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Surface and Sub Surface evaluation in Coated-Wire Electrical Discharge Machining (WEDM) of INCONEL® alloy 718

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Abstract

Wire Electrical Discharge Machining (WEDM) is one of the most versatile and useful technological processes for cutting complex shapes made of conductive materials such as those typical of aerospace applications. With the aim to optimize process parameters, this paper studies the surface and subsurface modifications of INCONEL® alloy 718 (UNS N07718) machined by WEDM using a Zinc coated brass wire. Machining was performed under roughing and finishing conditions by setting different values of discharge energy and wire feed rate. Surface roughness of the cut surfaces was measured as well as the micro-hardness profile on polished sections. WED-machined surfaces and their cross sections were also observed by Scanning Electron Microscope (SEM) and analyzed by Energy Dispersive X-ray Spectroscopy (EDS) to evaluate possible variations of the surface chemical composition. In this investigation, results are discussed as a function of the feed rate and of the single pulse discharge energy, which is determined by duration, peak current and discharge voltage of the discharge pulse. The research demonstrates that the required surface roughness can be achieved by properly setting the feed rate and the single pulse discharge energy on the WEDM machine. Experimental results also show that under the re-melted layer thickness no significant white layer formation or thermal modification occur, indicating that the chosen set of operating parameters minimizes secondary and unwanted chemical reactions.

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Keywords: Wire EDM; Roughness; INCONEL; Nominal discharge energy;

1. Introduction

Nickel based super-alloys exhibit high chemical and mechanical properties, even at elevated temperatures, and for this reason they are used for jet engines and gas turbines, as well as for reciprocating engines parts, rocket engines, and in nuclear, chemical and petrochemical industries [1,2]. However, the same characteristics that make these materials suitable for applications in extreme conditions are an issue when the material is shaped or machined. Machinability of age-hardened INCONEL®, such as 718, has been investigated by several researchers [3-7], and results demonstrate that this alloy can be machined with hard tools setting slow cutting conditions to prevent tool wear and machined surface damage [8-10]. Nevertheless, in order to achieve high productivity, it is necessary to use high cutting speed (for INCONEL® 718 speed over 50 m/min), which leads to a short tool-life, even in case of the expensive SiC whiskers reinforced ceramic tool [1,11-13]. An interesting alternative to conventional cutting processes is the Wire Electrical Discharge Machining (WEDM), that is a thermal process capable of machining conductive difficult-to-cut materials. It is a versatile and useful technological process for fabricating intricate and complex shapes. Nowadays, WEDM parameters optimization as function of surface and subsurface quality of the machined material is still an open issue.

Several authors have been studying the surface damage caused by the erosion in WEDM, analyzing the effect of material thermal properties and applied cutting parameters, such as on-time pulses, discharge voltage, dielectric fluid pressure and characteristics [14-17]. Scot *et al.* reported that discharge current, pulse duration and pulse frequency are the main significant control factors for both the material removal rate (MRR) and surface finish, while wire speed, wire tension

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and dielectric flow rate are less significant [18]. Other researchers performed studies on the influence of the dielectric flow pressure, peak current and t_{on}/t_{off} ratio on the MRR and surface roughness [19]. Tarng *et al.* investigated the effects of the no-load voltage and of the Servo reference Voltage (SV) on the average discharge gap [20]. As a matter of fact, the material removal mechanism of WEDM is a random process and there are many variables that interact with each other in a very complex way. So far in the literature reaserch papers about WEDM have considered the influence of each single parameter but the combined effect of several variables has been disregarded.

In order to have a comprehensive view, a reference variable that includes the interrelationships among regulating parameters should be observed for assessing the quality of machined surfaces. To this aim, in this investigation the nominal discharge energy per unit length is chosen as reference variable to explore the effects on the resulting surface and subsurface features of INCONEL® 718 specimens.

2. Materials and methods

Fig. 1 shows the schematic illustration of the WEDM process set-up used in this work. The machined material is a 40 mm diameter rod of INCONEL® 718, produced by hot extrusion process and subjected to the following heat treatments: solution treated for two hours at 1311 K and water cooled, age hardened for six hours at 1043 K and air cooled. In Table 1 and Table 2 the chemical composition and mechanical and physical properties of the material, as given by supplier, are listed. Tests are performed using a Charmilles Robofil 200 WED machine. The workpiece is cut by a 0.25 mm diameter wire made of Zinc coated brass (CuZn37).

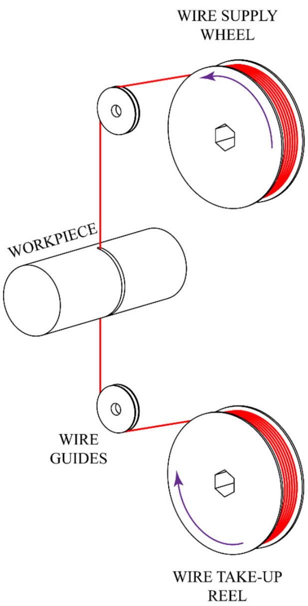

Fig. 1. Schematic illustration of the WEDM process set-up.

Table 1. Chemical composition of INCONEL® 718.

Element (% wt)							
Ni	Cr	Mo	Nb	Al	Ti	Fe	Co
52.8	18.33	3.05	5.16	0.63	1.05	*Bal*	0.166
Cu	V	W	Mn	Si	C	S	P
0.02	0.02	0.05	0.07	0.04	0.03	0.002	< 0.003

Table 2. Mechanical and physical properties of the INCONEL® 718 [21].

Yield strength $Y_{S(0.2\%)}$	986 MPa
Tensile strength UTS	1262 MPa
Elongation A_{50}	28.6 %
Area Reduction	48.6 %
Hardness $HV_{0.05}$	200 HV
Density	8190 kg/m³
Melting Range	1533 ÷ 1608 K
Specific Heat @ 293 K	425 J/(kg·K)
Thermal Conductivity @ 293 K	11.2 W/(m·K)
CTE @ 293÷373 K	$13 \cdot 10^{-6}$ K^{-1}

The coated tool allows to achieve a higher cutting rate as well as a higher cutting precision with respect to an uncoated one [22]. When a pulse is applied, part of the pulse energy is spent to heat up the wire locally and a part to overheat the wire coating, which evaporates. Therefore the wire undergoes a heat sink effect and the core material cools down. Consequently, the tension applicable to the wire can be increased and this allows to reduce the barrel effect and to increase the precision. Thus, the wire tension during tests is set to 15 N. Deionised water is used as dielectric medium (conductance 6.9 µS at T = 293 K). The use of deionised water is ideal for WEDM, where the fluid must enter the kerf, due to its low viscosity. The workpiece is submerged in the dielectric and a flow-assisted process is used, applying 2 bar to the upper jet and 1.5 bar to the lower jet. The sets of process parameters used in the experiments are listed in Table 3. The discharge voltage is kept constant during tests at 120V, whereas discharge current and pulse duration are set according to roughing or finishing process conditions to guarantee stable machining.

Surface roughness of the machined samples is measured by means of a stylus profilometer (DIAVITE DH-5) and WED-machined surfaces are observed by Scanning Electron

Table 3. Process parameters used in WEDM tests. The discharge voltage value is constant and equal to 120 V.

Test	Discharge current, *I* *(A)*	Pulse duration, t_{on} *(µs)*	Duty cycle, *d* *(-)*	Feed rate, *v* *(mm/min)*
ROUGHING				
#1	32	6.0	0.25	1.4
#2	24	4.0	0.20	1.3
#3	48	0.8	0.03	1.2
FINISHING				
#4	16	1.6	0.20	8.1
#5	8	0.8	0.16	8.3

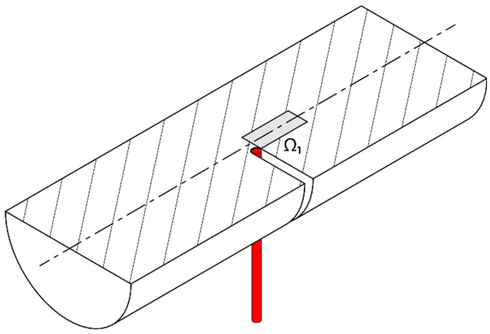

Fig. 2. Schematic illustration of the specimen axial section (2 mm × 5 mm) for subsurface inspection.

Microscope (SEM). In order to determine possible effects of the machining operation on the subsurface properties, the cut specimens were sectioned axially, along the normal to the machined surface as illustrated in Fig. 2. To this end, the machined surface was coated with Bakelite to preserve its integrity during the following sample metallographic preparation. The piece was sectioned and polished with diamond paste up to 1 µm and chemically etched using a solution consisting of 50 ml of glacial acetic acid, 50 ml of nitric acid and 75 ml of hydrochloric acid. The polymeric protective coating was removed soon after etching and the specimen was observed at SEM/EDS (Philips XL-30 with INCA X-sight Series Si(Li) EDS Detector) using both secondary and back scattered electrons. Moreover, in depth micro-hardness measurements were performed by means of a Remet HX-1000 Vickers microindenter on the section of the specimen machined in the Test #3 condition of Table 3. To have information about dispersion of results, each measurement was repeated six times.

From the perspective of machining energy, each pulse during the discharge process is an output of energy. On the other hand, the sparks are randomly activated during discharge in the regions where the electrodes are nearest or where the dielectric flow effectiveness is lowest [23]. Therefore, it is not possible to evaluate the number of sparks for a single cycle, and the efficiency and the energy of the single spark are unknown too. The nominal discharge energy is the maximum value that the discharge process can use to remove the material, but the efficiency of the process is affected by many variables such as the dielectric conductance, the dielectric flow, the gap value, the thermal conductivity, and the electric conductivity of the electrodes.

In this paper WEDM results are analyzed as a function of the nominal discharge energy per length (E) defined as

$$E = k \cdot \frac{V \cdot I}{v} \cdot \left(\frac{d}{d+1} \right) \quad (1)$$

where V is the discharge voltage (V), I is the mean nominal current (A), v is the feed rate (mm/min), d is the duty cycle, and k is the conversion constant, equal to $60 \cdot 10^3$. As a consequence the quantity defined in Eq. 1 is measured in J/m.

3. Results and discussion

Results are presented and discussed separately for surface and subsurface properties in the following two sections.

3.1. WED-machined surface

Average surface roughness measurements results are listed in Table 4 as a function of the nominal discharge energy per length (E) defined in Eq. 1. As expected, the surface roughness

Table 4. Surface roughness measurements.

Test	Discharge energy per length, E *(10^{-6} J/m)*	Surface roughness, R_a *(µm)*, mean (SD)*
#1	40.48	7.60 (0.58)
#2	26.79	4.82 (0.40)
#3	9.92	4.82 (0.22)
#4	2.84	2.31 (0.21)
#5	1.11	1.71 0.19)

* standard deviation in round brackets

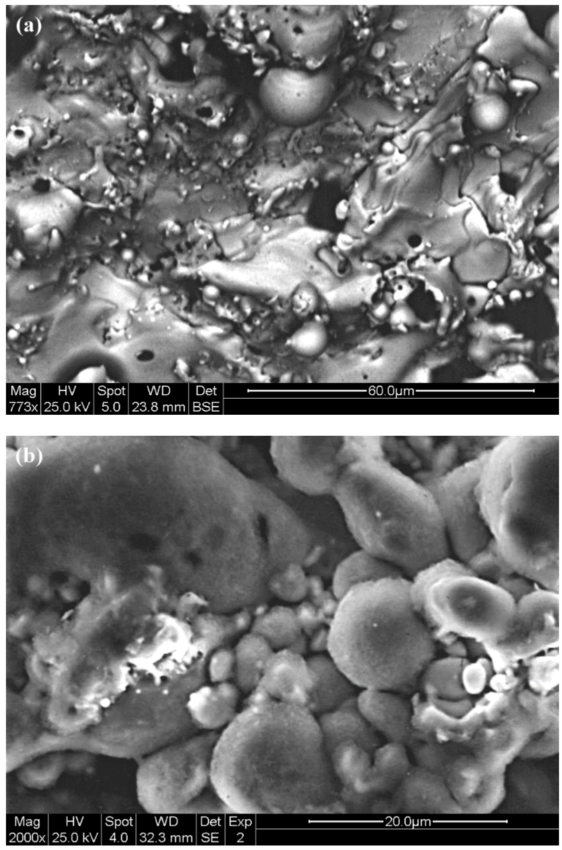

Fig. 3. SEM observations of WED machined surfaces obtained in roughing condition: (a) Test #3 ($E = 9.92 \cdot 10^{-6}$ J/m) and (b) Test #1 ($E = 40.48 \cdot 10^{-6}$ J/m).

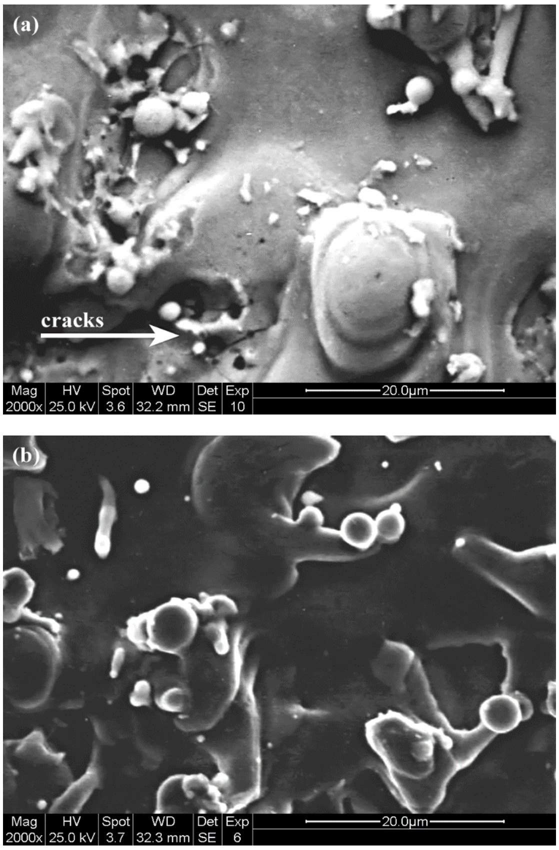

Fig. 4. SEM observations of WED-machined surfaces: (a) roughing condition Test #3 ($E = 9.92 \cdot 10^{-6}$ J/m), and (b) finishing condition Test #4 ($E = 2.84 \cdot 10^{-6}$ J/m).

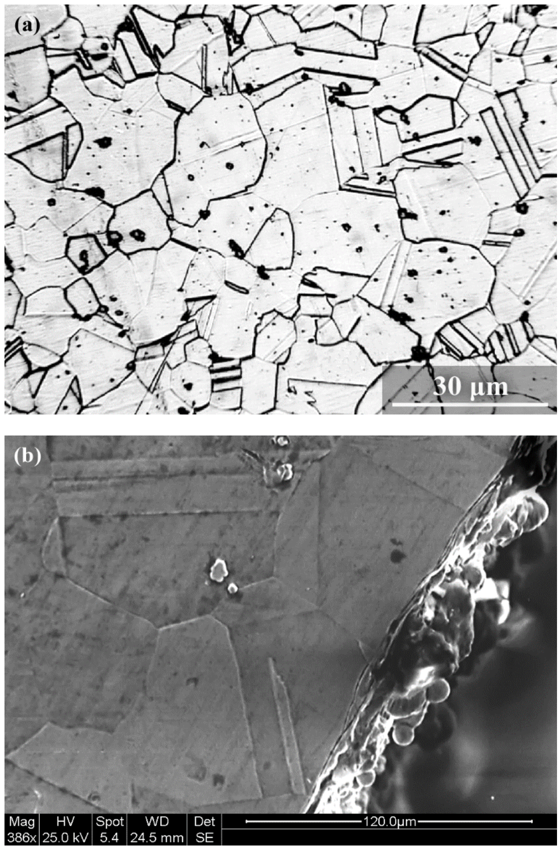

Fig. 5. (a) Microstructure of the starting material, before WED-machining, and (b) SE (Secondary Electrons) micrograph of a cross section of the machined sample (Test #3).

increases with increasing the discharge energy per length with the exception of Tests #2 and #3, where roughness values are comparable. The results can be justified by considering the processes taking place during the electrical discharge.

As a matter of fact, the nominal energy per length (E) is the sum of three factors. These are the energy that is used to remove material from the workpiece, the energy that is transmitted to the wire electrode, and the one that is transferred to the machining fluid. In the simplifying hypothesis that the partitioning of the energy among the three factors remains almost constant as the energy input changes, E-value results proportional to the amount of material that is removed from the workpiece. Thus, the measured increase of surface roughness could be explained by a higher energy transmitted to the material during cutting. A higher amount of energy increases the evaporation and recasting, thus altering the material surface morphology to a larger extent. The similar roughness values obtained in the Tests #2 and #3 could be the effect of a different partitioning of the energy. In fact the energy distribution is affected by pulse duration [24]. As the rate of energy transfer increases there is less time for the energy to be dissipated and thus more energy is conducted into the workpiece. Thus high energy with a large pulse duration could give outcomes similar to those obtained by a short pulse with low energy.

The SEM observations of surfaces resulting from WEDM Tests #1 and #3 are shown in Fig. 3. In both cases the re-deposited material is round-shaped and not homogeneously distributed on the surface. Numerous bubbles are visible on the surfaces and their aspect results spongy when duty cycle and nominal discharge energy per length values are high (Fig. 3b). In Fig. 4, rough and finished surfaces are compared. On the recast surface some cracks are visible as marked in Fig. 4a, but they are positioned parallel to the surface.

3.2. Subsurface properties

Fig. 5 shows the comparison between the microstructure of the starting material and the one of the machined sample, obtained by polishing the surface and etching according to the procedure previously described. No cracks are visible in the cross section, as shown in Fig. 5b. The outer layer is the recast one, formed by the molten metal solidifying. That layer lies on the INCONEL® 718 grains that were highlighted by the etching performed prior to SEM observations.

It is important to notice that there is no evidence of the typical white layer formation, indicating that most of the secondary and unwanted reactions are minimized by the chosen operating parameters set. As a matter of fact, in the applied operating conditions, no chemical interaction is observed between the INCONEL® 718 surface and the dielectric fluid.

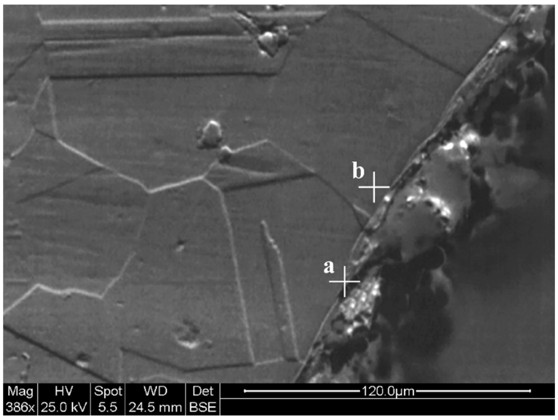

Fig. 6. BSE (Back Scattered Electrons) micrograph of a cross section of a WED-machined INCONEL® 718 sample (Test #3).

Table 5. Semi-quantitative EDS analysis of the recast region (a) and of a nearby region (b) in Fig. 6.

	Element (% wt)							
	Ti	Cr	Fe	Ni	Cu	Nb	Zn	others
(a)	1.44	19.42	18.62	34.91	13.11	2.14	7.39	2.97
(b)	0.88	19.35	22.29	55.04	1.01	1.44	-	-

Moreover, no significant decarburizing occurs, due to the intrinsically low carbon content of the investigated super-alloy. The microstructure appears unaltered by the WED-machining, despite the high thermal gradient experienced by the material. The geminates density does not appear significantly changed after machining, indicating that the formation of thermal geminates is reduced to the minimum. BSE (Back Scattered Electrons) micrograph and Energy-dispersive X-ray spectroscopy (EDS) analysis on a sample cross section are reported in Fig. 6 and Table 5 respectively. Table 5 shows that there is a decrease of the Nb percentage immediately below the recast layer. In agreement with previous results [25-27], EDS analysis of the machined surfaces revealed a Cu percentage slightly higher than the one of the original material. This could be ascribed to contamination from the brass wire. However, the tool contamination is localized in the recast layer and does not extend much further in the material. EDS analysis also shows that the recast layer presents a higher chromium concentration and Cr/Ni ratio is higher in region (a) in Fig. 6 with respect to region (b) and to the base material. This can be attributed to a localized scale formation, according to the mechanism of oxidation which involves the diffusion of Cr through the alloy to the scale/alloy or the scale/environment interface and its subsequent oxidation [28].

In Fig. 7 the micro hardness map is shown. No significant variation of the micro-hardness of the machined sample is detected with respect to the base material (210 $HV_{0.05}$), up to 200 μm from the machined surface. A slight decrease of the micro-hardness in the first 50 μm is observed, that could be ascribed to the local Nb depletion, as evidenced by EDS analysis.

4. Conclusions

Samples of INCONEL® 718 (UNS N07718) were cut using Wire Electrical Discharge Machining (WEDM) under different operating conditions. A Zinc coated brass wire was used to

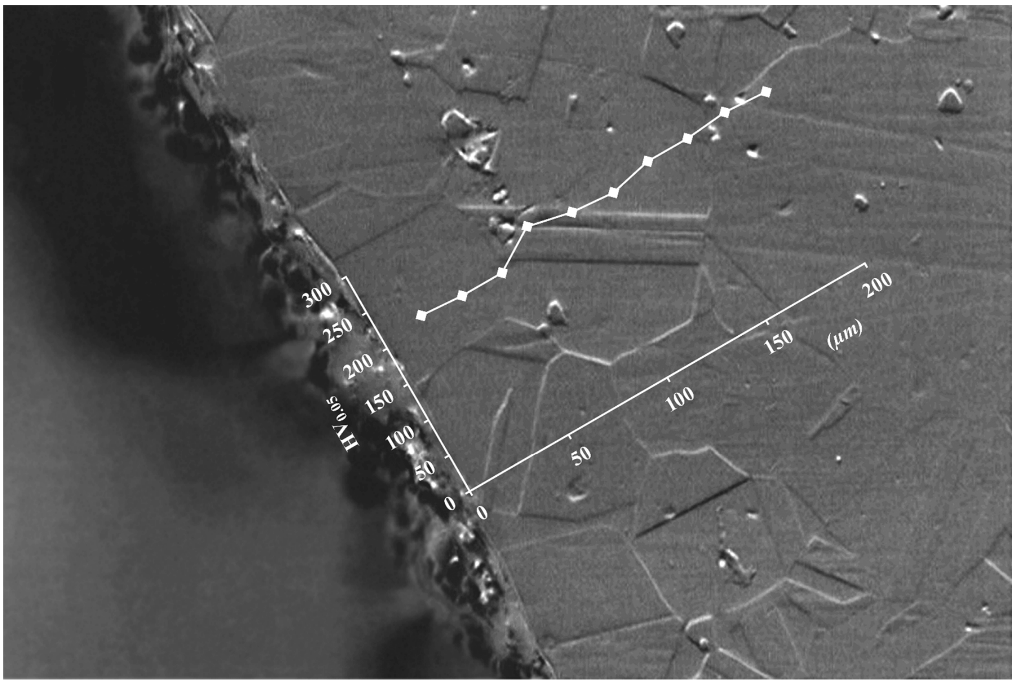

Fig. 7. Micro hardness profile as a function of depth from the WED-machined surface (Test #3).

ensure high precision machining. A comprehensive reference parameter, namely nominal energy per length (*E*), was defined as an indication of the amount of energy transferred to the workpiece per length of cut.

Experimental results showed that the surface roughness of the machined samples worsens as the *E*-value increases. A possible explanation is that the increase of energy per length causes more material to evaporate (and recast) from the workpiece, thus progressively altering its surface morphology. Analogously the recast layer morphology is affected by the *E*-value. In case of high nominal energy per length, the re-deposited material is round-shaped and spongy, while in case of low *E*-values, the deposited material appears more compact. On the other hand, the cutting parameters applied in the present study do not alter significantly the overall workpiece microstructure nor its composition, except for some expected Nb depletion and some Cu contamination from the tool, limited to the surface recast layer. Also micro-hardness values result slightly lower only in the first 50 μm from the surface of the machined sample. In the range of the studied process parameters, it could be stated that the nominal energy per length should be considered as a suitable parameter to properly set the WED-machining equipment in order to obtain the required surface roughness.

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