Journal of Basic and Applied Engineering Research
Print ISSN: 2350-0077; Online ISSN: 2350-0255; Volume 1, Number 3; October, 2014 pp. 78-84

http://www.krishisanskriti.org/jbaer.html

# Parametric Optimization of Wire EDM Process for Gear Cutting

**Kasinath Das Mohapatra[1], S. K. Sahoo[2]**
*[1, 2]Department of Mechanical Engineering, National Institute of Technology, Rourkela, India*

***Abstract:** This proposed work deals with the analysis and optimization of process parameters i.e.Single Pitch Error '$F_{pt}$' and Material Removal Rate (MRR) of Wire electric discharge machined (WEDMed) fine - pitch spur gears made of Copper. The gear has a Base diameter of 46.98 mm, Face width of 4.9 mm, Pitch circle diameter of 50mm and the wire is made of brass. Effects of four WEDM parameters namely Pulse-on time, Pulse-off time, Wire Feed rate and Wire Tension on the geometry of the spur gears were analyzed. The values of MRR and $F_{pt}$ of the gear obtained by the experiments were conducted and the WEDM parameters are optimized using Taguchi Quality loss function. The graphs were also plotted from the optimized results.*

***Keywords:** MRR, Spur gears, Wire Feed rate*

## 1. INTRODUCTION

Electrical discharge machining (EDM) is a non-conventional machining process, used for manufacturing of many complex or hard and electrically conductive material parts that are extremely difficult-to-cut by other conventional machining process. Erosion pulse discharge occurs in a small gap between the work piece and the electrodes which removes the unwanted material from the parent metal through melting and vaporizing in presence of dielectric fluid. Performance measures are different for different materials, process parameters as well as for dielectric fluids. Presence of metal particles in dielectric fluid diverts its properties, which reduces the insulating strength of the dielectric fluid and increases the spark gap between the tool and work piece. As a result, the process becomes more stable and metal removal rate (MRR) and the surface finish increases.

Gears are the major components in various devices such as motors and pumps, electronic and home appliances, business machines, automotive parts, timing devices, sophisticated toys, etc. Brass, Bronze, Aluminium, Stainless steel are the most commonly used materials for these gears. Gears made of brass are primarily used for motion transmitting gears which runs at very high speed. Therefore minimum running noise and accurate motion transfer are the two important desirable characteristics for these gears which depends on the amount of errors or deviations i.e. the error in the pitch of the gears. Spur gear is a cylindrical shaped gear in which the teeths are parallel to the axis. It has the largest applications and easy to manufacture. *Pitch deviation* determines the accuracy in the Motion transfer.

*Pitch deviation* is a type of location error and is related to the location of teeth on a gear.

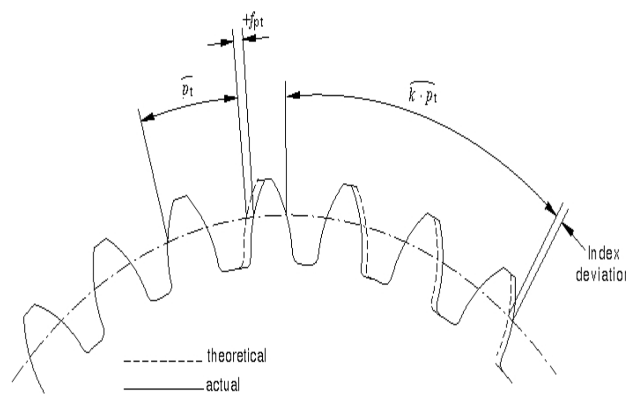


**Figure 1. Pitch deviation.**

The *pitch* is the distance between the corresponding points on two adjacent teeth of a gear along the pitch circle. Deviations in the pitch include single pitch deviation ($F_{pt}$) and accumulated pitch deviation which are measured at the middle of the tooth height along the pitch circle. The *accumulated pitch deviation* '$F_p$' is defined as the difference between the summation of the theoretical values of pitches and the summation of the actual values of the pitches for a given values of teeth.

## 2. EXPERIMENTAL WORK

The specific objectives of this present work is (i) to explore the use of WEDM as a superior alternative process for manufacturing high quality spur gears, (ii) to know the major trends of parameters of the gears with the WEDM parameters, and (iii) to optimize the WEDM parameters for achieving minimum pitch error of the spur gears and maximize the material removal rate (MRR).

Based on previous preliminary investigations, the authors have concluded that the WEDM process is capable enough to manufacture high quality spur gears. In WEDM the material is removed by the thermoelectric erosion process involving melting and vaporization caused by the electric spark generated by a pulsed DC power supply between the wire electrode and the work piece in the presence of a dielectric fluid, generally de-ionized water. Deviations in the geometry and dimensional accuracy of the WEDMed components mainly depends on the size, shape and distribution of the craters, and the positional variation of the wire (known as the Wire lag).

Voltage, Discharge current, Pulse- on time ($T_{on}$), Pulse-off time($T_{off}$), Wire feed rate ($W_F$), Wire tension ($W_T$) and dielectric flushing pressure are the important WEDM parameters. Pulse-on time and Pulse-off time are the two independent parameters describing the DC pulse power used in WEDM process .Other parameters namely the duty cycle (ratio of Pulse-on time to sum of Pulse-on time and Pulse-off time) and the pulse frequency (reciprocal of sum of Pulse-on time and Pulse-off time) are the dependent parameters.

**Table 1. Details of the WEDM Parameters used in the experimentation**

| Variable parameter | Symbol | Unit | Level | | | |
|---|---|---|---|---|---|---|
| | | | **I** | **II** | **III** | **IV** |
| Pulse on time | $T_{on}$ | µs | 110 | 112 | 114 | 116 |
| Pulse off time | $T_{off}$ | µs | 50 | 52 | 54 | 56 |
| Wire Feed Rate | $W_F$ | m/min | 3 | 4 | 5 | 6 |
| Wire Tension | $W_T$ | Kg-f | 6 | 7 | 8 | 9 |

The present study deals with the manufacturing of gears from a 3 mm thick rectangular copper plate of 10 mm length and 10 mm width of Ecocut CNC Wire EDM machine using brass wire as the electrode of 0.25 mm diameter and de-ionized water as dielectric.

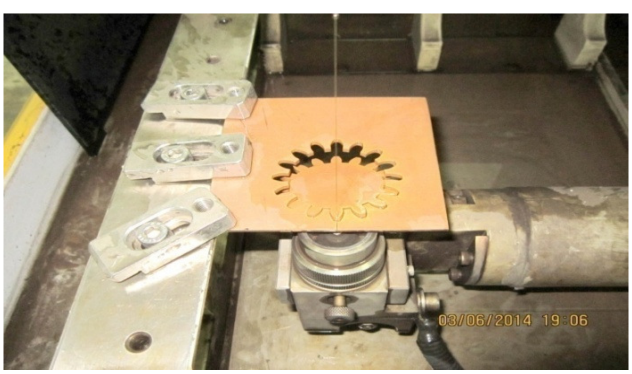


**Figure 2. Machining of copper plate having sixteen number of teeths.**

Four WEDM parameters (ie. Pulse- on time, Pulse-off time, Wire feed rate and Wire tension) were varied at four different levels each. Table 2 lists the variable and fixed parameters used in the experimentation of gear. The values and ranges of these parameters were chosen based on the preliminary experiments and the machine constraints.

**Table 2. Fixed parameters and gear specifications.**

| **Fixed Parameters** | | **Gear specifications** | |
|---|---|---|---|
| Wire Material | Brass | Material | Copper |
| Wire Diameter | 0.25mm | Profile | Involute |
| Servo Voltage ($S_V$) | 10 V | Pressure angle | $20^\circ$ |
| Discharge | 1A | Number of teeth | 32 |
| Current($I_P$) | (Full Current) | Tooth width | 4.90 mm |
| Dielectric | Distilled Water | Base diameter | 46.98 mm |
| Water Pressure ($W_P$) | 1kg/cm$^2$ | Pitch circle diameter | 50mm |
| Peak Voltage | ($V_P$) 11 V | | |

The Gear figure is obtained by giving appropriate data such as Pitch circle diameter ( PCD ), number of teeths, Pressure angle etc. 32 sets of experiments (L16array) were conducted (2 teeths 1 set) at four different levels and at four different parameters. Single pitch deviation and MRR were calculated from these experiments. Optimization of parameters are done to get the best results.

### *2.1 Calculation of Pitch error and MRR*

*Single pitch error* is the algebraic difference between the theoretical and actual measured values of a pitch for a pair of teeth or the deviation between the actual measured pitch values between any two adjacent tooth surface and the theoretical circular pitch.

Single pitch error ($F_{pt}$) = Theoretical circular pitch – Actual measured pitch values

Circular pitch can be calculated by the following formula

$$\text{Circular Pitch } (P) = \pi / P_d \quad (1)$$

Where $P_d$ is the Diametral Pitch and is calculated as the ratio of number of teeth to the Pitch circle diameter

Diametral Pitch ($P_d$) = N/D (2)

Where N is the number of teeth and D is the Pitch circle diameter in mm.

Now Theoretical Circular Pitch ($F_P$) = $\pi / P_d = \pi D/N$ (3)

*Material Removal Rate (MRR )* can be calculated by taking Cutting speed ($V_C$), Cutting Length (L), time and material thickness into consideration.

Cutting speed ($V_C$) can be calculated by
$V_C = 60.L/t$ $mmin^{-1}$ (4)

Where L is the Cutting length in mm and t is the time in seconds

The Material removal rate (MRR) can be calculated by the following formula
MRR = $V_C$*h*k $mm^3min^{-1}$ (5)

Where $V_C$ is the cutting speed in m/min, h is the thickness of workpiece in mm and k is the cutting thickness in mm.

*Other Parameters of Gears are taken as follows.* The Dedendum diameter is taken as 42.18 mm, Addendum diameter is taken as 56.25 mm, Base tangent Length is taken as 14.538 mm and number of teeths for span measurement is taken as 2.

### *2.2. Microscopic Image of Cutted Spur Gears*

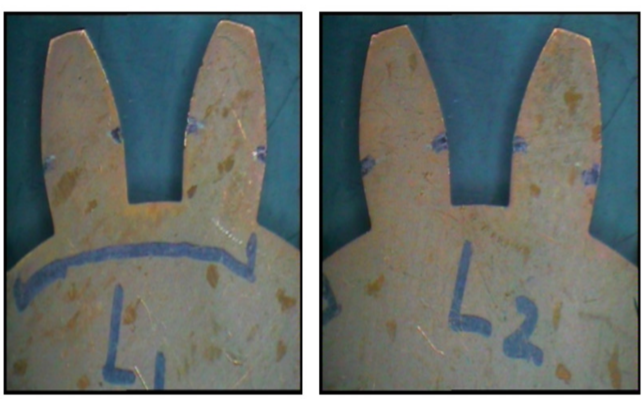

**Figure 3. Microscopic image of copper plate after cutting at 10 X optical zoom.**

For calculating Single pitch error, the measurement of at least two teeths are required. Therefore the left and right flanks of two equally spaced gear teeth were scanned by *Optical Microscope* at 10 X Zoom as shown in Figure 3. For each gear, the actual pitch deviation were calculated from *Caliper pro* software by averaging the mean values of the profile deviations of two left flanks (LF) and two right flanks (RF) as shown in Figure 3(a) and Figure 3(b). In this way, the machine measures the pitch error for all the sixteen flanks of one set of experiments on one plate. The actual pitch deviation of a particular gear is the average of the values of right flanks and the left flanks.


**Figure 3(a). Measurement of actual Pitch error of left flank using Caliper pro software.**


**Figure 3(b). Measurement of actual Pitch error right flank using Caliper pro software.**

## 3. ANALYSIS OF RESULTS

The selection and the development of the appropriate models have been carried out by using the statistical software, " Minitab and Caliper pro ". Table 3 presents the values of $F_{pt}$ and MRR corresponding to sixteen sets of experiments. $F_{pt}$ and MRR were calculated. Based on the experimental results given in Table 3, the effects of the WEDM parameters on deviations in the pitch and MRR are presented graphically. It can be observed that to minimize $F_{pt}$ and maximize MRR there exist an optimum ranges of Pulse on time, Pulse off time, Wire feed rate and Wire tension.

**Table 3. Values of Input parameters and output responses for different runs in calculating error and MRR.**

| SL No. | Input parameters | | | | Output Responses | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Actual $F_{pt}$ | | | Theoretical $F_{pt}$ | Error ($F_{pt}$) | Time(t)in sec | Length(l) in mm | $V_c$ in mm/min | MRR in $mm^3$/min |
| | $T_{on}$ | $T_{off}$ | $W_F$ | $W_T$ | LF | RF | Avg | | | | | | |
| 1 | 110 | 50 | 3 | 6 | 8.81 | 8.77 | 8.79 | 9.81 | 1.02 | 975 | 41.48 | 2.55 | 1.91 |
| 2 | 110 | 52 | 4 | 7 | 8.60 | 8.66 | 8.63 | 9.81 | 1.18 | 1062 | 41.10 | 2.32 | 1.74 |
| 3 | 110 | 54 | 5 | 8 | 8.51 | 8.70 | 8.60 | 9.81 | 1.21 | 1043 | 40.87 | 2.35 | 1.76 |
| 4 | 110 | 56 | 6 | 9 | 8.70 | 8.66 | 8.68 | 9.81 | 1.13 | 1065 | 41.17 | 2.31 | 1.73 |
| 5 | 112 | 50 | 4 | 8 | 8.76 | 8.90 | 8.83 | 9.81 | 0.98 | 1158 | 40.87 | 2.11 | 1.58 |
| 6 | 112 | 52 | 3 | 9 | 8.73 | 8.69 | 8.71 | 9.81 | 1.10 | 865 | 41.00 | 2.84 | 2.13 |
| 7 | 112 | 54 | 6 | 6 | 8.72 | 8.64 | 8.68 | 9.81 | 1.13 | 859 | 41.19 | 2.87 | 2.15 |
| 8 | 112 | 56 | 5 | 7 | 8.67 | 8.73 | 8.70 | 9.81 | 1.11 | 841 | 39.7 | 2.83 | 2.12 |
| 9 | 114 | 50 | 5 | 9 | 8.93 | 8.99 | 8.96 | 9.81 | 0.85 | 638 | 41.11 | 3.86 | 2.89 |
| 10 | 114 | 52 | 6 | 8 | 8.68 | 8.68 | 8.68 | 9.81 | 1.13 | 825 | 41.20 | 2.99 | 2.24 |
| 11 | 114 | 54 | 3 | 7 | 8.56 | 9.03 | 8.79 | 9.81 | 1.02 | 787 | 40.65 | 3.09 | 2.32 |
| 12 | 114 | 56 | 4 | 6 | 8.86 | 8.98 | 8.92 | 9.81 | 0.89 | 802 | 40.92 | 3.06 | 2.29 |
| 13 | 116 | 50 | 6 | 7 | 8.78 | 8.78 | 8.78 | 9.81 | 1.02 | 531 | 40.58 | 4.58 | 3.43 |
| 14 | 116 | 52 | 5 | 6 | 8.68 | 8.70 | 8.69 | 9.81 | 1.12 | 579 | 40.88 | 4.23 | 3.17 |
| 15 | 116 | 54 | 4 | 9 | 8.59 | 8.60 | 8.59 | 9.81 | 1.21 | 587 | 40.97 | 4.18 | 3.14 |
| 16 | 116 | 56 | 3 | 8 | 8.66 | 8.73 | 8.69 | 9.81 | 1.11 | 460 | 40.31 | 5.25 | 3.94 |

## 4. OPTIMIZATION TECHNIQUE USED IN THE EXPERIMENT

There are many techniques available for optimization. However in this study Taguchi Quality loss function technique is used for optimization of process parameters. Taguchi design is an orthogonal array method for designing the experimental procedure using different types of design like, two, three, four, five, and mixed level. In Taguchi a loss function is developed from the error. Uncontrollable factors which is also known as noise, causes error and results into loss. In WEDM, lower Pitch error and higher Material removal rate are the indications of better performance. For data pre-processing in the Taguchi quality loss function, Pitch error is taken as 'smaller the better' and Material removal rate is taken as the 'larger the better'.

***Steps for calculating Taguchi Quality loss function***

Consider the responses.

For Lower the better (LB)

Quality loss function $L_{ij}=Y_{ij}^2$(ie. Square of the responses)

***For Higher the better (HB)***

Quality loss function $L_{ij}=1/Y_{ij}^2$

where $Y_{ij}$=ith performance of the response table in the ith trial

**Calculation of Normalized Values**

$N_{ij}=L_{ij}/ L^*$

Where $L^*$=max $L_{ij}$

***Calculation of Total loss function***

$$Tij = \sum_{i=1}^{n} \text{WiNij}$$

Wi = Weightage which is always 1

The average is taken for calculating $T_{ij}$

***Calculation of S/N ratio for $T_{ij}$***

$N_J$ = -10log ($T_{ij}$)

## 5. RESULTS AND DISCUSSION

***Effect of pulse-off time***: Figure 4(a) and Figure 4(b) shows that increase in pulse-off time leads to increase in $F_{pt}$ and decrease in the MRR, because longer pulse-off time increases the discharge energy of the plasma channel resulting in increase in sparking efficiency. This leads to occurrence of violent spark which forms irregular shaped deeper craters and generation of high amount of forces which finally results in higher values of $F_{pt}$ and low values of MRR.

***Effect of pulse-on time***: It can be seen from Figure 4(a) and Figure 4(b) that with the increase in pulse-on time, $F_{pt}$ initially decreases, attains minimum value and then increases, but MRR increases. Increase in pulse-on time leads to the increase in MRR because strong electric field at higher $T_{on}$ facilitates the ionization of dielectric resulting in increase in the period of transferring the discharge energy to the electrode which results in rapid melting and evaporation of large amount of material. A shorter pulse-on time causes incomplete removal of the machined material from the gap between the wire and the work piece. Higher values of $T_{on}$ results in the increase in discharge energy and cutting rate. The residual debris causes short-circuit and vibrations in the wire. These vibrations cause wire lag which finally produces less deviations in profile and high increase in MRR.

***Effect of Wire feed rate***: At low Wire feed rate, $F_{pt}$ is lowest and MRR is highest .With the increase in $W_F$, $F_{Pt}$ increases but in case of MRR, at first it decreases, then increases to a certain point and then again it decreases. This can be explained by the fact that low Wire feed rate exposes the wire to bear more discharge energy per unit wire length which increases wire-lag, wire-breakage and non-uniform wear of the wire. All these factors leads to the increase in $F_{pt}$ and decrease in MRR. Increase in wire feed rate reduces the duration of spark concentration at a particular location on the wire thereby decreasing the wire-lag and wire-breakage which leads to low values of MRR and high values of $F_{Pt}$ . With the increase in $W_F$, cutting rates are higher.

***Effect of Wire Tension***: Increase in the Wire Tension results in increase in both MRR and $F_{pt}$. High water pressure and high induced reaction forces are the causes for increase in both $F_{Pt}$ and MRR.

### *5.1. Main Effect Plot Diagrams*

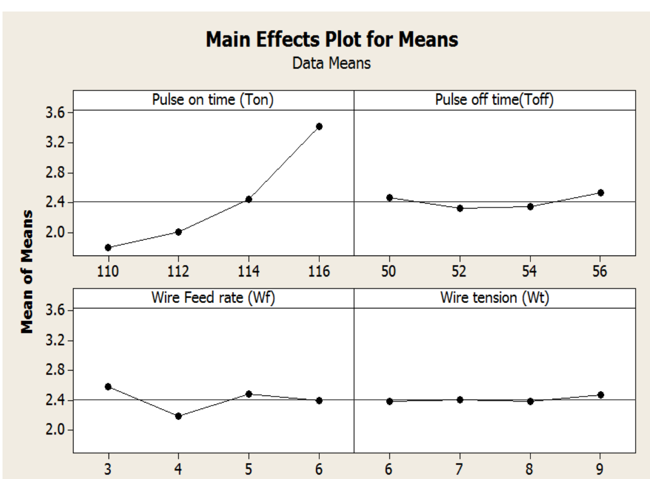


**Figure 4(a). Main effect plot diagram for variation of different input parameters with MRR.**

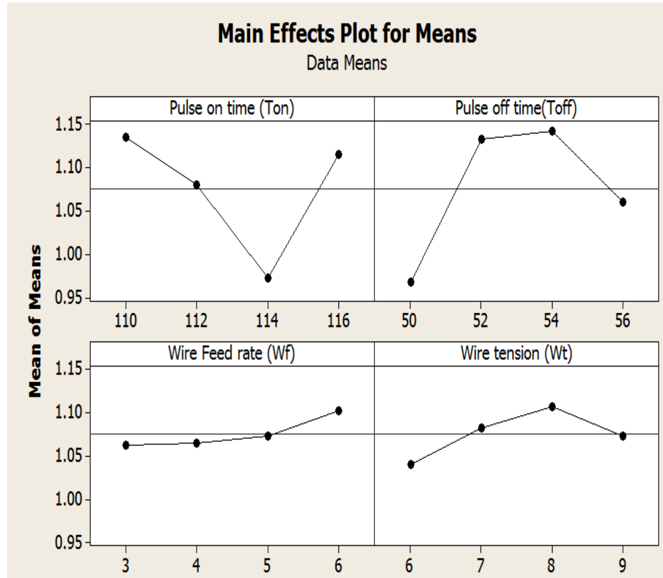


**Figure 4(b). Main effect plot diagrams for variation of different input parameters with pitch deviation.**

**Table 4. Optimization of process parameters.**

| SL No. | $T_{ij}$ | $N_{ij}$ |
|---|---|---|
| 1 | 0.752 | 1.237 |
| 2 | 0.820 | 0.861 |
| 3 | 0.831 | 0.803 |
| 4 | 0.916 | 0.381 |
| 5 | 0.779 | 1.084 |
| 6 | 0.630 | 2.000 |
| 7 | 0.644 | 1.911 |
| 8 | 0.638 | 1.951 |
| 9 | 0.360 | 4.436 |
| 10 | 0.622 | 2.062 |
| 11 | 0.536 | 2.708 |
| 12 | 0.470 | 3.279 |
| 13 | 0.409 | 3.880 |
| 14 | 0.490 | 3.098 |
| 15 | 0.554 | 2.564 |
| 16 | 0.439 | 3.575 |

**Table 5. Analysis of variance for pitch error**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| $T_{on}$ | 3 | 0.062 | 0.002 | 0.020 | 6.51 | 0.039 |
| $T_{off}$ | 3 | 0.078 | 0.078 | 0.026 | 8.13 | 0.03 |
| $W_F$ | 3 | 0.004 | 0.004 | 0.001 | 0.42 | 0.752 |
| $W_T$ | 3 | 0.009 | 0.009 | 0.003 | 0.97 | 0.51 |
| Residual error | 3 | 0.009 | 0.009 | 0.003 | | |
| Total | 15 | 0.164 | | | | |

**Table 6. Analysis of variance for MRR.**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| $T_{on}$ | 3 | 6.304 | 6.304 | 2.101 | 13.2 | 0.031 |
| $T_{off}$ | 3 | 0.108 | 0.108 | 0.036 | 0.23 | 0.872 |
| $W_F$ | 3 | 0.329 | 0.329 | 0.109 | 0.69 | 0.614 |
| $W_T$ | 3 | 0.023 | 0.023 | 0.078 | 0.05 | 0.983 |
| Residual error | 3 | 0.474 | 0.474 | 0.158 | | |
| Total | 15 | 7.240 | | | | |

Anova study tells us which Wire EDM parameters significantly affect the responses. It can be seen from Table 5 and Table 6 that for the Pitch Error, the significant parameter is Pulse on time and Pulse off time, where as for MRR, the significant parameter is Pulse on time only.

### *5.2. Main Effect Plot Diagram*

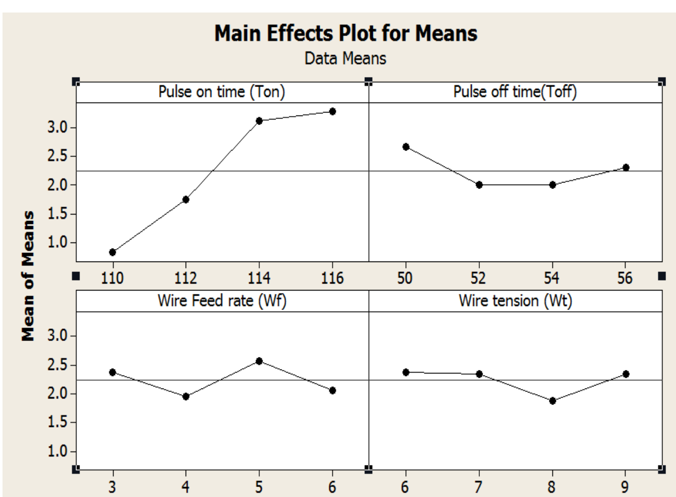


**Figure 5. Main effect plot diagram for Taguchi Quality loss.**

**Table 7. Anova table for Taguchi quality loss.**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| $T_{on}$ | 3 | 16.50 | 16.50 | 5.500 | 7.77 | 0.043 |
| $T_{off}$ | 3 | 1.173 | 1.173 | 0.391 | 0.55 | 0.681 |
| $W_F$ | 3 | 0.994 | 0.994 | 0.331 | 0.47 | 0.725 |
| $W_T$ | 3 | 0.680 | 0.680 | 0.229 | 0.32 | 0.810 |
| Residual error | 3 | 2.123 | 2.123 | 0.707 | | |
| Total | 15 | 21.47 | | | | |

From the Anova table it is clear that Pulse on time is a significant factor followed by Pulse off time, Wire feed rate and Wire tension. From the Main effect plot diagram it is seen that Pulse on time increases and pulse off time decreases. For optimization, the highest value is taken as the optimum result. So from the graph it is clear that Pulse on time is maximum at 116 µs, Pulse off time is maximum at 50 µs, Wire feed rate is maximum at 5 m/min and Wire tension is maximum at 6 kg-f.

## 6. CONCLUSIONS

Following are the conclusions made based on the experimental work and various results obtained.

a) Pulse-on time and pulse-off time were found to be highly significant parameters. Optimum ranges of Pulse on time and pulse-off time exist to minimize the deviations in the Pitch error and maximize in the MRR.

b) The single pitch deviation is significantly affected by the interaction between pulse-off time and Wire feed rate.

**c)** Main reasons of deviations in the Pitch of WEDMed gears are irregular shaped craters created due to the violent sparks having high discharge energy and wire-lag due to various forces generated during machining.

## REFERENCES

[1] Gokler, Mustafh, I., Ozanozgu, and Mithat, A., "Experimental investigation of effects of cutting parameters on surface roughenss in the WEDM process", *International Journal of Machine Tools and Manufacture,* 2000*,* Vol. 40(13), pp. 1831-1848.

[2] Antar, M.T., Soo, S. L., Aspinwall, D. K., Jones, D., and perez, R., "Productivity and Workpiece Surface Integrity of WEDM Aerospace Alloys Using Coated Wires", *Proceedings Engineering*, 2011, Vol. 19, pp. 3-8.

[3] Han, F., Jiang, J. and Yu**,** D., "Influence of machining parameters on surface roughness in finish cut of WEDM", *The International Journal of Advanced Manufacturing Technology*, 2007, Vol. 34(5), pp. 538-546.

[4] Mahapatra, S. S., and Patnaik, A., "Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method", *The International Journal of Advanced Manufacturing Technology*, 2007, Vol. 34 (9), pp. 911-925.

[5] Haddad, M. J., and Fadaei, T. A., "Material removal rate (MRR) study in the cylindrical wire electrical discharge turning (CWEDT) process", *Journal of Materials Processing Technology*, 2008, Vol.199(1.3), pp. 369-378.

[6] Tosun, N., and Cogun, C., " An investigation on wire wear in WEDM", *Journal of Materials Processing Technology,* 2003, Vol. 134 (3), pp. 273-278.

[7] Tosun, N., Cogun, C., and Tosun, G., "A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method", *Journal of Materials Processing Technology,* 2004, Vol. 152 (3), pp. 316-322.

[8] Mohammadi, A., Tehrani, A. F., Emanian, E., and Karimi, D., "Analysis of wire electrical discharge turning on material removal rate", *Journal of Materials Processing Technology*, 2008, Vol. 205 (1.3), pp. 283-289

[9] Townsend, D. P., *Dudley's Gear Handbook*, 2nd ed, New Delhi, Tata McGraw-Hill Publishing Company.

[10] Davis, J. R., "Gear Materials", *Properties and Manufacture*, 2nd ed. Ohio, ASM International, 2005

[11] Goch, G., "Gear metrology", *Ann CIRP,* 2003, Vol. 52(2), pp. 659–695.

[12] Normen, D. (DIN) Standard 3962, *Tolerances for cylindrical gear teeth*, © Beuth Veriag GmbH Berlin, Germany.

[13] Grzesik, W., "Advanced Machining Processes of Metallic Materials", 1st ed., *Oxford:Elsevier*, 2008

[14] Qin, Y., "Micro-manufacturing Engineering and Technology", 1st ed., *Oxford: Elsevier*, 2010

[15] Hsu, T. R., "MEMS and Microsystems Design", *Manufacture and Nano Scale Engineering, 2008,* 1st ed., New Jersey: John Willey & Sons,

[16] Tarng, Y. S., Ma, S. C., Chung, L. K., "Determination of optimal cutting parameters in wire electrical discharge machining", *Int J Mach Tools Manuf*, 1995, Vol. 35(12), pp.1693- 1701.