Analysis on Topography and Metallurgical Aspects of EDMed Work Surface of Inconel 718 Obtained Using Triangular Cross Sectioned Copper Tool Electrode

Thrinadh Jadam, Chandramani Upadhyay, *Saurav Datta, Soumya Gangopadhyay, Siba Sankar Mahapatra

Department of Mechanical Engineering
National Institute of Technology Rourkela-769008, Odisha, INDIA
*e-mail: sdattaju@gmail.com

***Abstract*—A case experimental research on Electro-Discharge Machining (EDM) of Inconel 718 super alloy using Copper tool electrode (of triangular cross section) has been delineated herein. Based on three controllable process variables viz. peak discharge current, pulse-on duration and gap voltage, experiments have been carried out to investigate their effects on influencing topography of the EDMed work surface in terms of Surface Crack Density (SCD). XRD tests have been carried out to compare metallurgy (various phases/precipitates present in bulk of the matrix material, extent of grain refinement, crystallite size, dislocation density) of the EDMed work surface with respect to 'as received' Inconel 718. Results, thus obtained, have also been compared to that of EDAX analysis.**

Keywords-Electro-Discharge Machining (EDM); Inconel 718; super alloy; Surface Crack Density (SCD); grain refinement; crystallite size; dislocation density

I. INTRODUCTION

Inconel 718 alloy is a Nickel-based super alloy. It has high strength and corrosion resistance at high temperatures. Inconel 718 alloy exhibits excellent tensile, fatigue, rupture, and creep strength at elevated temperatures. Because of its properties, this super alloy is used in many engineering applications. It is enormously used in manufacturing of hot sections in gas turbines, rocket motors, space crafts, pumps, and nuclear reactors.

As compared to conventional metals, machining of Inconel 718 is quite difficult because of its rapid work hardening tendency, low thermal conductivity, high tool wear rate (tool and workpiece as direct contact), high toughness as well as hardness and high bond energy between the abrasive particles [1]. Due to above difficulties, non-conventional methods: Electro-Discharge Machining (EDM), Electro-Chemical Machining (ECM), Ultrasonic Machining (USM), and Laser Beam Machining (LBM) etc. are preferred for machining of Inconel 718.

During conventional machining, Inconel 718 alloy experiences additional difficulties as compared to conventional metals. It requires more lubricant to cool the tool; it takes more cost towards disposal of waste and washing the machined components (which appeared nearly 4 times the cost of the consumed tools used in the cutting operations [2]. However, to overcome this, dry condition is recommended while machining of Inconel 718 and by using ceramic tools or coated tools. Aspects of EDM on Inconel 718 have been reported by previous researchers [3-7].

The objectives of the present work have been provided below.

1. To explore the effect of EDM parameters such as peak current (I_p), pulse-on time (T_{on}) and gap voltage (V_g) on Surface Crack Density (SCD) of the EDMed work surface during Electro-Discharge Machining (EDM) on Inconel 718 super alloy using Copper tool electrode with triangular cross section.
2. To study morphology of the EDMed work surface attributed due to the thermo-electrical phenomenon of EDM operations.
3. To understand metallurgical aspects of the EDMed Inconel 718 work surface such as phase transformation, extent of grain refinement, crystallite size, and dislocation density etc. that are expected to be influenced by the EDM operation as compared to that of 'as received' Inconel 718. Results are to be correlated to that of EDAX analysis.

II. EXPERIMENTAL DETAILS

Inconel 718 plates with dimension ($50 \times 50 \times 5$) has been used as workpiece material. The mechanical properties and chemical composition of Inconel 718 have been obtained from [8]. Pure copper rod (of triangular cross section) has been used as tool electrode.

Experiments have been conducted on EDM setup (Make: Electronica ELEKTRA PLUSPS 50ZNC EMS 5535, India). In this experiment, commercially available Rustlick™ EDM-30 oil has been used as dielectric fluid.

From the 'as received' Cu rod of circular cross section (25mm diameter), the required tool (of triangular cross section) has been manufactured by using CNC Lathe machine. Based on literature review, triangular and circular cross-sectioned electrodes offer maximum material removal rate under identical conditions in EDM process as compared to other cross-sections. So, to analyse the topography and metallurgical aspects of EDMed Inconel 718 workpiece, a triangular cross-sectioned electrode is selected. Here, Copper has been selected as electrode material because of its high electrical conductivity and corrosion resistance.

The electrode has been given shape through CNC lathe. The machining operation may develop micro-cracks and the cutting forces that are generated during machining may also create thermal stresses. The combination of all may deteriorate surface integrity of the tool material. This may affect EDM performance adversely. To elicit such happenings, very low feed rate and coolant have been used during execution of CNC turning operation. Moreover, after machining, electrode tool has been polished in wet condition by 220 grade emery paper. This has further helped to improve surface quality of the tool electrode.

During execution of EDM experiments, straight polarity (i.e. tool as cathode and workpiece as anode) has been maintained. The following process parameters have been chosen (Table I): peak discharge current, pulse-on time and gap voltage. The remaining parameters such as flushing pressure, duty factor, spark gap and machining time have been kept constant throughout experimentation (Table II). Machining operation (10minutes of each run) has been executed with few selected parametric settings.

After EDM operation, Surface Crack Density (SCD) of the EDMed work surface has been measured for each of the specimens. A snapshot of the EDMed end product of Inconel 718 has been provided in Figure. 1.

Surface Crack Density (SCD) is defined as the total length of cracks present (per unit area) on the machined surface. Surface crack density is used to evaluate severity of cracking. Surface cracks initiate at the top of the machined surface and gradually travel (propagate down) perpendicularly towards the white layer depth and finally to the extent of base or parent material. SCD varies with different EDM parameters. By increasing peak current, gap voltage and pulse-on time, SCD tends to increase. In the present investigation, the micro-graphs containing surface cracks developed onto the machined surface have been obtained by using Scanning Electron Microscope (Model: JSM-6390LV; Make: Jeol, Japan). Metallurgical analyses of the EDMed surface of Inconel 718 (as compared to 'as received' Inconel 718) have been carried out by using X-ray Diffraction Microscopy (Model: D8 ADVANCE with DAVINCI design; Make: BRUKER, Germany). Additionally, the chemical composition of 'as received' Inconel 718 as well as few EDMed work surfaces of Inconel 718 have been measured through Energy Dispersive X-ray Spectroscopy (EDS or EDAX) using Scanning Electron Microscope (SEM) (Make: JEOL, Model: JSM 6480 LV; Made in Japan). The morphology of the EDMed work surface has been shown in Figure 2.

III. RESULTS AND DISCUSSION

A. *Parametric Effect on SCD*

During EDM operation, depending on the parametric setting used, in some cases high discharge energy (per spark) is supplied in the working zone. This high spark energy melts more material from the work piece. This melted material is to be carried away by the using dielectric fluid. But, due to the inefficiency of the dielectric fluid, some amount of melted material is resolidified on the machined surface forming white layer. In fact, greater thermal stresses are developed in the EDMed surface because of high input energy. When these induced stresses exceed the ultimate tensile strength of the EDMed surface, cracks are initiated.

Increase in peak discharge current results in increased energy per spark (as energy per spark is directly proportional to the peak current). Due to high energy input, thermal stresses that are developed within the EDMed surface, assume relatively high value. When these induced stresses become more than the ultimate tensile strength of the EDMed surface, cracks are initiated on the surface and may propagate through the depth of white layer till the bulk of the parent material. Finally, while increasing peak current, more surface cracks are formed on the machined surface i.e. SCD appears more (Figure 3). SCD also increases with increase in pulse-on duration as well as gap voltage (Figures 4-5). This is because; discharge energy is directly proportional to pulse-on time as well as gap voltage.

B. *XRD and EDAX Analyses*

XRD spectra for 'as received' Inconel 718 has exhibited presence of Ni-Fe based solid solution matrix with peak patterns approximately matching to that of (chromium, cobalt, molybdenum, nickel) solid solution (Reference code: 35-1489; Chemical Formula: Ni-Cr-Co-Mo) (Figure 6). Studies in *X'Pert HighScore* software has revealed that, 'as received' Inconel 718 has consisted of cubic crystals system; the highest peak has been observed at crystallographic plane (1 1 1). In addition to that, some amount of carbide precipitates have also been found in different planes. For example, Cobalt Carbide (Reference Code: 44-0962; Chemical Formula: CoC_x) and Copper Nickel (Reference Code: 09-0205; Chemical Formula $Cu_{3.8}Ni$).

In comparison with 'as received' Inconel 718, XRD spectra of the EDMed work surface of Inconel 718 (obtained in at Run No. 7) has exhibited peak patterns of similar nature (Figure 7).

As compared to 'as received' Inconel 718, the XRD spectrum for the EDMed work surface of Inconel 718 obtained at [I_p=20A, T_{on}=300µs, V_g=24V] has exhibited approximately similar peak pattern. Considering 'Full Width Half Maxima' (FWHM) of the peaks, it has been inferred that significant grain refinement has been attributed due to the thermo-electrical effect of EDM operation which has resulted reduced crystallite size and increased value of dislocation density. Apart from the solid solution matrix of (Ni-Cr-Co-Mo), the EDMed work surface has exhibited precipitates of Nickel Aluminum Titanium Carbide (Reference Code: 19-0035; Chemical Formula: Ni_3(Al, Ti)C), Cobalt Carbide (Reference Code: 44-0962; Chemical Formula: CoC_x), and Nickel Carbide (Reference Code: 14-0020; Chemical Formula: NiC).

TABLE I. DOMAIN OF EXPERIMENT

Parameters	Unit	Notation	Levels of variation		
			1	2	3
Peak current (I_P)	[A]	A	10	15	20
Pulse-on-Time (T_{on})	[µs]	B	100	200	300
Gap voltage (V_g)	[V]	C	20	24	28

TABLE II. CONSTANT PARAMETERS

Parameters	Unit	Value
Duty Factor (τ)	[%]	Middle position (i.e. 6) on the control panel
Flushing pressure	[Kg/cm^2]	0.5
Polarity	-	Positive (workpiece +ve)
Spark gap	[µm]	50

Figure 1. EDMed work surface of Inconel 718

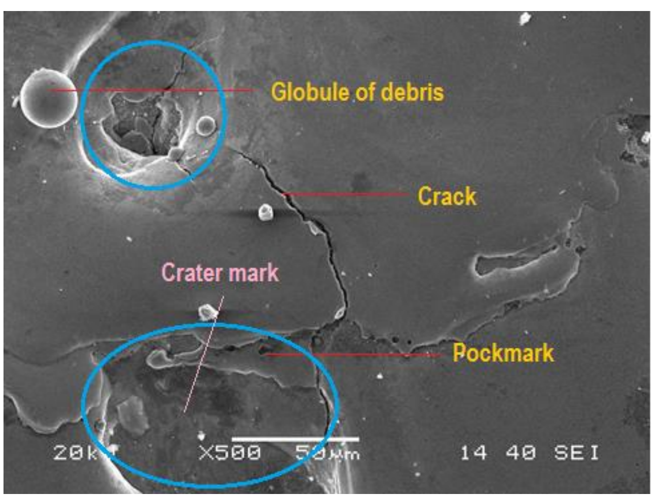


Figure 2. SEM image revealing irregularities on the surface of the EDMed Inconel 718 obtained at parameters setting [I_P=20A; T_{on}=300µs; V_g=20V]

The variation of crystallite size (L), and dislocation density (δ) for (1) 'as received' Inconel 718, and (2) EDMed work surface of Inconel 718 have also been examined. Considering a particular crystallographic plane (1 1 1) corresponding to the highest intensity peak selected from the peak pattern of XRD spectra, it has been observed that as compared to (1) 'as received' Inconel 718 (which corresponds to $L \sim 59.57\,\text{nm}$ and $\delta \sim 4.7203\times10^{-4}$), (2) EDMed work surface of Inconel 718 obtained at parameters setting: [I_P=20A; T_{on}=300µs; V_g=24V], has exhibited remarkable grain refinement followed by decrease in crystallite size $(L \sim 19.9477\,\text{nm})$ and consequently, increase in dislocation density $(\delta \sim 42.2319\times10^{-4})$.

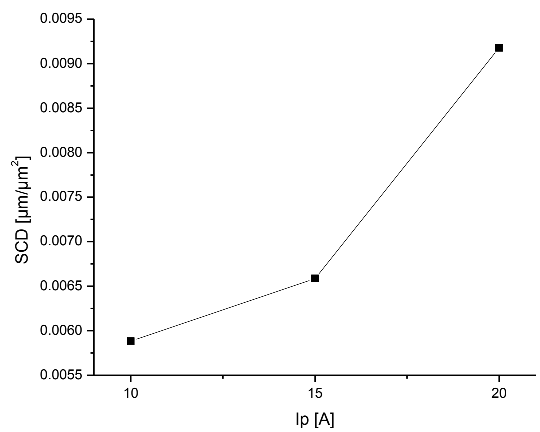


Figure 3. Effect of T_{on} on SCD for constant $(T_{on} = 300\mu s)$ and $(V_g = 28V)$

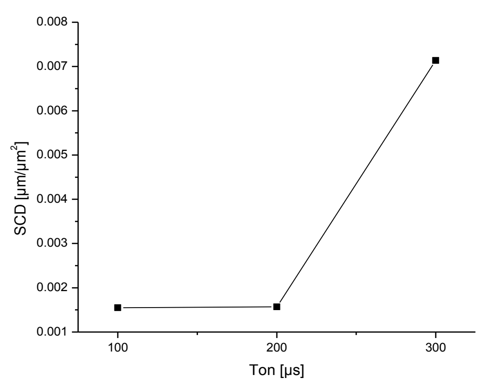


Figure 4. Effect of T_{on} on SCD for constant $(I_P = 20A)$ and $(V_g = 28V)$

EDAX elemental spectra revealing chemical composition of 'as received' Inconel 718 and EDMed Inconel 718 work surface obtained at parameters setting [I_p=20A, T_{on}=300µs, V_g=20V] have been shown in (Figures 8-9), respectively. It has been observed that as compared to 'as received' Inconel 718 (Figure 8), the relative carbon content onto the machined surface has increased during EDM operation for the specimen obtained at parameters setting [I_p=20A, T_{on}=300µs, V_g=20V] (Figure 9). Carbon enrichment onto the machined surface during EDM operation can be explained by the phenomenon of dielectric cracking (pyrolysis of dielectric fluid). As a consequence, the EDMed work surface of Inconel 718 is expected to exhibit higher hardness value as compared to that of ‘as received’ Inconel 718.

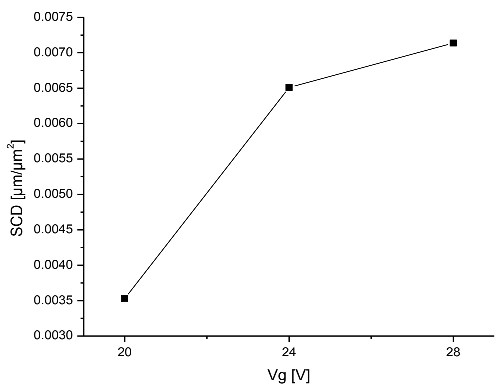


Figure 5. Effect of V_g on SCD for constant $(I_P = 20A)$ and $(T_{on} = 300\mu s)$

IV. Conclusion

The conclusions of the current research have been pointed out below.

SCD increases with increase in peak current, pulse-on duration and gap voltage.

Pyrolysis of the dielectric fluid (during EDM operation) has resulted carbon enrichment onto the EDMed work surface.

EDM has resulted significant grain refinement at the EDMed work surface followed by decrease in crystallite size and increase in dislocation density.

No significant phase change has been found attributed in the Inconel 718 work material during EDM operation.

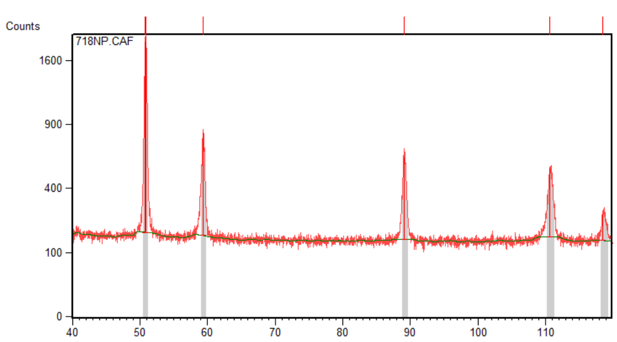


Figure 6. XRD spectra for ‘as received’ Inconel 718

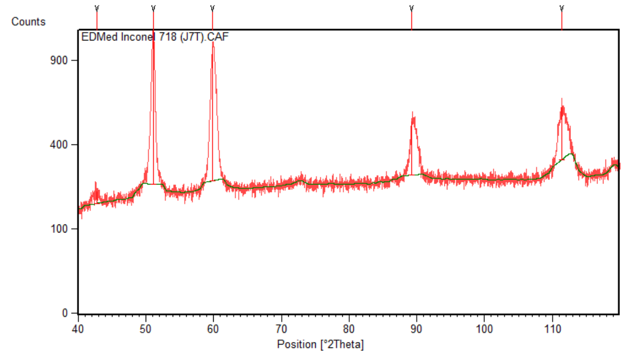
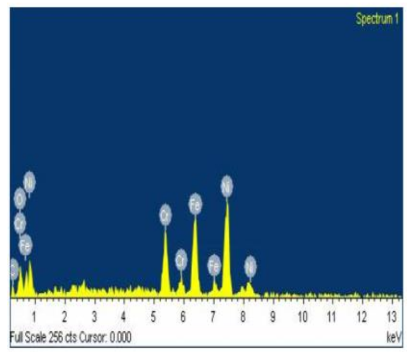
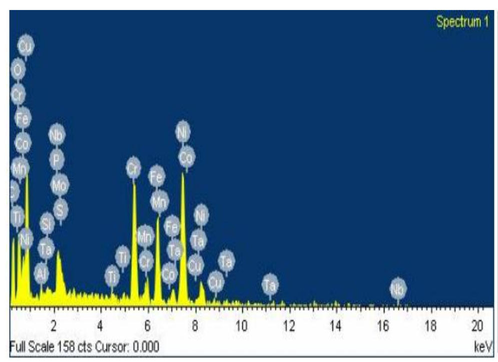


Figure 7. XRD spectra for EDMed work surface of Inconel 718 obtained at parameters setting [I_p=20A, T_{on}=300µs, V_g=24V]



Element	Weight%	Atomic%
C K	10.43	30.40
O K	9.10	19.90
Cr K	12.83	8.63
Fe K	24.92	15.62
Ni K	42.71	25.45
Totals	100.00	

Figure 8. EDAX elemental spectra revealing chemical composition of ‘as received’ Inconel 718 parent material



Element	Weight%	Atomic%
C K	62.51	85.78
O K	4.76	4.91
Al K	0.14	0.08
Si K	0.10	0.06
P K	0.09	0.05
S K	-0.16	-0.08
Ti K	0.29	0.10
Cr K	6.79	2.15
Mn K	0.12	0.03
Fe K	6.05	1.79
Co K	0.20	0.06
Ni K	16.00	4.49
Cu K	0.45	0.12
Nb L	1.92	0.34
Mo L	0.76	0.13
Ta M	-0.01	0.00
Totals	100.00	

Figure 9. EDAX elemental spectra revealing chemical composition of the EDMed work surface of Inconel 718 obtained at parameters setting [I_p=20A, T_{on}=300µs, V_g=20V]

References

[1] A.R.C. Sharman, J.I. Hughes, and K. Ridgway, “Workpiece surface integrity and tool life issues when turning Inconel 718 nickel based super alloy,” Machining Science and Technology, vol. 8, no. 3, pp. 399–414, 2004.

[2] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquere, V. Zerrouki, and J. Vigneau. “A review of developments towards dry and high speed machining of Inconel 718 Alloy,” International Journal of Machine Tools and Manufacture,vol. 44, no.4, pp. 439–56, 2004.

[3] O. Yilmaz, and M.A. Okka. “Effect of single and multi-channel electrodes application on EDM fast hole drilling performance,” International Journal of Advanced Manufacturing Technology,vol. 51, no.1-4, pp. 185–94, 2010.

[4] Mustafa Ay, Ulaş Çaydaş, and Ahmet Hasçalık “Optimization of micro-EDM drilling of inconel 718 superalloy,” Int J Adv Manuf Technol, vol. 66, no. 5, pp. 1015–1023, 2013.

[5] P. Sengottuvel, S. Satishkumar, and D. Dinakaran "Optimization Of Multiple Characteristics Of EDM Parameters Based On Desirability Approach And Fuzzy Modeling," Procedia Engineering, vol. 64, pp. 1069 – 1078, 2013.

[6] L. Li, Z. Y. Li, X. T. Wei, and X. Cheng "Machining Characteristics of Inconel 718 by Sinking-EDM and Wire-EDM," Materials and Manufacturing Processes, vol. 30, no.8, pp. 968–973, 2015.

[7] U. A. Dabade, and S. S. Karidkar "Analysis of response variables in WEDM of Inconel 718 using Taguchi technique," Procedia CIRP, vol. 41, pp. 886 – 891, 2016.

[8] http://www.specialmetals.com/assets/documents/alloys/inconel/inconel-alloy-718.pdf