ratio) of each responses corresponding to each factor level also has a maximum and a minimum value. 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 maximum 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 maximum values (for each input factor). There are three optimum parameter settings corresponding to the three response factors. The combination of input factor levels, for which optimum settings will be obtained, is given in Table 11.

Using these three optimum parameter settings, three verification experiments has been carried out and the experimental results are shown in Table 11.

Table 10: Optimal Parameter Settings of Input Factors

Physical Requirement	Optimal Combination			
	T_{ON}	T_{OFF}	feed	Sensitivity
Maximum MRR	32	6	100	10
Minimum OC	32	6	80	10
Minimum RC	31	6	80	9

Table 11: Verification Experimental Results & Calculation of Various Response Factors.

Verification Exp. for	MRR	OC	Ra
Max. MRR	1.82	0.404	2.93
Min. OC	1.53	0.296	3.16
Min. Ra	1.65	0.331	2.31

VII. DISCUSSION

A. Effect of Input Factors on Material Removal Rate (MRR)

From figure 6, it is observed that increased pulse-on time (T_{on}) for certain limit i.e. (31μs to 32 μs) causes higher MRR, which is also theoretically established. But an again increase of pulse-on time (T_{on}) from 32 μs to 33 μs results in lower MRR. This is due to fact that here no interaction of input factors has been considered, although some interaction effect may be present there.
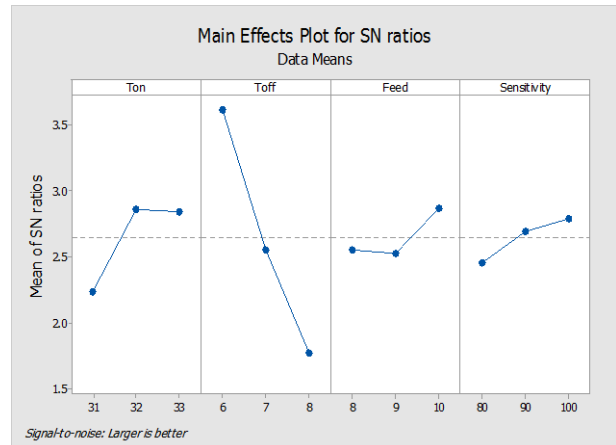

Fig. 6. S/N Ratio Curve for MMR

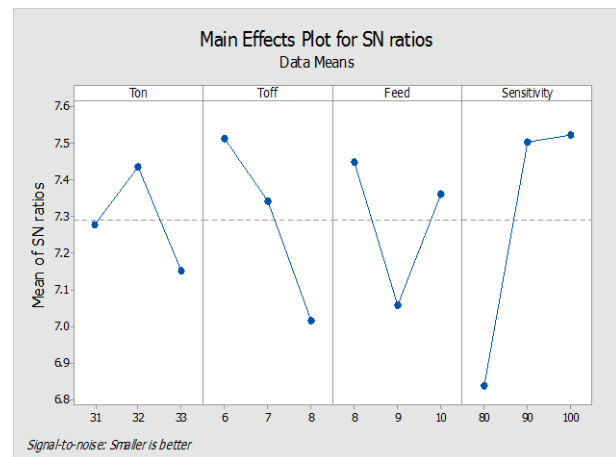B. Effect of Input Factors on Overcut (OC)

Fig. 7. S/N Ratio Curve for OC

From the Figure 7, it is observed that S/N ratio curve for overcut (OC) has an increasing trend with increase of pulse-on time (T_{on}) up to certain limit i.e. from 31μs to 32 μs and thendecreased suddenly for 33μs.

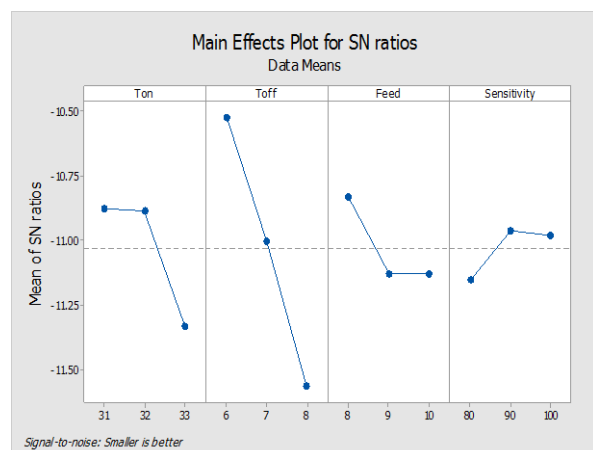C. Effect of Input Factors on Surface Roughness (Ra)

Fig. 8: S/N Ratio Curve for Ra.

From figure 8, it is observed that S/N ratio curve for Surface roughness has an decreasing trend of Ton for 31µs to 32µs and then decreases suddenly for 32µs to 33µs.

VIII. DISCUSSION ON VERIFICATION EXPERIMENT

From Table 11, it has been observed that the prediction errors for material removal rate (MRR), Overcut (OC) and Surface Roughness (Ra) are within the acceptable range. Hence the additive model is valid for these optimum parameter settings. So it can be concluded that the combinations of parameters tend to reach towards optimum settings.

IX. CONCLUSION

Increased pulse-on time and Feed causes higher MRR, which is also theoretically established. Pulse off time and sensitivity cause relatively less effect on MRR. S/N ratio curve for overcut (OC) has an increasing trend with increase of pulse-on time (T_{on}) up to certain limit and then decreases so Pulse on time and Pulse off time having favorable effect on Overcut. Surface roughness is mainly influenced by the sensitivity. Other three factors having favorable effect on Ra. Taguchi L9 orthogonal matrix experiment, no interactions between the input factors are considered. But some interaction effect may be present during the experiment. This may result in some observations which do not go with the theoretical belief. Some portion of the material is conductive and some portion is non-conductive. But WEDM requires conductive workpiece. So the composite properties of the workpiece may also lead to some observations which contradict the theoretical belief.

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