Modeling and Analysis of Various Errors of Miniature Spur Gear in Wire-cut EDM of Inconel-718

T. Paul, S. Chakraborty* and D. Bose

Manufacturing Technology, Department of Mechanical Engineering
National Institute of Technical Teachers Training and Research, Kolkata-700106, India

Abstract

To manufacture components with intricate shapes and profiles, Wire electrical discharge machining (WEDM) is widely accepted as non-traditional machining process. This paper has dealt with the development in the material science that leads to the development of advanced engineering material like super alloy i.e. Inconel-718. An alternative competitive process is WEDM to manufacture complex Inconel part geometries. Therefore, it is observed that manufacture of micro spur gear with high dimensional accuracy is a very challenging task by WEDM process. Five process parameters like Pulse-on-time, Pulse-off-time, Wire feed, Gap voltage and Peak current upto 5 levels are chosen as an input parameter. This paper is focused on the aspects related to the material removal rate and dimensional accuracy which are the most important parameters from economical aspects as well as from the point of view of selecting the optimum condition of processes. In addition, the present work also proposes the development of mathematical model to predict the Pitch error, Addendum error, Dedendum error and Tooth thickness error by using RSM. It is seen that the material removal rate is high when the peak current and Ton is at extreme. It has also been concluded that at high discharge energy the rate of errors increases along with the formation of dominant coral reef (SEM analysis). Random micro voids also occur at low discharge energy. Thus, optimum input parameters are obtained by using Multi objective optimization to achieve minimum errors in the gear profile. ANOVA is used to identify the significant process parameters.

Keywords: WEDM, Miniature Spur Gear, Material Removal Rate (MRR), various errors, Optimization, Regression Models, ANOVA

1. INTRODUCTION

In industrial, scientific and domestic applications miniature gears are extensively used. Typical applications of this gear are mostly shown in robotic drives, smart toys, timer mechanisms, precision scientific instruments, robotics drive, miniature pumps and motors. The conventional process of generating meso gears consist of gear stamping, gear hobbing, powder metallurgy, gear extrusion, and die casting. But there are certain limitations i.e. post finishing operations are necessary in gear stamping for avoiding poor edge definition, in gear extrusion there is a problem of die wear, in gear hobbing process tool marks occur on the flanks of the gear, accuracy of gears are poor for die casting, and to arrange various fine powder of gear materials is one of the challenging task in the powder metallurgy process [1-3]. Through the international standers, the quality of micro geometry parameters of a gear is determined by AGMA (American gear manufacturing association) and DIN (Deutsche normen). Better quality gear is indicated by Higher AGMA number or lower DIN number and vice versa [4]. In [5] it has been proved that low discharge energy is the most significant factor for better quality gear. To achieve best quality gears the experimental research decided to identify the most significant parameters (Peak current, Pulse on time, Pulse off time, Gap voltage, and Wire feed rate) within the feasible ranges [6]. The effect of the five parameters on accumulated pitch deviation and total profile deviation has been described in [7]. In [8] the effect of wire feed rate, peak current and pulse off time on outside diameter and chordal tooth thickness of the best quality miniature gear has been determined. The difficulty in adopting the traditional manufacturing processes for producing micro gears can be attributed mainly due to the development of new materials with a low machinability, dimensional and accuracy requirement for precision application and a higher production rate and economy.

For the present study Inconel-718 alloy has been chosen as work piece material for manufacturing gear.Inconel-718 alloy is nickel based super alloy. It has a very high strength and high corrosion resistant. Inconel-718 is widely used in turbo machinery industry due to their outstanding mechanical properties [9]. It is very difficult task to machine an advanced material like Inconel alloys by using conventional mechanical processes such as broaching, milling or grinding [10]. WEDM process is an alternative competitive process to manufacture complex Inconel part geometries. For the transmission of motion smoothly, a fine pitch gears are generated by implementing brass wire during machining. Inconel-718 typically finds application in gas turbines, rocket motors, space craft and nuclear reactors and pumps. This paper particularly dealt with the generation of the best quality miniature gear by the best feasible combination of the input parameters.

2. DETAILS OF EXPERIMENTATION

2.1. Selection of Process Parameters

The parameters selection is based on certain consideration to input parameters and output parameters. Table 1 shows the machining parameters of the present investigation.

2.2 Controllable Parameters and Their Limits

The identification of process parameters and to define the level of each factor has been formed to be equally crucial to the successes of any optimization problem. The controllable parameters their actual and decided ranges along with the different levels are shown in Table 2.

* Corresponding Author Email: sadananda116@gmail.com

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Table 1: Input and Output Parameters

Input Parameters	Output Parameters
1. Pulse-on-time (µs)	1. Material removal rate (mm^3/min)
2. Pulse-off-time (µs)	2. Surface roughness(µm)
3. Wire feed (mm/min)	3. Various errors (Pitch error, Addendum error, Dedendum error, Tooth thickness error)(mm)
4. Gap voltage (volts)	
5. Peak current (A)	

Table 2: Controllable Parameters and Their Limits

Notations (Coded names)	Controllable parameters	Levels/Limits				
		-2	-1	0	1	2
A	Wire feed rate (m/min)	30	45	60	75	90
B	Peak current (A)	1	2	3	4	5
C	Pulse-on-time (µsec)	20	30	40	50	60
D	Pulse-off-time (µsec)	3	5	7	9	11
E	Gap voltage (Volts)	40	50	60	70	80

2.3 Design of Miniature Gear

Design Calculation is represented in Table 3.

i. Module = 0.7mm
ii. Numbers of teeth (N) =10
iii. Pressure Angle (°) = 20°

Table 3: Design Calculation of Miniature Gear

Sl No	Terms	Formula	Dimensions (mm)
1	Module	P.C.D/N	0.7
2	Circular Pitch	π x m	2.19
3	Addendum	0.318 x C.P	0.69
4	Addendum circle diameter	P.C.D +(2 x Addendum)	8.4
5	Clearance	C.P/20	0.11
6	Dedendum	Addendum x clearance	0.81
7	Dedendum Circle Diameter	P.C.D - (2 x Dedendum)	5.4
8	Tooth Thickness	C.P/2	1.1

3. RESULTS AND DISCUSSION

The details physical and geometrical aspects of the miniature gears are given in the following sections.

3.1 Optimal Levels of Process Parameters for Single Responses

By using Response Surface Methodology the optimum level of process parameters has been achieved to obtain the best quality miniature gears. In this study, Table 4 shows the optimal levels of process parameters for single responses.

Table 4: Optimal Levels of Process Parameters for Single Responses

Response	Optimal Values				
	A	B	C	D	E
MRR	30	5	60	3	70
SR	60	3	20	6	60
Pitch error	30	3	60	7	40
Addendum error	75	3	20	5	80
Dedendum error	30	1	60	6	40
Tooth thickness error	60	3	30	5	80

3.2 Analysis of Variance (ANOVA)

The effect of parameters on responses is carried out by ANOVA. Different parameters are having a relative significance value and it is determined by the calculated F-values for various responses. The Analysis of Variance (ANOVA) and F-ratio test have been performed to check the adequacy of the model as well as the significance of the individual model co-efficient. It can be appreciated the P value is less than 0.05 (Table 5- Table 8) which means the model is significant at 95% confidence level. In the present investigation ANOVA analysis is concluded that wire feed is not significant factor for pitch error, Dedendum error and Addendum error but Ip, Ton, Toff and Gv are the significant factor as given in Table 5- Table 7. For Tooth thickness error, all parameters (as chosen in this study) are significant.

Table 5: ANOVA for Pitch Error

Factors	DOF	SS^2	MS	F	P
W.F	1	0.00018	0.00018	1.00	0.325
Ip	1	0.001530	0.001530	8.50	0.000
Ton	1	0.042197	0.042197	234.38	0.000
Toff	1	0.112954	0.112954	627.41	0.000
GV	1	0.000072	0.000072	0.40	0.002
Error	31	0.005581	0.000180		
Total	51	0.346489			
S= 0.0134176 R-sq= 98.39% R-sq(adj)= 97.35%					

Table 6: ANOVA for Dedendum Error

Factors	DOF	SS^2	MS	F	P
W.F	1	0.000000	0.000000	0.00	0.569
Ip	1	0.000040	0.000040	0.27	0.000
Ton	1	0.085110	0.085110	585.79	0.000
Toff	1	0.057570	0.057570	396.24	0.000
GV	1	0.000241	0.000241	1.66	0.000
Error	31	0.004504	0.000145		
Total	51	0.300798			
S= 0.0120537 R-sq= 98.50% R-sq(adj)= 97.54%					

3.3 MATHEMATICAL MODEL

The empirical models are developed for Addendum error, Dedendum error, pitch error and tooth thickness error based on the experimental value using MINITAB 16 and the models are represented in Equation 1, 2, 3 and 4.

Table 7: ANOVA for Addendum Error

Factors	DOF	SS^2	MS	F	P
W.F	1	0.000910	0.000910	3.70	0.064
Ip	1	0.003660	0.003660	14.87	0.000
Ton	1	0.093354	0.093354	379.34	0.000
Toff	1	0.195776	0.195776	795.53	0.000
GV	1	0.014273	0.014273	58.00	0.000
Error	31	0.007629	0.000246		
Total	51	0.589016			
S= 0.0156874	R-sq= 98.70%	R-sq(adj)= 97.87%			

Table 8: ANOVA for Tooth Thickness Error

Factors	DOF	SS^2	MS	F	P
W.F	1	0.05103	0.05103	25.25	0.000
Ip	1	0.23069	0.23069	114.15	0.000
Ton	1	0.00115	0.00115	0.57	0.000
Toff	1	0.98819	0.98819	488.98	0.000
GV	1	0.07038	0.07038	34.83	0.000
Error	31	0.06260	0.002021		
Total	51	3.68793			
S= 0.0449544	R-sq= 98.30%	R-sq(adj)= 97.21%			

The models have maintained a noble relationship between parameters and their respective responses. The models are having the value of R^2 above 0.95.

PITCH ERROR = 1.917 + 0.00583 W.F - 0.1787 Ip - 0.02969 Ton - 0.2622 Toff - 0.00048 G.V + 0.000057 W.F * W.F + 0.01653 Ip * Ip + 0.000112 Ton * Ton + 0.012351 Toff * Toff + 0.000087 G.V * G.V + 0.000458 W.F * Ip - 0.000003 W.F * Ton + 0.000057 W.F * Toff - 0.000241 W.F * G.V + 0.001194 Ip * Ton - 0.00139 Ip * Toff + 0.000131 Ip * G.V + 0.001342 Ton * Toff + 0.000079 Ton * G.V + 0.000163 Toff * G.V (1)

ADDENDUM ERROR = 9.629 - 0.00745 W.F - 0.2492 Ip - 0.01775 Ton - 0.1733 Toff - 0.00896 G.V + 0.000065 W.F * W.F + 0.03472 Ip * Ip - 0.000018 Ton * Ton + 0.008854 Toff * Toff - 0.000138 G.V * G.V + 0.000863 W.F * Ip - 0.000010 W.F * Ton + 0.000215 W.F * Toff - 0.000073 W.F * G.V + 0.001728 Ip * Ton - 0.00290 Ip * Toff - 0.000837 Ip * G.V - 0.001757 Ton * Toff + 0.000529 Ton * G.V + 0.001342 Toff * G.V (2)

DEDENDUM ERROR = 6.520 + 0.00178 W.F + 0.0541 Ip - 0.04123 Ton - 0.2977 Toff - 0.00999 G.V + 0.000004 W.F * W.F - 0.00253 Ip * Ip + 0.000197 Ton * Ton + 0.010552 Toff * Toff + 0.000034 G.V * G.V - 0.000456 W.F * Ip + 0.000021 W.F * Ton + 0.000032 W.F * Toff - 0.000032 W.F * G.V - 0.000120 Ip * Ton - 0.00203 Ip * Toff + 0.000107 Ip * G.V + 0.002287 Ton*Toff + 0.000066 Ton * G.V + 0.000728 Toff * G.V (3)

TOOTH THICKNESS ERROR = 9.195 - 0.04687 W.F - 1.4280 Ip - 0.08128 Ton - 0.5617 Toff - 0.0553 G.V + 0.000437 W.F * W.F+ 0.07017 Ip * Ip - 0.000012 Ton * Ton + 0.02861 Toff * Toff - 0.000021 G.V * G.V + 0.005160 W.F * Ip - 0.000128 W.F * Ton + 0.001156 W.F * Toff - 0.000361 W.F * G.V + 0.010530 Ip * Ton - 0.01592 Ip * Toff + 0.007726 Ip * G.V - 0.000620 Ton * Toff + 0.001054 Ton * G.V + 0.001430 Toff * G.V (4)

3.4 PHYSICAL ASPECT OF MINIATURE GEAR

3.4.1. Various Error Measurement

Appropriate selection of parameters is essential to reduce the various types of error. It has been observed that at Wire feed rate 75m/min, Peak current 2A, Pulse on time 50µs, Pulse off time 5µs and gap voltage 70 V the best miniature gear has been manufactured. All miniature spur gear images have been taken by Leica Metallurgical Microscope and then manually measure the dimension through analysis software. Fig. 3(a) shows the measurement of tooth thickness and Fig. 3(b) shows measurement of the Addendum and Dedendum circle Diameter. The output parameters experimental values is 2.0385 mm^3/min for MRR, 0.19100 µm for Pitch error, 7.8950 µm for Addendum error, 4.3310 µm for Dedendum error, and 0.1820 µm for tooth thickness error. Few microscopic views during the measurement time of the miniature gears have been added below.

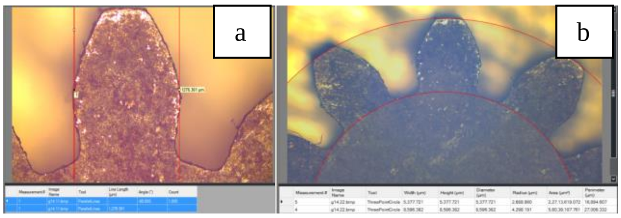

Fig. 3 (a) Measurement of the tooth thickness (b) Measurement of the Addendum and Dedendum Circle Diameter

3.4.2. Microstructure Characterization

The best quality gear that has been manufacture by WEDM on the combination of Wire feed rate 75m/min, Peak current 2A, Pulse on time 50µs, Pulse off time 5µs and gap voltage 70 V. In the present investigation the Fig. 4(a) depicts the SEM image of best quality gear. Similarly it has also been observed that at maximum peak current (5A), wire feed is 60m/min, pulse on time is 40µs, gap voltage is 60V and pulse off time is 7µs, the maximum error has been achieved that has been shown in Fig. 4(b). Minimum thermal impact takes place on the material surface at the lowest discharge energy.

4. MULTI-OBJECTIVE OPTIMIZATION

In the present investigation the multi-objective optimization suggests the desirability of combination of input variable to satisfy the goal. A multi objective optimization technique is used to incorporate RSM to find out the optimum solutions as combination of factors by fitting the regression model for all the responses. According to desirable function analysis, Fig. 5 shows the desirable value of input parameters. It also shows the optimal value of Wire feed rate 33.63m/min, Peak current 1.24A, Pulse on time 60µs, Pulse off time 8.25µs and gap voltage 40 V, which gives the best performance result.

Table 9 shows the predicted value and actual value of different responses. In the confirmation test it is clear that the error value is within the range and it is below 5%, so the model is acceptable.

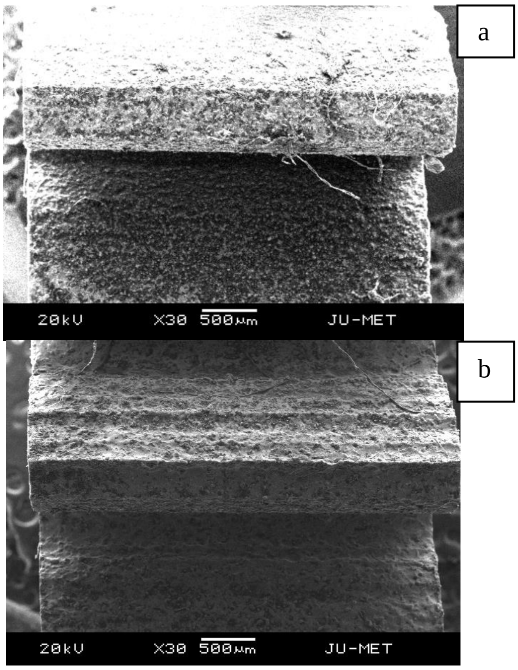

Fig.4 (a) SEM image of the best quality miniature gear tooth (b) SEM image of the worst quality miniature gear tooth

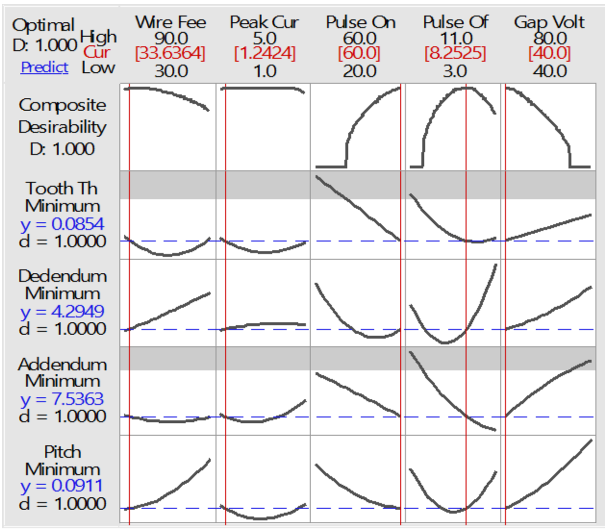

Fig.5 Optimal Graph

Table 9: Confirmation Test

Response	Predicted Value	Actual Value	Error
Tooth Thickness	0.0854	0.0892	4.2600
Dedendum	4.2949	4.167	3.0693
Addendum	7.5363	7.269	3.6772
Pitch	0.0911	0.0937	2.7748

5. CONCLUSION

In the present work, the various errors, as well as surface related inaccuracy of the miniature gear that are produced in WEDM process, are quantitatively and qualitatively interpreted and examined. The generation of the regular shaped craters is preferred to achieve for better surface integrity and geometric accuracy of the WEDM products.

- The main factors that affect the gear profile (geometrical profile) are Peak current, Pulse on Time and Gap Voltage. The outcome works also suggest that to achieve the best quality gear there should be a strongly implementation of low discharge energy parameters.
- The best quality miniature gears had the following experimental value 2.0385mm^3/min for MRR, 0.19100 µm for Pitch error, 7.8950 µm for Addendum error, 4.3310 µm for Dedendum error, and 0.1820 µm for tooth thickness error.
- SEM analysis also states that the best quality gear has achieved crack free surface structure as well as the surface of the gear tooth overlapped by flat, shallow, and regular shaped craters.
- Multi-objective optimization is adopted in this study for getting best solution and it is proved that the optimization technique is fitted for this investigation.
- High quality miniature gears with the best tribological properties and also with a better functional performance characteristics can be achieved by WEDM or in other words WEDM is an ideal choice for the generation of high quality miniature gears.

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