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Evaluating the electrical discharge machining (EDM) parameters with using carbon nanotubes / MOHAMMADZADEH SARI, Mehdi; Noordin, M. Y.; Brusa, Eugenio. - In: IOP CONFERENCE SERIES: MATERIALS SCIENCE AND ENGINEERING. - ISSN 1757-8981. - STAMPA. - 40:(2012). (Intervento presentato al convegno International Conference on Structural Nano Composites (NANOSTRUC 2012) tenutosi a Cranfield (UK) nel 2-4 July 2012) [10.1088/1757-899X/40/1/012019].

Availability:
This version is available at: 11583/2497494 since:

Publisher:
IOP

Published
DOI:10.1088/1757-899X/40/1/012019

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05 March 2024

Evaluating the electrical discharge machining (EDM) parameters with using carbon nanotubes

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Abstract. Electrical discharge machining (EDM) is one of the most accurate non traditional manufacturing processes available for creating tiny apertures, complex or simple shapes and geometries within parts and assemblies. Performance of the EDM process is usually evaluated in terms of surface roughness, existence of cracks, voids and recast layer on the surface of product, after machining. Unfortunately, the high heat generated on the electrically discharged material during the EDM process decreases the quality of products. Carbon nanotubes display unexpected strength and unique electrical and thermal properties. Multi-wall carbon nanotubes are therefore on purpose added to the dielectric used in the EDM process to improve its performance when machining the AISI H13 tool steel, by means of copper electrodes. Some EDM parameters such as material removal rate, electrode wear rate, surface roughness and recast layer are here first evaluated, then compared to the outcome of EDM performed without using nanotubes mixed to the dielectric. Independent variables investigated are pulse on time, peak current and interval time. Experimental evidences show that EDM process operated by mixing multi-wall carbon nanotubes within the dielectric looks more efficient, particularly if machining parameters are set at low pulse of energy.

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 [1,2]. EDM erodes material in the path of electrical discharges generating an arc between an electrode tool and the work piece. EDM manufacturing is quite affordable and suitable when high accuracy is required. Nevertheless, EDM process has some problems such as generation of high heating on the electrically discharged material and formation of white layer in work piece, decreasing the quality of surface roughness and the product life. Carbon nanotubes (CNTs) display unexpected strength and unique electrical properties and are effective thermal conductors. They can absorb the heat from the electrical discharged material and decrease the amount of white layer. CNTs came only recently and lately to the manufacturing industries to improve the machining performance. Among the literature dealing with CNTs some specialized contributions were recently focused on the EDM improvement. Guu [3] proposed the EDM process for machining the surface morphology and roughness of the AISI D2 steel; Prabhu et al. [4,5] analyzed the surface characteristics of tool steel material by using multi-wall CNTs to improve the surface finish of material to the nanometer size. Guu [6] based his analysis on the effect of EDM on surface characteristics and damage of the AISI D2 tool steel, while Prabhu [5] proposed an approach to generate a nanosurface of Inconel 600 material by grinding process, by using single-wall CNTs. Pecas [7] proposed a EDM process with powder mixed dielectric and compared it with the normal condition of EDM to analyse the surface quality. A deeper investigation about the improvement of the EDM parameters in case of multi-wall CNTs application was not yet proposed. Therefore, this paper evaluates through some experiments the benefits introduced by CNTs in the EDM process.

2. Selected materials

A preliminary investigation of the results obtained through the traditional EDM process was performed. AISI H13 steel was selected as a tool material. It is a chromium-molybdenum-vanadium-alloyed steel. EDM is extensively used as non-conventional material removal process and consists of machining electrically conductive materials by using some precisely controlled sparks occurring between an electrode and a work piece, in 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. The AISI H13 steel is 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 production runs and molding of parts in thermosetting plastic. Main properties are summarized in Table 1.

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 (approx. 185 HB)	
Colour code	Orange/Violet	
Hardness	52 HRc	45 HRc
Tensile strength	1820 MPa	1420 MPa
Yield strength	1520 MPa	1280 MPa

Table 2. Properties of MWCNTs used in this study.

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

CNTs were used for this investigation. They are allotropes of carbon with a cylindrical nanostructure [8]. 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 several configurations, 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 CNTs used in this experimental activity are described in Table 2.

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 Scanning Electron Microscope (SEM) was used to analyze and measure the thickness of the altered surface layer such as recast layer, heat affected zone and microcracks (Fig.2). Each specimen was made of the AISI H13 tool steel. The work pieces were prepared to size of 10x10x10 mm. Hardness of specimen was measured as 53 HRC. The electrode material is copper, having circular section of diameter d=4.9 mm. The dielectric fluid used in the EDM process was kerosene. Up to 80 litres 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.4). Copper electrode was used as a negative polarity during the EDM process, while the specimen was the positive one.

Figure 1. Formtracer CS–5000.

Figure 2. Scanning electron microscope (SEM)

Figure 3. EDM Charmilles Roboform 100.

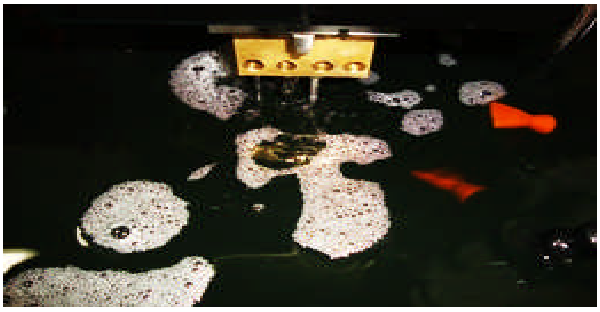

Figure 4. Mix of kerosene and MWCNTs in the dielectric used for the experiments.

4. Experimental investigation

EDM process is characterized when some relevant parameters are measured. The peak current, the pulse on time and the interval time completely define the operating conditions of the EDM machine. Response in terms of machining effectiveness is detected if the material removal rate, the electrode wear rate, the surface roughness and the recast layer are known. Design of Experiments was based on the factors and levels described in Table 3. Experiments were carried out according to the ANOVA analysis. Three factors were selected for each step of the investigation, leading to perform up to eight experiments. Table 4 summarizes the procedure followed in each run.

Table 3. Factors and levels for the EDM process analysis.

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

Table 4. List of the EDM runs performed and analysed.

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

In the first step of the investigation, experiments were performed by implementing the conventional method, without using carbon nanotubes. A precision balance was used to measure the weight of work piece and electrode, 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 Scanning Electron Microscope (SEM). In the second step of this 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). A separate tank was used for machining with using MWCNTs. Even in this case relevant parameters were measured as previously described. Results were finally compared to determine the effect of using multi-wall carbon nanotubes during the EDM process.

5. Results and discussion

Maximum value of Material Removal Rate (MRR) is a significant indicator of the efficiency and cost of the EDM process. It can be calculated by dividing the difference between the weight of work piece before (w_b) and after (w_a) machining, respectively, found by weighing each specimen, against the machining time (t_n). CNTs in the dielectric flow increase the MRR. Benefit is appreciable, as Table 5 shows.

Table 5. Material removal rates.

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

Electrode wear depends on the dielectric flow in the machining zone. If flow is turbulent, an increasing in electrode wear is appreciated. Electrode Wear Ratio (EWR) can be defined as the ratio of the weight of material used of the electrode (EWW) and of work piece (WRW), respectively, being expressed as a percentage. As Table 6 shows, CNTs mixed in dielectric decrease the electrode wear rate, since heating is lower. It was demonstrated that during the EDM, CNTs can absorb the heat leading to have a better flowing of the electric current.

Table 6. Electrode wear rate ratios.

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

On the surface of the work piece a large number of craters is formed by the discharge energy produced by the EDM process. Therefore surface quality depends upon the energy per spark, peak current, pulse on and off time. Performance of the EDM with CNTs was evaluated in this case by resorting to the computation of the arithmetic surface roughness value. Measurements were performed on the surface of the holes by means of the Mitutoyo-Formtracer CS 5000.

Table 7. Surface roughness.

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

Table 7 demonstrates that thermal properties of MWCNs allow a good absorption of heat, during the EDM, thus leading to reduce the thickness of recast layer and increase the quality of surface roughness. When a larger amount of heat is transferred into the work piece, dielectric looks increasingly unable to clear away the molten material. Surface roughness is consequently decreased.

Table 8. Machining parameters of different runs during the EDM.

Run	P: Peak Current [A]	A: Pulse on time [μs]	B: interval time [μs]
1	24	12.8	50
2	8	12.8	50
3	24	50	50
6	8	12.8	12.8
7	24	12.8	12.8

Recast layer produced on the surface of work piece induces the aging of material and affects the surface roughness. It was measured directly by the SEM to compare the results obtained with and without using CNTs. Before the inspection by SEM, 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 analysed on specimens n.1,2,3,6 and 7. Thickness of recast layer was compared as it looks at SEM, like in Fig.5. Each run was characterized as is described in Table 8. Moreover, results shown in Table 9 make clear that using CNTs mixed in the dielectric flow improves and minimizes the thickness of recast layer. As it was observed in case of the surface roughness, the heat absorption operated by MWCNTs, during the EDM, leads to thinner recast layer. Table 9 summarizes the average thickness of white layer.

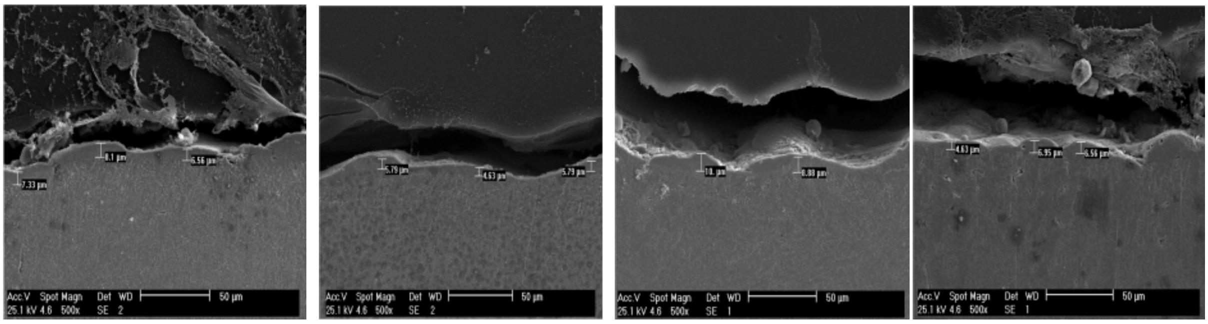

Figure 5: Sequence of recast layer measurements performed by SEM in: run 1 without CNTs, with using CNTs, in run 2 without CNTs and with using CNTs.

Table 9. Comparison of white layer thickness without and with using CNTs in EDM.

Thickness of white layer cast [μm]	Without using Carbon nanotubes	With using Carbon nanotubes
Sample 1	9.4	6.05
Sample 2	7.33	5.07
Sample 3	11	6.95
Sample 6	5.20	3.95
Sample 7	7.59	5.53

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. Experimental evidences show that 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 better and heat can be effectively absorbed by the CNTs, if machining parameters are set to have a low pulse of energy.

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