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ORIGINAL ARTICLE

Effect of the powder concentration and dielectric flow in the surface morphology in electrical discharge machining with powder-mixed dielectric (PMD-EDM)

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Abstract The addition of powder particles to the electrical discharge machining (EDM) dielectric fluid modifies some process variables and creates the conditions to achieve a higher surface quality in large machined areas. This paper presents a new research work that aims to study the improvement in the polishing performance of conventional EDM when used with a powder-mixed-dielectric (PMD-EDM). The analysis was carried out varying the silicon powder concentration and the flushing flow rate over a set of different processing areas and the effects in the final surface were evaluated. The evaluation was done by surface morphologic analysis and measured through some quality surface indicators. The results show the positive influence of the silicon powder in the reduction of crater dimensions, white-layer thickness and surface roughness. Moreover, it was demonstrated that an accurate control of the powder concentration and flushing flow is a requirement for achieving an improvement in the process polishing capability.

Keywords Powder-mixed dielectric · Electrical discharge machining · EDM polishing · Silicon powder · Surface morphology

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1 Introduction

Since 1940 a considerable research effort has fostered a deep understanding, prediction and control of the electro-discharge machining process (EDM). In agreement with the comprehensive paper of Ho and Newman [1] several and distinct areas have been thorougly researched. One of the preferential areas is related to the surface quality analysis, namely the study of EDM finishing and polishing steps. The concern with this topic can be justified by the comparatively low performance of EDM in these phases [2]. Actually, the low discharge energy and the small electrode-workpiece distance lead to difficulties in gap cleaning, to the capacitive effect enhancement and to the discharge ignition delay [3, 4]. Regardless of the possibility of obtaining very fine surface finishing with EDM (surface roughness below 0.1 μm of R_a) the referred process constraints generate the occurrence of abnormal discharge, long process times and overall surface heterogeneity [5, 6]. In conventional EDM, the referred surface roughness values are only achievable for copper electrode areas below 10 cm^2 [7].

Several research approaches have been undertaken to increase the EDM surface quality and polishing process performance, namely the discharge process modification [8, 9], the electrode morphology [10, 11] and the electrode orbital movement [12, 13]. Approaches based on the conjunction of the EDM process with the electrochemical machining [14–17], with ultrasonic machining [18] and with a contouring robot [19] were also followed. Another research approach, which is presenting promising and reliable results, consists of the use of conductive and semi-conductive powder materials suspended in the dielectric [1, 20, 21].

In fact, the addition of these type of particles in the dielectric promotes the gap increasing and results in a drastic reduction of both the capacitive effect influence and the abnormal discharge occurrence [3, 22]. The stability of the process increases and consequently the polishing time and the influence of the electrode area in the surface roughness are reduced [9, 23]. Moreover, even for large electrodes, the occurrence of stable discharges all over the electrode area results in homogeneous surfaces with lower roughness [4, 6].

This process, called powder-mixed dielectric (PMD-EDM) by Mohri [22], has been investigated since 1980 with three main aims. Besides the study regarding the EDM finishing and polishing phase, some authors assessed PMD-EDM performance under roughing discharge parameters in order to increase the metal removal rate (MRR) and decrease the tool wear ratio (TWR) [5, 24–27]. Furthermore it was also studied and evaluated as a surface treatment process taking advantage of the presence of powder particles with a controlled composition in the gap [28–30]. The most relevant research works related to the finishing and the polishing phase performance will be discussed further since this paper focuses the use of PMD-EDM as a technological process to generate high quality final surfaces.

Using finishing discharge energy levels and graphite powder suspended in the dielectric, Jeswani [24] reported that the powder concentration has an important influence on the discharge process, increasing both the gap distance and the discharging rate. For his particular conditions the best results were achieved for a powder concentration of 4 g/l within a range of 0.25 to 6 g/l. For lower concentrations the gap increasing is not enough to promote the discharge stability and for higher concentrations the higher gap distance generates discharge inefficiency [24]. Mohri et al. [6, 22] and Narumiya et al. [23] used silicon, aluminium and graphite as powder materials for concentration ranges between 2 and 40 g/l. Their results showed that the gap distance increases with the powder concentration and is larger for the aluminium powder but there is no direct relation between the surface roughness and the gap distance. In fact, the best results concerning the surface roughness were achieved for low powder concentrations levels and for silicon and graphite powders. The use of a pulse generator with capacity for high discharge frequency and the increase of the polishing time allow the generation of sound surfaces with a lower surface roughness even for large electrode areas [6]. The influence of other powder materials was investigated by Yan and Chen [31] and Ming and He [32]. According to the authors the powder particles contribute to the reduction of surface cracks and to the smoothness and homogenisation of the white layer. The lowest surface roughness levels and a correct balance between the discharge energy density and the discharge rate were observed for a powder concentration within the range of 2 to 5 g/l. Uno and Okada [33] studied the influence of the steel type under a single EDM polishing regime and a silicon powder concentration of 23 g/l. The authors found that the presence of the powder particles, besides, generate the increasing of the gap distance also reduces the discharge impact force. Following the authors this latter phenomena is the main reason for the formation of smoother craters since the molten material is not impelled to leave the discharge crater. Moreover the authors observed a radial solidification process and a homogeneous and reduced ionisation time when compared with the simple dielectric process condition. Despite this conclusion the results found later by Tamura and Kobayashi [34] revealed that the effect of the force caused by motions of the gas bubble on crater formation is insignificant. From the experiments performed with simple kerosene for the cases of reverse and straight polarity the authors observed that the impact force is the same regardless of polarity, whereas the shape of the crater was strongly dependent on the polarity. With regards to the steel composition Uno and Okada [33] found that the presence of higher carbon content and of coarse carbides in the steel inhibits a fine polishing surface independently of the dielectric condition.

The work developed by Wong at al. [35] confirms the results achieved by the previous researchers. Accordingly the best surface finishing was obtained for silicon and graphite powders with a low powder concentration (2 g/l). The authors state that in the PMD-EDM the powder material must have a significant level of electrical conductivity but not too high since the increasing of the gap distance beyond a certain limit deteriorates the discharge process. Additionally Tzeng and Lee [5] found that the combination among the powder type, particle size and its concentration is critical for the PMD-EDM performance. Although their research analysed only the MRR and the TWR, it made an important contribution to the understanding of the phenomena related to the PMD-EDM process, later confirmed by Zhao et al. [25]. The PMD-EDM process stability can be accomplished through the control of the particle-size powder and the use of an efficient flushing system [5]. This system must assure a uniform concentration all over the processing zone and a complete removal of the eroded particles from the gap. The increase of the gap distance causes the reduction of both the energy density and the gas bubble pressure that, reducing the discharge erosive power and resulting in the formation of smoother and larger craters. The authors also observed an increase of the discharging transitivity and frequency that promotes a more efficient and stable material removal process all over the processing zone [5, 25]. Chow et al. [27] found that a multiple discharge effect is created within a single pulse discharge due to the dispersion of the discharge energy. A

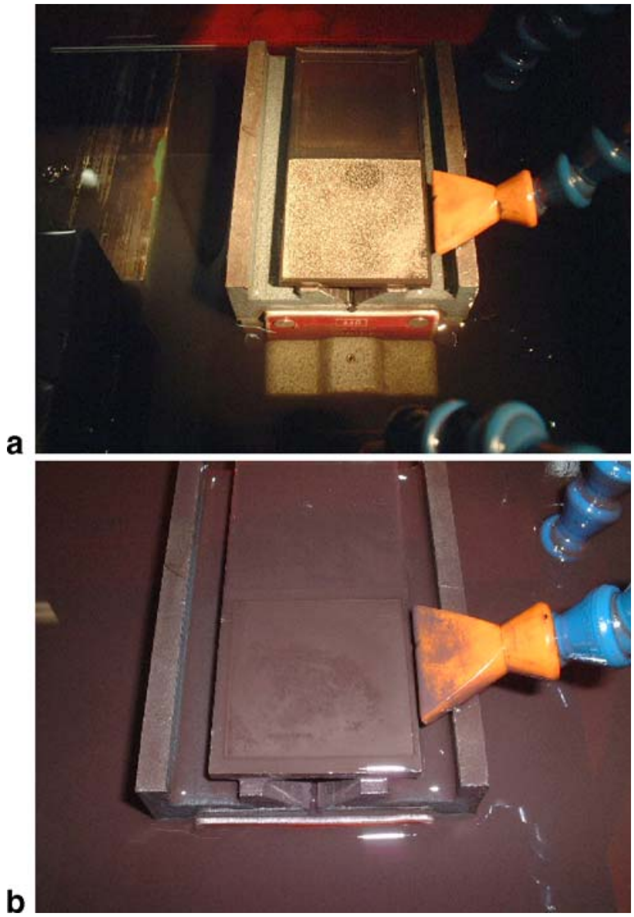


Fig. 1 Flushing nozzle and 1600 mm^2 machined sample **a)** with conventional dielectric conditions and **b)** with silicon powder suspended in dielectric

single input pulse generates several discharge spots because the added powder facilitates the bridging effect and minimizes the insulating strength of the dielectric fluid. So both the probability of abnormal discharge occurrence and the capacitive effect influence are significantly reduced, allowing the generation of a lower surface roughness, a lower polishing time and a reduced influence of the electrode area.

Klocke et al. [26] used silicon powder with an average particle size of 10 µm and 10 g/l flushing flow to study the effect of powder suspended dielectrics in the thermal influenced zone. Through the use of a high speed framing camera, the authors found the particle suspended in the dielectric change the thermal material removal mechanism. During the discharge silicon particles store heat energy. The transfer of this energy to the workpiece after the discharge process is balanced with the rapid cool down of the molten surface. Therefore silicon powder suspended in the dielectric promotes a softer transition from the white layer into the matrix material than the observed with powder-free dielectric.

In the work presented by Peças and Henriques [4], a silicon powder concentration of 2 g/l was used. This was the first published work that refers the use of a sequence of regimes (independent combination of discharge parameters) instead of a unique polishing regime. The used sequence simulates an EDM operation with the finishing electrode beginning with roughing regimes, followed by finishing regimes and ending up with polishing regimes. This sequence was tested for normal and PMD-EDM dielectric conditions in several copper electrode areas and for two polishing times. The silicon presence in the gap in the polishing regimes allows a significant reduction of abnormal discharge occurrence and of the final surface roughness. The authors found that increasing of the polishing time induces a clear improvement of the surface quality if the PMD-EDM conditions are used and only a fair improvement for the conventional EDM conditions.

From the published research results it is possible to conclude that silicon and graphite are the two powder materials that allow a clear increase of the discharge stability and a consistent improvement of the surface roughness. Additionally the powder concentration and the grain size are critical for the process performance, ranging typically between 1 to 20 g/l and 1 to 15 µm respectively. Far over the relevance of these conclusions, one should notice that there is no systematic knowledge concerning the effect of the powder concentration in the crater morphology, in the surface roughness and in the process stability. In addition there is not enough data to assess the influence of the flushing flow in the PMD-EDM process performance since this parameter is often omitted in the referred publications. Finally, the majority of the experimental configurations used in the research work aims to find the process conditions to allow the minimisation of the surface roughness. So, most of the published results were based on specifically developed pulse generators, used workpiece and electrode surfaces properly prepared for the polishing phase and applied a unique EDM regime (in which the process parameters are set). This approach is ideal for optimising the process parameters and interpreting the PMD-EDM phenomena. Nevertheless, it is not enough to assess the influence of the process parameters and the integral impact of the PMD-EDM process in a representative way.

Actually, the EDM process involves two main phases performed by two electrodes. The roughing electrode pene-

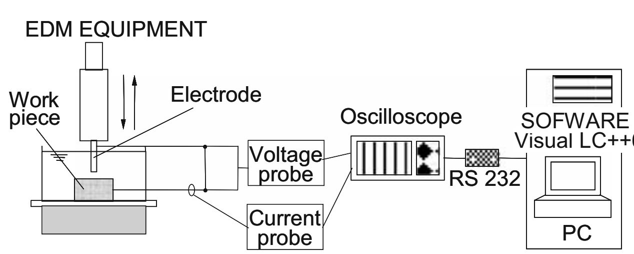


Fig. 2 Monitoring system set-up

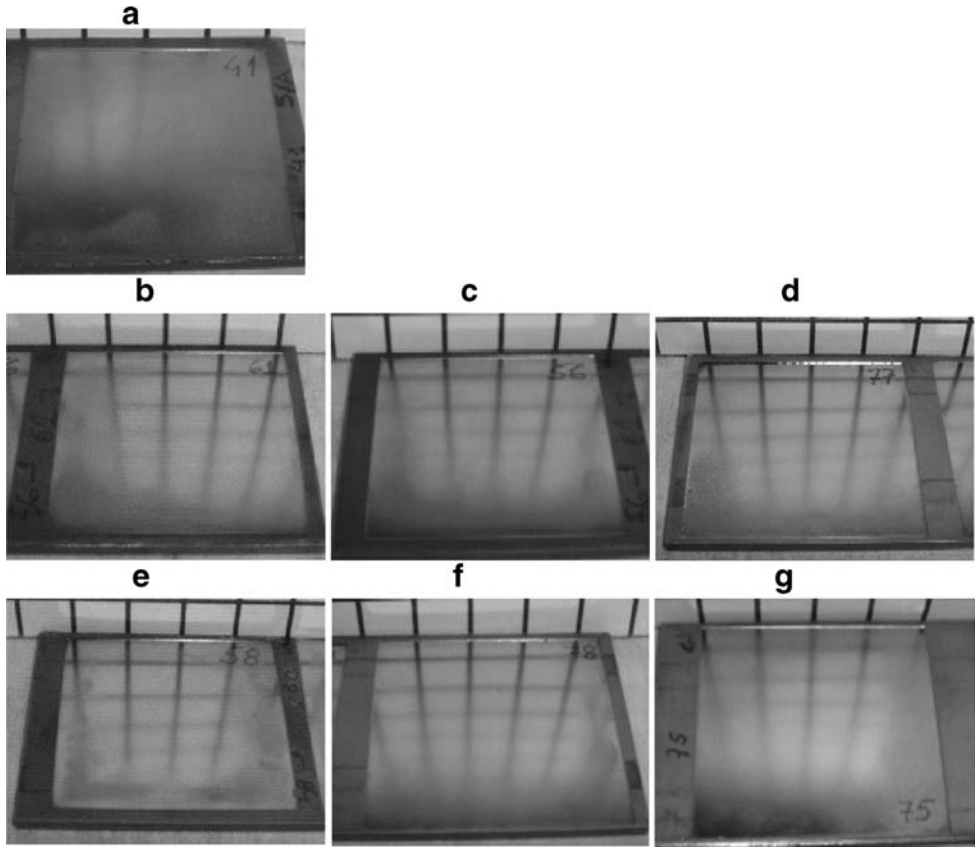


Fig. 3 Images of the samples obtained for different silicon powder concentrations. **a)** 0 g/l, **b)** 1 g/l, **c)** 2g/l, **d)** 3 g/l, **e)** 5g/l, **f)** 10 g/l and **g)** 20 g/l (copper electrode area: 1600 mm^2; flow: 1 l/min)

trates in the workpiece in order to remove material and generate a machined shape in it. Afterwards, the finishing electrode is used to reduce the surface roughness to a target value. Besides it would be possible to make use of a third electrode to the polishing phase, it is also reasonable to continue using the finishing electrode throughout the EDM regimes with low discharge energy in order to perform the surface polishing. This approach was the one selected as the basis of the experimental design used in the research presented in this paper. A sequence of regimes was used to study the influence of the powder concentration and dielectric flow in the final surface morphology. In order to assess the impact of the PMD-EDM, the tests were carried out for several copper electrode areas and in two different dielectric conditions: conventional EDM conditions and EDM with silicon powder particles suspended in the dielectric.

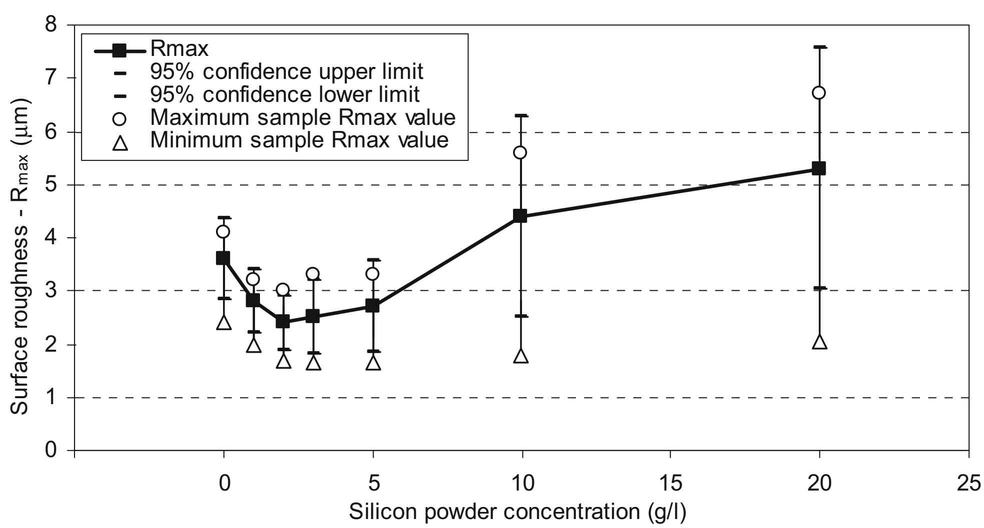


Fig. 4 Influence of the silicon powder concentration on the surface roughness (copper electrode area: 1600 mm^2 ; flow: 1 l/min)

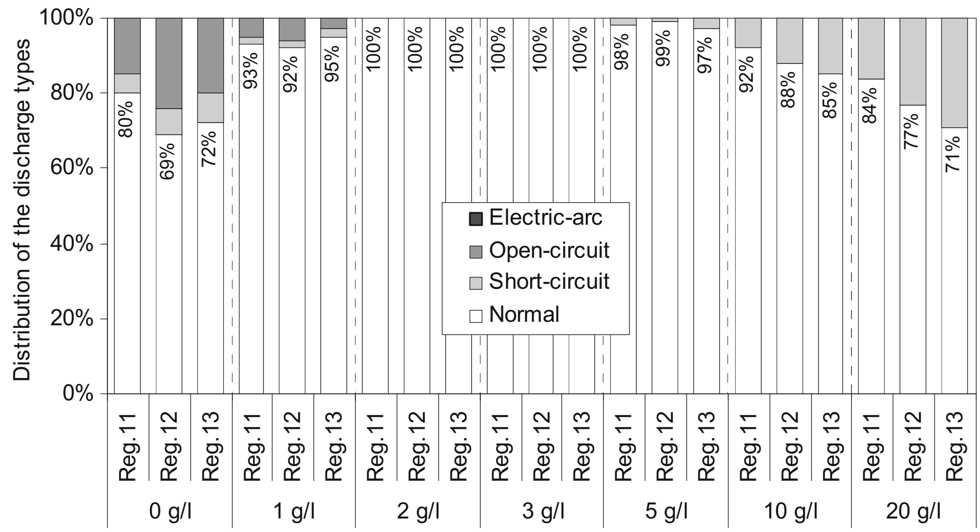


Fig. 5 Influence of the powder concentration in the discharge type distribution for last three polishing regimes (copper electrode area: 1600 mm^2; flow: 1 l/min)

2 Experimental setup, materials and surface analysis

To perform the experiments an EDM programme was selected based on the parameter generator expert system of the industrial equipment used (Charmilles Roboform 2000). This programme is a typical sequence of machining regimes (13 regimes) used with the finishing electrode in a conventional EDM operation. The electrode penetration on the workpiece was set-up to 0.5 mm and the orbital movement was implemented after the roughing regimes. In the finishing and polishing regimes the negative polarity was used. The tests were conducted with conventional dielectric conditions (kerosene-Castrol SE Fluid 180) and with powder-mixed dielectric for the same parameter setting (Fig. 1). The powder material used was 99.5% pure silicon with an average particle size of 10 µm (maximum 15 µm). The silicon powder was added only in the last three polishing regimes, and the polishing time was set up to 100 min. In order to avoid the contamination of the equipment filtering devices and the sedimentation of the powder particles a circulation system based on a mud-type pump was implemented. A direct jet design was used for gap flushing with one nozzle for the tests with an electrode area below 3200 mm^2 and with two nozzles for the 3200 and 6400 mm^2 electrode areas. The tests were carried out on hardened mould steel AISI H13 workpieces (54 HRc).

The powder concentration, the flushing flow and the electrode area were varied during the tests in order to assess their influence over the process technological performance, measured through the craters' average diameter and depth, the white-layer thickness, the final surface roughness and the type of discharges occurred. Crater diameters were measured by optical microscope observation in six different spots of each sample machined surface. These data were computed in order to obtain the average and the maximum and minimum values of the sample craters' diameters. A similar procedure was used for the analysis of the white layer. Moreover these measurements were preceded by a metallographic preparation (abrasive disks and etching with nital at 2% during 15 s). In accordance with Rebelo et al. [36] the roughness parameter R_z, average of the maximum pick to valley distance measured in five reference zones in one profile, is a fair approximation to the craters' depth. The surface roughness was evaluated in 16 different points covering all the sample area using the R_{max} roughness measure, which is the high value of peak to valley obtained for one measurement. Data were computed to obtain the average value and the standard deviation of the roughness for each sample. The type of discharges that occurred was monitored for each regime. The monitoring system developed (Fig. 2) identifies the normal discharges as discharges occurred in between the range of ± 30% of the reference voltage. The electric-arc discharge type is detected for discharge voltage above 70% of the ionisation voltage. The short-circuit discharge type is identified for discharge voltage below 7 V. Finally, the open circuit discharge type is pointed for long ionization time, meaning that the dielectric condition (ex.: contamination) inhibits the discharge ignition.

3 Results and discussion

3.1 The influence of the silicon powder concentration

In this section the results of a set of tests designed to assess the influence of the silicon powder concentration in the surface morphology are presented. The powder concentration was varied from 0 g/l (conventional conditions) to

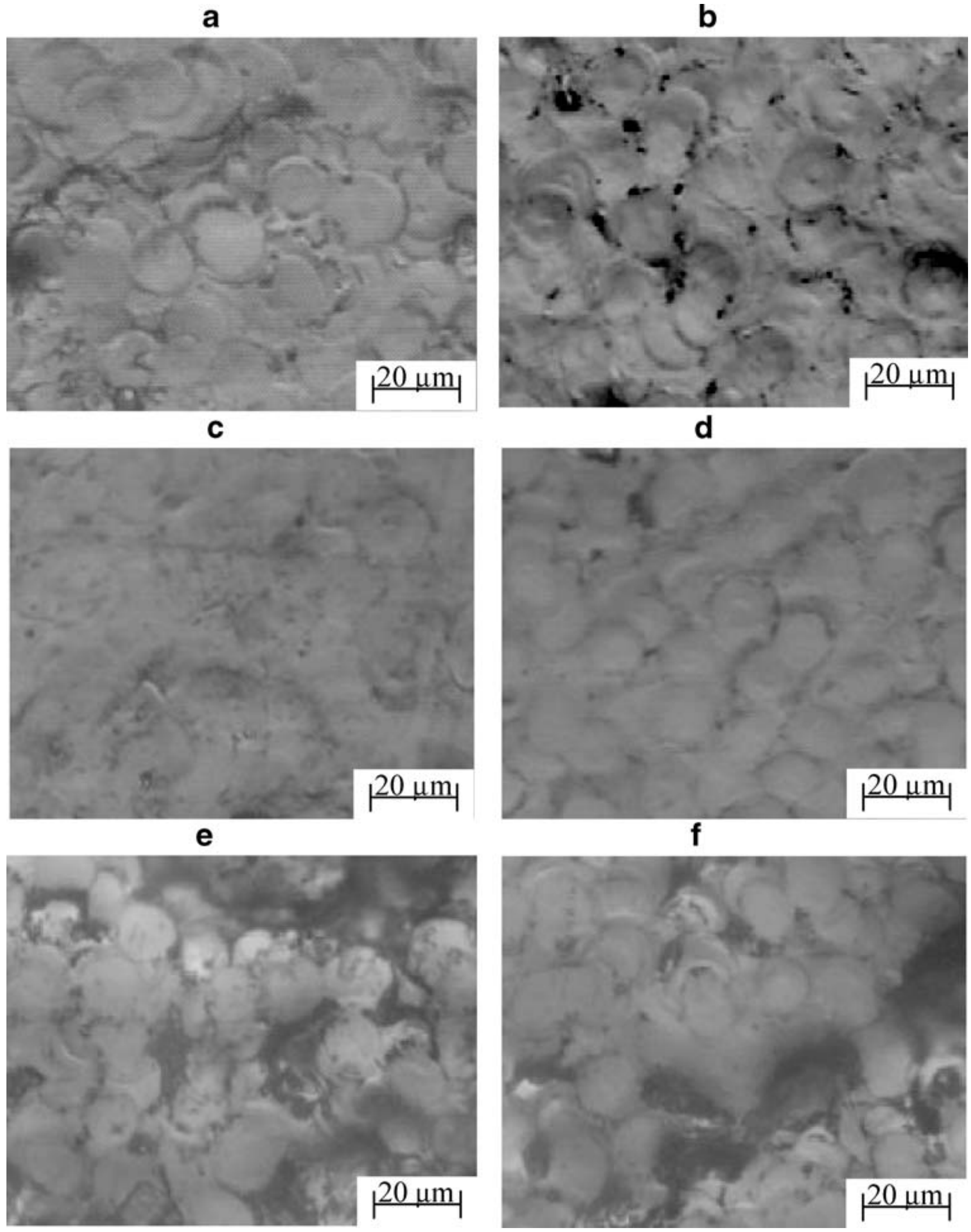


Fig. 6 Surface topography of samples machined for several powder concentrations. Images gathered by optical microscope in the central region of the samples. **a)** 0 g/l, **b)** 1g/l, **c)** 2g/l, **d)** 5g/l, **e)** 10 g/l and **f)** 20 g/l (copper electrode area: 1600 mm^2; flow: 1 l/min)

20 g/l. A copper electrode with 1600 mm^2 of square surface area was used with a constant dielectric flow rate of 1 l/min.

Figure 3 presents images of the samples performed with different silicon powder concentrations. By visual observation it is possible to verify the positive influence of the silicon powder in the surface reflection. Nevertheless for the higher concentration samples an increase of the light dispersion can be observed.

Through the analysis of the Fig. 4 it is possible to quantify the mentioned behaviour through the variation of the surface roughness. Actually the rise of the silicon concentration from 0 to 2 g/l promotes a decrease of the surface roughness. However, for a higher concentration the R_{max} values increase directly with the silicon concentration. One can also observe that for the 10 and 20 g/l samples the surface roughness heterogeneity increases dramatically.

The process monitoring analysis emphasises the extreme influence of the silicon powder on the discharge process stability (Fig. 5). Without silicon in the dielectric, one can observe the occurrence of mainly open-circuit abnormal discharges and a small incidence of short-circuiting, which occurrence decreases for 1 g/l silicon concentration. For 2 and 3 g/l the abnormal discharges are fully eliminated meaning, this is the concentration range that maximizes the process efficiency. For higher concentration rates a direct dependence of the abnormal discharges occurrence with the powder concentration is observed. Additionally the occurred abnormal discharge are solely of short-circuit type

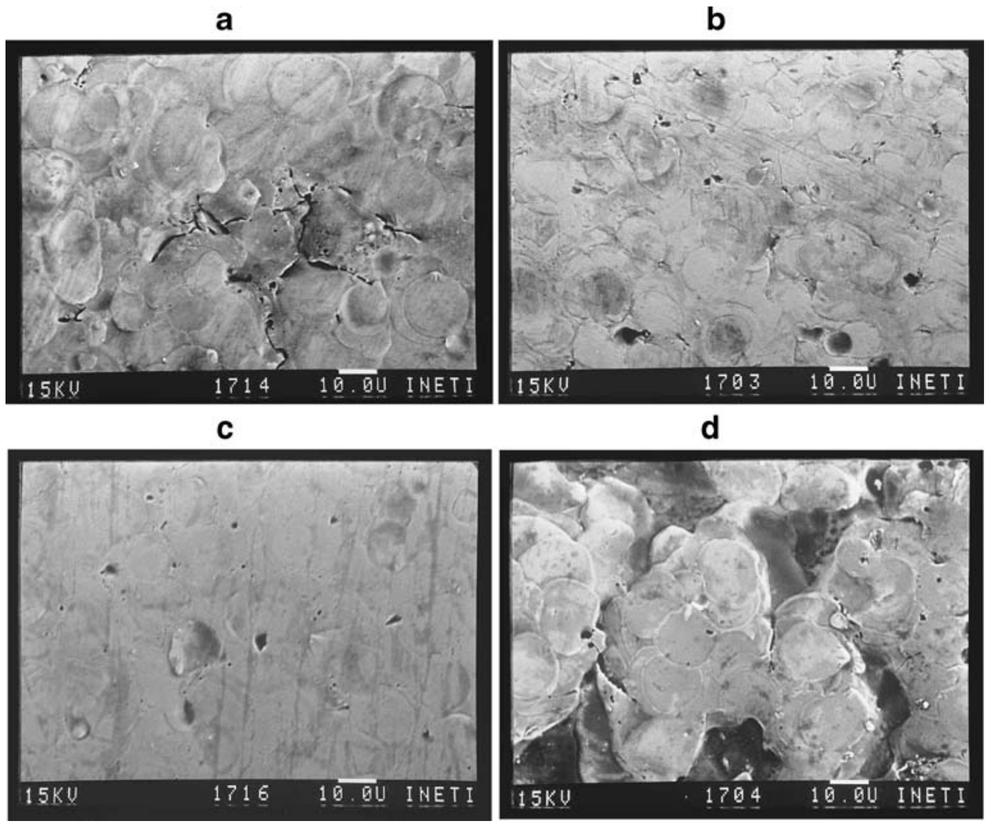


Fig. 7 Surface topography of samples machined for several powder concentrations. Images gathered by scanning electron microscope in the central region of the samples. **a)** 0 g/l, **b)** 1g/l, **c)** 2 g/l and **d)** 20 g/l (copper electrode area: 1600 mm^2; flow: 1 l/min)

what can be explained by an excess of powder particles in the gap promoting the formation of particle bridges between the electrode and the workpiece.

The observation of the surface craters formed for the several silicon powder concentrations explains the surface roughness distribution and allows the understanding of the effects of the abnormal discharges. The presence of a high concentration of silicon powder contributes to the formation of valleys on a matrix of smooth discharges (Fig. 6). Since there is a matrix formed by smooth craters, one can conclude the discharge process is not significantly affected by the powder concentration increasing (Fig. 7d). Nevertheless the presence of excessive particles of silicon powder causes the occurrence of short-circuiting that can be pointed out as one of the main reasons for the formation of the referred deep valleys. These irregularities contribute to the increase of the roughness and surface heterogeneity. Actually the surface roughness for the highest powder concentration is even superior to the observed for powder-free dielectric in which only small percentage of short-

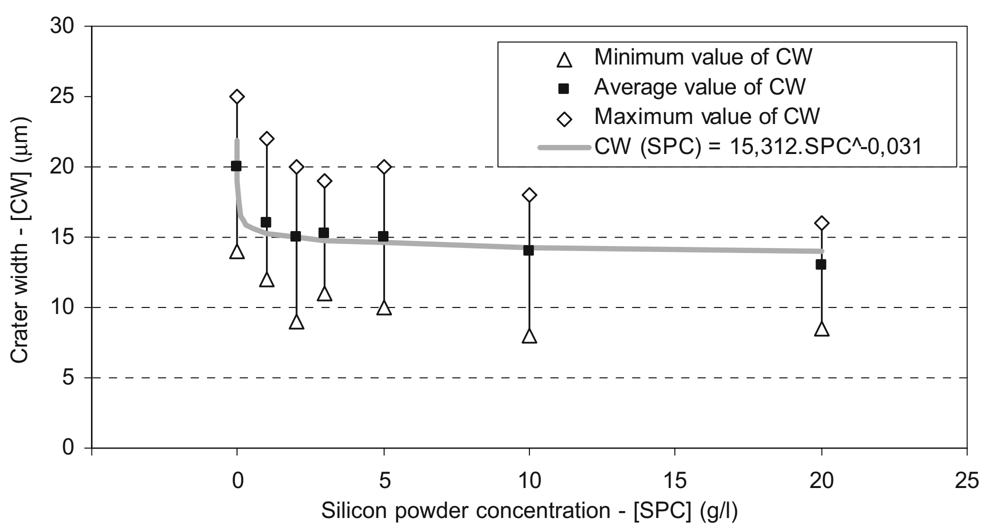


Fig. 8 Crater width distribution with the silicon powder concentration (copper electrode area: 1600 mm^2; flow: 1 l/min)

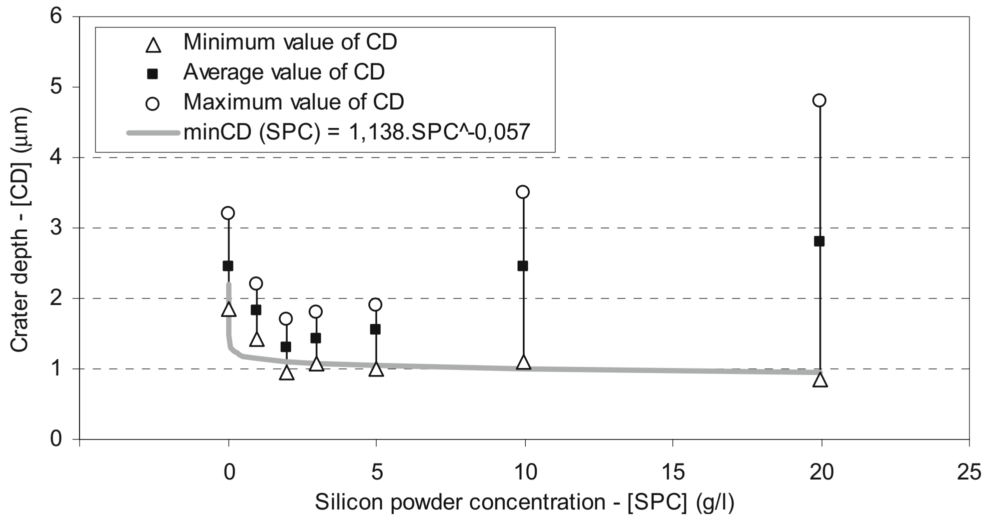


Fig. 9 Crater depth distribution with the silicon powder concentration (copper electrode area: 1600 mm^2; flow: 1 l/min)

circuiting was observed. The other abnormal discharge type observed in the powder-free dielectric condition is the open-circuit. Indeed it represents a difficulty in the discharge ignition, but it does not generate a defect in the machined surface. The use of silicon powder concentration in the range of 1 to 3 g/l promotes the formation of slightly smoother craters resulting in the reduction of the surface roughness. Even when observed with the scanning electron microscope it is difficult to identify the craters' borders in the sample with the lowest surface roughness obtained for a silicon powder concentration of 2 g/l (Fig. 7c).

Following the procedure described in Sect. 2 each sample crater's diameters were measured (Fig. 8). It must be noticed that for the 10 and 20 g/l samples only the normal discharge craters were measured (the ones that compose the "matrix") since the referred deep valleys cannot be considered strictly as discharge craters. The results show that the use of silicon powder generates the reduction of the matrix craters' diameter even for the higher concentration range. This behaviour follows a negative power equation (nPE) represented in Fig. 8. The reduction of the craters' diameters with the increase of silicon powder concentration can be explained through a phenomena described by Chow et al. [27]. In accordance to these authors the presence of powder particles promotes several discharging paths within one single input pulse. The discharging energy is dispersed and a single input pulse can generate several discharging spots. So with the increase of the powder concentration this effect can be more accentuated with an even more evident discharge distribution that decreases the size of each crater.

Withregards to the average crater depth, the measuring technique was based on a roughness meter so it was not possible to avoid the inclusion of the effect of the abnormal valleys in the collected values. As illustrated in Fig. 9 the presence of powder particles causes the reduction of the average crater depth for the low concentration range and the increase of it for the high concentration range. However, the distribution of the minimum crater depth with the silicon powder concentration follows an nPE. This is an expected behaviour due to the phenomena referred for the crater diameter. Additionally the increase of the powder particles quantity tends to increase the gap distance. And larger gaps reduce the discharge channel impulsive force contributing to the formation of smoother craters [33].

The use of silicon powder generates a more homogeneous and thinner white-layer (Fig. 10). The distribution of the white-layer thickness with the powder concentration reveals a similar behaviour to the other surface character-

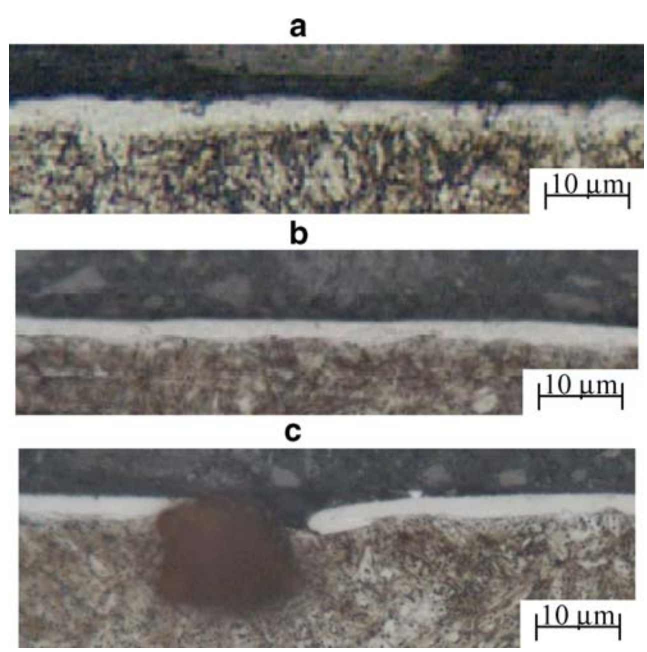
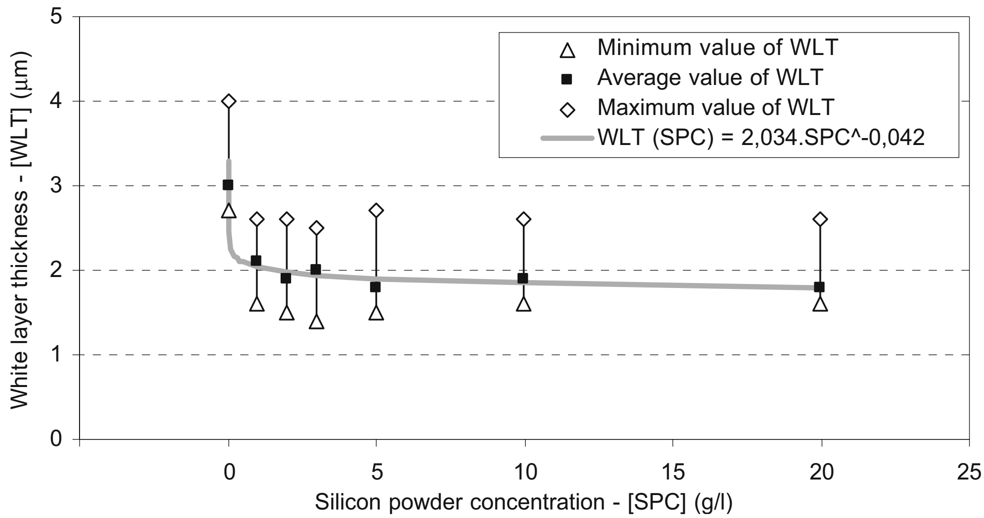


Fig. 10 Samples cross-section revealing the white-layer for several silicon powder concentrations. **a)** 0 g/l, **b)** 2 g/l and **c)** 20 g/l (copper electrode area: 1600 mm^2; flow: 1 l/min)

Fig. 11 White-layer thickness distribution with the silicon powder concentration (copper electrode area: 1600 mm^2; flow: 1 l/min)



istics (Fig. 11). The increase of the discharging rate due to the increase of the process stability and the reduction of the impulsive forces mentioned by Uno and Okada [33] contribute to form a denser and smooth white-layer. As shown in Fig. 10c the deep valleys are clearly identified in the cross-section observation. In these valleys all the material is volatilised and expelled due to the violent discharging process resulting in the absence of white-layer.

3.2 The influence of the dielectric flow rate

In this section the results of a set of tests designed to assess the influence of the dielectric flow in the surface morphology are presented. The powder concentration was set up to 2 g/l for the tests with silicon suspended dielectric. The dielectric flow rate was varied from 0.5 to 2.5 l/min for the several electrode areas between 100 to 6400 mm^2. In Fig. 12 one can observe there is a dielectric flow rate that minimises the surface roughness or beyond which there is no roughness decrease. This behaviour is similar for both dielectric conditions and the flow rate level that minimises the surface roughness is independent of the dielectric condition.

As expected this reference flow rate increases with the electrode area. Indeed for larger areas, it is more difficult to remove the eroded particles from the gap zone. In this condition, and particularly in the roughing and finishing regimes, the dielectric removal power for a small flow rate is not enough to clean efficiently the gap zone. So an excessive presence of eroded particles contributes to the machined surface deterioration. This phenomenon is clearly detected in the abnormal discharges distribution with the dielectric flow rate (Fig. 13). Actually, for flow rates lower than the one that minimises the surface roughness one can observe an extreme percentage of abnormal discharges from regime 1 to 10. This percentage decreases when the

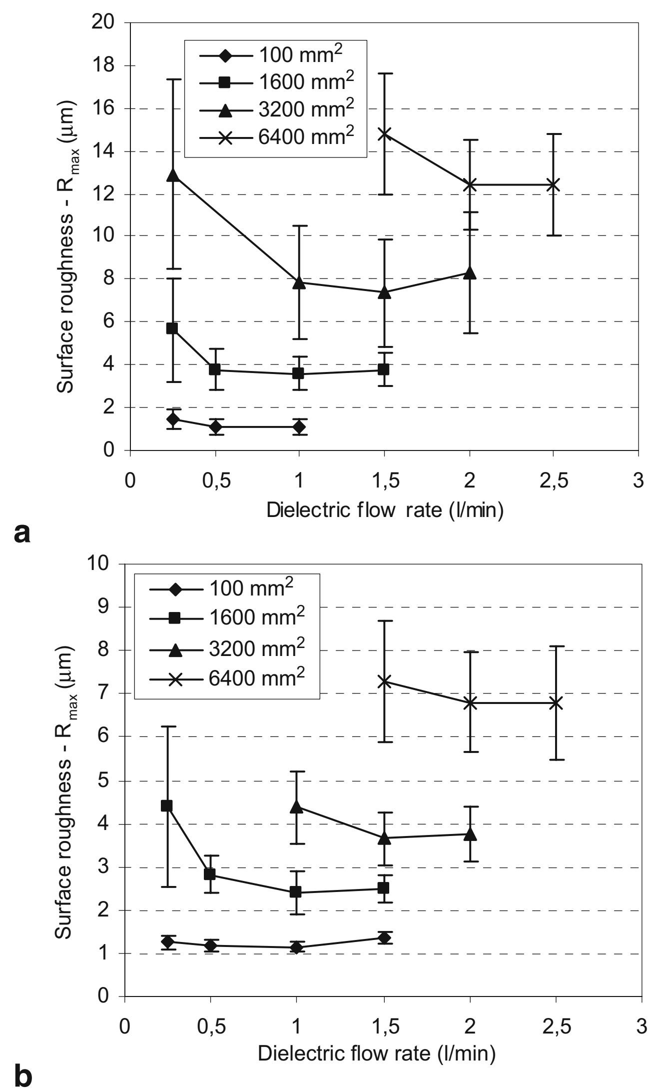


Fig. 12 Dielectric flow rate influence on the surface roughness for several electrode areas. **a)** Conventional dielectric condition (0 g/l), **b)** PMD-EDM dielectric condition (95% confidence interval; silicon powder 2 g/l)

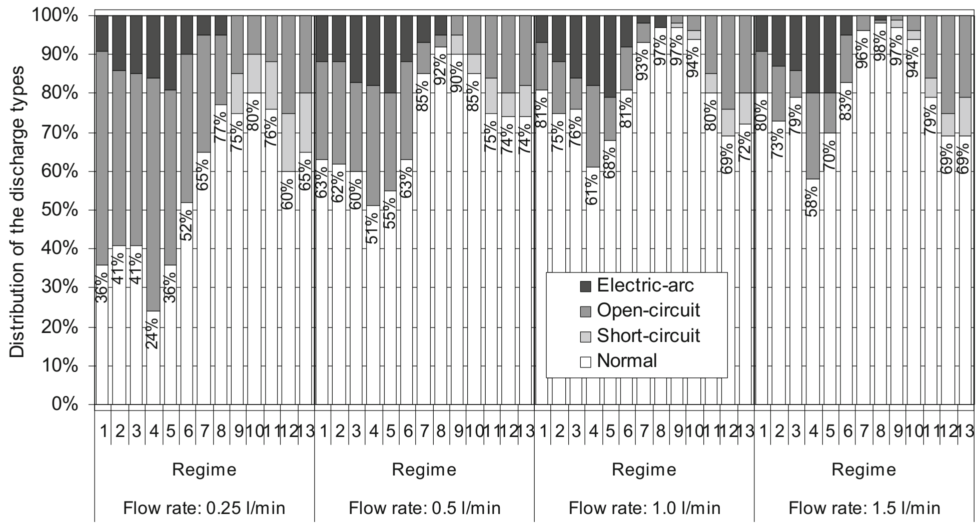


Fig. 13 Influence of the dielectric flow rate in the discharge type distribution (copper electrode area: 1600 mm^2; silicon powder concentration: 0 g/l)

flow rate is increased. For higher flow rates, two types of situations can occur: 1) An excessive dielectric pressure can create instability in the discharge zone contributing to the surface roughness deterioration, as mentioned by Chow et al. [27]. 2) The dielectric flow rate increase beyond certain limits does not produce additional effect in the surface roughness since its power is wasted in workpiece and electrode walls. These two situations can be observed in Fig. 12.

With regards to the last three polishing regimes for the conventional dielectric condition the gap distance is so small that even with high dielectric flow rates the gap cleaning is not effective (Fig. 14). With the use of silicon powder suspended in the dielectric, it is possible to observe also the occurrence of abnormal discharges for low dielectric flow rate. Actually since the powder particles increase the gap distance the cleaning action of the dielectric is fruitful if the flow rate is sufficiently strong to remove the eroded particles. For the particular case of 1600 mm^2 the use of dielectric flow rate higher than 1.0 l/min avoids the occurrence of abnormal discharges promoting the reduction of the surface roughness.

The samples topography analysis allows one to validate the behaviours mentioned above. As exhibit by images a) and d) of Fig. 15 the surface obtained with a very low dielectric flow rate show the polishing regimes discharge craters over a matrix with waviness and defects. The abnormal discharges occurred during the polishing regimes are a potential cause for the small size defects. The abnormal discharges during the roughing and finishing regimes contributing to the formation of large craters (valleys) are the apparent cause of the waviness presented by the surface. With the continuous discharge firing of the subsequent polishing regimes these valleys become smoother and less deep, but are not fully eliminated. So, when low dielectric flow rates are used a large percentage of abnormal discharge occurs in the higher energy regimes introducing important defects on the machined surface. The subsequent regimes of lower energy are unable to eliminate these large defects and moreover introduce small size

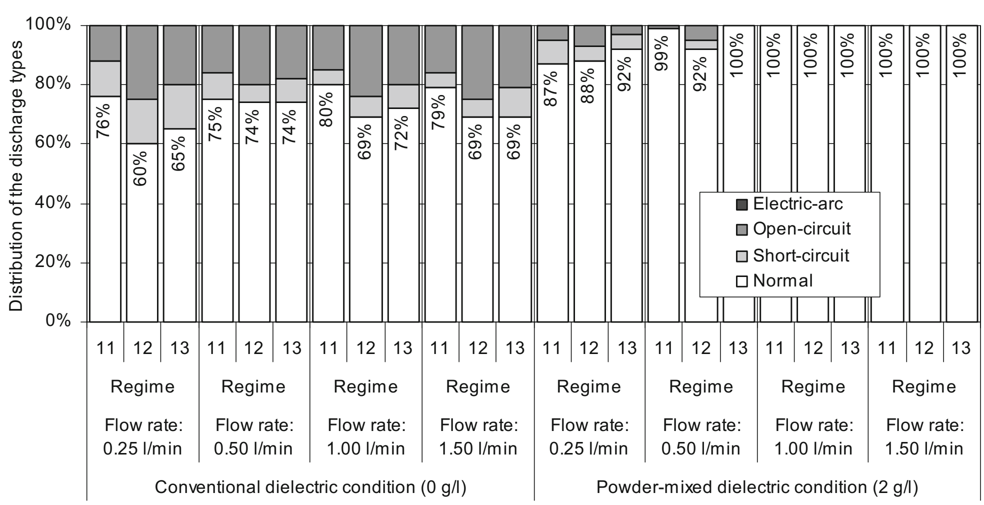


Fig. 14 Influence of the dielectric flow rate in the discharge type distribution for the last three polishing regimes (copper electrode area: 1600 mm^2)

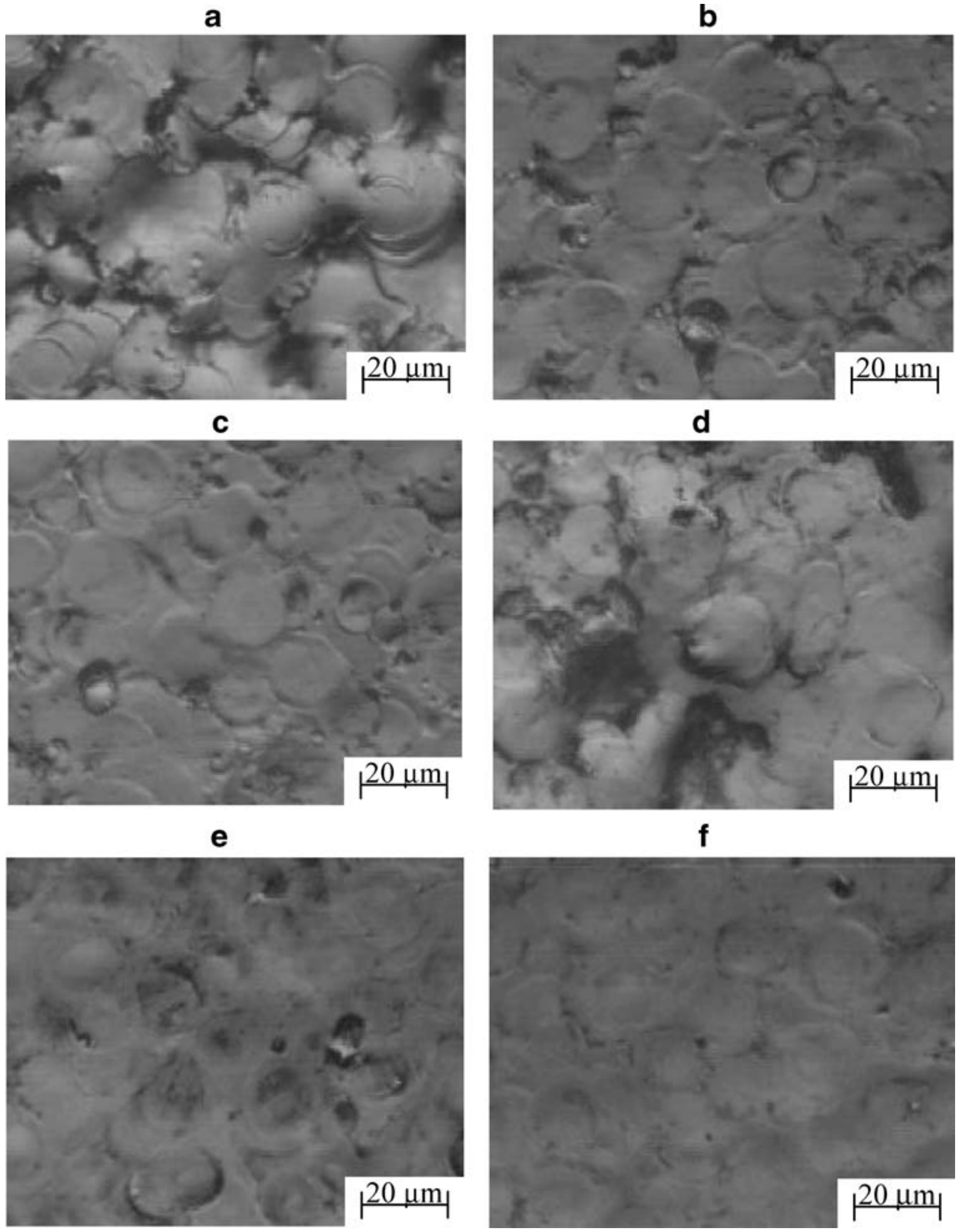


Fig. 15 Surface topography of the samples machined for different dielectric flow rates. Images gathered by optical microscope in the central region of the samples. **a)** 0 g/l and 0.25 l/min, **b)** 0 g/l and 0.5 l/min, **c)** 0 g/l and 1.0 l/min, **d)** 2g/l and 0.25 l/min, **e)** 2 g/l and 0.5 l/min and **f)** 2 g/l and 1.0 l/min (copper electrode area: 1600 mm^2)

defects due to the poor flow rate. With the increase of the dielectric flow rate these phenomena are less evident meaning the gap cleaning occurs more efficiently.

The diameter of the craters is not significantly affected by the dielectric flow rate variation for the both dielectric conditions tested (Fig. 16). On the other hand, this process parameter affects the depth of the craters in a way directly related to the phenomena described above. Deep craters are identified for lower dielectric flow rate and crater depth tends to become constant with its increasing (Fig. 17). The dielectric condition exhibits a significant influence in the crater dimensions since with the use of silicon powder the crater width is reduced about 5 µm and the crater depths is reduced about 1 µm. So, the use of the PMD-EDM conditions contributes to the formation of smaller and less deep craters, but does not change the craters' dimension behaviour with the dielectric flow rate variation.

4 Conclusions

The experimental research work carried out intended to contribute to the generation of knowledge related to the effect of silicon power particles suspended in the EDM dielectric in the quality of the final surface. Two parameters of the process were studied over several electrode areas: the

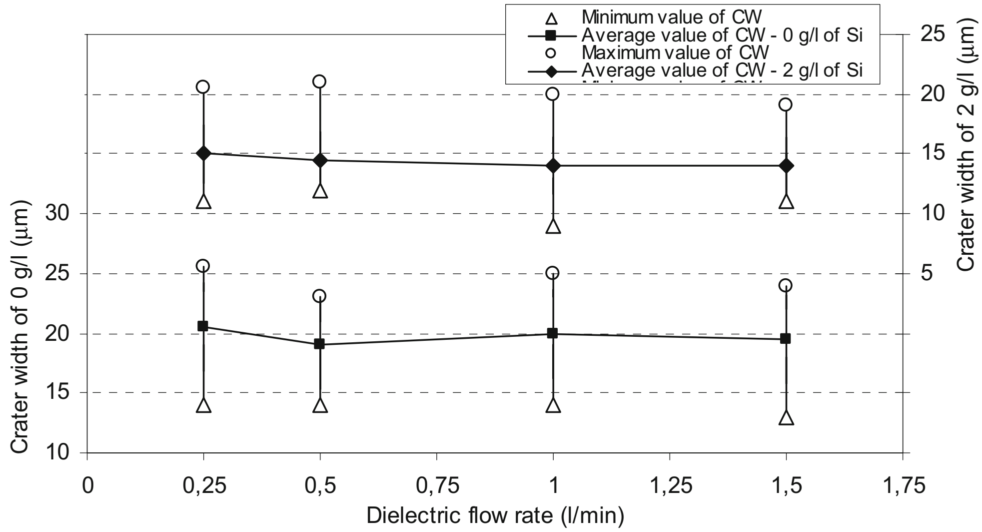


Fig. 16 Crater width distribution with the dielectric flow rate for the two dielectric conditions (copper electrode area: 1600 mm²)

powder concentration and the flushing flow rate. The quality was evaluated through the morphologic analysis of the surface and measurement of its roughness and craters and white-layer dimensions.

Some conclusions can be undertaken. Crater diameter, crater depth and the white-layer thickness are reduced by the use of silicon powder particles suspended in the dielectric. This reduction is evident even for a small level of powder concentration. The increase of the silicon content for higher values only slightly reduces the crater dimensions. This behaviour can be mathematically described by negative power type equations. Nevertheless short-circuiting occurs for the higher concentration range that causes the formation of deep valleys in a matrix fulfilled by smooth discharge craters. So the stated behaviour is only observed without considering the referred defects. Therefore, for the particular experimental configuration used, one can conclude that the powder concentration that enables a better surface morphology is in the range of 2 to 3 g/l.

The performance of the polishing regimes, measured by the percentage of abnormal discharges, is affected by the dielectric flow rate when the silicon powder is used. On the contrary, for conventional dielectric the flushing flow rate does not seem to have any influence in the number of abnormal discharges. With regards to the surface quality, there is a dielectric flow rate that minimises the surface roughness for each electrode area. For larger flow rates, there is no positive effect in the surface morphology. For smaller flow rates abnormal discharging occurs in the roughing and finishing regimes that introduce important defects in the surface. These defects are not eliminated by the subsequent low energy discharges generating the increase of the surface roughness even when silicon powder is used in the dielectric.

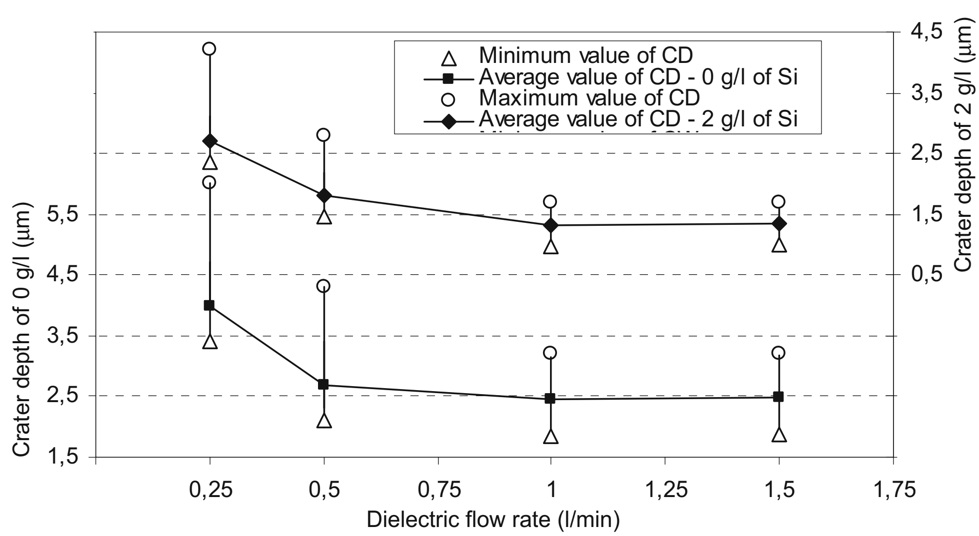


Fig. 17 Crater depth distribution with the dielectric flow rate for the two dielectric conditions (copper electrode area: 1600 mm²)

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