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.

• 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 workpiece is burr-free after completion and saved from heat damage because very little is actually generated during the procedure that would harm the material.

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.
• 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 (°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 observes 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 2 that the main effects 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 effects
may be 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

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Sr. No.} & \text{Factors} & \text{Levels} \\
\hline
1 & T_{on} (\mu s) & 31 & 32 & 33 \\
2 & T_{off} (\mu s) & 6 & 7 & 8 \\
3 & Feed (mm/min) & 80 & 90 & 100 \\
4 & Sensitivity & 8 & 9 & 10 \\
\hline
\end{array}
\]

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

| Experiment | 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          |

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

| Level | Pulse-on Time Ton | Pulse-off Time Toff | 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 squares of | 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 Ton | Pulse-off Time Toff | 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 response 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 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](image)

B. Effect of Input Factors on Overcut (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 then decreased suddenly for 33μs.

![Fig. 7. S/N Ratio Curve for OC](image)

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

![Fig. 8. S/N Ratio Curve for Ra.](image)
From figure 8, it is observed that S/N ratio curve for Surface roughness has an decreasing trend of $T_{on}$ 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.

### REFERENCES

[1] S. S. Mahapatra and Amar Pataki, “Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method”, International Journal of Advance Manufacturing Technology, P.1-15

[2] Jatinder Kapoor, Sehjpal Singh, Jaimal Singh Khamba. “Recent Developments in Wire Electrodes for High Performance WEDM”, Proceedings of the World Congress on Engineering, Vol. II June 30 - July 2, 2010, London, U.K.

[3] Muthu Kumar, Suresh Babu, Venkataramy and Raajendhiren. “Optimization of the WEDM Parameters on Machining Incoloy 800 Super alloy with Multiple Quality Characteristics” International Journal of Engineering Science and Technology Vol. 2(6), 2010, 1538-1547.

[4] Pujari S. Rao and Koonam Ramji. “Effect of WEDM conditions on surface roughness: A Parametric Optimisation using Taguchi method”, International Journal of Advanced Engineering Sciences and Technologies Vol No. 6, Issue No. 1. 041 – 048.

[5] Y. M. Puri and N. V. Deshpande “Simultaneous Optimization of multiple quality characteristics of WEDM based on fuzzy logic and Taguchi technique” Mechanical Engineering, VNIIT, Naiapur, India,ypuri@yahoo.co.in

[6] Sorana D. Bolboacă Lorentz Jäntsch. “Design of Experiments: Useful Orthogonal Arrays for number of experiments from 4 to 16”. ISSN 1099-4300 © 2007 by MDPI.