Studies on Surface Topography and Metallurgical Aspects of EDMed Work Surface of Super Alloy Inconel 718

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Abstract

A case experimental research towards investigating aspects of Electro-Discharge Machining (EDM) on Inconel 718 super alloy using Copper tool electrode 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 various process performance features like Material Removal Rate (MRR); Surface Crack Density (SCD) and White Layer Thickness (WLT) onto the top surface of the EDMed end product. Additionally, EDAX analysis has been carried out to investigate the extent of carbon enrichment onto the machined surface as affected during pyrolysis of the dielectric fluid whilst executing EDM operation. 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, strain and dislocation density) of the EDMed work surface with respect to 'as received' Inconel 718. Results, thus obtained, have also been compared to that of micro-hardness test data.

Keywords: Electro-Discharge Machining (EDM); Inconel 718; super alloy; Surface Crack Density (SCD); White Layer Thickness(WLT); grain refinement; crystallite size; crystallite strain; dislocation density.

1. Research Background

Inconel 718 is a nickel, chromium and molybdenum based super alloy. It has the property of excellent high yield tensile and creep rupture; and oxidation resistance at elevated temperatures. It can resist a severely corrosive environments, pitting and crevice corrosion. Niobium addition makes it age hardening which allows annealing and welding without spontaneous hardening during heating and cooling. The addition of niobium acts with the molybdenum to stiffen the alloy's matrix and provide high strength without a strengthening heat treatment. This nickel steel alloy is fabricated and may be welded in either the annealed or age hardened condition. This super alloy is used in a variety of industries such as aerospace, automotive, chemical processing, marine engineering, pollution-control equipment, and nuclear reactors, gas turbine engine parts. [Source: http://megamex.Com/inconel_ 718 .html].

Machining of Inconel 718 is very difficult using traditional techniques. It is because of rapid work hardening. It is included in the group of materials termed as '*difficult-to-cut*' because it has the unique property of superior high temperature strength. Work hardening tends to plastically deform either the workpiece or the tool after the machining pass. Machining of Inconel requires huge cutting forces because strength of this alloy at elevated temperatures is quite high. It also generates enormous heat at the tool tip. Therefore, Inconel 718 is machined using an aggressive but slow cut with a hard tool, and with minimum number of passes. Alternatively, the majority of the machining can be performed with the workpiece in a solutionized form, with only the final steps being performed after age hardening. [Source: https://en.wikipedia.org/wiki/Inconel#Machining].

For machining of Inconel 718, non-conventional machining is more preferable than conventional machining Li et al. [1]; Aggarwal et al. [2]. Some example of non-conventional machining for machining of Inconel 718 is Electro-Discharge Machining (EDM), plasma-enhanced machining, cryogenic machining, ultrasonic vibration assisted machining. Electro-discharge machining is the most preferred non-conventional machining operation suited for Inconel super alloys. It is because the machine requires reduced machining stresses, lesser work hardening effect and lesser metallurgical damage on the workpiece Manohar et al., [3].

In EDM, the most significant process factors that influence the machining performance are peak current, pulse-on time. Karthikeya and Arun[4];.Ramakrishnan and Karunamoorthy [5] described the development of Artificial Neural Network (ANN) models and multi-response optimization technique 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 viz.

material removal rate and surface roughness were optimized concurrently using multi-response signal-to-noise (MRSN) ratio and Taguchi's parametric design approach.

Newton et al. [6] experimentally found that the average recast layer thickness increased primarily with energy per spark, peak discharge current, and current pulse duration for WEDM of Inconel 718.In addition to that the recast material was found to possess in-plane tensile residual stresses, as well as lower hardness and elastic modulus than the bulk material. Ay et al. [7] used the gray relational analysis method to optimize the micro-electrical discharge machining (drilling) process of Inconel 718 in consideration with multi-performance characteristics (hole taper ratio and hole dilation).

Lin et al. [8] applied Grey-Taguchi method to achieve multiple performance characteristics such as low electrode wear, high material removal rate and low working gap during micro milling electrical discharge machining process on Inconel 718 super alloy. Additionally, the influences of peak current, pulse on-time, pulse off-time and spark gap on electrode wear (EW), material removal rate (MRR) and working gap (WG) were analyzed. Manohar et al. [3] examined the effect of electrode bottom profiles while machining Inconel 718 by considering the process parameters like discharge current and pulse-on time. The work stated that electrodes of convex bottom profile performed better than flat or concave profiled electrodes. The performance of EDM was evaluated in terms of lesser recast-layer, better surface finish for plain surface machining.

Aggarwal et al. [2] carried out empirical modeling of process parameters of the WEDM 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 were selected as input. The performance was measured in terms of cutting rate and surface roughness. Li et al. [1] focused on the machining characteristics of Inconel 718 by Wire-EDM and Sinking-EDM with a Cu-SiC electrode, respectively. Material removal efficiency, surface roughness, surface topography, surface alloying, and electrode wear have been characterized. The fabricated Cu-SiC electrode for Sinking-EDM exhibited better performance in terms of material removal rate, surface roughness, and electrode wear. The higher melting temperature and fine microstructure of SiC contributed to the lower electrode wear of the Cu-SiC electrode than as compared to the traditional Cu electrode.

Nomenclature

EDM	Electro-Discharge Machining
I_p	Peak Current
T_{on}	Pulse-on Time
τ	Duty Factor
R_a	Surface Roughness (Roughness Average)
WLT	White layer Thickness
TWR	Tool (Electrode) Wear Rate
MRR	Material Removal Rate
SCD	Surface Crack Density

2. Objectives

1. To investigate the effect of EDM parameters (peak current, pulse-on time and gap voltage) on Material Removal Rate (MRR), Surface Crack Density (SCD) and White Layer Thickness (WLT) during Electro-Discharge Machining (EDM) on Inconel 718 super alloy using Copper tool electrode (of circular cross section).
2. To study surface morphology of the EDMed work surface affected by the thermo- electrical phenomenon that is incurred during execution of EDM operation.
3. To study the effect of dielectric cracking in promoting carbon enrichment onto the machine surface of EDMed Inconel 718 through EDAX analysis.
4. To understand the effect of EDM on influencing metallurgical aspects of the work surface in terms of phase information, extent of grain refinement, crystallite size, strain, dislocation density etc. as compared to that of 'as received' Inconel 718.
5. To investigate the effect of EDM variables on micro-hardness of the EDMed work surface (to be measured at the mid-depth of the white layer) as compared to that of 'as received' Inconel 718.

3. Experimental details

EDM process factors (variables) can be divided into two major groups.

1) Non-electrical Parameters
a) Injection flushing pressure
b) Rotational of speed electrode
2) Electrical Parameters
a) Peak current
b) Polarity
c) Pulse duration
d) Power supply voltage

Many authors have categorized the EDM parameters into five categories.

1) Dielectric fluid: type of dielectric, temperature, pressure, flushing system
2) Machine characteristics: servo system and stability stiffness, thermal stability and accuracy
3) Tool: material, shape, accuracy
4) Workpiece
5) Adjustable parameters: discharge current, gap voltage, pulse duration, polarity, discharge frequency, and capacitance.

Peak discharge current (also called peak current): During execution of EDM operation, MRR and TWR both increase with increase in peak discharge current. This is due to the fact that an increase in peak discharge current eventually causes an increase in the pulse energy that leads to an increase in heat input rate onto the workpiece and thereby increased rate of melting as well as evaporation.

Spark-on time (pulse-on time or pulse duration): The duration (per cycle) in which the current is allowed to flow through the discharge gap. The energy input is directly proportional to the pulse-on duration; hence, an increase in pulse duration results in increased material removal rate.

Gap voltage: It is the potential difference applied between two electrodes (tool and workpiece). Gap voltage is also directly related to the energy input supplied onto the workpiece. Therefore, increase in gap voltage results in increased heat input and hence increased volumetric material removal rate.

Duty cycle (may be expressed as duty factor): It is a percentage of the pulse-on time relative to the total cycle time.

$$\tau = \frac{T_{on}}{T_{on} + T_{off}}$$

Flashing pressure: Flushing is a process of removing the burr and other materials from the machining area. Pressurized electrolyte is passed through the gap between tool and work piece to reach the working zone. The flushing pressure is supplied by the pump in the dielectric circulation system during EDM operation.

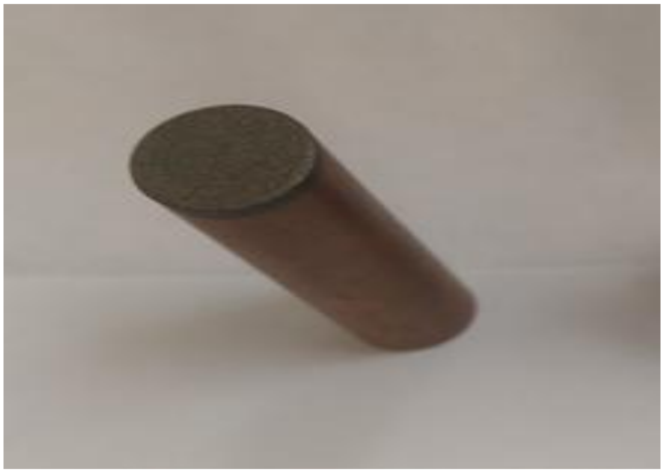
Polarity: In EDM, spark is generated by applying voltage between the electrode and the workpiece. Here, one of them is set as 'positive' and another is set as 'negative'. When workpiece severs as Anode (i.e. positive) and tool electrode as Cathode (negative); the arrangement is called straight polarity. If the arrangement is reversed it is then called reverse polarity.

Spark gap: The spark gap is distance between the electrode and the workpiece that is maintained during execution of the EDM process. Spark gap can be maintained by the servo system attached within the EDM setup.

Experiments have been conducted on EDM setup (Make: Electronica ELEKTRA PLUSPS 50ZNC EMS 5535; Country : India). Inconel 718 plates of dimension ($50 \times 50 \times 5$) have been used as workpiece material. The chemical composition (Nickel-50-55, Chromium-17-21, Molybdenum -2.8-3.3, and Niobium -4.75-5.5) and mechanical properties of Inconel 718 have been taken from Rahul et. al.[9].

During EDM experiments, a pure copper rod of circular cross section (having 12 mm diameter) has been used as tool electrode (Fig. 1). From this copper rod circular cross-section is manufactured by using lathe machine. Copper has thus been taken as tool material because of its stability under sparking conditions. The Cu exhibits relatively less electrode wear and produces good surface finish.

Fig. 1: Copper tool electrode



Commercially available grade Rustlick™ EDM-30 (ITW Professional Brand) oil (with Specific Gravity: 0.80 @ 25° F; Viscosity: 36 SSU @ 100°F (38°C);3.11 cSt. @ 100°F (38°C); Flash Point: 200° F; Dielectric Strength: 45KV) has been used as dielectric medium. [Source: http://www.belmont4edm.com/]

During conduction of the experiments, straight polarity (tool as cathode and workpiece as anode) has been maintained. The following process parameters like peak discharge current (I_p), pulse-on time (T_{on}), gap voltage (V_g) etc. have been considered as control variables; each has been varied at three discrete levels (Table 1). The other parameters such as flushing pressure, duty factor, spark gap and machining time have been maintained constant throughout experimentation (Table 2). The following machining performance features have been measured: Material Removal Rate (MRR), surface roughness (R_a), Surface Crack Density (SCD), and White Layer Thickness (WLT) etc. A snapshot of the machined surfaces of Inconel 718 has been provided in Fig. 2.

Chemical composition of (i) ‘as received’ Inconel 718, and (ii) EDMed surface of Inconel 718 have also been detected by Energy Dispersive X-ray Spectroscopy (EDAX or EDS) (Model No.: JSM.6480LV, manufactured by Hitachi, Japan).Additionally, phase analysis of Inconel 718 base metal and EDMed work surface have also been carried out by using XRD i.e. X-ray Diffraction microscopy (Model: D8 ADVANCE with DAVINCI design, Make: BRUKER, Germany).

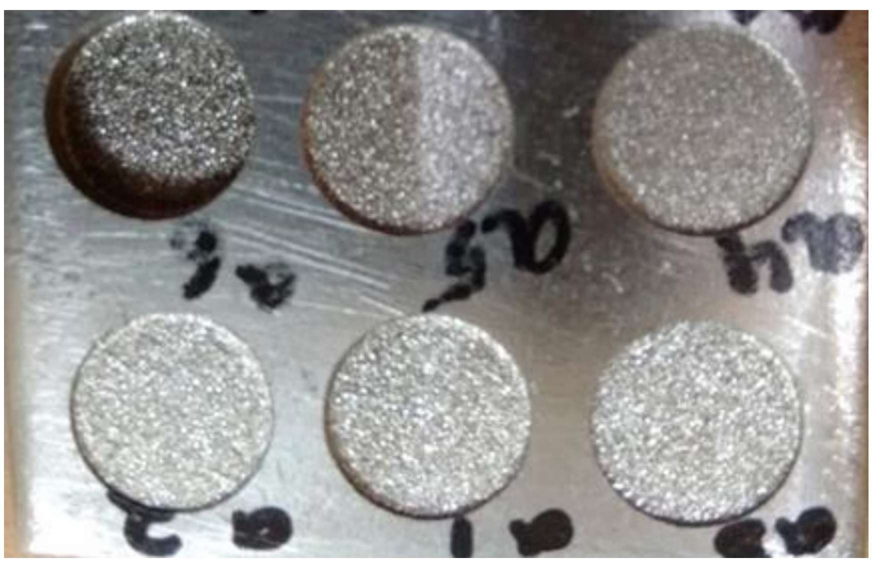
Table 1: Domain of experiments: Machining control parameters

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 2: Parameters kept at constant values

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
Machining time	[t_m]	10 minutes

Fig. 2:EDMed work surfaces of Inconel 718



4. Results and Discussion

3.1 Parametric Influence

The effect of pulse-on time (T_{on}) on MRR for a constant setting of I_P and V_g (20A, 28V) has been shown in Fig. 3.1. It has been observed that with increase in (T_{on}), volumetric material removal rate has exhibited a linearly increasing trend. This may be due to the fact that increase in pulse duration in turn increases energy input per spark and consequently results in high erosion of the parent material at the machining zone. This in turn creates larger craters of relatively higher depth and hence results in increase in MRR.

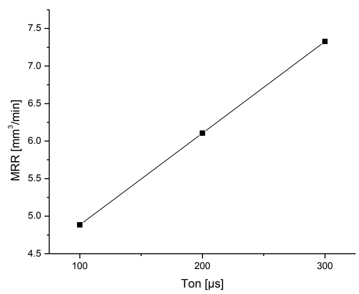


Fig. 3.1: Effect of T_{on} on MRR for constant I_P and V_g (20A, 28V)

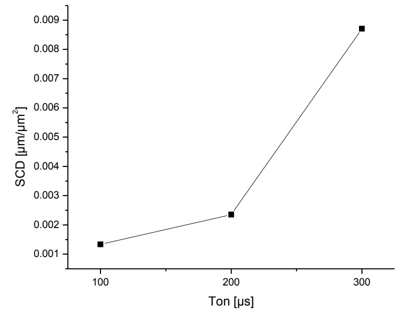


Fig. 3.2: Effect of T_{on} on SCD for constant I_P and V_g (20A, 28V)

As more material is removed with increase in spark discharge energy, dielectric fluid appears increasing ineffective to carry away eroded particle from the machined zone completely. This in turn results in resolidification of the debris (of larger extent); and hence, increase of white layer thickness. Due to high energy input, induced thermal stress developed within the EDMed surface assumes a relatively high value. When this thermal stress exceeds the ultimate tensile strength of the EDMed surface, cracks do initiate and tend to propagate over the surface as well as in a direction vertically downward through the extend of white layer depth and finally towards unaffected parent material. The rate of formation of white layer being relatively less as compared to the rate of surface cracking, crack density and also crack opening width both increase with increase in pulse-on duration (Fig. 3.2).

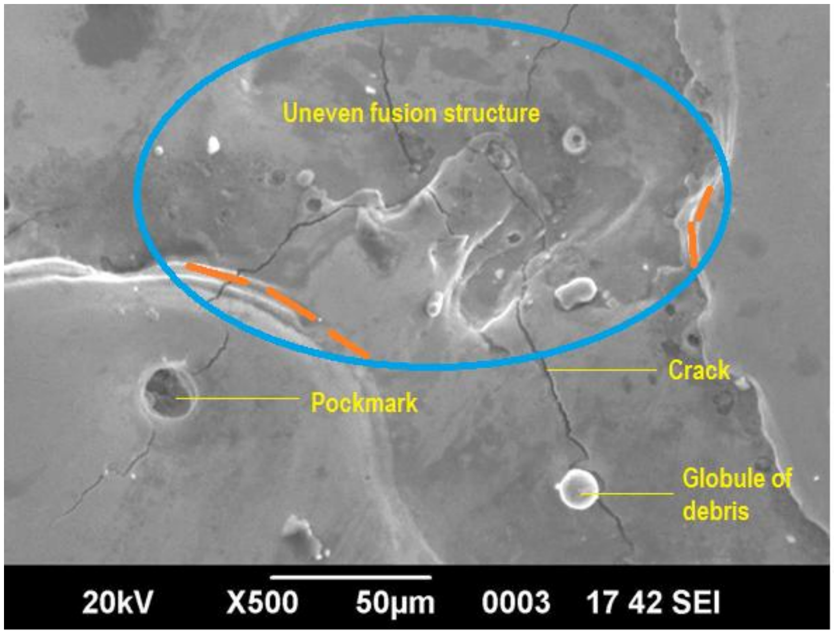
3.2 Analysis of SEM micro-graphs

3.2.1 Surface irregularities

Different types of irregularities have been found appeared after electro-discharge machining on Inconel 718 (Fig. 4.1). Crack developed on the EDMed surface is one of the major irregularities. The workpiece and the tool are subjected to severe cyclic pressure and temperature loadings. Due to this, crack is formed on the surface. Cracks are

usually microscopic dimensions. It is observed under high magnification. Generally the crack density increases with increase in carbon enrichment onto the machined zone during dielectric cracking. In some cases, cracks penetrate across the white layer (also called recast layer) and terminate at the interface with underlying material. Cracks seldom penetrate beyond the recast layer. The formation of crack increases with increase of peak current, pulse-on time and gap voltage Lee et.al.[10].

Fig.4.1: SEM image revealing irregularities on the surface of EDMed Inconel 718 obtained at parameters setting [I_P=20A; T_{on}=300μs; V_g=28V](Run No. 3)



Other defects such as globules of debris, pockmark and crater mark etc. are formed on the machined work surface. The molten material which is not completely flushed out gets deposited on the workpiece and hence, by magnification the EDMed surface is observed to be covered with overlapping craters, pockmark, globules of derbies etc.J. Rebelo et.al. 1998[11]. Pockmarks are formed by entrapped gases escaping from the re-deposited material. It is observed that at low peak current and low pulse duration, the craters appear shallow; and, the pockmarks are less in number;whereas, at high peak current and pulse duration, the cratersappear deeper and more pockmarks are found to be developed.S.H. Lee and X.Li,[12].

The white layer is formed by the molten material which is not flushed away by the dielectric, but resolidifies on the sample's machined surface upon cooling (Fig. 4.2). This white layer is quite hard. The white layer thickness is mainly influenced by the pulse-on duration. If the pulse-on duration increases; then, the white layer thickness also increases. It is because the amount of molten metal which is swept away by the dielectric is constant. Therefore, as more heat is transferred into the sample (as the pulse-on duration increases), the dielectric is increasingly found ineffective to clear away the molten material, and so it accumulatesonto the top surface of the sample. During subsequent cooling, this molten material resoldifies to form the white layer. It is also found that the white layer thickness increases with increase in current and gap voltage. It is because higher current and gap voltage in turn increases higher energy input which melts more material. If the volume of molten material increases; then, it is difficult to be flushed out completely. So, the white layer thickness tends to increase. Rajendran et al.[13].

3.3 EDAX and XRD Analysis

EDAX elemental spectra revealing chemical composition of (i) 'as received' Inconel 718, and (ii) the EDMed work surface of Inconel 718 (obtained at parameters setting: I_P=20A; T_{on}=300μs; V_g=28V) have been shown in Fig. 7.1 and Fig. 7.2, respectively. It has been observed that as compared to 'as received' Inconel 718 (Fig. 7.1), the relative carbon content on the EDMed work surface has been found more. This has been attributed from the EDAX analysis of EDMed surface obtained at parameters setting: (I_P=20A; T_{on}=300μs; V_g=28V) run no 3 (Fig. 7.2). 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 values as compared to that of ‘as received’ Inconel 718.

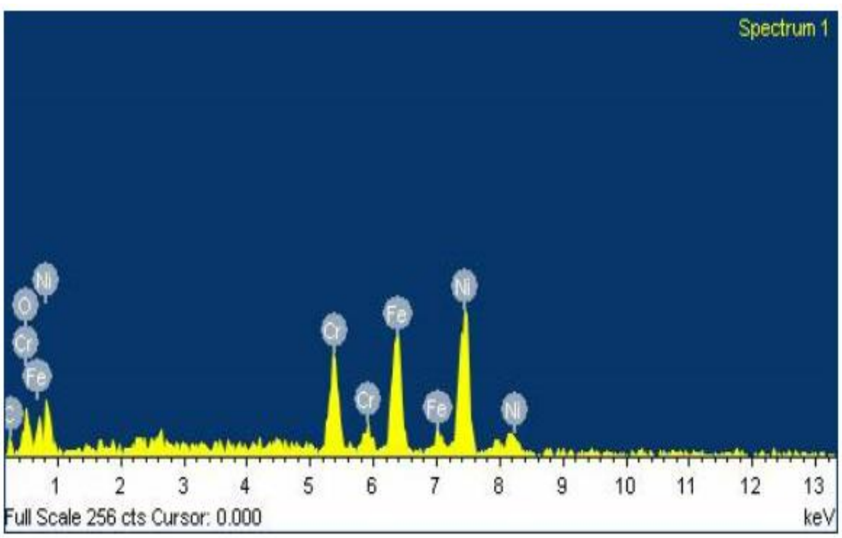
XRD spectra for ‘as received’ Inconel 718 has exhibited presence of Ni-Fe based solid solution matrix with peak patterns approximately matching to that of (Chromium, Cobalt, Molybdenum, Nickel) (Reference Code: 35-1489; Chemical Formula: Ni-Cr-Co-Mo) (Fig. 8.1). Studies in X’Pert *High Score* software has revealed that, the specimen has consisted of cubic crystal system; the highest intensity peak has been observed at crystallographic plane (1 1 1).

In addition to that, some amount of carbide precipitates has also been found at different planes. For example, Cobalt Carbide (Reference Code: 44-0962; Chemical Formula CoC_x) and Copper Nickel (Reference Code: 09-0205; Chemical Formula $Cu_{3.8}Ni$).

As compared to the ‘as received’ Inconel 718, the XRD spectrum of the EDMed work surface (obtained at Run No. 3) has exhibited peak patterns of similar nature (Fig. 8.3).

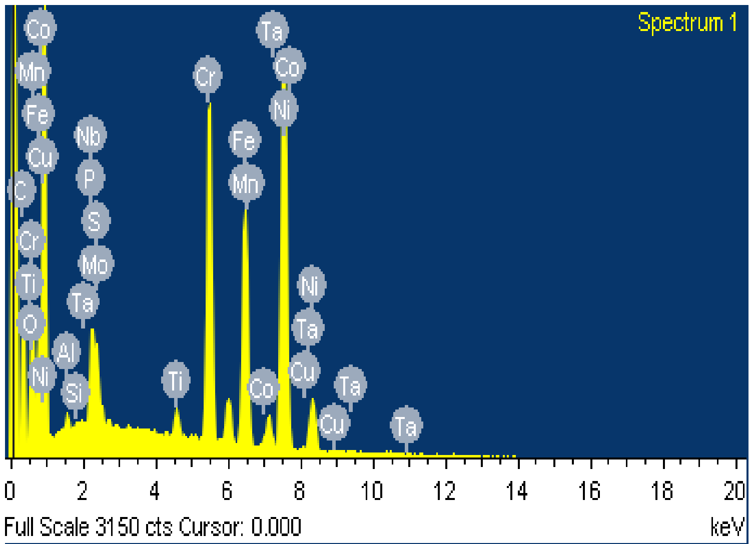
Considering ‘Full Width Half Maxima’ (FWHM) of the highest intensity peak, it has been observed that as compared to ‘as received’ Inconel 718, EDMed work surface has experienced significant grain refinement (attributed due to the thermo-electrical effect of EDM) resulting reduced crystallite size and increased dislocation density (Table 5). However, for case of XRD analysis of the EDMed work surface (obtained at Run No. 3), formation of Aluminium Nickel Carbide (Reference Code: 29-0058; Chemical Formula: $AlNi_3C_{0.5}$), Cobalt Carbide (Reference Code: 44-0962; Chemical Formula: CoC_x), Nickle Carbide (Reference Code: 14-0020; Chemical Formula: NiC) and Nickel Niobium (Reference Code: 23-1274; Chemical Formula: Ni_8Nb).

Fig. 7.1: EDAX elemental spectra revealing chemical composition of ‘as received’ Inconel 718



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	

Fig. 7.2: EDAX elemental spectra revealing chemical composition of EDMed work surface of Inconel 718 obtained at parameters setting [I_P=20A; T_{on}=300µs; V_g=28V][Run No. 3]



Element	Weight%	Atomic%
C K	23.98	55.21
O K	6.83	11.81
Al K	0.34	0.35
Si K	0.09	0.09
P K	0.06	0.06
S K	0.06	0.05
Ti K	0.73	0.42
Cr K	13.59	7.23
Mn K	0.04	0.02
Fe K	12.72	6.30
Co K	0.17	0.08
Ni K	34.90	16.44
Cu K	0.29	0.13
Nb L	4.13	1.23
Mo L	2.04	0.59
Ta M	0.01	0.00
Totals	100.00	

Fig. 8.1: XRD spectra for 'as received' Inconel 718

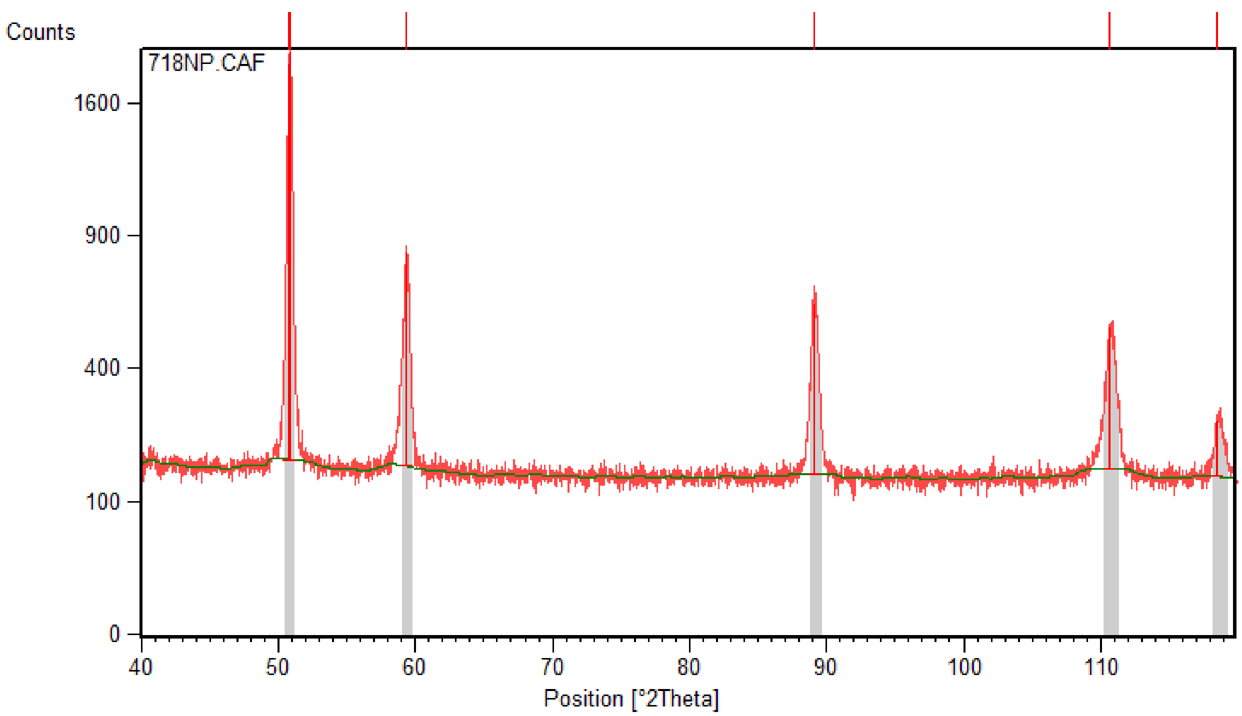


Fig. 8.3: XRD spectra forEDMed work surface of Inconel 718 obtained at parameters setting[I_P=20A; T_{on}=300µs; V_g=28V][Run No.]

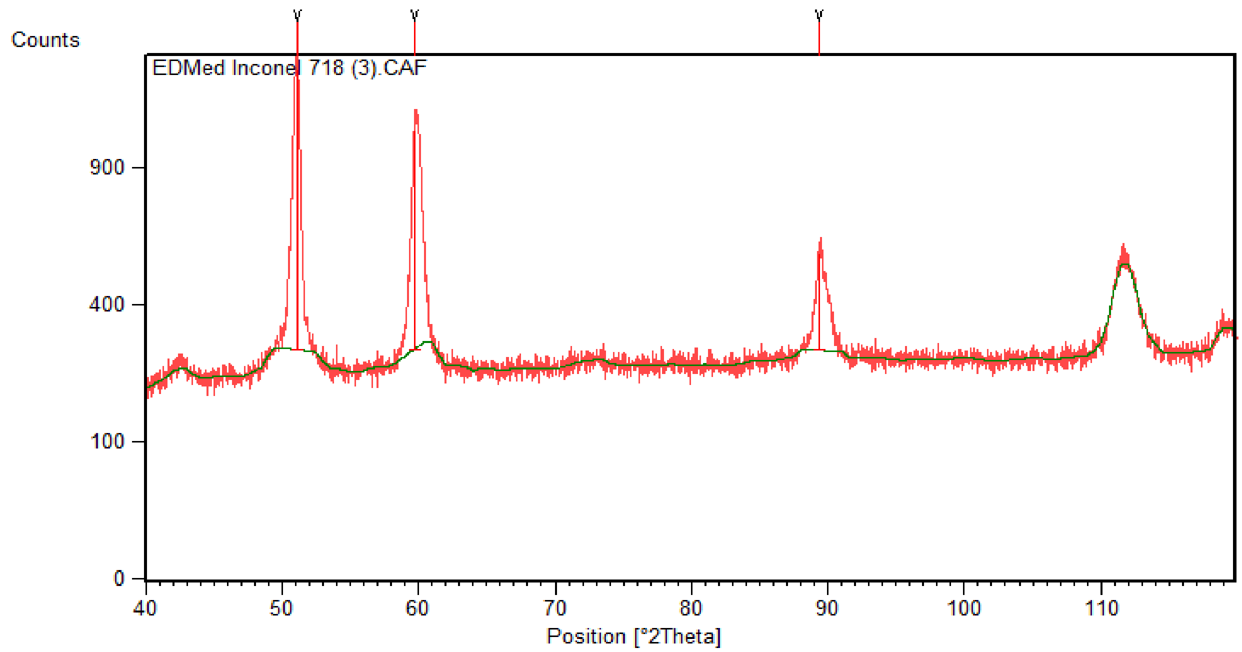


Table 5: The variation of crystallite size (L), and dislocation density (δ) for (1) 'as received' Inconel 718, (2) 'Annealed' Inconel 718, (3) EDMed work surface of Inconel 718 obtained by using parameters setting (Run No. 3)

Sl. No.	Data of the highest intensity peak of XRD for different specimens	2θ $(^0)$	FWHM (β_L) (rad)	Crystallite size (L) (nm)	Miller indices (h,k,l)	Inter planner spacing between the atoms $(d)(A^0)$ (Obtained from *Bragg's Law*)	Lattice constant $(a)(A^0)$	Dislocation density (δ) $\times 10^4$
(1)	'As received' Inconel 718	50.8989	0.002996	59.57	(1 1 1)	2.083	3.6078	4.7203
(3)	EDMed work surface of Inconel 718 obtained by using parameters setting [Run No. 3]	51.1749	0.0077577	23.0322	(1 1 1)	2.07299	3.5905	31.728

Conclusion

The following conclusions are found from the above reasearch.

1. Different types of surface irregularities(i.e. crater marks,glouble of debris,,pock marks) are found on the surface of EDMed Inconel 718 and this iiregularities are more compare to parent material. However the irregularities depends upon the EDM process parameters settings.
2. From EDAX analysis,It is found that the carbon content is increased in the EDMed specimen as compare to parent materials.Due to carbon enrichment the white layer thickness is increased on the EDMed part as compare to as received material.
3. XRD analysys stated that there is no phase transformation occurred in Inconel 718 after EDM process. However grain refinement is observed.
4. Here the graphs representing the variatin of MRR,SCD,WLT with respect to Pulse-on time.It has been observed that MRR,SCD,WLT is directly proportiuonal to Pulse-on time.The increase of pulse-on time in return result increased energy input during the machining process which increases MRR,SCD,WLT.

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