THE INFLUENCE OF THE MACHINING PARAMETERS ON THE PERFORMANCE OF DIE SINKING ELECTRICAL DISCHARGE MACHINING

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Abstract. *Die sinking electrical discharge machining (EDM) is a process widely employed for the manufacture of moulds and dies owing to the fact that the hardness of the work material do not affect the performance of the operation, albeit it may be influenced by the thermal and electrical conductivity and melting point of both electrode and work materials. Due to the high peak temperatures achieved during machining, defects on the workpiece such as cracks and heat affected zones are typically observed after EDM, therefore, the judicious selection of the machining parameters is critical for the success of the operation. The principal aim of this work is to investigate the influence of the process parameters (pulse duration, duty factor, current and electrode material) on the removed volume, tool wear and dimensional and geometrical deviations when die sinking EDM AISI H13 hot work die steel. In general, the results indicated that the elevation in pulse time resulted in lower removal rates, probably due to inefficient flushing of debris caused by the shorter time interval. Additionally, the orientation deviations and the cavity corner area and electrode corner wear were reduced, whereas the dimensional tolerance and surface roughness were elevated. The elevation of the duty factor promoted higher material removal, wider tolerances and larger cavity corner area and electrode corner wear, in addtion to lower surface roughness. Increasing electrical current resulted in higher volume removed and dimensional accuracy, together with a reduction in the angularity deviation, better surface finish and lower cavity corner area and electrode wear. Finish EDM promoted considerably lower removal rate together with better surface finish, lower tool wear and rounding of the cavity corner. The copper electrode provided removal rates slightly higher in comparison with the graphite electrode, however, the overall quality of the machined surface was superior using the graphite electrode.*

Keywords*: electrical discharge machining, AISI H13 steel, copper electrode, graphite electrode*

1. INTRODUCTION

Electrical discharge machining (EDM) is basically a process by which removal of workpiece material is achieved by sparks between a tool electrode and workpiece, with associated melting and vaporisation caused by high temperatures. The workpiece being machined and the tool electrode (usually made from graphite, copper or brass) are generally covered in a dielectric fluid and are connected to a direct current power supply (EDM generator) delivering periodic pulses of energy. There is no physical contact between workpiece and tool and the gap separating them is maintained under servo control. The physics of an EDM spark is so complex that Eubank *et al.* (1993) assert that it is impossible to provide a complete numerical solution, therefore, work must be focused on what is supposed to be the dominant effect. Furthermore, according to these authors, superheating (and not vaporization) is the dominant mechanism responsible spark erosion.

EDM is used for machining electrically conductive workpiece materials that are difficult to cut with conventional processes such as turning, drilling and milling (e.g., hardened tool steels, nickel-based superalloys and titanium alloys). EDM is well suited to the production of components with complex geometry and is applied to a very wide range of operations including the manufacture of moulds and dies (e.g., plastic injection moulds, forging dies and die-casting dies), as reported by Niwa and Furuya (1995), surface texturing of steel rolls (Aspinwall *et al.*, 1991), surface alloying (Uno *et al.*, 1999), surface colouring (Minami *et al.*, 2001), production of aircraft engine components (Aas *et al.*, 2001), production of components for electronic industries (Rooij, 1995) and manufacture of components for dentistry (e.g., fixed-removable implant prostheses, titanium-ceramic crowns), Van Roekel (1992).

There are different variations of EDM, all of which use the same physical principle. These processes are die sinking EDM (McGeough, 1988), wire EDM (Guitrau, 1997), micro EDM (Masuzawa, 2001), electrical discharge texturing (McGeough, 1988), electrical discharge grinding (Thoe *et al.*, 1996) and EDM fast hole drilling (Sommer, 2000). However, the most used processes are die sinking and wire EDM.

Die sinking EDM, also known as ram EDM, vertical EDM or plunge EDM, is generally used to produce blind cavities. The sparks along an electrode with the desired shape combined with the movement of the tool in relation to the workpiece produces a cavity in which the image shape of the tool is reproduced on the workpiece. Therefore, one can infer that the dimensional and geometrical accuracy of the machined cavity depends on the accuracy of the electrode and on changes in the shape of the electrode, i.e., wear, taking place during the process.

Electrode wear is influenced by a range of factors including electrode and dielectric materials, dielectric flushing (type, pressure and flow rate) dielectric condition (temperature and filtration), electrode rotation and generator parameters. These factors also affect other quality characteristics of the machined part such as surface roughness besides playing a fundamental role in the process performance.

1.1 Electrode wear and geometrical accuracy

The geometrical accuracy of the machined cavity can be affected by changes in the shape of the electrode during the machining process. The change in shape is most commonly associated with electrode wear. However, material that builds up in the electrode body during the process may also affect the geometrical accuracy.

The most common type of wear takes place in the corner of the electrode (corner wear). This is undesirable as important shape details are not reproduced in the part. For instance, in case there is a requirement for machining flat bottomed (blind) cylindrical holes with sharp corner, corner electrode wear will affect the quality of the part. Likewise, tapered electrode wear will result in tapered holes, particularly when deep holes are produced. Patel *et al.* (1989) proposed an analytical model to predict the wear of copper electrode when EDM steel based on solving the partial differential equation which governs temperature distribution (unsteady-state heat conduction).

Berkan (1983) associated corner electrode wear with the electrical fields that tend to be stronger in the vicinity of the surface edges which create better conditions for local discharges to occur. Mohri *et al.* (1995) observed that corner electrode wear is remarkably higher than longitudinal wear at the beginning of machining. This was associated with carbon (from the cracked oil-based dielectric fluid) attached to the bottom of the electrode but not to its edge portion. According to the authors the precipitation of carbon on the electrode surface tends to decrease wear.

Tapered electrode wear occurs due to the lateral electrical discharges as a result of conductive particles (coming from the machined part or electrode) being flushed up the sides of the electrode (McGeough, 1988). Therefore, it is expected that flushing efficiency is an important aspect affecting tapered electrode wear. According to Wijers (1991), electrode rotation improves flushing and, consequently, reduces tapered wear. In addition to that, it has been reported that both electrode and dielectric materials can be important factors affecting tapered wear. Tsai and Masuzawa (2004) argued that electrode materials with high thermal conductivity (e.g., Ag, Cu) possess lower tapered wear than those with low thermal conductivity (e.g., Ti, Ni). Leão *et al.* (2005) found that brass electrodes can present very high tapered electrode wear when drilling deep holes in nickel alloys using deionised water as dielectric fluid. The authors observed significant reductions in tapered wear after using a water-based dielectric composed by alcohols and organic salts.

Materials that build-up in the electrode surface during the machining process may also affect the geometrical accuracy of the part. These materials (present in the dielectric fluid) are composed by debris that comes from electrode and workpiece material and by the chemical decomposition of the dielectric. Li and Hon (1994) have shown that electrode build-up phenomenon depends on a combination of machining parameters (pulse duration, pulse interval, polarity and electrode material). Pulse duration is the most important factor when polarity is positive. The type of dielectric seems to be another important factor. Build-up of material was observed on the end of the electrodes when roughing machining workpiece material AISI H13 using hydrocarbon oil and graphite electrodes. The build-up material formed a ring at the electrode perimeter approximately 0.225 mm thick, thus affecting the geometrical accuracy of the workpiece. However, the author did not observe any material build-up after using a water-based dielectric and keeping constant other machining parameters.

1.2 Generator parameters

Besides geometrical accuracy, other quality characteristics specified for machined parts include dimensional accuracy and surface roughness. Both academic and commercial literatures report a strong correlation between the generators parameters (e.g., electrical current, voltage, pulse time, interval time and frequency) and the quality of the machined parts. Moreover, the generator parameters greatly affect the process performance in terms of cycle times and electrode wear.

Electrical current is the primary source of heat in EDM and thus, the main parameter affecting material removal rate (both in the electrode and in the workpiece) and workpiece quality. If the value of current is set at 1 A, for instance, the cathode will emit 6.25×10^{18} electrons per second. These electrons, travelling at the speed of light (Jameson, 2001), and the positive ions (travelling at a lower speed due to their higher mass) have their kinetic energy turned into heat when they collide with the surface of the electrodes. The heat generated is directly proportional to the value of electrical current. Higher values of current result in higher workpiece material removal rate at the expense of higher electrode wear, lower dimensional accuracy, thicker heat affected zone and higher surface roughness. However, an excessively high peak current decreases workpiece material removal rate as observed by some researchers, such as Lee and Li (2001) and Iwai *et al.* (2001).

There are two types of voltages in EDM: the high voltage and the machining voltage. High voltage or open circuit voltage is the difference in electric potential between electrode and workpiece that is responsible for the breakdown of the dielectric insulation; i.e.; the high voltage ionises the small gap that exists between electrode and workpiece so that sparks can occur. High open circuit voltage increases the gap width and overcut and, as consequence, decreases the dimensional accuracy. It also influences the amount of wear on the corners of the electrode tip, where the electric field is more intense (Lee and Li, 2001). Tsai *et al.* (2003) reported a drastic increase in material removal rate and electrode wear with the increase of open circuit voltage. However, it has been reported by Lee and Li (2001) that an excessively high voltage results in a steep fall in the material removal rate and considerable increase of relative electrode wear.

After dielectric breakdown, the voltage applied between electrode and workpiece drops to the point where the electrical current reaches the maximum value and, as a consequence, the sparks attain their maximum power. The voltage remains constant during the occurrence of the sparks, i.e., during machining. This constant voltage is the machining voltage or the gap voltage. Singh *et al.* (1985) investigated the influence of gap voltage on EDM performance. They found that both workpiece and electrode erosion rates are higher for lower values of gap voltage.

The pulse duration is the period in which sparking takes place (electric current flows in the machining gap) and material removal occurs. The higher the pulse duration, the higher the energy in the gap and thus, higher levels of material removal rate, overcut and heat affected zone will be obtained. A number of authors (DiBitonto, 1989; Lee and Li, 2001; Mohan *et al.*, 2004; Spur and Schönbeck, 1993), have however, observed that material removal rate decreases if the pulse time is too high. Nevertheless, longer pulses are more beneficial for electrode wear (Amorim and Weingaertner, 2004).

While sparking takes place during the pulse time, the pulse interval is the period in which the debris is removed from the gap by the implosion of gas bubbles and by the flushing action of the dielectric. The interval time depends, essentially, on the amount of debris to be removed, which is related to parameters such as peak current and pulse time (high peak current and pulse time values lead to high material removal rates and thus more debris). If flushing conditions are suitable (dielectric pressure is high enough), the pulse interval can be short, resulting in low machining cycle times. However, if the interval time is too short, DC arcing may take place due to insufficient gap deionisation (Luo, 1998). The excess of debris in the gap may also provoke short circuits. On the other hand, if the pulse time is too long, machining cycle time will increase.

Frequency is the measure of the number of times the electrical current is switched on and off. It is the inverse of the total EDM unit pulse cycle (pulse time plus interval time). It has been reported (Singh et al. 1985; McGeough 1988; Storr, 1999) that low values of frequency result in high material removal rates, whereas high frequency results in low material removal rates with surface finish and higher electrode wear.

1.3. Aims and objectives

In order to achieve a satisfactory performance in EDM, electrode wear and machining time should be minimal. Moreover, the quality of the machined part should be in accordance with very strict specifications. However, lower machining time usually results in higher electrode wear and inferior quality of the machined part. These EDM process outputs depend on a number of factors and on a complex interdependence/interaction among these factors. The objective of this work is to investigate the effect of generator parameters and electrode material on the process performance and particularly on the quality of a hardened tool steel part machined using die sinking EDM. The quality characteristics that will be analysed are dimensional and geometrical accuracy and surface roughness

2. EXPERIMENTAL PROCEDURE

A bar of AISI H13 hot work die steel (243 mm x 262 mm x 23 mm) quenched and tempered to an average hardness of 45 HRC was used as work material. Electrolytic copper and graphite electrodes with dimensions of 20 mm x 20 mm x 50 mm were tested. The electrodes presented a cylindrical hole with ∅4 mm at the centre for delivering the dielectric fluid. As a consequence, the effective cross section area of the electrodes was approximately 387 mm^2.

The tests were carried out on a die sinking electrical discharge machine (Engemaq EDM 200NC series L) with maximum voltage of 300 V and maximum current of 60 A. Each test was performed using a fresh electrode, which was the positive pole. Hydrocarbon oil (Arclean Electron by Archem) was used as dielectric fluid. A portable roughness meter (Taylor-Hobson model Surtronic 25) with a stylus radius of 5 µm and set to a cut-off of 0,8 mm was employed to measure surface roughness parameters (average surface roughness R_a and maximum peak-to-valley roughness R_t). The dimensional and geometrical (orientation) deviations of the machined cavities were measured using a coordinate measuring machine (Tesa model Micro Hite 3D) with resolution of 1 µm and using a ruby probe with ∅2 mm. The wear on the electrodes was measured using a digital camera (Pixelink PL-A662 with resolution of 1280 x 1024 pixels) attached to a toolmaker's microscope and connected to a computer equipped with a software for image processing (UTHSCSA ImageTool, release 3.0).

The cutting conditions employed in the experimental programme are given in Tab. 1. They were selected based on the directions presented in the equipment manual and preliminary tests. Each test run was carried out during 15 minutes.

The influence of the principal EDM parameters, namely pulse time duration, duty factor, current, severity of the operation and electrode material can be assessed comparing different test runs. The influence of pulse length on removal rate, dimensional and geometric tolerances and tool wear can be estimated comparing the results from test runs 3 and 5, nevertheless, these results must be analysed cautiously owing to the fact that duty factor was also altered with pulse length. Comparing test runs 2 and 5 one can assess the effect of duty factor and the influence of current can be analysed comparing the results from tests 2 and 4. A comparison between finishing and roughing conditions can be drawn observing the results related to tests 1 and 4 and the effect of the electrode material can be evaluated comparing test runs 2 and 6. At the end of all tests, the dimensions of the electrodes and cavities were measured. In order to measure surface roughness and rounding of the corners, the workpiece was cut using wire EDM, as indicated in Fig. 1.

In the present work, the duty factor is calculated as the ratio of pulse length (pulse time on) to the sum of pulse length and time interval between two pulses (pulse time off). Alternatively, the ratio between pulse time on and off, known as duty cycle can be used. In both cases the relationship between pulse times on and off is taken into account, in contrast to the frequency, which can give identical values using rather distinct values of pulse time duration and interval and, therefore, cannot accurately represent the process.

Table 1. Cutting conditions employed in the experimental work.

Test run	Electrode	Pulse length t_{on} (μs)	Pulse interval t_{off} (μs)	Duty factor DT $(t_{on}/t_{on}+t_{off})x100$ (%)	Current I (A)
1	Graphite	100	12	89	6
2	Graphite	200	17	92	36
3	Graphite	300	192	61	36
4	Graphite	200	17	92	51
5	Graphite	200	300	40	36
6	Copper	200	17	92	36

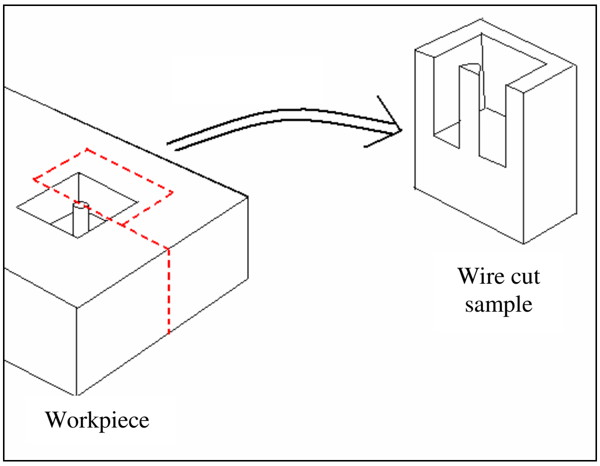


Figure 1. Schematic diagram of wire EDM of the workpiece.

No replicates were carried out during the experimental work. The seven machined cavities and corresponding electrodes were observed under the microscope in order to measure the deviations on the former and wear on the latter, as indicated in Fig. 2. As outputs, the following parameters were investigated: cavity depth, dimensional deviation (percentage difference between the dimensions of cross sections of the machined cavities and corresponding electrodes), geometrical deviations (orientation deviations of parallelism and angularity), surface roughness of the bottom of the cavities (average surface roughness R_a and maximum peak-to-valley roughness R_t), corner area at the bottom of the cavity not machined due to electrode wear and worn area at the corner of the electrode. Considering that the purpose of the evaluation of the cavity corner area and electrode corner wear was to confront the results obtained under distinct machining conditions, a non-dimensional unit was employed, indicated as an asterisk (*). Each output was measured twice and the average values were used to plot the graphs related to each machining condition.

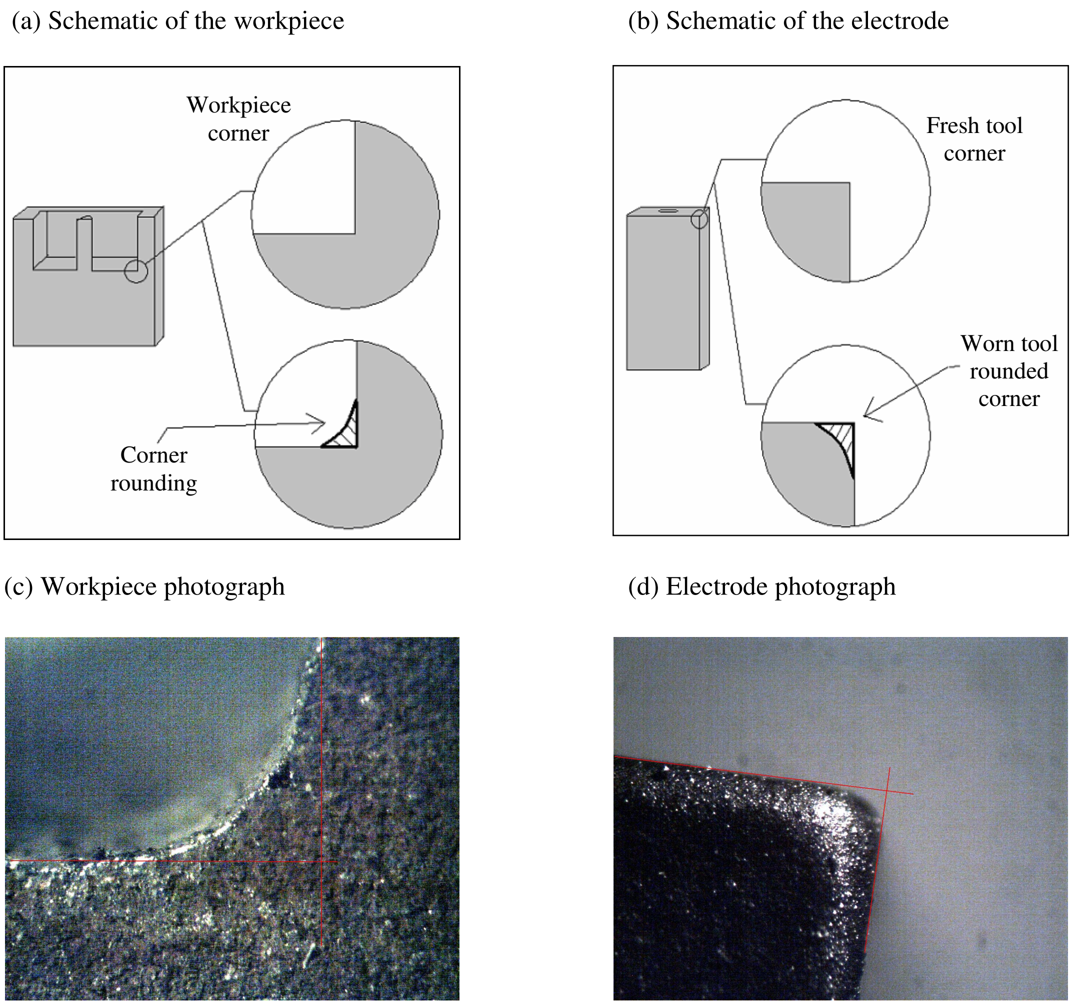
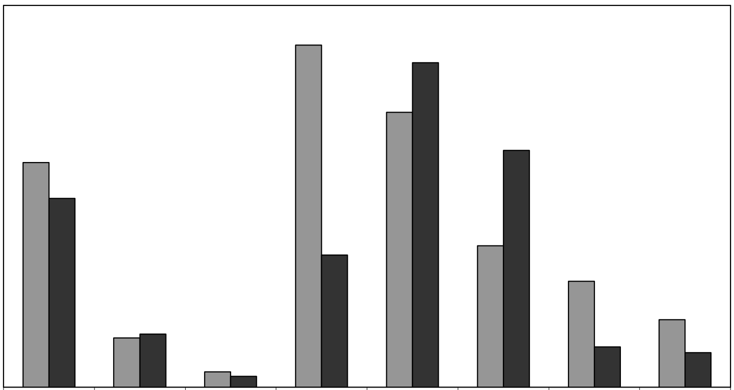


Figure 2. Schematic diagrams representing the cavity dimensional deviation (Fig. 2a) and electrode wear (Fig. 2b) and photographs of the cross section of the cavity (Fig. 2c) and electrode wear (Fig. 2d).

3. RESULTS AND DISCUSSION

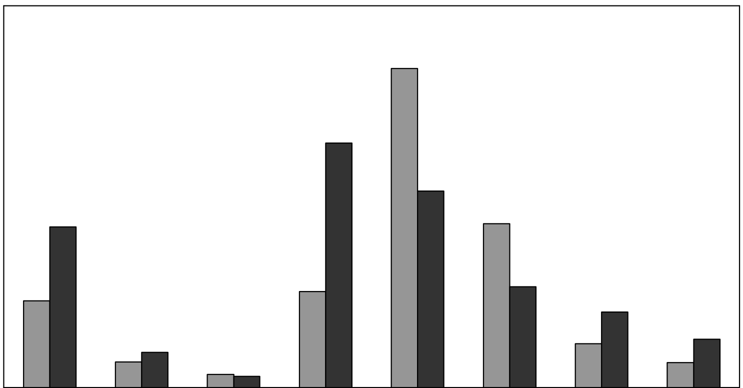
Figures 3 to 7 present the influence of the principal EDM parameters on the performance of the operation. The effect of pulse length (test runs 3 and 5) is given in Fig. 3, where it can be seen that increasing pulse duration from 200 to 300 μs leads to a reduction in the machined depth (removal rate), parallelism and angularity deviations and both workpiece corner area and electrode corner wear. In contrast, dimensional deviation and surface roughness values were increased. An increase in pulse duration while the remaining parameters are kept unaltered means that the energy for material removal is available for a longer period. As a consequence, the material removal is expected to increase and wider tolerances and rougher machined surface should be obtained. In addition to that, lower tool wear rate should be observed (Patel *et al.* 1989; Benedict, 1987 and McGeough, 1988). The results presented in Fig. 3 agree fairly with theory, except for machined depth. One possible reason for that may be the fact that in order to increase pulse duration, the duty factor was elevated from 40 to 61%. Therefore, the time interval (pulse time off) required for flushing the debris away from the cutting zone was reduced from 300μs (test run 5) to 192 μs (test run 3). As a consequence, inefficient flushing may have occurred, leading to the elevation of the gap voltage and the retraction of the servo system until the gap is clear and infeed is resumed. Furthermore, Patel *et al.* (1989) report that the flushing efficiency is not affected by pulse length, depending mainly on electrical current.



	Depth (mm)	Dimensional deviation (%)	Parallelism (mm)	Angularity (1/10000)	Ra (μm)	Rt (x10-1 μm)	Workpiece corner area *	Electrode worn area *
ton=200μs	5.89	1.28	0.41	8.96	7.20	3.70	2.77	1.77
ton=300μs	4.94	1.39	0.29	3.47	8.50	6.20	1.05	0.90

Figure 3. Effect of pulse duration on the performance of electrical discharge machining of H13 tool steel with graphite electrode (I=36 A).

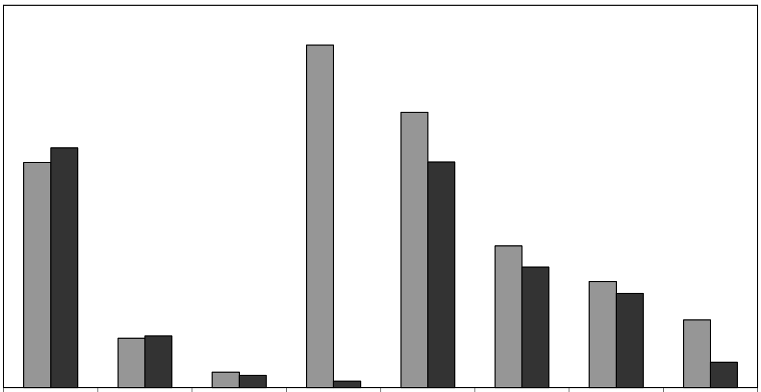
Figure 4 shows the effect of duty factor on the performance of the EDM of AISI H13 tool steel with a graphite electrode. In opposition to the previous results, in this case the remaining parameters, including pulse length, were unchanged (see Tab. 1, test runs 2 and 5). The results indicate an elevation in the material removal (machined depth) as the duty factor is elevated owing to the increase in the discharge frequency from 2000 Hz to 4608 Hz. As a result from the higher material removal, wider tolerances and an increase in the cavity and electrode areas are obtained. Interestingly, better surface finish was obtained, as reported by McGeough (1988).



	Depth (mm)	Dimensional deviation (%)	Parallelism (mm)	Angularity (1/10000)	Ra (μm)	Rt (x10-1 μm)	Workpiece corner area *	Electrode worn area *
DT=40%	3.18	0.93	0.48	3.52	11.70	6.00	1.61	0.91
DT=92%	5.89	1.28	0.41	8.96	7.20	3.70	2.77	1.77

Figure 4. Effect of duty factor on the performance of electrical discharge machining of H13 tool steel with graphite electrode (t_{on}=200 μs and I=36 A).

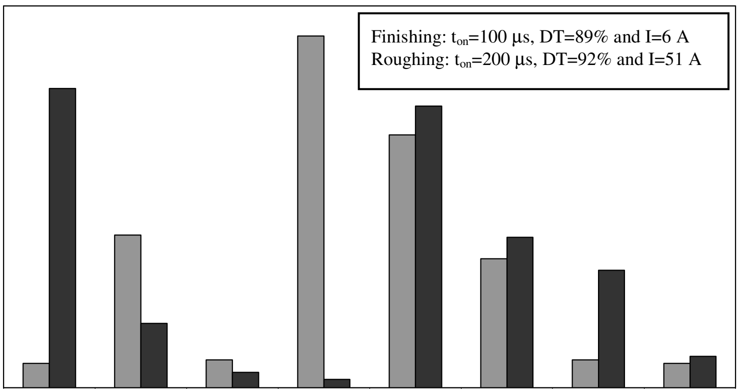
Figures 5 and 6 show, respectively, the findings concerned with the influence of electrical current and cutting condition (finishing or roughing) on the performance of the operation. The elevation of current from 36 to 51 A (test runs 2 and 4) results in higher energy concentration, therefore, higher removal rate and tool wear are expected together with wider tolerances. These findings agree with Patel *et al.* (1989), who compared the theoretical and experimental influence of current on removal rate and found similar results when EDM steel with copper electrode employing current values from 2.64 to 68 A. Observing Fig. 5 it can be noticed that in spite of a moderate increase in the dimensional accuracy and material removal, opposite results were obtained for the other characteristics, i.e., a sharp reduction in the angularity deviation was reported, together with an unexpected decrease in the values of roughness and areas of the cavity and electrode. Furthermore, test run 4 represents the highest material removal rate (162 mm^3/min) obtained when EDM H13 tool steel with graphite electrode.



	Depth (mm)	Dimensional deviation (%)	Parallelism (mm)	Angularity (1/10000)	Ra (µm)	Rt (x10-1 µm)	Workpiece corner area *	Electrode worn area *
I=36A	5.89	1.28	0.41	8.96	7.20	3.70	2.77	1.77
I=51A	6.27	1.35	0.32	0.17	5.90	3.15	2.46	0.66

Figure 5. Effect of current on the performance of electrical discharge machining of H13 tool steel with graphite electrode (t_{on}=200 µs and DT=92%).

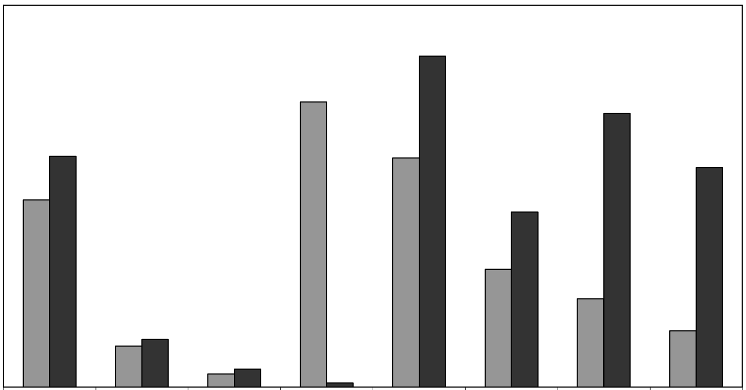
Comparing finish and rough EDM operations, see Figure 6 (test runs 1 and 4), it can be noted that when roughing parameters are selected the machined depth (material removal) increases drastically owing to the energy available for melting and vaporizing the work material. Consequently, poorer surface finish is obtained, as indicated by the R_a and R_t values. In addition to that, higher tool wear is observed and, as a result, the rounding at the bottom of the cavity is increased. Nevertheless, tighter dimensional and geometric deviations were obtained under the roughing condition. It is important to point out that when switching from finish to rough EDM all three parameters (pulse duration, duty factor and current) are changed, therefore, the effect of each factor cannot be assessed separately.



	Depth (mm)	Dimensional deviation (%)	Parallelism (mm)	Angularity (1/10000)	Ra (µm)	Rt (x10-1 µm)	Workpiece corner area *	Electrode worn area *
Finishing	0.51	3.20	0.59	7.37	5.30	2.70	0.58	0.51
Roughing	6.27	1.35	0.32	0.17	5.90	3.15	2.46	0.66

Figure 6. Effect of the cutting condition on the performance of electrical discharge machining of H13 tool steel with graphite electrode.

Finally, the results related to the influence of the electrode material on the performance of the operation are presented in Figure 7 (test runs 2 and 6). These findings suggest that the copper electrode provides superior material removal (machined depth) together with tighter angularity deviation, whereas the graphite electrode was responsible for closer dimensional and parallelism deviations, lower surface roughness and smaller workpiece corner area and electrode corner wear. According to McGeough (1988), copper electrodes allow high material removal rates and are highly stable in sparking, providing, for some work materials, superior surface finish than graphite. In the present work, the highest material removal rate (187 mm^3/min) was obtained using the copper electrode (test run 6), in spite of the fact that a considerably lower current was employed in comparison to test run 4 carried out using graphite electrode (36 A against 51 A). On the other hand, the higher melting point of graphite results in lower electrode wear.



	Depth (mm)	Dimensional deviation (%)	Parallelism (mm)	Angularity (1/10000)	Ra (µm)	Rt (x10-1 µm)	Workpiece corner area *	Electrode worn area *
Graphite	5.89	1.28	0.41	8.96	7.20	3.70	2.77	1.77
Copper	7.25	1.50	0.56	0.13	10.40	5.50	8.60	6.90

Figure 7. Effect of the electrode material on the performance of electrical discharge machining of H13 tool steel (t_{on}=200 µs, DT=92% and I=36 A).

4. CONCLUSIONS

After conducting die sinking electrical discharge machining tests on hardened AISI H13 tool steel using graphite and copper electrodes under various machining conditions, the following conclusions can be drawn:

- An increase in pulse time resulted in lower removal rates, probably due to inefficient flushing of debris caused by the shorter interval time. Additionally, the orientation deviations and the cavity corner area and electrode corner wear were reduced, whereas the dimensional tolerance and surface roughness were elevated.
- The elevation of the duty factor promoted higher material removal, wider tolerances and larger cavity corner area and electrode corner wear. Moreover, lower surface roughness was obtained.
- With regard to the electrical current, its elevation from 36 to 51 A promoted a slight increase in removed volume and dimensional accuracy, together with a reduction in the angularity deviation, better surface finish and lower cavity corner area and graphite electrode corner wear.
- Using the finish EDM condition considerably lower removal rate is obtained in addition to lower surface roughness, lower tool wear and rounding of the cavity corner, albeit wider dimensional deviations were produced.
- The copper electrode provided removal rates slightly higher in comparison with the graphite electrode, however, the quality of the machined surface assessed in terms of roughness and dimensional and parallelism deviations was superior when the graphite tool was employed.

ACKNOWLEDGEMENTS

The authors would like to thank FAPEMIG (grant TEC 281/06) and CNPq/PIBIC for funding this research project.

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