RESEARCH ARTICLE OPEN ACCESS

Process Parameters Optimization of Wire Electrical Discharge Machining for Inconel 601 using Gray Relational Analysis

Kumar Shatrughan[1], Verma Sanjeev[2]
Research scholar, Mechanical Engineering Department, Punjab College of engineering & Technology, Lalru, Mohali.
Associate Professor, Mechanical Engineering Department, Punjab College of Engineering & Technology, Lalru, Mohali.
Corresponding Author; Kumar Shatrughan

ABSTRACT: Inconel 601 is one of the potential materials applicable in aerospace, chemical industries and nuclear reactor applications, due to excellent resistance to high temperature, oxidation and corrosion over the conventional metals. A full scale application of such advanced materials is often hindered by the low stock removal, tool wear and high cost of machining, when the super alloys are machined by conventional machining processes. The increasing demand of machining of complex shape geometries and their high surface finish has further strengthened the need of non-conventional machining processes. Among the various processes, Wire Electrical Discharge Machining (WEDM) process is capable to accurately machine the parts with varying hardness or complex profiles.
KEYWORDS: Inconel 601, Mini tab, Taguchi's, WEDM.

Date of Submission: 21-02-2019 Date of acceptance: 10-03-2019

I. INTRODUCTION

The development in manufacturing industries has led to the demands for advanced materials such as composites, ceramics and super alloys, having high hardness, toughness and impact resistance. Challenges encountered during conventional machining of such materials are complex shape, high precision, surface quality, and machining costs. Conventional machining processes include turning, boring, milling, shaping, broaching, slotting, grinding etc. However, there arises difficulty in machining of advanced materials through conventional machining processes. The production of fine holes and intricate shapes profile in thin and brittle jobs is very difficult by conventional methods.

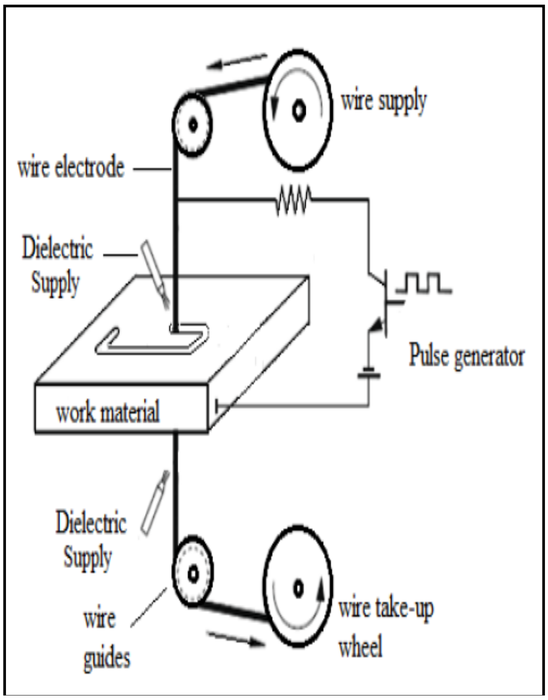
The process of piercing, stamping and extrusion do not work efficiently on brittle materials because of their limited plasticity. These materials may develop cracks or may even crumble under such processes. The non-conventional machining processes are suggested for such situations. Electrical Discharge Machining (EDM) and its variants such as Wire Electrical Discharge Machining, Electrical Discharge Drilling, etc. Abrasive Jet Machining (AJM), Ultrasonic Machining (USM), Water Jet Machining (WJM), Abrasive Water Jet Machining (AWJM), are some of the non-conventional machining processes.

Table 1: Properties of Inconel 601

Property	Metric
Density	84040 kg/m3
Melting Point	1350 °C
Co-Efficient of Expansion	2.8 μm/m °C (20-100°C)
Modulus of Rigidity	79 kN/mm^2
Modulus of elasticity	205.8 kN/mm^2
Specific Heat	410 J/kg K
Thermal Conductivity	9.8 W/m K

II. BASIC PRINCIPLE OF WEDM PROCESS

The WEDM machine tool comprises of a main worktable on which the work piece is clamped; an auxiliary table and wire drive mechanism. It is driven by the D.C servo motors. The travelling wire is continuously fed from wire feed spool and collected on take up spool which moves though the work piece and is supported under tension between a pair of wire guides located at the opposite sides of the work piece. A series of electrical pulses generated by the pulse generator unit is applied between the work piece and the travelling wire electrode, to cause the electro erosion of the work piece material. As the process proceeds, the controller displaces the worktable carrying the work piece transversely along a predetermined path programmed in the controller. While the machining operation is continuous, the machining zone is continuously flushed with de-ionized water passing through the nozzle on both sides of work piece. The de-ionized water is used as a dielectric fluid. A setup of wire electrical discharge machining is shown in the figure.



Schematic diagram of the basic principle of WEDM Process

III. PROCESS PARAMETER OF WIRE EDM

The process parameters that affect WEDM process are classified as electrical parameters and non-electrical parameters.

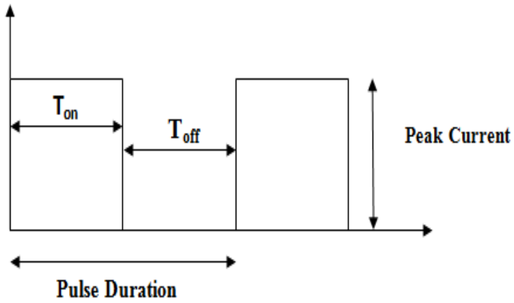
Electrical parameters:

1. Pulse on Time

The pulse on time is the current flowing in each cycle (Fig.1.10). During this time the voltage is applied across the electrodes. It is referred as T_{on} and represents the duration of time in micro seconds, µs. The T_{on} setting time range available on the machine tool is 1-131 (µs). The single pulse discharge energy increases with increasing T_{on} period, resulting in higher cutting rate. With higher values of Ton, however, surface roughness tends to be higher. The higher value of discharge energy may also cause wire breakage.

2. Pulse off Time

The pulse off time is the time in between the two simultaneous sparks occurs during this part of cycle the voltage is absent. It is referred as T_{off} and represents the duration of time in micro seconds, µs. The T_{off} setting time range available on the machine tool is 00 – 63 (µs). With a lower value of T_{off}, there are more number of discharges in a given time, resulting in increase in the sparking efficiency. As a result, the cutting rate also increases. Using very low values of T_{off} period, however, may cause wire breakage which in turn reduces the cutting efficiency. As and when the discharge conditions become unstable, one can increase the T_{off} period.



Series of Electrical Pulses at the Inter Electrode Gap

3. Peak Current

Peak current is the maximum value of the current passing through the electrodes for the given pulse and it is represented by IP. The IP setting current range available on the machine is 10–230 ampere. Increase in the IP value will increase the pulse discharge energy which in turn can improve the cutting rate further.

4. Spark Gap Voltage

The spark gap voltage is a reference voltage for the actual gap between the work piece and the wire used for cutting. It is represented by SV. The SV voltage range available on the present machine is 00 – 99 (V).

Non-Electrical parameters

1. Electrode material

Engineering materials having higher thermal conductivity, electrical conductive, melting point and cheapness are used as a tool material for Wire EDM process of machining. Copper and brass wire are used as a tool electrode in Wire EDM. They all have good wear characteristics and betters sparking condition for machining. In present work, Brass wire electrode with 0.25mm diameter has been used.

2. Wire Feed

Wire feed is the rate at which the wire-electrode travels along the wire guide path and is fed continuously for sparking. The wire feed range available on the present WEDM machine is 1–15 m/min. It is always desirable to set the wire feed to maximum. This results in less wire breakage, better machining stability and slightly more cutting speed.

3. Wire Tension

Wire tension determines how much the wire is to be stretched between upper and lower wire guides. This is a gram-equivalent load with which the continuously fed wire is kept under tension so that it remains straight between the wire guides. More the thickness of job more is the tension required. Improper setting of tension may result in the job inaccuracies as well as wire breakage. The wire tension range available on the machine is 1-15 (g).

4. Flushing Pressure

Flushing Pressure is for selection of flushing input pressure of the dielectric. The flushing pressure range on this machine is either 1 (High) or 0 (low). High input pressure of water dielectric is necessary for cutting with higher values of pulse power and also while cutting the work piece of more thickness. Low input pressure is used for thin work piece and in trim cuts.

5. Servo Feed

Servo feed setting decides the servo speed; the servo speed, at the set value of SF, can vary in proportion with the gap voltage (normal feed mode) or can be held constant while machining (with constant feed mode).

IV. TAGUCHI EXPERIMENTAL DESIGN

Dr. Genichi Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on orthogonal array experiments which gives much reduced variance for the experiment with optimum settings of control parameters. Thus the marriage of Design of Experiments with optimization of control parameters to obtain best results is achieved in the Taguchi Method. Orthogonal Arrays (OA) provide a set of well balanced (minimum) experiments and Dr. Genichi Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results. Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost. Taguchi methods have been used successfully in Japan and the United States in designing reliable, high quality products at low cost in such areas as automobiles and consumer electronics.

Taguchi’s methods focus on the effective application of engineering strategies rather than advanced statistical techniques. The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns.

In Taguchi method, the results of the experiments are analyzed to achieve one or more of the following objectives:

- To establish the best optimum condition for a product or process.
- To estimate the contribution of individual parameters and interactions.
- To estimate the response under the optimum condition.

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trends of influence of each parameter. The knowledge of contribution of individual parameters is a key in deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine the parameters which are more sensitive to the response.

Table 2: Standard layout of Taguchi’s L_9 (3^4) orthogonal array

Run order	Factors			
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

V. EXPERIMENTATION

Work material

In present study, plate of Inconel 601, (150x80x8mm). Inconel 601 have tensile strength of 1103 Mpa, compressive strength of 2200 Mpa and hardness value of 120 HRc. It has excellent oxidation and scaling resistance at temperatures up to 1093 °C, with an exceptional fatigue resistance, high corrosion resistance and high temperature strength.

Inconel 601 also possesses a high degree of formability and shows better weld ability than many highly alloyed nickel-base alloys. Inconel 601 is used in chemical processing, aerospace and marine engineering, pollution-control equipment, and nuclear reactor applications.

Composition of work material

Work material Inconel 601, which is basically alloy of nickel-chromium and molybdenum and the composition of the same is presented in the Table

Table 3: Composition of work material

C%	Ni%	Cr%	Mo%	Nb%	Co%	Mn%	Si%	P%	S%	Ti%
0.087	64.3	20.57	8.37	3.25	0.40	0.36	0.25	0.014	0.012	0.15

Specification of tool material

The chemical composition and mechanical properties of brass wire are shown in Table

Table 4: Composition of Brass Wire

Component	Wt.%
C	60-63
Zn	35.5
Pb	2.5-3.7
Fe	Max 0.35
Other	Max 0.5

Table 5: Mechanical properties of Brass Wire

Mechanical properties	Metric
Ultimate Tensile Strength	338-469 MPa
Tensile strength, Yield	124-310 MPa
Elongation at Break	53%
Modulus of Elasticity	97 GPa
Bulk Modulus	140 GPa
Poisson's Ratio	0.31
Machinability	100%
Shear Modulus	37 GPa

Table 6: Specification of WEDM machine used in the present study

Electronica Machine Tools Ltd, Pune	
Model	Elektra sprincut 734
Design	Fixed column, moving table
Table size	440 X 650
Max. work piece height	200 mm
Max. work piece weight	500 Kg
Main table traverse (x, y)	300, 400 mm
Auxiliary table traverse (U, v)	80, 80 mm
Wire electrode diameter	0.25 mm(standard)
Dielectric fluid	Deionized Water
Generator	ELPULS-40 A DLX
Interpolation	Linear & Circular
Least input increment	0.0001 mm
Least command input (X,Y,U,V)	0.0005 mm
Input power supply	3 Phase, AC 415 V, 50 HZ
Connected load	10 KVA
Average power consumption	6-7 KVA

Process parameters

In the present research work on the basis of literature review peak current (I_p), Pulse on time (T_{on}), Wire tension (WT) and feed rate (WFR) have been considered as process parameters. Thus, each process parameters were assigned three levels based the preliminary experiment conducted.

Table 7: Process parameters considered and their level

Factor	Name	Symbol	Unit	Levels		
A	Peak current	I_p	A	60	100	140
B	Pulse on time	T_{on}	µs	108	118	128
C	Wire tension	WT	N	8	9	10
D	Wire feed rate	WF	m/min	6	8	10

Table 8: Parameters kept constant during experiments

Parameters	Symbol	Unit	Value
Pulse off time	T_{off}	µs	52
Dielectric fluid pressure	WP	kgf/cm^2	15
Spark gap voltage	SV	V	45
Servo feed	SF	mm/min	2100
Cutting Tool	Brass wire of diameter 0.25mm		
Work piece height	8mm		

VI. EXPERIMENTAL DESIGN

In the present research work, L_9 orthogonal array has been chosen for the purpose of investigation. The number of treatment condition is equal to the number of row in orthogonal array and must be equal to or greater than the degree of freedom of different parameters considered. As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has two degree of freedom (DOE). This gives a total of 8 degree of freedom for four process parameters namely peak current, pulse-on time, wire tension and wire feed rate selected in present study. The total degree of freedom for the four factors is 8. So, the array selected fulfils the criterion for selection of array. Experimental layout of L_9 (3^4) orthogonal array used in present work is shown in Table.

Table 9: Experimental lay out using L9 (3^4) orthogonal array

Run	Peak Current I_p(A)	Pulse-ON time T_{on} (µs)	Wire Tension WT (N)	Wire feed rate, WFR (m/min)
1	60	108	8	6
2	60	118	9	8
3	60	128	10	10
4	100	108	9	10
5	100	118	10	6
6	100	128	8	8
7	140	108	10	8
8	140	118	8	10
9	140	128	9	6

Table 10: Experimental results of present work

Run	Peak Current Ip(A)	Pulse-ON time Ton (µs)	Wire Tension WT (N)	Wire feed rate, WFR (m/min)	Performance Measures					
					MRR (mm^3/min)	MRR (mm^3/min)	Average (mm^3/min)	SR (µm)	SR (µm)	Average (µm)
1	60	108	8	6	136.4	138.8	167.6	0.87	0.89	0.88
2	60	118	9	8	227.6	231.2	229.4	1.42	1.56	1.49
3	60	128	10	10	234.8	237.2	236	1.58	1.62	1.60
4	100	108	9	10	143.6	146	144.8	0.97	0.99	0.98
5	100	118	10	6	288.8	291.2	290	1.66	1.70	1.68
6	100	128	8	8	353.6	356	354.8	1.75	1.77	1.76
7	140	108	10	8	156.8	158.6	157.7	1.19	1.24	1.21
8	140	118	8	10	294.8	296	295.4	2.00	2.14	2.07
9	140	128	9	6	395.6	399.2	397.4	2.74	2.67	2.70

VII. RESULT AND DISCUSSIONS

This chapter contains the analysis of the result obtained from the present work. The effect of various process parameters during wire electrical discharge machining of Inconel 601 with Brass tool electrode will be studied. The experimental data has been collected from the experiments, and will be optimized with Taguchi based grey relational analysis (TGRA) using MATLAB software and MINI TAB software.

Table 11: Normalization of the experimental result for performance measures: MRR, SR

Exp. run	Data normalizing			
	MRR		SR	
Ideal value	1	2	1	2
1	1.0000	1.0000	0.4737	0.4737
2	0.718	0.7172	0.5745	0.5739
3	0.7033	0.7043	0.5976	0.5968
4	0.9701	0.9702	0.4880	0.4852
5	0.6049	0.6060	0.6016	0.6008
6	0.5178	0.5190	0.6205	0.6153
7	0.9196	0.9113	0.5192	0.5205
8	0.5956	0.5985	0.6796	0.7048
9	0.4737	0.4737	1.0000	1.0000

Table 12: GRG for each experimental run

Exp run	GRG	Order
1	0.7368	1
2	0.6457	7
3	0.6503	5
4	0.7279	3
5	0.6036	8
6	0.5667	9
7	0.7166	4
8	0.6462	6
9	0.7350	2

Table 13: Response Table for Grey Relational Grade

Levels	Ip (A)	Ton (μs)	WT (N)	WF (m/min)
1	0.6776	0.7271	0.6636	0.6499
2	0.6327	0.6318	0.6418	0.7035
3	0.7000	0.6513	0.6195	0.6568
Delta	0.0673	0.0953	0.0441	0.0536
Rank	2	1	4	3

VIII. CONCLUSION

In the experimental work, attempts to determine the optimal parametric setting for response characteristics namely material removal rate and surface roughness. In addition, to optimize for all the two responses, the Taguchi Based Grey Relational Analysis (TGRA) adopted to optimize the complicated inter-relationship among multi-performance characteristics. It is observed that the TGRA greatly simplifies the multi-optimization, and moreover do not require any complex mathematical objective computations. The various conclusions which have been observed from result and discussions are given below:

1. The greatest GRG value provide optimal parametric setting are peak current (Level 3), pulse on time (Level 1), wire feed rate (Level 1), wire tension (Level 2) which mean that the optimal process parameters, 140 A peak current, 108 µs pulse on time, 9 g wire tension, 6 m/min wire feed rate.
2. The response table for grey relational grade makes ranks which decides the most effective parameters namely pulse on time (rank 1), peak current (rank 2), wire feed rate (rank 3), wire tension (rank 4).
3. The pulse on time has the strongest effect among the other process parameters used to study the multi-performance characteristics, followed by peak current, wire feed rate and wire tension.
4. When pulse on time and peak current increases, higher MRR were achieved due to the larger discharge energy.
5. It is seen that cutting rate almost remains constant with increase in the wire tension. Though, with increase in wire tension, the machining stability increases as vibrations get restricted. It is absented that the increment in wire tension does not have much influence on cutting rate.
6. The surface roughness has an increasing trend with the increased pulse on time and peak current.
7. Wire tension and wire feed rate affect less on surface roughness and surface roughness slightly decrease with an increase in wire tension and wire feed rate.

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Kumar Shatrughan" Process Parameters Optimization of Wire Electrical Discharge Machining for Inconel 601 using Gray Relational Analysis " International Journal of Engineering Research and Applications (IJERA), Vol. 09, No.03, 2019, pp. 60-67