Role of Multi-Wall Carbon Nanotubes on the main parameters of the Electrical Discharge Machining (EDM) process

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M. Mohammadzadeh Sari · M. Y. Noordin · E. Brusa

Abstract Electrical discharge machining is a very accurate non-traditional manufacturing process for creating tiny aper-tures, complex shapes and geometries within mechanical parts and assemblies. Its performance is evaluated in terms of sur-face roughness, existence of cracks, voids, and recast layer on the surface of product. The high heat generated on the electri-cally discharged material during the electrical discharge ma-chining (EDM) process unfortunately decreases the quality of product. In this paper, the high strength and unique electrical and thermal properties of multi-wall carbon nanotubes are used to improve the EDM performance when machining the AISI H13 tool steel, by means of copper electrodes. Material re-moval rate, electrode wear rate, surface roughness, and recast layer were measured in presence of carbon nanotubes in the dielectric, then compared to the outcome of traditional EDM. Experiments show that mixing multi-wall carbon nanotubes within the dielectric makes the EDM more efficient, particu-larly if machining parameters are set at low pulse of energy.

Keywords Carbon nanotube · Electrical discharge machining · Surface roughness · Recast layer · Material removal rate · Electrode wear rate

1 Introduction

Electrical discharge machining (in the following simply EDM) is one of the most accurate manufacturing processes available for creating complex geometries within parts and assemblies. An overview of the most recent techniques and features of the EDM process was proposed by Jamson [7], Ghoreishi and Atkinson [2], Ho and Newman [6], although some new advances are now available and currently tested. As Ho and Newman [6] clearly stated in their contribution, using thermal energy to machine conductive part is a unique feature of the electrical discharge machining to manufacture mold, die, aerospace, and rather complicated components. EDM erodes material in the path of electrical discharges by generating an arc between the electrode tool and the work piece. It is therefore a quite affordable and suitable manufacturing process when a high accuracy is required. Nevertheless, the EDM approach shows some problems such as generation of high heating on the electrically discharged material and formation of white layer in the work piece, thus decreasing the quality of surface roughness and the product life. Recent advances in nanotechnology show that carbon nanotubes (CNTs) display unexpected strength and unique electrical properties and are effective thermal conductors, as well as Dresselhaus et al. [1] describes in his state of arts about properties of CNTs. Therefore, carbon nanotubes can be used in the EDM process to absorb the heat from the electrical discharged material and decrease the amount of white layer. Some specialized contributions in the literature were recently focused on the EDM improvement through the CNTs. Prabhu and Vinayagam [10] proposed an approach to generate a Nano surface of Inconel 600 material in grinding process by using single-wall CNTs, they [11] also analyzed the surface characteristics of tool steel mate-rial by using single-wall CNTs to improve the surface finish of material to the nanometer size. Mai et al. [8] very recently demonstrated some benefits in using the CNTs in the EDM process, thus highlighting the current interest of industry for this approach. Nevertheless, a deep investigation about the improvement of the EDM parameters in case of using multi-wall CNTs was not yet proposed nor experimentally

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Table 1 Properties of the AISI H13 tool steel

Property	Description	
Composition [%]	C 0.39; Si 1.0; Mn 0.4; Cr 5.3; Mo 1.3; V 0.9	
Delivery condition	Soft annealed (approximately 185 HB)	
Color code	Orange/violet	
Hardness	52 HRC	45 HRC
Tensile strength	1,820 MPa	1,420 MPa
Yield strength	1,520 MPa	1,280 MPa

documented by resorting to several machining parameters, even in some very recent contributions [12]. A deep analysis of the main process parameters affecting the EDM process was performed by Guu [3, 4], while he investigated the use of EDM process for machining the surface morphology and roughness of the AISI D2 steel. Pecas and Henriques [9] proposed an EDM process with powder-mixed dielectric and compared it with the normal conditions of the EDM to analyze the surface quality. Those contributions motivated the approach proposed in this paper, being aimed at evaluating through some experiments the benefits introduced by multi-wall CNTs mixed in the dielectric fluid on the typical parameters of the EDM process.

2 Selected materials

Study was first focused on a selected material to perform a preliminary investigation of the results obtained through the traditional EDM process. The AISI H13 steel was selected as a tool material. It is a chromium–molybdenum–vanadium-alloyed steel, widely used in industry for some applications. It was machined by the EDM, being a non-conventional material removal process. It consists of machining electrically conductive materials by using some precisely controlled sparks occurring between an electrode and a work piece, in the presence of a dielectric fluid. It is a thermal process; therefore, material is removed by heat, generated by the spark. EDM is only applicable to electrically conductive materials, like hardened steel, titanium, hastelloy, kovar, inconel, and carbide.

Table 2 Physical properties of copper electrode

Physical properties	
Electrical resistivity (μΩ/cm)	1.96
Electrical conductivity compared with silver (%)	92
Thermal conductivity (W/m K)	268–389
Melting point (°C)	1,083
Specific heat (cal/g °C)	0.092
Specific gravity at 20 °C (g/cm^3)	8.9
Coefficient of thermal expansion (×10^{-6} °C^{-1})	6.6

Table 3 Properties of MWCNTs used in this study

Property	Description
Outer diameter	<8 nm
Length	10 to 30 m
Purity	>95 wt%
Ash	<1.5 wt%
Specific surface area	>500 m^2/g
Electrical conductivity	>10^{-2} S/cm

2.1 AISI H13 tool steel

The AISI H13 steel is a hot work tool steel with overall good ductility, toughness, wear resistance, and harden ability and machinability. It is evenly known as DIN 1.2344 and EN X40CrMoV5. It assures a good resistance to abrasion at both low and high temperatures, high level of toughness and ductility, uniform and high level of machinability and polish ability. Moreover, it shows a good high-temperature strength and resistance to thermal fatigue, excellent through-hardening properties and a very limited distortion during hardening. Selection of this material was motivated by the number of applications as tools for extrusion, dies, backers, die holders, liners, dummy blocks, stems, plastic molding applications, injection molding of thermoplastics, long pro-duction runs, and molding of parts in thermosetting plastic. Main properties are summarized in Table 1.

2.2 Electrode material

Copper electrodes have been used primarily in resistance capacitance circuits where higher voltages are employed.

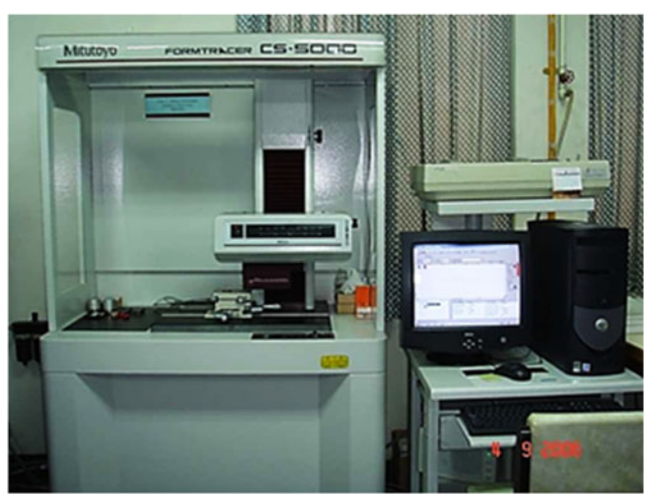

Fig. 1 Formtracer CS-5000

Fig. 2 Scanning electron microscope (SEM)

They are quite popular in the EDM equipments. Therefore they were selected to be used in this investigation. The electrode of the experimental test has a circular cross section whose diameter is 4.9 mm. Physical properties of copper are displayed in Table 2.

2.3 Multi-wall carbon nanotubes

A particular layout of carbon nanotubes was selected for this investigation. Actually they are allotropes of carbon with a cylindrical nanostructure. Henrich et al. [5] discovered that these cylindrical carbon molecules have novel properties that make them potentially useful in many applications as electronics, optics, and other fields of materials science. They exhibit extraordinary strength and unique electrical properties and are efficient thermal conductors. Among sev-eral configurations, multi-wall carbon nanotubes (MWCNTs) consist of multiple rolled layers of graphite. Interlayer distance is close to the distance between graphene layers in graphite, i.e., approximately equal to 3.4 Å. Relevant properties of the MWCNTs used in this experimental activity are described in Table 3. In terms of production and cost, MWCNTs may be interesting for industrial application and were consequently tested.

Fig. 3 EDM Charmilles Roboform 100

Table 4 Factors and levels for the EDM process analysis

Factor	Name	Units	Type	Low level (−1)	High level (+1)
P	Peak current	Ampère	Number	8	24
A	Pulse on time	µs	Number	12.8	50
B	Interval time	µs	Number	12.8	50

3 Experimental setup

To perform the EDM and measuring its relevant parameters, some facilities were used at the Universiti Teknologi Malaysia. The arithmetic surface roughness was measured on the machined surface by using the Mitutoyo Formtracer CS-5000 shown in Fig. 1. This equipment measures the surface roughness on plane, groove, and cylinder. A scan-ning electron microscope (SEM) analyzed and measured the thickness of the altered surface layer such as recast layer, heat affected zone, and micro cracks (Fig. 2). Each specimen was made of the AISI H13 tool steel. The work pieces were prepared to size of 10×10×10 mm. Hardness of specimen was measured as 53 HRC. The dielectric fluid used in the EDM process was kerosene. Up to 80 L of liquid were used to fill the tank connected to the EDM equipment. Specimens were sparked on the die-sinking EDM machine Charmilles Roboform 100 (Fig. 3). Copper electrode was used as a

Table 5 List of the EDM runs performed and analyzed

Std	Run	*P* (peak current) [A]	*A* (pulse on time) [µs]	*B* (interval time) [µs]
1	6	8	12.8	12.8
2	2	8	12.8	50
3	8	8	50	12.8
4	4	8	50	50
5	7	24	12.8	12.8
6	1	24	12.8	50
7	5	24	50	12.8
8	3	24	50	50

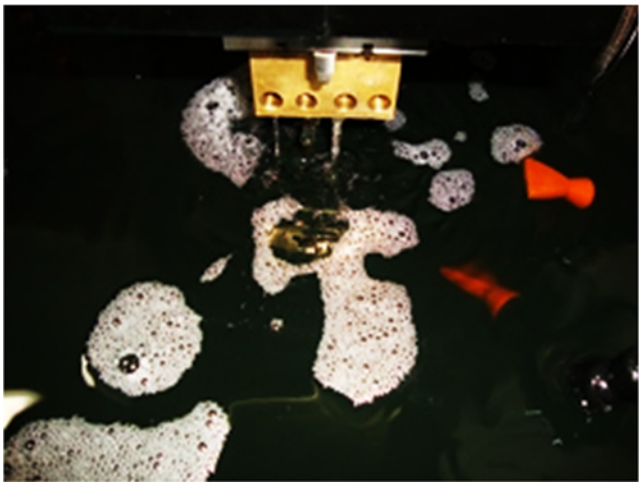

Fig. 4 Mix of kerosene and MWCNTs in the dielectric used for the experiments

negative polarity during the EDM process, while the specimen was the positive one.

4 Experimental investigation

A full characterization of the EDM process is performed when some relevant parameters are measured [7]. In particular, the peak current, the pulse on time, and the interval time completely define the operating conditions of the EDM machine, while operating on the machined product. In the meanwhile, response in terms of the machining effectiveness is appreciated if the material removal rate, the electrode wear rate, the surface roughness, and the recast layer are measured and known. To implement the proposed investigation a preliminary design of experiments was performed. It was based on the factors and levels described in Table 4. Experiments were then carried out according to the ANOVA analysis. Three factors were selected for each step of the investigation, leading to perform up to eight experiments. The voltage was set at 80 V during each experiment. Table 5 summarizes the procedure followed in each run.

In a first step of the investigation, experiments were performed by implementing the conventional EDM method, i.e., without using carbon nanotubes in the dielectric fluid. A precision balance was used to measure the weight of work piece and electrode, respectively, just before and after each machining process. Electrode wear and material removal rates for each run of the performed experiments were measured. Machined surface roughness of each specimen was detected by the surface roughness tester. Thickness of recast layer on the surface of specimens was measured by the SEM. In the second step of the study, the multi-wall carbon nanotubes were mixed in the dielectric fluid in proportion of 1 g of MWCNTs for each liter of kerosene (Fig. 4). According to [10, 11], this quantity looked a good compro-mise between the cost of the addition and the effects pro-duced on the process. Moreover, it could be interpreted as a reference concentration to scale the effects on the machined product. A separate tank was used for machining with using MWCNTs. Even in this case, relevant parameters were measured as it was previously described. Results were finally compared to determine the effect of multi-wall carbon nanotubes.

5 Results and discussion

Experiments consisted first of the EDM machining of each specimen. Precision balance was used to measure the weight of work pieces before and after the machining process, as Tables 6 and 7 show. In those tables, the data relating the weight of work pieces during the machining in both conditions with and without using carbon nanotubes mixed in dielectric are collected. Machining time of each experiment is evenly added.

Symbols in Tables 6 and 7 correspond to the weight of work piece before machining, W_b, weight of work piece after machining, W_a, weight of electrode before machining, E_b, and weight of electrode after machining, E_a. It can be

Table 6 Experimental result of EDM without using CNT

Run	W_b	W_a	Difference	E_b	E_a	Difference	Time of machining
1	5.2938	5.1612	0.1326	17.7629	17.7305	0.03240	00:43
2	5.8975	5.7770	0.1205	17.5430	17.5167	0.02630	30:08
3	5.2404	5.1172	0.1232	17.4064	17.3701	0.03630	01:02
4	5.3845	5.2388	0.1457	11.6973	11.6787	0.01860	09:46
5	5.0883	4.9805	0.1078	11.5691	11.5388	0.03030	00:42
6	5.6184	5.5074	0.111	11.4151	11.3844	0.03070	32:43
7	5.1072	5.0128	0.0944	11.2684	11.2309	0.03750	01:18
8	4.9197	4.7910	0.1287	11.0993	11.0819	0.01740	06:37

Table 7 Experimental result of EDM with using CNT

Run	W_b	W_a	Difference	E_b	E_a	Difference	Time of machining
1	4.9643	4.6355	0.3288	16.5637	16.4680	0.0957	01:43
2	5.1521	5.0210	0.1311	19.1099	19.0839	0.0260	32:46
3	5.1241	4.9583	0.1658	16.7057	16.6589	0.0468	01:03
4	5.1407	4.9932	0.1475	18.8915	18.8755	0.0160	07:49
5	5.2603	5.0125	0.2478	16.505	16.4510	0.0540	00:59
6	4.9048	4.47860	0.4262	16.2003	16.0920	0.1083	43:49
7	5.3389	5.2261	0.1128	16.3468	16.3065	0.0403	01:16
8	5.0987	4.9636	0.1351	16.3536	16.3374	0.0162	05:47

remarked that machining time was usually quite short, although some exceptions were found. In those cases, the reason of so longer time has to be found in the different amount of electric current and related values of pulse and interval times. Ratio between the weight of the electrode and of the work piece is almost constant in all the tests performed, being the first at least three times the second one. As tables show, some difference in the weight changes before and after machining can be observed for a given machining time, if MWCNTs are used. In general, weight reduction seems to be larger in the work piece when CNTs are used.

5.1 Material removal rate

Maximum value of material removal rate (MRR) is a significant indicator of both the efficiency and cost of the EDM process. It is defined as the ratio between the difference of the weight of work piece before (w_b) and after (w_a) machining, respectively, found by weighing each specimen, and the machining time (t_m):

$$\mathrm{MRR} = (\mathrm{w_b} - \mathrm{w_a})/t_m [\mathrm{g/min}] \tag{1}$$

As Table 8 shows, MWCNTs in the dielectric flow increase the MRR. This effect can be attributed to the electrical and thermal properties of CNTs. Actually, they can act as good conductors between the electrode and work piece, thereby enabling a more effective transfer of current to the work piece resulting in higher material removal rate. Benefit can be appreciated, although it could be even improved if a suitable compromise of the CNTs concentration mixed in the dielectric fluid and the machining time can be found. In particular, a higher concentration may improve the conductivity of the system, but above a certain concentration (close to 5 g/l) the machining time could be unsuitable for practical application, as it was observed by Mai et al. [8]. It can be remarked that the most effective combination of settings looks the sixth one. It corresponds to a lower peak of current, shorter pulse time, and shorter interval time between two consecutive pulses.

5.2 Electrode wear rate

A similar benefit was observed even for the electrode wear rate, being depending on the dielectric flow in the machining zone. If flow is turbulent, an increasing in electrode wear is appreciated. To appreciate some difference, the electrode wear ratio (EWR) is defined as the ratio between the weight of material used of the electrode (EWW) and of work piece (WRW), respectively, expressed as a percentage:

$$\mathrm{EWR} = (\mathrm{EWW/WRW}) \times 100\% \tag{2}$$

As Table 9 shows, MWCNTs mixed in dielectric fluid decrease the electrode wear rate. This effect is related to the lower heating. CNTs show the relevant property of being capable of absorbing the heat, while simultaneously can conduct the electric current with a small resistance, associated to a reduced heating. Therefore use of CNTs leads to the reduction of the heat generated during the EDM process,

Table 8 Material removal rates measured on the specimens in both the EDM processes

Run	1	2	3	4	5	6	7	8
(A) Without MWCNTs [g/min]	0.1850	0.0039	0.1192	0.0149	0.1540	0.0039	0.0726	0.0194
(B) With MWCNTs [g/min]	0.1915	0.0040	0.1579	0.0188	0.2519	0.0099	0.0890	0.0233
Difference ($B-A$) [g/min]	0.0065	0.0001	0.0387	0.0039	0.0979	0.006	0.0164	0.0039
$(B-A)/A \cdot 100$ [%]	3.5	2.6	3.25	2.62	6.36	154.0	22.6	20.1

Table 9 Electrode wear rate ratios specimens in both EDM conditions

Run	1	2	3	4	5	6	7	8
(A) Without MWCNTs	0.2433	0.2182	0.2946	0.1283	0.2812	0.2765	0.3972	0.1351
(B) With MWCNTs	0.2911	0.1983	0.2822	0.1084	0.2180	0.1978	0.3572	0.1199
Difference ($B-A$)	0.0478	−0.0199	−0.0124	−0.0199	−0.0632	−0.0787	−0.0400	−0.0152
$(B-A)/A \cdot 100$ [%]	19.65	−9.12	−4.21	−15.51	−22.48	−28.46	−10.07	−11.25

Table 10 Surface roughness specimens in both EDM conditions

Run	1	2	3	4	5	6	7	8
(A) Without MWCNTs [μm]	3.704	2.284	5.094	2.768	3.055	2.405	2.689	2.675
(B) With MWCNTs [μm]	3.013	2.090	3.354	2.537	2.760	2.348	2.285	2.390
Difference ($B-A$) [μm]	−0.691	−0.194	−1.74	−0.231	−0.295	−0.057	−0.404	−0.285
$(B-A)/A \cdot 100$ [%]	−18.66	−8.49	−34.16	−8.35	−9.66	−2.37	−15.02	−10.65

thereby decreasing the electrode wear rate. Evidences show that higher peak current and longer interval time may lead to a larger electrode wear, while short pulse and interval times associated to a lower current give the best improvement, when MWCNTs are used. This trend was then confirmed even for what concerns some other performances, as it shall be documented in next paragraphs.

5.3 Surface roughness

It is well-known that during the EDM process, a number of craters are formed on the surface of the work piece by the discharge energy produced by the system. The surface quality consequently depends upon the energy per spark, peak current, pulse on and off time. Performance of the EDM with MWCNTs was evaluated. The value of arithmetic surface roughness was computed by measuring first on the surface of the work piece the dimensions of the craters, by means of the Mitutoyo Formtracer CS-5000.

Reduction of the surface roughness is one of the most impressive results of the application of MWCNTs to the EDM process as Table 10 shows. Trends of all the tests performed is positive, although where peak current is larger and interval time longer the benefit is largely appreciated. Moreover, thermal properties of MWCNs allow a good absorption of heat, during the EDM, thus leading to reduce the thickness of recast layer (so called white layer) and increasing the quality of surface roughness. When a larger amount of heat is transferred into the work piece, dielectric fluid looks increasingly unable to clear away the molten material and surface roughness is consequently decreased. In case of heating reduction, dielectric fluid operates as a good conductor and EDM effect on the machined material is appreciably better.

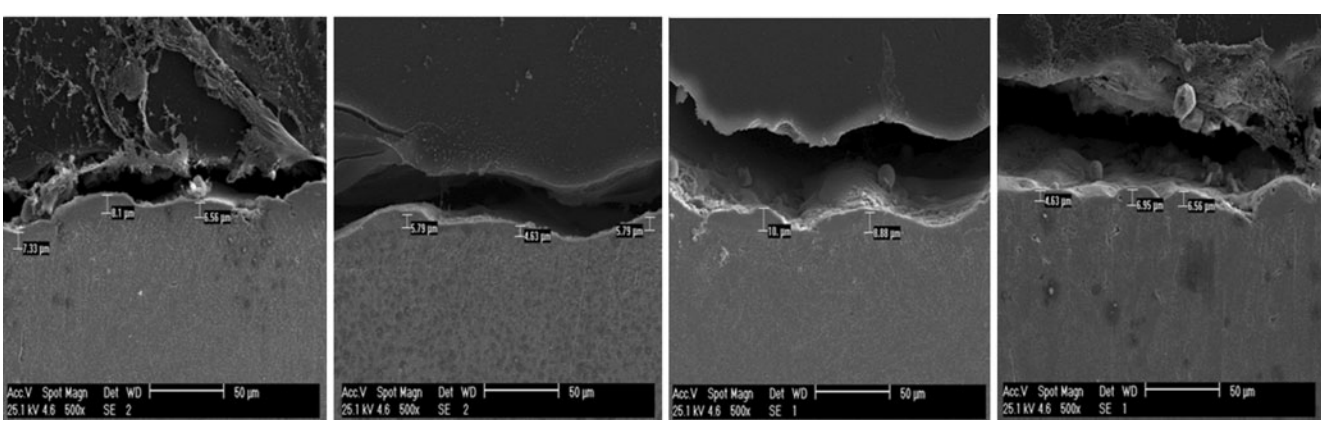

Fig. 5 Sequence of recast layer measurements performed by SEM in: run 1, without and with CNTs, run 2 without and with CNTs

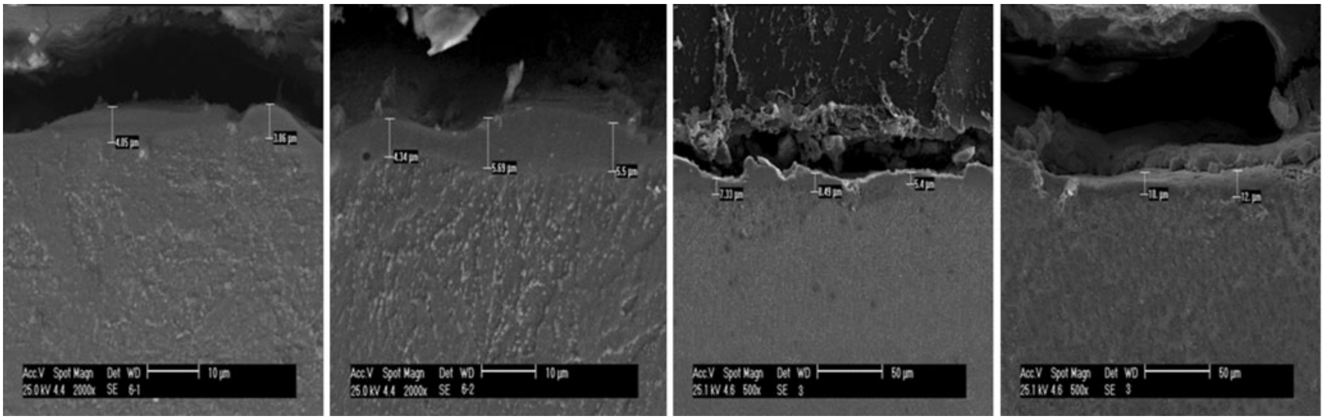

Fig. 6 Sequence of recast layer measurements performed by SEM in: run 3 without and with CNTs, run 6 without and with CNTs

5.4 Recast layer

Strictly connected to the performance of the EDM measured in terms of surface roughness is the thickness of recast layer being produced on the surface of the workpiece. It induces the aging of material thus affecting the surface roughness. During the experiments, recast layer was measured after machining and directly by the SEM to compare the results obtained with and without using CNTs, respectively. Before the inspection, each work piece was machined, mounted, grinded, and polished. Etching was evenly performed, with a solution of 100 ml of ethanol, 5 ml of HCL and one gram of picric acid. Effects upon the recast layer were analyzed on specimens 1, 2, 3, 6, and 7. Thickness of recast layer was compared as it looks at SEM (Figs. 5, 6, and 7). Results are shown in Table 11. MWCNTs improve and minimize the thickness of the recast layer because of the larger heat absorption operated. Each analysis could define an average thickness of white layer, to be compared with the others, although this value is only indicative of the real and non uniform distribution of material detected by the SEM in each case.

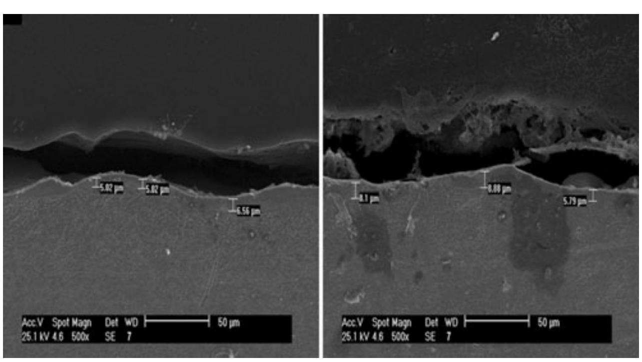

Fig. 7 Sequence of recast layer measurements performed by SEM in: run 7 with and without CNTs

6 Conclusion

A technological improvement of the Electrical Discharge Machining with copper electrode was proposed by including Multi wall Carbon Nanotubes into the dielectric liquid. Several machining parameters were considered and measured. According to the results above described the best combination of peak current, pulse time, and interval which leads to achieve the best result in terms of all the relevant machining performances measured during the experiments corresponds to the case in which all these parameters are set at the lowest level considered in this study. Experimental evidences show that multi-wall carbon nanotubes give better surface compared to the traditional EDM process. Thickness of recast layer is smaller when CNTs are used. Electrode wear rate and material removal rate are improved due to the better flow of electricity, being the heat effectively absorbed by the dielectric fluid including the MWCNTs. A smoother surface is obtained when machining is performed at a lower pulse of energy. The result obtained in this preliminary study looks promising for some practical applications to improve the efficiency of the EDM process, although a deeper investigation is needed to define quantitative criteria to set up the machining parameters for a given concentration of MWCNTs in the dielectric.

Table 11 Comparison of white layer thickness without and with using CNTs in EDM

Thickness of white layer cast [μm]	Without using MWCNTs	With using MWCNTs	Difference (%)
Sample 1	9.4	6.05	−35.64
Sample 2	7.33	5.07	−30.83
Sample 3	11	6.95	−36.82
Sample 6	5.20	3.95	−24.04
Sample 7	7.59	5.53	−27.14

Conflict of interest The authors declare that they have no conflict of interest.

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