Optimization of Electrical Discharge Texturing for Large Surfaces using Genetic Algorithm

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Abstract

Electrical discharge texturing (EDT) enables large area texturing in components such as mill rolls and bio-implants, where random overlay textures are suitable. Such large area texturing requires maintaining similar surface roughness values at all locations for consecutive samples made with same electrode under similar experimental conditions. The goal of the current work is to optimize EDT process towards minimizing the factors affecting large area texturing of rougher surfaces. Experiments were performed on Ti6Al4V samples with copper as electrode and paraffin oil as dielectric varying the parameters namely peak current, pulse on-time and input voltage at levels suitable for rough texturing. It was found that under those experimental conditions that the copper tool shows mass gain due to carbon deposition in contrast to the usual mass reduction due to erosion, which is in agreement with the experimental results under similar conditions in literature. Hence to ensure uniform texture production, a multi-objective optimization of the EDT process is performed with aims of reduction in mass change of tool electrode (MCT) and change in surface roughness of tool electrode ($(S_{a|final} - S_{a|initial})_{tool}$), and improvement in material removal rate (MRR) and surface roughness (S_a) of workpiece, using genetic algorithm. The optimized values for MCT, $(S_{a|final} - S_{a|initial})_{tool}$, MRR and S_a obtained are -0.06 mg/min, 2.69 µm, 6.62 mg/min, and 8.73 µm, respectively, obtained at parameter setting of 20 A, 200 µs and 80 V of peak current, pulse on-time, and input voltage, respectively.

Keywords: EDT, EDM, Surface texturing, Surface roughness.

1. INTRODUCTION

Large area texturing using EDM finds application in mill rolls [1], ortho-implants [2], and solar cells [3]. Each of these applications require different surface roughness values which can be provided through electrical discharge texturing (EDT), the texturing variant of EDM. The range of roughness parameter, arithmetic mean height (S_a) obtained through EDT is from 2.4 µm to 21 µm [4]. This enables EDM to be a process which can do both primary machining and random texturing on 'difficult-to-machine' materials such as Ti6Al4V.

The titanium alloy Ti-6Al-4V is a super-alloy which finds applications in the fields such as aerospace [5] and bio-implants [6]. The EDM treated Ti-6Al-4V alloy shows better cell growth than conventionally used plasma spraying process [2]. This has been attributed to the carbon layer formation on the textured surfaces along with more favorable microstructure shape and distribution [2]. Hence, development of stable texturing of Ti-6Al-4V surfaces using EDT offers a lot of applications.

The current work studies the challenges faced in texturing large areas through EDT and to perform an optimization of the process to enable a stable texturing process for a longer duration using genetic algorithm.

2. CHALLENGES IN LARGE AREA TEXTURING WITH EDT

EDT of large areas using areas of similar size is not applicable in cases where samples of different sizes are to be textured or if the texture required is on very large area. The solution in such cases is texturing large areas using EDM through milling action by an electrode with comparatively much smaller texturing area. Though this simplifies the texturing process to a large extent by utilizing an easily available form of electrode, there are certain challenges faced in this method, which are discussed below.

i) Tool wear

The tool wear leads to slope formation in the textured area and the reduction in texturing area of tool due to face wear and side wear of the tool, respectively. Though different methods [7-8] of compensation of tool face wear are provided, side wear of tools still offers challenge in texturing and milling applications of EDM.

ii) Roughness of tool surface

As the texturing progresses, the surface of tool acquires a rough finish from the initial smooth finish owing to material removal in shape of hemispherical craters due to sparking. This leads to a variation in the roughness of the textures generated on the work surface during the progression of the process.

iii) Material deposition on tool surface

Carbon layer deposition happens on tool surface while using hydrocarbon dielectric during EDM [9]. This carbon layer protects the electrode due to its high boiling temperature and high thermal resistance [9]. However, this carbon layer leads to reduced discharge efficiency [10]. The carbon layer formation is found to be advantageous in texturing of ortho implants [2]. Chen et al. [10] found that EDM of Ti-6Al-4V in presence of a hydrocarbon dielectric leads to a significant layer of carbon deposition on the electrode surface which leads to retardation of the process.

These effects are required to be minimal to ensure a uniform texturing on work surfaces using EDT.

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3. EXPERIMENTAL SETUP AND METHODOLOGY

Experiments were performed on the machine Electronica S50 CNC EDM. Precision milled Ti-6Al-4V samples of dimensions 40 x 20 x 5 mm^3 were the workpieces. The tool selected was copper electrode of 100 mm diameter, with its end face used for texturing. The work and tool surfaces are polished with SiC papers of grit size 220 to 600 to obtain a smooth reflective finish. This is to reduce the effect of any initial roughness or waviness of work or tool surface on the final texture obtained on the work surface after EDT.

The parameters varied for experimentation are pulse on-time, peak current, and gap voltage. Experiments to be performed were selected according to Central Composite Design (CCD). Thus, a total of 20 experiments were conducted according to the design which includes 6 central point runs. The parameters used for the experiments were as shown in Table 1.

Table 1 Parametric Settings for experimentation

Fixed parameters					
Workpiece	Ti6Al4V				
Electrode	Copper rod electrodes				
Dielectric	Paraffin oil				
Polarity	Normal				
Speed	No rotation				
Duty factor (%)	25				
Depth of slot (mm)	0.3				
Controlled parameters					
	-2	-1	0	+1	+2
Pulse-on-time (μs)	100	200	300	400	500
Current (A)	10	20	30	40	50
Voltage (V)	35	50	65	80	95
Responses measured	Surface roughness		MRR/MCT		
Apparatus used	Alicona Infinite Focus Microscope		Sartorius weighing balance		

The study being conducted with the aim of obtaining a stable large area texturing through EDT, the responses considered were material removal rate (MRR), surface roughness (S_a) of workpiece, mass change of tool electrode (MCT), and change in surface roughness of tool electrode ($(S_{a|final} - S_{a|initial})_{tool}$). The surface roughness parameter measured was an area (or texture) surface roughness parameter known as arithmetic mean height (S_a). This was because area (3D) surface roughness parameters better represent the surface texture as compared to profile (2D) surface roughness parameters.

4 RESULTS AND DISCUSSION

The regression analysis of the data has been performed using statistical softwares like MINITAB and DESIGN EXPERT. The effects of the parameters such as peak current, pulse on-time and input voltage on different responses are discussed in the following subsections.

4.1 Material Removal Rate (MRR)

The main effect plots for MRR are shown in Fig.1. Regression analysis showed that peak current, pulse on-time and input voltage are the significant parameters affecting MRR. Peak current shows the highest significant influence on MRR. It could be seen that with respect to peak current, MRR shows a steady increase. This is because with increasing peak current the material removed per individual spark increases, and thereby increasing the MRR. However, MRR initially shows an increase up to 200 μs and then a decrease for higher values with respect to pulse on-time. This is due to molten material re-solidification at higher pulse durations. Input voltage has the least significance and it is seen that there is a slight increase in MRR with an increase in gap voltage from 35 V to 95 V.

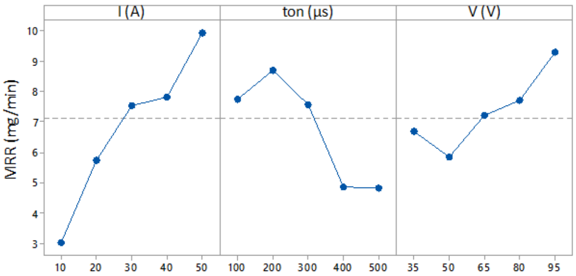

Fig. 1. Main effect plots for MRR (mg/min)

4.2 Surface Roughness of Workpiece (S_a)

The main effect plots for S_a are shown in Fig.2. Regression analysis showed that peak current and pulse on-time are the significant parameters affecting S_a. Surface roughness S_a shows an increase with increasing peak current. This is due to increasing crater size at higher peak current which in turn leads to higher S_a [11]. However, with pulse on-time, S_a shows an increase up to 200 μs and then shows a decrease at higher on-time values. This is because crater depth increases and crater radius decreases at higher pulse on-times which leads to shallow valleys and hills [11].

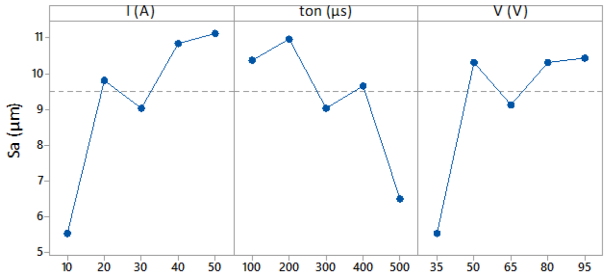

Fig. 2. Main effect plots for S_a (μm)

4.3 Mass Change of Tool (MCT)

Tool mass change is considered for measuring tool wear instead of much more accurate tool dimension change because of the uneven dimension change at different locations during tool wear resulting in unreliable data. The density of the carbon layer is much lesser that that of the base material copper of the electrode. Hence, for the lowest value of MCT obtained which is zero, there is an increase in tool dimensions. Therefore, in all experiments the volume of carbon deposited is higher than the volume of copper eroded.

The main effect plots for MCT are shown in Fig.3. Regression analysis showed that peak current, and pulse on-time are the significant parameters affecting MCT. The mass change in tool is obtained by subtracting tool wear rate (TWR) from material deposition rate (MDR). Tool wear is due to crater formation on the tool surface during sparking. Carbon layer formation on the tool surface leads to an increase in mass due to material deposition. At certain parameter settings, these two effects were found to cancel out each other. However, in most of the experiments, it was seen that there was an increase in mass of the tool after EDM which means material deposition rate was higher than tool wear rate. For an optimal texturing process, it is desired that the mass change of tool remains closer to zero. It is seen that MCT increases with increasing current and pulse on-time. This is due to higher carbon layer deposition due to breakdown of a larger region of dielectric at these high parametric conditions.

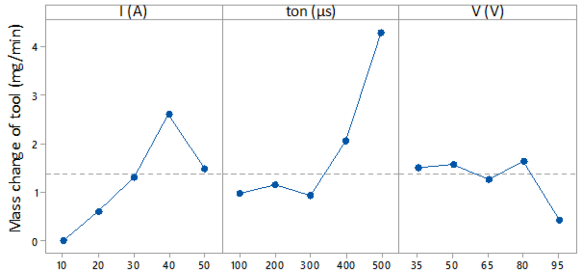

Fig. 3. Main effect plots for MCT (mg/min)

4.4 Roughness Change of Tool $(S_{a|final} – S_{a|initial})_{tool}$

The main effect plots for $(S_{a|final} – S_{a|initial})_{tool}$ are shown in Fig.4. Regression analysis showed that peak current and pulse on-time are the significant parameters affecting roughness change of tool. The tool surface is initially polished with SiC papers to keep the effect of initial surface roughness of tool surface on the textured surface minimal. S_a range for the polished tool surfaces were 1.5 to 1.9 µm. It is desired that the roughness of the consumable tool used for texturing does not show a large variance so as to ensure a uniform texturing. It was found that S_a value on the tool surface varied from 2.6 to 5.4 µm for experimentation at different parameter settings. The roughness change in tool is seen to increase with increasing peak current. This is due to larger crater dimensions at higher peak current leading to taller hills and deeper valleys compared to the polished tool. The roughness change in tool is observed to decrease with increasing pulse on-time. This is due to shallow craters at higher pulse on-times on the tool surface. Also, the carbon layer deposition on the tool surface at higher values of pulse on-time leads to a decrease in surface roughness.

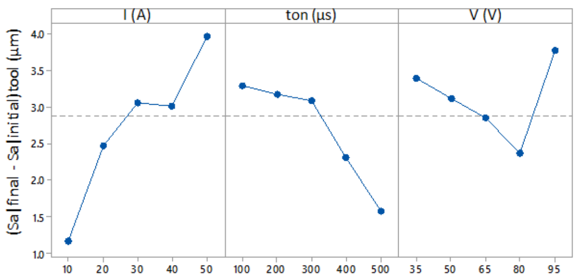

Fig. 4. Main effect plots for $(S_{a|initial} – S_{a|final})_{tool}$ (µm)

5 OPTIMIZATION FOR LARGE AREA TEXTURING

It is desired to obtain stable large surface texturing at high MRR and high surface roughness. This requires that the tool wear and tool roughness change remains minimal. Hence a multiple objective optimization is desired to be conducted with the objectives of maximizing MRR and S_a and minimizing MCT and $(S_{a|initial} – S_{a|final})_{tool}$. Statistical models obtained through regression analysis are used to form the objective function for the optimization problem. An evolutionary optimization method known as genetic algorithm is used for optimization. Genetic algorithm shows good efficiency in optimization of manufacturing processes [12].

For conducting optimization in genetic algorithm, the objective function is defined as follows

Minimize $f(A,B,C) = MCT + (S_{a|final} – S_{a|initial})_{tool} + (1/MRR) + (1/S_a)$ (1)

subjected to

$-1 \leq A \leq 1$

$-1 \leq B \leq 1$

$-1 \leq C \leq 1$

where A, B, and C represents the peak current, pulse on-time and input voltage, respectively in coded form. The levels -1 and 1 represent the values 20 A and 40 A, 200 µs and 400 µs, and 50 V and 80 V of peak current, pulse on-time and input voltage, respectively. Regression analysis of experiments conducted using CCD experimental design gives statistical models that are valid within -1 to +1 level range. Hence the -2 and +2 levels of the factors are not considered during optimization. MCT, $(S_{a|final} – S_{a|initial})_{tool}$, MRR, and S_a represent the model equation in coded form. Coded form of regression equations are selected to simplify the optimization process. The regression equations of these responses are given in Table 2.

Table 2 Regression equations of responses in coded form

	Regression equations
MCT	$= 1.38 + 0.68 * A + 0.64 * B – 0.12 * C$ (2)
$(S_{a\|final} – S_{a\|initial})_{tool}$	$= 2.89 + 0.49 * A – 0.43 * B – 0.14 * C$ (3)
MRR	$= (103.61 + 36.28 * A – 32.83 * B + 22.93 * C) ^{\wedge} (1 / 2.3)$ (4)
S_a	$= 9.48 + 0.96 * A – 0.82 * B + 0.61 * C$ (5)

The fitness function is computed using the following equation:

$T = (1 / f)$ (6)

A code was written in MATLAB for the optimization of the process using Genetic Algorithm. The following parameter settings were selected for coding of genetic algorithm.

Number of chromosomes = 80

Length of chromosomes = 48

Probability of crossover, $p_c = 0.8$

Probability of mutation, $p_m = 0.05$

Number of generations, n = 100

The convergence of genetic algorithm is shown in Fig. 5. It could be seen that the objective function *f(A,B,C)* converges to an optimum value of 2.8956 after 41 generations. For further generations up to 100, the objective function value remains same. Hence the optimum value is considered to have reached at 41st generation.

The optimized values for MCT, $(S_{a|initial} – S_{a|final})_{tool}$, MRR and S_a obtained are -0.06 mg/min, 2.69 µm, 6.62 mg/min, and 8.73 µm, respectively. This is observed at a parameter setting of 20 A, 200 µs and 80 V.

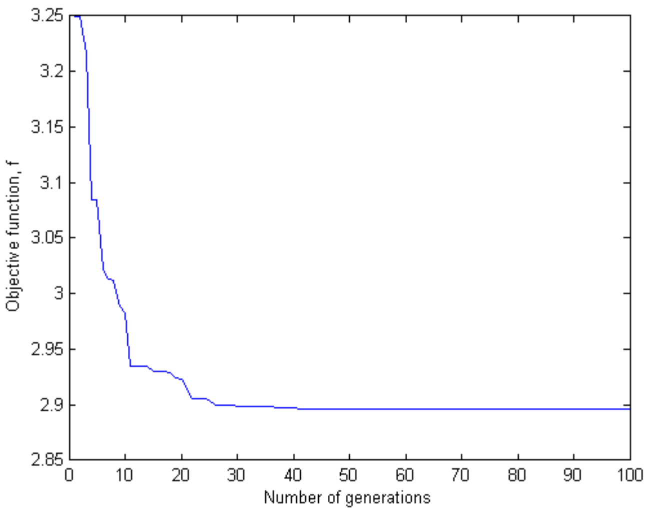

Fig. 5. Convergence of Genetic Algorithm

6 CONCLUSIONS

This work studies the challenges faced in large area texturing and attempts to optimize the process towards obtaining a stable electrical discharge texturing for large area. The following are concluded:

1. The major challenges in implementing large area texturing using EDT are tool wear, increase in roughness of tool and material deposition on the tool.
2. Higher values of pulse on-time though results in lesser tool roughness, causes an increase in carbon layer deposition on the tool surface which leads to a decrease in discharge efficiency.
3. With increasing peak current, MRR and S_a of workpiece increases. However, the unwanted effect of mass change in tool and roughness change in tool are also enhanced with increasing peak current.
4. The optimized values for MCT, $(S_{a|initial} - S_{a|final})_{tool}$, MRR and S_a obtained are -0.06 mg/min, 2.69 µm, 6.62 mg/min, and 8.73 µm, respectively, obtained at the parameter setting of 20 A, 200 µs and 80 V.

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