Some Aspects of Surface Integrity Study of Electro Discharge Machined Inconel 718

S. Rajesha[1]*, A. K. Sharma[1], Pradeep Kumar[1]
[1] Mechanical and Industrial Engineering Department, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand-247667, India.
[*] Corresponding author: rajeshashivanna@gmail.com

Abstract: Inconel 718 superalloy is widely used in many applications requiring higher material strength. Electro Discharge Machining (EDM) is a popular process for machining this superalloy owing to its high thermal resistance and high hardness. In the current work, electro discharge machining was carried out on Inconel 718 using 99.9% pure copper as an electrode with tubular cross section. Thirty two sets of machining trials were conducted as per the design of experiments using the central composite design (CCD) method. The effect of process parameters like pulse current, duty factor, sensitivity, gap control and dielectric flushing pressure on the formation of recast layer, heat affected zone and spattered EDM surface was analysed. Machined samples were characterized for few surface integrity factors through field emission scanning electron microscope (FE-SEM), and surface roughness measurement. The microstructures of the EDM processed Inconel 718 reveal formations of a white layer on the machined surface. It was observed that the process parameters, base material properties and white layer composition have significant influence on crack formation and its propagation. Different modes of crack propagation were identified. Surfacial and vertical cracking were predominantly observed in the recast layer; most of the vertical cracks were found to have progressed till the end of the recast layer. The interferential zone acted as a barrier to crack propagation due to the non-homogeneities of metallurgical phases. Crack propagation was observed varying significantly with pulse current and duty factor.

Keywords: EDM, Inconel 718, Recast layer, Microstructure, Surface finish.

1. Introduction

Electro discharge machining is a non conventional machining process, which is extensively used in industry for processing of difficult-to-machine materials and different shapes with reasonable precision. At present, EDM is a widely accepted machining technique used for all types of conductive materials including metals, metallic alloys, graphite, composites and ceramic material. It is based on the principle of removing material from the workpiece by means of repeated electrical discharges created by an electric pulse generator at short intervals between two electrodes (tool and workpiece). The electric sparking causes the workpiece temperature to rise above melting point leading to material removal in the molten state and evaporation. Molten material between the workpiece and tool gap is flushed using dielectric fluid. Some molten materials experience a resolidification due to critical cooling by the fluid. This layer is a mix of carbon elements of dielectric fluid, melting workpiece and melting electrode. Post machining, this layer forms a recast structure with micro-cracks and craters during resolidification.

The phenomenon of surface modification has been investigated in the EDM process for over five decades. It was first reported by Barash and Kahlon [1965], when mild steel was eroded in liquid medium paraffin using a copper electrode. After the process, it was noticed that the workpiece was coated with a very hard layer which was difficult to remove. This was attributed to the carburization of the layer due to the hydrocarbon medium and its subsequent quenching. High surface hardness, excellent thermal stability and better wear resistance of the white layer and its phase transformation have also been reported by Venkatesh and Parasnis [1972]. The EDM machined surface was characterized by Lee et al. [1988 and 1992]. The authors had investigated the depth of the recast layer and quantified it with respect to the process parameters and surface roughness. It was reportead that with constant dielectric fluid flushing the condition, the thickness of recast layer shows a relationship with the pulse energy irrespective of the tool material (steel). Marafona and Wykes [2000] found that while machining with low current intensity and length pulse duration, a layer of carbon was deposited on the tool leading to reversal in tool wear. Further, to improve the material removal rate (MRR) with nominal increase in tool wear rate (TWR), a high current intensity can be used. Analysis also showed that the layer contained carbon content and steel elements such as iron and chromium. It was likely that the carbon came from the dielectric medium.

Klocke et al. [2004] investigated the influence of powder suspended dielectrics on the recast layer of Inconel 718 EDMed surface. They reported that physical properties of the powder additives play an important role in changing the recast layer composition and morphology. Bhattacharyya et al. [2007] investigated some surface integrity aspects of an EDMed surface and reported that peak current and pulse-on duration significantly influence various criteria of surface integrity such as surface roughness. Che-ChungWanga [2009] investigated the formation of recast layer using L18 orthogonal arrays and reported that larger pulse duration and positive polarity of the workpiece could create a thicker recast layer than negative polarity, while machining Inconel 718. Tsai et al. [2003] observed that recast layers are difficult to remove due to high cohesion and hardness compared to the base material and induce poor surface quality. Such recast structures greatly affect fatigue strength and shortens service life [Abu Zeid, 1997]. Thus, relevant literatures indicate there is ample scope for studying the effect of various process parameters on surface integrity of Inconel 718 electro discharge machined surface.

In the present work, Inconel 718 was the workpiece material and 99.9% pure copper as electrode for experiments using an NC-EDM machine. Thirty two sets of machining trials were conducted as per the Response Surface Method (RSM) with central composite design. The effect of process parameters like pulse current, duty factor, sensitivity, gap control and dielectric flushing pressure on formation of recast layer and spattered EDM surface were analysed. Machined samples were characterized for some surface integrity factors through field emission scanning electron microscope (FE-SEM) and 3D surface profilometer.

2. Experimental Procedure

The experiments were conducted using a ZNC-EDM machine (Sparkonix Ltd., India). Inconel 718 material of dimensions, 21 mm diameter and 20 mm length was used as workpiece for the experimental trails. Inconel 718 has an average hardness value of 414 Hv. A cylindrical tube of 12 mm external and 9 mm internal diameter made of 99.9% pure electrolytic copper was used as the electrode. Commercially available kerosene (electrical cond.: 1.6×10-14Sm^{-1}, and dynamic Viscosity: 0.92mPas) was used as the dielectric fluid. The experimental set-up is shown in the Fig. 1.

The workpiece was cut by wire EDM (make: Electronica, EL10-VGA, India) prior to trails. A special fixture was designed to hold the cylindrical work pieces to eliminate any possibility of misalignment. The work pieces were connected to positive polarity while the electrode was maintained at negative polarity. A side flushing method was employed for dielectric fluid to flush through nozzle. During the experiments, the hole depth of 20 mm and diameter of 12 mm was machined throughout. The process parameters and depth of cut was programmed in the NC controlled unit. The servo moves up 5 mm above the initial position after completion of machining.

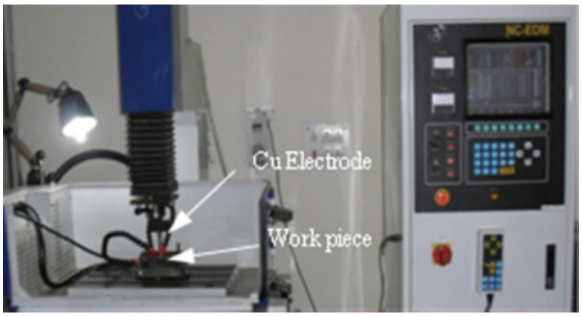

Fig. 1. Pictorial view of the experimental set-up

Table 1 Levels of process parameters used in the experiments.

S. No.	Process Parameters	Symbol.	Level				
			-1.57	-1	0	+1	1.57
1.	Pulse Current (A)	A	6	9	12	15	18
2.	Duty Factor	B	0.67	0.72	0.77	0.82	0.87
3.	Sensitivity Control	C	3	4	5	6	7
4.	Gap control	D	0	1	2	3	4
5.	Flushing Pressure (Kg/cm^2)	E	0	0.25	0.5	0.75	1

The process parameters and their levels were decided based on trail experiments and are shown in the Table 1. The experiments were performed according to the plans arrived at using design expert version 6.1 (DE V6.1). The experiment matrix of RSM with coded levels is shown in the Table 2. Fig. 2 shows a photograph of the copper electrode used and the workpiece before and after machining.

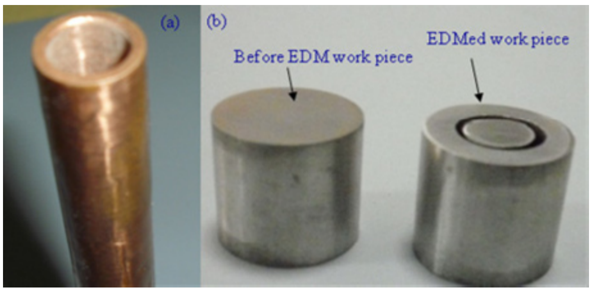

Fig. 2. (a) Cu electrode, (b) Inconel 718 work piece

Table 2 Experimental matrix of the CCD (RSM)

Experiment no.	Process Parameters (coded levels)				
	A	B	C	D	E
1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	-1
4	1	1	-1	-1	1
5	-1	-1	1	-1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	1
8	1	1	1	-1	-1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1
17	-1.57	0	0	0	0
18	1.57	0	0	0	0
19	0	-1.57	0	0	0
20	0	1.57	0	0	0
21	0	0	-1.57	0	0
22	0	0	1.57	0	0
23	0	0	0	-1.57	0
24	0	0	0	1.57	0
25	0	0	0	0	-1.57
26	0	0	0	0	1.57
27	0	0	0	0	0
28	0	0	0	0	0
29	0	0	0	0	0
30	0	0	0	0	0
31	0	0	0	0	0
32	0	0	0	0	0

3. Results and Discussion

32 sets of experiments were performed during the investigation. Machined surfaces were cut perpendicular to the tool (machining) direction and polished well by a rotary polishing machine using 600, 800 and1200 mesh size silicon carbide abrasive sheets. Further polishing was carried out with velvet and diamond paste at 100 rpm for about 15 min and cleaned with acetone. Both sectional and surface of the EDM machined Inconel 718 workpieces were examined for surface integrity factors through a field emission scanning electron microscope.

3.1 Recast Layer Formation

The effect of the process parameters on the recast layer thickness of EDM processed Inconel 718 workpiece using the copper electrode was examined. The results are illustrated in Figs. 3–5. The SEMs of the cross section of the EDMed surfaces are presented in the Figs. 3(a)–5(a), while the Figs. 3(b)–5(b) show the EDMed surfaces. It was observed from the microstructure of the machined surfaces that the thickness of the recast layer increases as the pulse current increases. As the current increases, intensity of the spark also increases leading to an increase in size of craters, consequently the quantity of the molten material produced per unit time increases. Meanwhile, the dielectric flushing may not be capable of instantly removing all the molten material produced due to the high pulse current. During the subsequent rapid cooling, molten material re-solidifies to form thick recast layer with deep craters. The thickness of this recast layer formation will depend upon the volume of molten material produced during the machining due to high pulse current and the flushing pressure of dielectric fluid. This is supported by observations made from SEM micrographs (Figs. 3(a), 4(a) and 5(a)).

It is observed from Figs. 5(a) that recast layer thickness increases with increases in the duty factor. When the duty factor increases, the pulse on duration also increases in comparison with pulse off duration. Larger pulse on duration allows the electro discharge energy to penetrate deeper into the material causing increase in the volume of the molten material. The increased volume of molten material does not get removed by the dielectric fluid flushing duration. This eventually results in thicker recast layer. However, from the Fig. 3(a) it is observed that although there is an increase in duty factor, the recast layer thickness is not large. This may be due to an optimum combination of the other process parameters like sensitivity control, gap control and high flushing pressure. Here, the molten material and EDMed debris are effectively flushed away from the machining zone due to the high flushing pressure which, in turn, helps in minimizing the thickness of the recast layer.

3.2 Surface Crack

The surface crack density varies with changes in pulse current for different pulse-on durations due to rapid quenching of the molten material and shrinkage stresses after each electro discharge. It is observed from the Figs. 3(b), 5(b) and 6 that surface crack density increases with pulse current for a constant duty factors. Overall, it was observed that the surface crack increases with increasing pulse current. Fig. 6 shows that at low pulse current, white layer formation is more uniform with reduced micro cracks. More intensive cracking was noticed around craters and locations where there is a presence of peak [Fig. 5(b), and 7]. Fig. 7 also exhibits an increase in the surface crack intensity due to an increase in duty factor and induced stress. From the analysis of the SEM micrographs, it was observed that cracks were consistently progressing perpendicular to the machining direction and barely penetrating beyond the recast layer. However, Fig. 5 shows severe cracking in the parent material parallel to machined direction too, due to high pulse current and other parametric combinations owing to a step rise in the temperature of the workpiece above the critical point. This causes an increase in energy inside the material and sudden quenching leads to higher thermal stresses in parent the material leading to the observed severe crack formation.

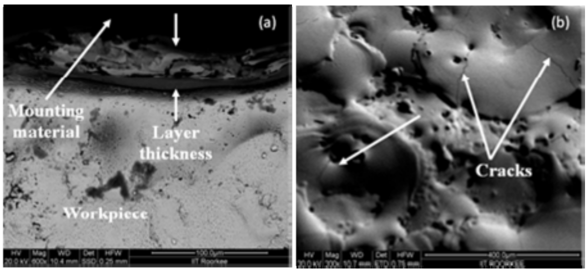

Fig. 3. SEM micrograph of Exp. Run No.27

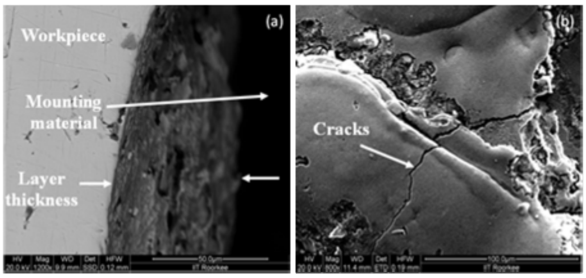

Fig. 4. SEM micrograph of Exp. Run No.2

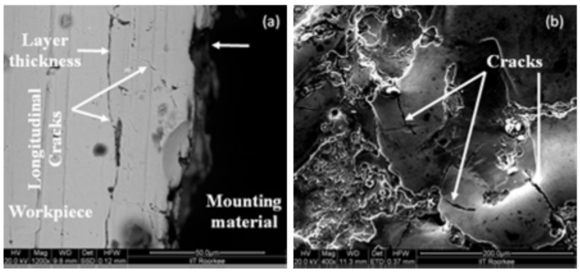

Fig. 5. SEM micrograph of Exp. Run No. 18

Fig. 6. SEM micrograph of Exp. Run 17

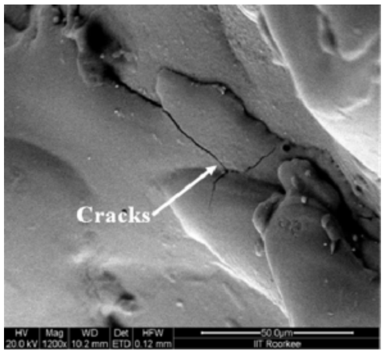

Fig. 7. SEM micrograph of Exp. Run No. 7

3.3 Chemical Composition of the Recast Layer

The principle of electro discharge machining involves developing sparks between the electrode and the workpiece. During electric sparking, the workpiece and tool temperature rises above the melting point leading to material removed in its molten state and evaporation. Molten material between the workpiece and the tool is flushed away using the kerosene dielectric fluid. The dielectric fluid is exposed to high temperature and reacts with oxygen to form carbon and carbon monoxide. Some of the carbon particles mix with the molten material and form a recast layer, allowing further quenching beside that with the tool material and some molten materials experience evaporation along with carbon monoxide. Meanwhile the carbon and alloys of the parent material start solidifying on the surface of the tool electrode. This layer minimises the wear rate of the tool to some extent leading to reduction in material removal rate. Table 3 shows the difference between the chemical composition of the recast layers and the parent material. The presence of copper in the recast layer indicates the tool erosion during the machining. Hardness of the recast layer increases significantly due to higher carbon percentage in the layer. Table3 and SEM micrograph of machined surface indicate presence of carbon in the EDMed surface of the workpiece.

Table 3 Chemical composition of EDM processed Inconel 718 workpiece surface (recast layer).

Elements	Before the EDM Process (workpiece)	After the EDM process (recast layer)
	Av. Weight %	Av. Weight %
Ni	51.05	33.72
Fe	19.95	13.35
Cr	18.83	12.76
Nb	5.52	5.22
Mn	0.03	0.00
C	0.04	13.65
Co	0.04	0.00
Al	0.26	0.22
Si	0.04	0.28
Ti	1.08	0.93
Mo	3.1	4.50
Cu	0	5.67
O	0	2.24
Other	0.06	7.47
	100.00	100.00

3.4 Surface Roughness

The effects of the various process parameters on the surface roughness were evaluated using the optical profile meter (Make: Veeco V2, India). The surface roughness (R_a) value varies with pulse current and duty factor. Average surface roughness while machining with higher pulse current is observed to be less as shown in Fig. 8 while compared with that of Fig. 9. The influence of the duty factor on roughness is, on the other hand, observed to be in the similar trend as that of crack formation. Higher duty factor is attributed to transmission of high pulse energy, which accelerates severe cracking on the recast layer resulting in poorer surface finish. Thus, it indicates that an increase in duty factor greatly affects the surface quality. Figs. 10 and 11 illustrate that an increase in pulse current also increases the R_a value. The higher input power associated with increase in pulse current causes more distortion on the machined surface due to more frequent molten material expulsion. This leads to an increase in R_a value.

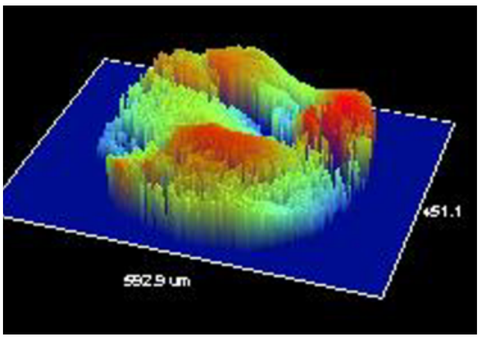

Fig. 8. 3D Profile of surface roughness [Exp. Run No.2; R_a 5.36μm]

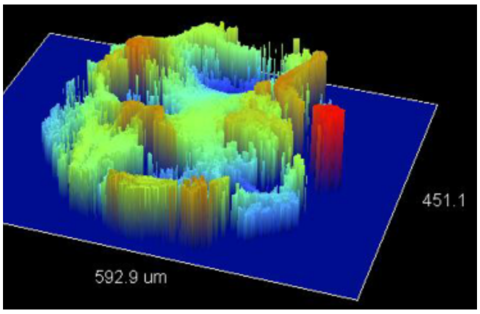

Fig. 9. 3D Profile of surface roughness [Exp. Run No.7; R_a 6.41μm]

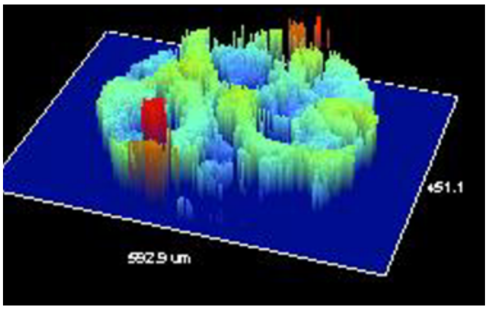

Fig. 10. 3D Profile of surface roughness [Exp. Run No.17; R_a 2.36μm]

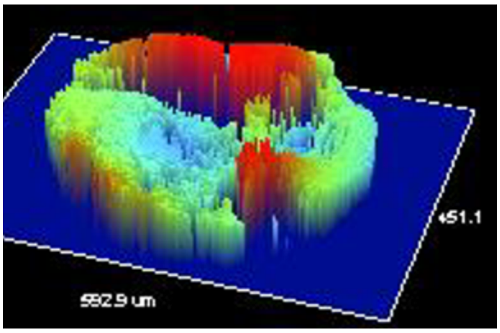

Fig. 11. 3D Profile of surface roughness [Exp. Run No. 18; R_a 9.96μm]

4. Conclusions

Experiments were carried out on Inconel 718 material in a ZNC-EDM. From the preliminary results, the following conclusions are drawn:

- Thickness of the recast layer increases with increase in the duty factor and pulse current.
- Crack formation is due to induced stress during sudden quenching of molten material with dielectric fluid.
- Micro cracks are formed even at low pulse current.
- Major crack propagation is perpendicular to the direction of tool electrode.
- Intensive cracking is centered around craters and peaks.

- Complex carbides are formed along with eroded tool material and get deposited in the recast layer.
- Surface roughness is highly influenced by duty factor followed by pulse current.

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