Parametric Optimization of Micro-EDM during Micro-Slits Generation on Inconel 600 using CCD and GRA

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Abstract

This paper reports on the use of foil electrodes for the generation of micro-slits i.e. rectangular micro-holes on Inconel 600 in a single pass with much reduced machining time. The process parameters such as voltage, duty ratio and sensitivity were chosen to study the machining performance. Copper foil of 240 µm thick was selected as a tool electrode. Since the accuracy of tool shape directly affects the feature geometry hence, wirecut-EDM is used for tool shaping. The experiments were planned using central composite design procedure. The performance measures were the volumetric material removal rate, Tool wear rate and micro-slits area overcut. Twenty randomized experiments were performed twice and mean response is considered for analysis to achieve accuracy in the result. The response table and the grey relational grade graph for each level of the machining parameters have been established and optimal process parameters were determined. The results of confirmation experiment showed an improved machining performance of Micro-electrical discharge machining. Using this approach, the achieved volumetric material removal rate of 0.005436 mm^3/min which was 29% improvement over initial machining settings.

Keywords: Micro-electrical discharge machining, Inconel 600, Foil electrodes, Central composite design, Grey relational analysis, Volumetric material removal rate, Tool wear rate and Micro-slits area overcut.

1. INTRODUCTION

With the growing demand of miniaturizations, micro-electrical discharge machining (micro-EDM) is becoming increasingly important to manufacture micro and miniature parts. Micro slits i.e. rectangular hole is an important 3D micro feature used in bio-medical components/devices and slits for scientific instrumentation. Other applications includes computational fluid dynamics (CFD) and electronic parts, slits on guideways and slideways for lubrication, spring locking systems and locking slits for automobile parts, surface to surface lubrication in MEMS devices. Most common method of fabrication of micro-slits is Laser beam machining (LBM). However, the complexity of the process, set up cost, dimensional and geometrical accuracy of the feature produced limits the use of LBM [1,2]. Micro-EDM is a non-traditional machining technology that has been found to be one of the most efficient technologies for fabricating micro-features. The non-contact nature of the process makes it possible to use a long and thin electrode for the machining. Also, very little force between tool and workpiece makes it capable for machining almost every conductive material, regardless of its hardness [3,4]. Although micro-EDM plays an important role in micro-feature machining and having many advantages, it has also some disadvantages. One of them is that it is a rather slow machining process; the other is that while the workpiece electrode is being machined, the tool electrode also wears at a significant rate which leads to shape inaccuracies [5].

The major performance measures that are generally studied in the micro-EDM are material removal rate, tool wear, surface quality, dimensional and geometrical accuracy of micro-parts [6,7]. In order to get desired machining performance such as more material removal, reduced excessive tool wear and improved dimensional accuracy in micro-EDM, the process parameters should be optimized. Kurafuji and Masuzawa [8] demonstrated the first application of micro-EDM by drilling a minute hole in 50 µm thick carbide plate. Since then, several authors have presented and discussed on major issues in micro-EDM, development, modeling, and optimization of the process in order to improve its machining performances. For the fabrication of 3D micro features using micro-EDM, the most common technique is scanning of tool electrode. Lim and Rahman [9] proposed the concept of linear scanning of traditional pin shaped tool electrode for engraving on the work surface by using Micro-EDM. Furthermore, relatively high tool wear limits the continuous use. Yan and Kaneko [10] Attempted to fabricate microgrooves with varied cross-sections by electro discharge machining. From the results, they observed significant tool wear which can be reduced with the proper selection of discharge energy. Apart from this, some notable researcher have shown that Foil tool electrode can be used instead of the pin shaped electrode in micro EDM for the micromachining of straight-line features in electrically conductive work materials. The machining time also reduced considerably. Yeo and Murali [11] proposed a new technique to increase the material removal rate by using foil as a tool electrode in machining of micro-grooves and micro-slits in brass. Using this technique, they achieved material removal rates as high as 0.002 mm^3/ min. Kuo and Huang [12] Reported the application of series of micro-disk electrodes for the generation of micro-slits of size 10 µm. Again, Murali and Yeo [13] proposed the concepts of fast EDM and gravity-assisted micro-EDM for the generation of high aspect ratio micro-grooves with the help of foil micro-electrodes with longitudinal and lateral actuation.

In this work, the rectangular cross-section foil tool used for the generation of micro-slits i.e. rectangular micro-holes on Inconel 600 in a single pass. The performance of the micro-EDM process is evaluated in terms of the volumetric material removal rate (VMRR), tool wear rate (TWR), and the slit area overcut. The process parameters such as voltage, duty ratio and sensitivity were chosen to study the machining performance. Appropriate selection and optimization of parameters may improve the machining cycle time, reduce excess tool wear and improve micro-feature quality. Hence, grey relational analysis

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technique is used to optimize the process parameters for desired output values of the machining performances.

Table 1
Shows the chemical composition of the Inconel 600 alloy work material.

Element	Composition (wt. %)
Ni	77.38
Cr	16.2
Fe	6.3
C	0.016
Mg	0.09
S	0.004
Si	0.002
Cu	0.006

2. EXPERIMENTAL DETAILS

The experimental work is conducted using a micro-EDM system, Hyper10 EDM, to generate micro-slits. The machine can be programmed for the positioning increment of 0.1 μm in the X, Y and Z-axes. The X- and Y-axes provide the longitudinal and lateral movement of the work table while Z-axis provides the vertical movement of machine spindle on which foil tool electrode is mounted securely into the collet. The Inconel 600 alloy sheet having dimensions (100×25×0.5) mm was fixed into the acrylic pot present on the setup with the help of fixture and magnetic clamps in order to get better positional accuracy. Here, the tool material used is copper foil having thickness of 240 μm so that it will not get deflected due to the flushing of dielectric used. Foil tool electrodes were shaped by wirecut-EDM in order to have dimensional accuracy. The dimensional measurement of the micro-slits was done using a Zeta instrument as shown in Figure 1.

Table 2
Process parameters and their levels (central composite)

Process Parameters	Symbol	Level				
		-1.68	-1	0	1	1.68
Voltage (V)	A	115	130	145	160	175
Duty ratio (%)	B	44.44	45.45	46.15	46.66	47.05
Sensitivity (%)	C	20	30	40	50	60

2.1 Design of Experiment and Optimization

In the present study, experiments were designed on the basis of statistical design of experiment technique such as the central composite design (CCD) proposed by Myers and Montgomery [14] to reduce the size of experiments without loss of accuracy. This design consists of 8 cube points, 6 center points in cube and 6 axial points. The strategy of complete randomization was adopted for conducting the experiments. Grey relational analysis was employed to execute the multi-performance optimization to find a unique optimal machine parameter setting for all the performance characteristics. Three most influencing process parameters were selected and each parameter was designed to have five levels which are shown with their codes in Table 2.

2.2 Measurement of Performance characteristics

2.2.1 Volumetric material removal rate

In this study, VMRR is to be calculated from the geometry of the micro-slit produced (Eq. 1). For simplicity, we considered the dimensions of micro-slit at the bottom is similar to that of dimensions of top surface of micro-slit otherwise which may be slightly different due to the tool electrode wear [15].

$$VMRR \approx \frac{L \times W \times H}{T} \qquad (1)$$

Where L, W and H is the length, width, thickness of the plate and T is the machining cycle time.

2.2.2 Tool wear rate

It is the volume of tool eroded during machining per unit time and calculated by weight difference method i.e. weight before machining and weight after machining measured on Sartorius (CP423S) having d = 0.001g.

2.2.3 Micro-slit area overcut

It is the extra material removed by the tool that exceeds the dimensions of micro feature produced and calculated by the difference between micro-slit area and tool area.

2. GREY RELATIONAL ANALYSIS

Grey relational analysis is used to analyze and select the optimal machining conditions of micro-EDM process on the multiperformance characteristics, namely volumetric material removal rate, tool wear rate and micro-slit area overcut in the experimental studies. The grey relational analysis includes the various steps such as [16]:
Step 1: Normalize the experimental results of each response variable.
Step 2: Calculate the grey relational coefficient for each response variable.
Step 3: Calculate the grey relational grade by the mean value of grey relational coefficient.
Step 4: Performs the response table and response graph for each level of the process parameters.
Step 5: Recognize the noticeable and unnoticeable variable factors and select the optimal level of the process parameter.
Step 6: Confirms test and verifies the optimal levels of process parameter.

3.1 Results of response table

Since the grey relational grade represents the level of correlation between the reference sequence and the comparability sequence, the greater value of the grey relational grade means that the comparability sequence has a stronger correlation to the reference sequence. In other words, regardless of category of the performance characteristics, a greater grey relational grade value corresponds to better performance [16]. Therefore, the optimal level of the machining parameters is the level with the greatest grey relational grade value and which is indicated by an asterisk (*). Based on the grey relational grade values given in Table 4, the optimal machining performance for maximum material removal rate and minimum tool wear rate and slit area overcut were obtained for 175 V voltage, 50% sensitivity and 46.66 duty ratio.

3.2 Confirmation test results

Since the optimal level of the process parameters is selected, the confirmation test is conducted to verify the improvement of performance characteristics. The results of confirmation experiment are compared with the initial conditions of design operating parameters. Table 5 shows the compared results of the selected optimal and initial design of machining parameters. Consequently, it is shown clearly the above performance characteristics in the micro EDM process are greatly improved through this study.

Table 3

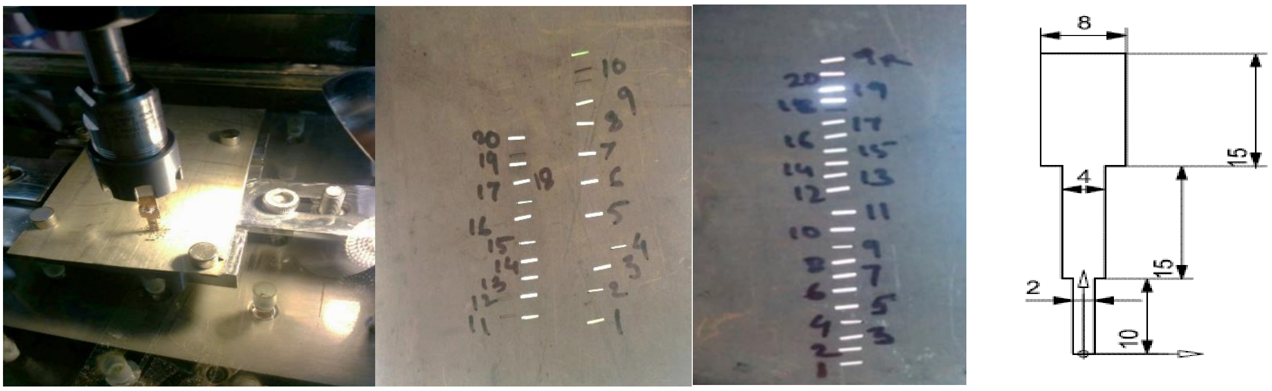
Shows normalization, grey relational coefficient and grey relational grade of the performance characteristics

Exp. No.	Normalization			Grey relational coefficient			Grey relational grade	Rank
	VMRR (mm^3/min)	TWR (mg/min)	Slit area overcut(mm^2)	VMRR (mm^3/min)	TWR (mg/min)	Slit area overcut(mm^2)		
1	0.1991	0.1408	0.6044	0.3843	0.3678	0.5583	0.4368	13
2	0.5571	0.6485	0.1584	0.5302	0.5872	0.3727	0.4967	8
3	0.1399	0.0515	0.4357	0.4694	0.3452	0.4698	0.4281	16
4	0	0.3347	0.5740	0.3334	0.4291	0.5398	0.4341	15
5	0.1323	0.7136	0.5417	0.3656	0.6358	0.5217	0.5077	6
6	0.5846	0.0236	0.4331	0.5462	0.3386	0.4686	0.4511	10
7	0.1943	0.6365	1	0.3829	0.5790	1	0.6539	2
8	0.4695	0.6277	0.5688	0.4852	0.5732	0.5371	0.5318	4
9	0.0391	0.4808	0.5326	0.3422	0.4906	0.5169	0.4499	11
10	1	0.2754	0.3936	1	0.4083	0.4519	0.6201	3
11	0.2737	0	0.4815	0.4077	0.3334	0.4909	0.4106	18
12	0.3572	0.25	0.2417	0.4375	0.4	0.3974	0.4116	17
13	0.2868	0.7078	0.5720	0.4121	0.6312	0.5388	0.5274	5
14	0.1166	0.2166	0.2074	0.3614	0.3896	0.3868	0.3792	20
15	0.2898	0.3871	0.4705	0.4131	0.4492	0.4857	0.4493	12
16	0.2250	0.7136	0.4654	0.3921	0.6358	0.4833	0.5037	7
17	0.2446	0.6084	0.3742	0.3982	0.5608	0.4441	0.4677	9
18	0.6261	1	0.5442	0.5722	1	0.5231	0.6984	1
19	0.2717	0.4779	0	0.4071	0.4892	0.3334	0.4099	19
20	0.2614	0.5494	0.1868	0.4037	0.5260	0.3807	0.4368	14

Table 4

Response table for grey relational grade

Process parameter	Grey relational grade						
	-1.681	-1	0	1	1.681	Max-Min	Ranking
Voltage (V)	0.4499	0.4921	0.4695	0.4932	0.6201*	0.1702	1
Duty ratio (%)	0.4106	0.4731	0.4942	0.5120*	0.4116	0.1014	3
Sensitivity (%)	0.5274	0.4489	0.4858	0.5361*	0.3792	0.1569	2
Mean Grey relational grade: 0.4802 and Predicted Grey relational grade: 0.7078							



(a) (b) (c) (d)

Figure 1 (a) During micro-slits generation, (b) & (c) Micro-slits generated on Inconel 600 plate and (d) Schematic of tool electrode shaped by wirecut-EDM (All dimensions are in millimeter, mm)

4 CONCLUSIONS

The paper has presented the successful use of foil tool for the generation/fabrication of micro-slits on 0.5mm thick Inconel 600 sheet using micro-EDM. Among three process parameters studied, the voltage has the highest influence on machining performances followed by sensitivity and duty ratio. Through this approach, the machining performance of micro-EDM can be improved in terms of material removal, tool wear and geometrical accuracy of micro slit or similar micro feature that can be fabricated in a single-pass of tool electrode. The presented approach is simple and effective for machining complex 3D micro shapes.

Table 5

Comparing results of the initial and optimal process parameters

Process parameters	Unit	Initial setting	Optimal setting
Voltage (A)	V	145	175
Duty ratio (B)	%	46.15	46.66
Sensitivity (C)	%	40	50
VMRR	mm^3/min	0.003861	0.005436
TWR	mg/min	0.027778	0.038431
Slit area Overcut	mm^2	0.1864	0.2067

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