Optimization of Electro-Discharge Machining Responses of Super Alloy Inconel 718: Use of Satisfaction Function Approach Combined with Taguchi Philosophy

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Abstract
Inconel 718 is a Nickel-based super alloy which possesses high strength, high temperature resistance. This super alloy is mainly used in the applications of automobile, aerospace and defence industries. Due to the extreme toughness and work hardening characteristic of the alloy, the problem of machining Incone1 718 has become a great challenge. In this work, machinability aspects of Inconel 718 have been experimentally investigated during Electro-Discharge Machining (EDM) using Copper tool electrode. Based on five-factor-five-level L_{25} Orthogonal Array (OA), experiments have been conducted by varying the following controllable process parameters viz. OCV (gap voltage), peak current (I_P), Pulse-on Time (T_{on}), Duty Factor (τ) and Flushing Pressure (F_p). Machining performance has been evaluated in terms of multiple responses such as Electrode Wear Ratio (EWR), Roughness average R_a (of the EDMed surface), Surface Crack Density (SCD) and White Layer Thickness (WLT). Aforesaid performance features have been treated as objective functions towards optimization assuming that these correspond to Lower-is-Better (LB) requirement. The goal has been to determine the best setting of controllable process parameters within selected experimental domain to achieve satisfactory machining performance. Owing to the limitation of Taguchi's optimization philosophy i.e. it cannot solve multi-response optimization problem; the concept of satisfaction function has been attempted in this research to obtain satisfaction values of individual responses, thus, facilitating aggregation of multi-response features into an equivalent single index. A distance measure has been computed next which basically determines the separation of each experimental setting (alternative) with respect to the ideal expectation (satisfaction). Finally, this distance function has been optimized (minimized) by Taguchi method.

Keywords: Inconel 718; Electro-Discharge Machining (EDM); Orthogonal Array (OA); satisfaction function; Taguchi's optimization philosophy

1. Introduction and State of Art

Inconel 718 is a Nickel-based super alloy [1]. It finds huge application mainly in the aerospace industry, particularly, in the hot sections of gas turbine engines due to its extreme high temperature strength and high corrosion resistance of Inconel 718. But peculiar characteristics of Inconel 718 such as low thermal conductivity, strong work hardening tendency, presence of abrasive carbide particles, affinity to react with tool material etc. make it difficult-to-machine. Hence, it is classified as ''Difficult-to-Cut" material [2].

It has been experienced that for machining of high-strength, super-tough, less electrically conductive materials such as the aerospace materials including Inconel 718, conventional routes or traditional machining processes are not suitable [3]. In this context, non-conventional machining operations especially EDM has been found ample applications towards processing of such super alloys to obtain intricate shape of the finished part component with desired level of accuracy/dimensional precision, good surface finish. EDM process is carried out due to the thermo-electrical energy between the work piece and the tool electrode. A pulse discharge occurs in a small gap between the work piece and the electrode; the process removes unwanted material (debris) from the parent metal through melting and vaporising. The electrode and the work piece must have electrical conductivity in order to generate the spark

[4].

Ramakrishnan and Karunamoorthy [5] developed of Artificial Neural Network (ANN) models and performed multi-response to predict and select the best cutting parameters of Wire Electro-Discharge Machining (WEDM) of Inconel 718. Experiments were performed under different cutting conditions of pulse-on time, delay time, wire feed speed, and ignition current. The responses (namely material removal rate and surface roughness) were optimized concurrently using Multi-Response Signal-to-Noise (MRSN) ratio in addition to Taguchi's parametric design approach. It was identified that the pulse-on time, delay time and ignition current were the most influencing parameters than wire feed speed on the performance characteristics. Newton et al. [6] conducted an experimental investigation to determine the main EDM parameters responsible for recast layer formation on Inconel 718. It was found that average recast layer thickness increased primarily with energy per spark, peak discharge current, and current pulse duration. The recast material was found to possess in-plane tensile residual stresses, as well as lower hardness and elastic modulus than the bulk material. The peak discharge current, current pulse duration and energy per spark appeared to be the driving factors in determining average recast layer thickness. Table feed rate indirectly influenced energy per spark, which had a resulting effect on average recast layer thickness. The wire diameter and spark cycle (voltage-off time) settings did not display a significant effect on average recast layer thickness.

Lin et al. [7] addressed exploration of grey-Taguchi method for optimization of micro-milling electrical discharge machining process parameters of Inconel 718 alloy to achieve multiple performance characteristics such as low electrode wear, high material removal rate and low working gap. The influences of peak current, pulse-on time, pulse-off time and spark gap on various response features were analysed. Peak current and spark gap were found as two important parameters to achieve optimum results.

Aggarwal et al. [8] carried out empirical modelling of WEDM process parameters for Inconel 718 using Response Surface Methodology (RSM). The parameters such as pulse-on time, pulse-off time, peak current, spark gap voltage, wire feed rate, and wire tension etc. were selected as input variables keeping others constant. The performance was measured in terms of cutting rate and surface roughness. During this research, the pulse-on time appeared as the most influencing factor for cutting rate and surface roughness of Inconel 718. It was observed that the cutting rate increased with the increase in pulse-on time; while, it decreased with increase in spark gap voltage and pulse-off time. For surface roughness, the pulse-on time significantly interacted with peak current and spark gap voltage. It was also found that surface roughness increased with the increase in pulse-on time and decreased with the increase in spark gap voltage.

The aim of the present investigation is to obtain an optimal setting of process parameters including OCV (gap voltage), peak current, Pulse-on Time, Duty Factor and Flushing Pressure on performance characteristics of EDM on Inconel 718 work material in terms of EWR, R_a, SCD and WLT. An integrated optimization route combining satisfaction function approach and Taguchi method has been proposed herein.

2. Experimental Details

Flat Inconel 718 plates of dimension $(50 \times 50 \times 5)$ have been used as work material. The chemical composition (wt%) of Inconel 718 is [Ni-50.50, Fe-20.24, Cr-18.16, Nb-5.02, Mo-2.91, Ti-1.05, Al-0.62, Co-0.15, Si-0.08, Mn-0.07, Cu-0.06, C-0.05, P-0.008, Ta-0.003, B-0.003]. A pure copper rod of circular cross section $(\phi 20)$ has been used as tool electrode (Fig.1a). The experiments have been carried out on die sinking EDM setup (Make: Electronica ElektraPlusPS 50ZNC, India). Commercially available EDM oil with specific gravity of 0.763 has been used as dielectric fluid. Polarity has been kept positive (i.e. workpiece positive). In the present work, five controllable process variables (parameters) have been selected based on literature survey. The selected process parameters have been open circuit voltage (OCV) (also called gap voltage, V_g), peak current (I_p), pulse-on time (T_{on}), duty factor (τ) and flushing pressure (F_p). Each process parameter has been varied at five discrete levels Table 1 as per configuration of parametric setting available with the setup.

Table 1: Machining control parameters: Domain of variation

Parameters	Unit	Notation	Levels of variation				
			1	2	3	4	5
OCV/ Gap voltage (V_g)	[V]	A	50	60	70	80	90
Peak current (I_P)	[A]	B	3	5	7	9	11
Pulse-on-Time (T_{on})	[μs]	C	100	200	300	400	500
Duty Factor (τ)	[%]	D	65	70	75	80	85
Flushing Pressure (F_p)	[bar]	E	0.2	0.3	0.4	0.5	0.6

The design of experiment has been selected based on 5-level-5-factor L_{25} Orthogonal Array (OA) shown in Table 2. Experiments have been conducted as per 25 factorial settings. Both workpiece and tool have been immersed in dielectric fluid. The machining duration has been kept constant (10 minutes) for each experimental run. The responses studied herein have been Electrode Wear Ratio (EWR), Roughness average (R_a) and Surface Crack Density (SCD) (on the machined surface) and White Layer Thickness (WLT) developed over the EDMed surface. The snapshot of EDMed workpiece has been shown in (Fig. 1b).

Table: 2 Design of experiment (L_{25} OA)

Sl. No	L_{25} OA (Factors are in coded form)					Sl. No	L_{25} OA (Continued) (Factors are in coded form)				
	A	B	C	D	E		A	B	C	D	E
1	1	1	1	1	1	14	3	4	1	3	5
2	1	2	2	2	2	15	3	5	2	4	1
3	1	3	3	3	3	16	4	1	4	2	5
4	1	4	4	4	4	17	4	2	5	3	1
5	1	5	5	5	5	18	4	3	1	4	2
6	2	1	2	3	4	19	4	4	2	5	3
7	2	2	3	4	5	20	4	5	3	1	4
8	2	3	4	5	1	21	5	1	5	4	3
9	2	4	5	1	2	22	5	2	1	5	4
10	2	5	1	2	3	23	5	3	2	1	5
11	3	1	3	5	2	24	5	4	3	2	1
12	3	2	4	1	3	25	5	5	4	3	2
13	3	3	5	2	4						

The definitions of various response measures along with their computational formulae have been provided below.

1. Electrode Wear Ratio (EWR): EWR can be defined as the ratio of wear weight of electrode to the wear weight of workpiece expressed in percentage [9]. This can be computed using the following Eq. (1).

$$EWR\% = \frac{(W_{ei} - W_{ef})}{(W_{wi} - W_{wf})} \times 100\% \tag{1}$$

Here W_{ei} and W_{ef} are initial and final weight of the tool electrode, respectively; and, W_{wi} and W_{wf} are initial and final weight of the workpiece, respectively.

2. Surface Roughness: Arithmetic average roughness, or R_a, is the arithmetic average of the heights of surface irregularities (peak heights and valleys) with respect to the mean line, measured within the sampling length. The measurement of surface roughness (R_a value) of the EDMed surface has been made with portable stylus type profilometer, Talysurf (Model: Taylor Hobson, Surtronic 3+), with cut-off length (L_c) of 0.8 mm, sample length (L_n)

of 4 mm, and filter CR ISO.

(a) (b)

Fig. 1 (a) Copper tool electrode
Fig. 1(b) EDMed workpiece Inconel 718

3. Surface Crack Density (SCD): To measure the surface crack density, the top surface morphology of the EDMed surface has been studied using Scanning Electron Microscopy (SEM) (Model, Joel JSM-6480LV, Japan) at magnification of $\times 500$. For a particular sample, SEM images have been captured in three different locations and corresponding surface crack densities have been collected. The average of these three has been considered for that particular specimen. For a particular sample area, the total crack length has been measured using PDF-X Change Viewer Software. The total crack length divided by the specimen area provides the measure of SCD.

4. White Layer Thickness (WLT): The white layer (also called recast layer) is the result of the re-solidification of the melted material which do not get completely flushed off from the EDMed surface by the dielectric fluid. However, the white layer formed by EDM process results an increase of surface roughness value; it makes the surface hard and brittle, and decreases the fatigue strength due to the presence of micro-cracks and micro-voids [10]. The image of white layer has then been viewed under SEM (Model: Joel JSM-6480LV, Japan) with a magnification of ×1000. The thickness of the white layer has been measured by ImageJ Software at five different locations across each cross-sectioned specimen and an average value has been considered for further analysis.

3. Methodology

3.1 Satisfaction Function

The concept of the satisfaction functions as a powerful tool to aggregate simultaneously several quality characteristics [11]. The satisfaction functions are not necessarily linear and symmetric as in the case of fuzzy membership functions. The general shape of the satisfaction function where $S(x)$ is the satisfaction function associated with deviation x; x_{id} the indifference threshold x_o is the dissatisfaction threshold; and x_v is the veto threshold [12]. The DM is fully satisfied when the deviation x is within the interval $[0, x_{id}]$. Therefore, within the range of indifference $[0, x_{id}]$, the deviation x is not penalised and the DM's satisfaction level will be at its maximal value of 1. Outside this interval, where $x \in [x_{id}, x_o]$, the DM's satisfaction functions is decreasing monotonously. Besides, any solution leading to a deviation that exceeds the veto threshold x_v will be rejected. Briefly, satisfaction function converts the deviations in the interval of $[x_{id}, x_v]$ to a satisfaction value in the interval of $[0,1]$. in this work; satisfaction function approach has been used to convert machining performance parameters viz. EWR, R_a, SCD and WLT to satisfaction values between 0 and 1, regardless of their physical units. When no information about the preference of the DM is available, the satisfaction function is assumed to be linear [13-17].
Using the values obtained from the satisfaction functions for each machining characteristics, a distance function has

been explored to combine these values into a composite number. This function is similar to Euclidean norm. The parametric setting which corresponds to the minimum distance d from the ideal point (ideal satisfaction values for each of the performance characteristics) is the most suitable one.

$$d_T = \left[\sum_{i=1}^{n} (1 - S_i)^2 \right]^{1/2} \tag{2}$$

Assume that there exist a total n number of performance characteristics; S_i is the satisfaction value of i^{th} response. When the value of EWR, R_a, SCD and WLT (individually) is at the minimum of the set, it provides the best satisfaction. Fig. 2 shows the satisfaction function (Lower-is-Better; LB) that has been used herein.

3.2 Taguchi Method

Optimization of process responses (and thereby evaluation of optimal setting of process parameters) is the key step in the Taguchi method to achieve high product quality as well as satisfactory process performance without increasing cost [18]. However, originally Taguchi method was designed to optimize single performance characteristics. According to Taguchi method, the Signal-to-Noise (S/N ratio) is the ratio where signal represents the mean (desired value) of the response and noise represents the deviation. The total distance measure (d_T) (obtained in Eq. 2) has been treated as single objective function and finally optimized (minimized) by Taguchi method. Since d_T is desired to be the minimum, therefore, Lower-is-Better (LB) characteristic is used for S/N ratio calculation (Eq. 3).

$$\left.\frac{S}{N}\right|_{(LB)} = -10 \log \left[\frac{1}{T} \sum_{i=1}^{T} y_i^2 \right] \tag{3}$$

Here y_i represents response characteristic value on i^{th} experimental run (corresponds to a particular parameters setting). Also T indicates the total number of trials.

4. Data Analysis: Results and Discussions

Experimental data as obtained through experiments as per design shown in Table 2 have been utilized to compute satisfaction values of individual responses. Satisfaction value has been carried out to eliminate criteria conflict (however, there has been no criteria conflict in the present case) and dimensional (unit) effect. It's just a procedure for data normalization.

For computing satisfaction values of individual responses viz. EWR, R_a, SCD and WLT (all correspond to LB type because least value is the most desired one), the following formula has been used (Eq. 4).

$$S_i^*(j) = \left.\frac{x_{\max}(j) - x_i(j)}{x_{\max}(j) - x_{\min}(j)}\right|_{i=1,2,\ldots,25;\ j=1,2\ldots\ldots,4} \tag{4}$$

Here $S_i^*(j)$ is the normalized data (satisfaction value) for i^{th} experimental run $(i = 1,2,\ldots,25)$ against j^{th} response; $x_i(j)$ is the experimental data for i^{th} experimental run against j^{th} response; $x_{\min}(j)$ is the minimum value of the data series $x_i | i = 1,2,\ldots,25$; $x_{\max}(j)$ is the maximum value of the data series, and $j = 1,2,3,4$.

As the present research aims at optimizing multi-response features in relation to EDM of Inconel 718 by applying satisfaction function and distance measure based Taguchi approach; computation of satisfaction values for all of the responses (LB type) has been carried out as per Fig. 2. The satisfaction values against individual responses for all experimental runs have been computed using (Eq. 4) (Refer to Table 3). The total distance measure (d_T) for each of the experimental runs has been computed next (using Eq. 2) and tabulated in Table 3.

The total distance measure (d_T) has been treated as single objective function and finally optimized (minimized) by Taguchi method. Table 4 exhibits mean response (S/N ratio of d_T) values for different factorial settings; the same has been plotted in (Fig. 3a) in order to predict the optimal setting. The optimal setting appears as ($A_4B_2C_1D_5E_5$) i.e. V_g=80V, I_P=5A, T_{on}=100µs, τ =85% and F_P=0.6 bar. The predicted S/N ratio of d_T as obtained through Taguchi analysis at the setting ($A_4B_2C_1D_5E_5$) appears as (5.34749 dB); which seems to be the highest as compared to the entries of S/N ratios for all experimental settings (Refer to Table 3). This infers that prediction result is satisfactory. Predicted optimal setting has also been verified through confirmatory test.

In addition to that SEM images of the EDMed Inconel 718 surfaces have been analysed too. The machined surface of Inconel 718 has been found containing an uneven fusing structure, globules of debris, crater marks, surface cracks, pockmarks and deposition of melted material etc. as shown in (Fig. 3b). Representative snaps revealing existence of surface crack and white layer over the EDMed surface have been shown in Fig 4a and Fig. 4b, respectively.

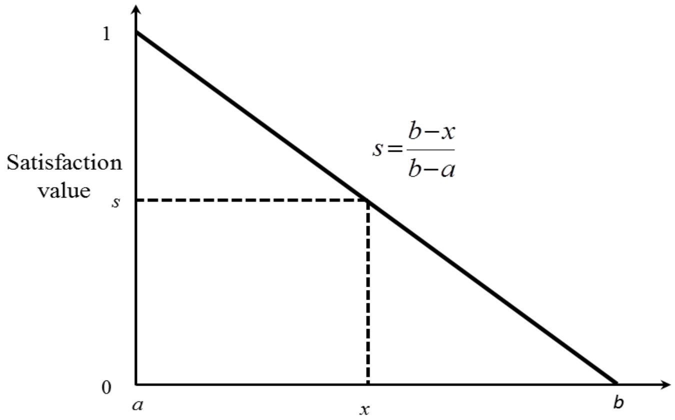

Fig. 2. Degree of satisfaction chart for a characteristic where the minimum value provides the best satisfaction (Lower-is-Better; LB type)

5. Conclusion

The contributions of above mentioned work have been summarized below.

- The proposed satisfaction function and distance based approach in conjugation with Taguchi's philosophy has been proposed here to determine an appropriate combination of EDM parameters (gap voltage, peak current, pulse-on-time, duty factor and flashing pressure) to improve machining performances in terms of EWR, R_a, SCD and WLT, simultaneously. In view of the limitation of traditional Taguchi method to solve multi-response optimization problems, the proposed satisfaction function and distance based approach seems helpful in aggregating multiple response features into an equivalent single index (i.e. d_T in the present case) which can been optimized finally by Taguchi method.
- The optimal process parameters setting appears as ($A_4B_2C_1D_5E_5$) i.e. OCV=80V, I_P=5A, T_{on}=100μs, τ =85% and F_P=0.6 bar
- Mean response table (mean S/N ratio of d_T) indicates that open circuit voltage (OCV) is the most significant parameter to influence machining performances.
- SEM images of EDMed surfaces of Inconel 718 have also been examined as well. It has been concluded that by proper tuning of process parameters surface defects, irregularities, probability of formation of cracks, white layer etc. can be substantially reduced.

Table 3: Computed satisfaction values, total distance measure and corresponding S/N ratio

Sl. No.	Satisfaction values of individual responses				Total distance measure (d_T) [Lower-is-Better]	Corresponding S/N ratio [dB]	Predicted S/N ratio [dB]
	$S_i(1)$	$S_i(2)$	$S_i(3)$	$S_i(4)$			
1	0.6128	0.7967	0.2331	0.2859	1.1355	-1.10374	5.34749
2	0.9573	0.4878	0.1729	0.1996	1.2605	-2.01086	
3	0.9888	0.1463	0.2857	0.9159	1.1163	-0.95562	
4	0.9564	0.0568	0.3985	0.4675	1.2397	-1.86633	
5	0.9673	0.3333	0.3609	0.7212	0.9653	0.30675	
6	0.0000	0.8049	0.2632	0.3370	1.4215	-3.05494	
7	0.7289	0.7235	0.2782	0.8856	0.8271	1.64884	
8	0.9549	0.2763	0.2782	0.7605	1.0507	-0.42957	
9	0.9618	0.3251	0.2481	0.0000	1.4221	-3.05860	

10	0.9559	0.0894	1.0000	0.7007	0.9595	0.35910	
11	0.9407	0.8983	0.0000	0.1221	1.3359	-2.51548	
12	0.9721	0.5854	0.1955	0.0595	1.3055	-2.31554	
13	0.9879	0.3739	0.1579	0.0568	1.4110	-2.99054	
14	0.9929	0.2195	0.7218	0.2357	1.1273	-1.04079	
15	0.9806	0.0732	0.4812	0.3337	1.2540	-1.96595	
16	0.8582	0.7398	0.1278	0.5456	1.0271	-0.23225	
17	0.8626	0.6178	0.2406	0.6120	0.9446	0.49504	
18	0.9759	0.3821	0.6090	0.5928	0.8373	1.54238	
19	0.9915	0.5690	0.7895	0.4465	0.7325	2.70385	
20	1.0000	0.0568	0.5940	0.4022	1.1882	-1.49779	
21	0.7390	1.0000	0.2481	0.7389	0.8376	1.53927	
22	0.9583	0.5690	0.5414	1.0000	0.6307	4.00354	
23	0.9504	0.3659	0.3985	0.7103	0.9221	0.70444	
24	0.9511	0.1382	0.5489	0.1518	1.2915	-2.22189	
25	0.9925	0.0000	0.6692	0.3362	1.2451	-1.90408	

Table 4: Mean response (S/N ratio of d_T) table: Prediction of optimal setting by optimizing d_T

Level	Mean response values at different factorial levels				
	A	B	C	D	E
1	-1.1260	-1.0734	0.7521	-1.4542	-1.0452
2	-0.9070	0.3642	-0.7247	-1.4193	-1.5893
3	-2.1657	-0.4258	-1.1084	-1.2921	0.2662
4	0.6022	-1.0968	-1.3496	0.1796	-1.0812
5	0.4243	-0.9404	-0.7416	0.8138	0.2774
Delta	2.7679	1.4610	2.1017	2.2681	1.8667
Rank	1[#]	5	3	2	4

The most significant process parameter

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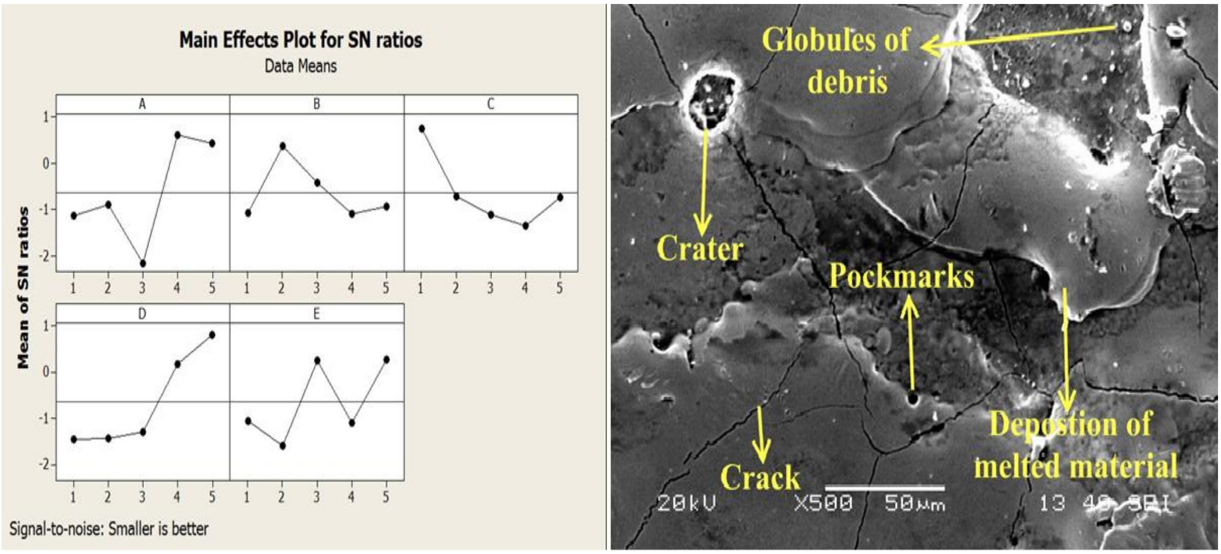
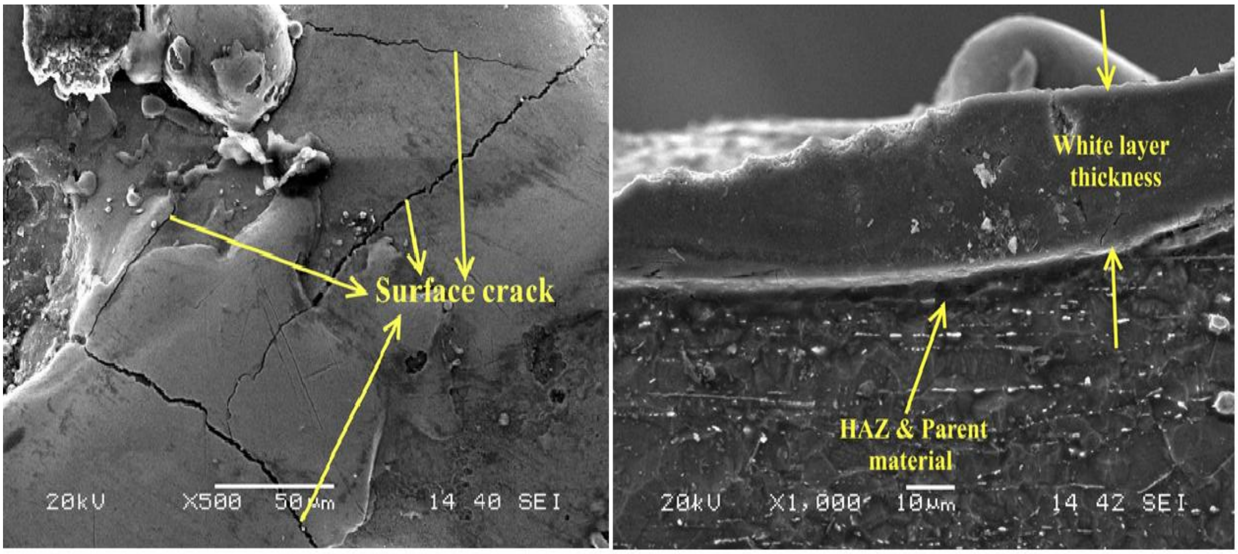


(a) (b)

Fig. 3 (a). Prediction of optimal setting ($A_4B_2C_1D_5E_5$) by optimizing d_T
Fig. 3 (b). Characteristics of EDMed surface of Inconel 718 obtained at (V_g=60V, I_P=3A, T_{on}=200µs, τ =75%, F_P=0.5 bar)



(a) (b)

Fig.4 (a). SEM image revealing existence of surface cracks on EDMed Inconel 718 (V_g=70V, I_P=11A, T_{on}=200µs, τ =80%, F_P=0.2 bar)
Fig. 4(b). SEM image revealing existence of white layer on EDMed Inconel 718 (V_g=70V, I_P=11A, T_{on}=200µs, τ =80%, F_P=0.2 bar)