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ORIGINAL ARTICLE

Surface modification of AISI H13 tool steel with silicon or manganese powders mixed to the dielectric in electrical discharge machining process

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Abstract In electrical discharge machining (EDM) process, one of the most important aspects is the surface quality of the workpiece. When a uniform and thick recast layer is achieved with characteristics of low roughness, high hardness, and the absence of pores and micro-cracks, it acts as a kind of coating. Such surface is required by mold-making industry, where the molds are subjected to chemical and abrasive wear, and the surface needs to present high resistance against corrosion and abrasive forces. The use of powder particles suspended in the dielectric is a way to provide such improvement and, at the same time, avoiding the need for subsequent polishing. This work investigated the influence of silicon and manganese powders with fine particle sizes, using two different concentrations, suspended in the dielectric when EDM machining AISI H13 tool steel. It evaluated the surface roughness, hardness, and the chemical composition and micro-structure of the recast layer; using X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) techniques. The best results were obtained for silicon powder; presenting the surface roughness improved about five times, when compared to the conventional EDM process, as well as a thick and uniform recast layer without micro-cracks and pores. The silicon and the manganese powders also promoted an increase of the recast layer hardness of about 40 % when compared to the conventional EDM process.

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Keywords Powder mixed EDM · Silicon powder · Manganese powder · Surface modification

Nomenclature

i_e	Discharge current [A]
u_i	Open circuit voltage [V]
u_e	Discharge voltage [V]
t_e	Discharge duration [µs]
t_i	Pulse duration [µs]
t_0	Pulse interval time [µs]
t_p	Pulse cycle time (t_i+t_0) [µs]
V_e	Electrode wear rate [mm^3/min]
V_w	Material removal rate [mm^3/min]
ϑ	Volumetric relative wear (V_e/Vw) [%]
τ	Duty factor (t_i/t_p) [%]

1 Introduction

Electrical discharge machining (EDM) is a non-conventional machining process widely applied to manufacture complex high precision components, regardless of the material hardness. The electrical discharge machining process is a thermoelectric phenomenon and according to [1] and other researchers such as [2–5] the material removal in electrical discharge machining is associated with the erosive effect produced when spatially and discrete discharges occur between two electrical conductive materials. Sparks of short duration are generated in a liquid dielectric gap separating tool and workpiece electrodes. The electrical energy released by the generator is responsible to melt a small quantity of material of both electrodes by conduction heat transfer. Subsequently, at the end of the pulse duration, a pause time begins and forces that can be of electric, hydrodynamic, thermodynamic, and spalling nature remove the melted pools. A part of the molten and vaporized material is flushed away by the flow of the dielectric across the gap, and the rest is solidified in the recently formed crater and next to the surroundings. This process continues until the geometry of the workpiece is completed.

Due to its thermoelectric material removal mechanism, a multilayered heat affected zone is created at the surface of the workpiece [6]. Above the base material, a heat affected zone is formed by the thermal influence of the electrical discharges. On top of the surface, there is the resolidified (white) layer, formed by the unflushed molten metal that resolidified in the crater. This layer is characterized by its hardness and brittleness, frequently presenting micro-cracks and pores. The material forming this layer comes from both the molten pool and the electrode and workpiece debris present in the dielectric.

The thermal phenomena of the EDM process directly influences the chemical, physical, and microstructural characteristics of the superficial zones of the material and consequently have important effects on the functionality of workpieces. These effects are important in application like injection molding where the plastic injection molds are generally characterized by being exposed to chemical and abrasive wear during the molding cycle [7]. In order to fulfill the increasing demands of high precision components with low surface roughness, wear and chemical resistance, many EDM developments have been focused on the workpiece surface integrity improvement. An important research area in this field is related to the use of powder in the dielectric fluid during EDM machining [8]. The process called powder mixed EDM (PMEDM) aims to improve surface integrity to obtain near mirror surfaces and also to improve the corrosion and abrasion resistance of the component [9]. The addition of a suitable fine powder in the dielectric fluid contributes positively for the EDM process efficiency, as it improves the breakdown characteristics of the dielectric by reducing its strength and increasing the gap between the electrode and workpiece [10]. In addition, the plasma channel becomes wider with powders suspended in the dielectric, decreasing discharges density and generating shallower craters. As a consequence, the flushing of debris is more uniform and the process becomes more stable, enhancing the machining rate and surface finish.

The use of powders suspended in the dielectric affects directly the resolidified layer. PMEDM increases the working gap and disperses the discharges more randomly throughout the surface. Furthermore, as described in [11] when using low levels of discharge current i_e together with low discharge duration t_e values, the suspended particles in the dielectric can melt on the surface of the workpiece, generating new phases on the resolidified layer. As a result, the wear and chemical

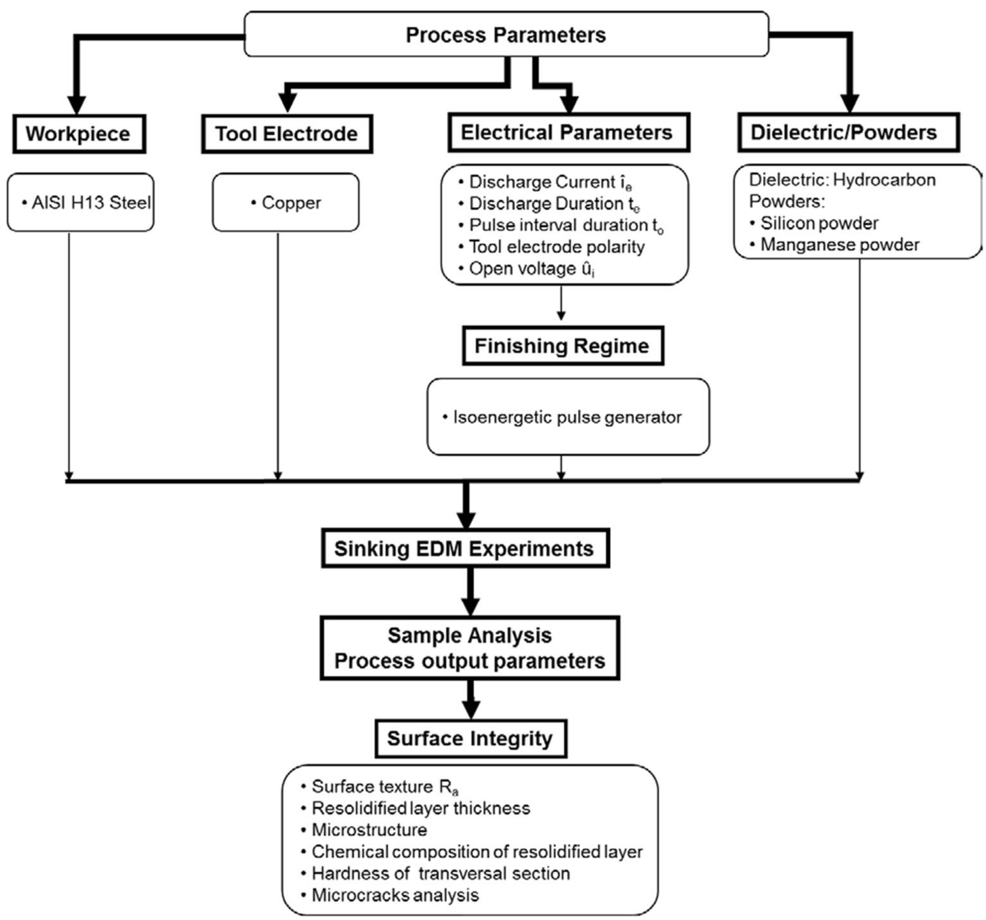


Fig. 1 Experimental methodology applied in the research

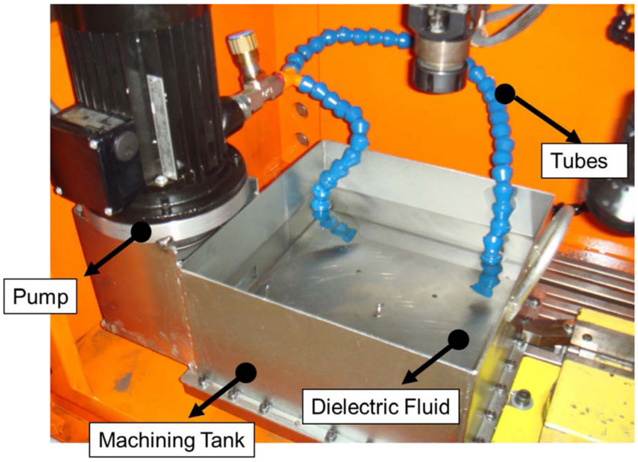


Fig. 2 Machining tank designed to conduct the experiments, detailing the recirculation pump and the pipes used to orient the dielectric fluid in the working gap

resistance of the surface can be improved. The formation of a resolidified layer containing molten suspended particles depends also on the pulse interval time t_0, where lower values are preferred as they improve the chances of powder aggregation on the workpiece surface. Negative tool polarity plays also an important role on the formation of a uniform recast layer with aggregated powder, because the discharge density is lower on the workpiece (anode) and the craters generated are shallower, increasing the amount of molten material that resolidifies on the workpiece surface.

The literature reports many investigations on different powder materials for PMEDM like Ni, Co, Fe, Al, Cr, Cu, Ti, C (graphite), Si, and Mo [12]. Jeswani [10] and Simao et al. [13] reported that the use of graphite in PMEDM can generate the formation of residual austenite on the workpiece surface due to the high concentration of carbon on the resolidified layer. Furatani et al. [14] studied the use of suspended titanium powder in EDM with a rotating electrode. The authors observed that titanium carbide (TiC) were formed on the surface of the workpiece, improving its hardness and wear resistance. Similar results were found by Mohri et al. [15] when using a tungsten electrode for the aggregation of titanium powder. Narumiya et al. [16] evaluated the effects of aluminum suspended powder during EDM of tool steel and reported a uniform resolidified layer with a surface roughness of 0.6 μm. Simao et al. [13] also obtained a low surface roughness when using PMEDM with aluminum, but the author concluded that the aluminum particles were agglomerated on the dielectric fluid due to electrostatic forces, influence the EDM process stability. According to Stevens [11], a thin and uniform layer can be formed with the application of tungsten powder suspended on the dielectric, where 9 % of tungsten was adhered on the workpiece surface, improving surface hardness and corrosion resistance.

Silicon (Si) powder is also used in PMEDM since it improves the surface integrity of the workpieces and also modifies its surface [17]. Mohri et al. [15] and Peças et al. [18] showed that the use of silicon powder with a particle size of less than 15 μm and a concentration of 2 to 15 g/L can achieve surface roughness (R_{max}) of less than 2 μm. The work of [19] showed that a powder concentration of 2 g/L led to a mirror surface. A key success factor for Si is its low specific weight (2.33 g/cm^3), which promotes an adequate powder suspension in the dielectric and uniform powder concentration. Similar works were investigated by [20], [21], and [22]. On the other hand, so far, few works have reported the use of important alloying elements such as manganese (Mn) powder on surface modification by PMEDM, as recently reported by Kumar et al. [12]. The authors also point out that the majority of studies are related to EDM performance measures, such as workpiece material removal rate, electrode wear, and surface roughness instead of being focused on surface modification. In the work of [11], coarse particle size of 60 μm of manganese powder was applied for PMEDM and it was observed poor surface quality. Supported by the aforementioned arguments, this work aimed to investigate the influence of fine particle sizes of silicon and manganese powders (<5 and <10 μm) at two levels of concentration in the dielectric fluid on the surface modification of an EDM machined AISI H13 tool steel workpiece by using PMEDM. The effect of different EDM electrical and non-electrical parameters on the formation of the resolidified layer was evaluated in terms of its surface roughness, presence of micro-cracks and pores, hardness, chemical, and phase composition. The main objective is to provide useful information to the mold-making industry, where the plastic injection molds are generally characterized by being exposed to chemical and abrasive wear during the molding cycle.

Table 1 Properties of silicon and manganese powders used in the experiments

Powder	Average particle size (μm)	Purity (%)	Specific mass (g/cm^3)
Silicon—Si	<5	99	2.33
Manganese—Mn	<10	99.5	7.47

Table 2 Powder concentration and EDM parameters used for the experiments

Powder material	Powder concentration in dielectric (g/L)	Discharge current i_e (A)	Discharge duration t_e (μs)	Pulse interval time t_0 (μs)	Tool electrode polarity
Silicon	5	2	6.4	100	Negative
Manganese	5				
Silicon	15	6			
Manganese	10				

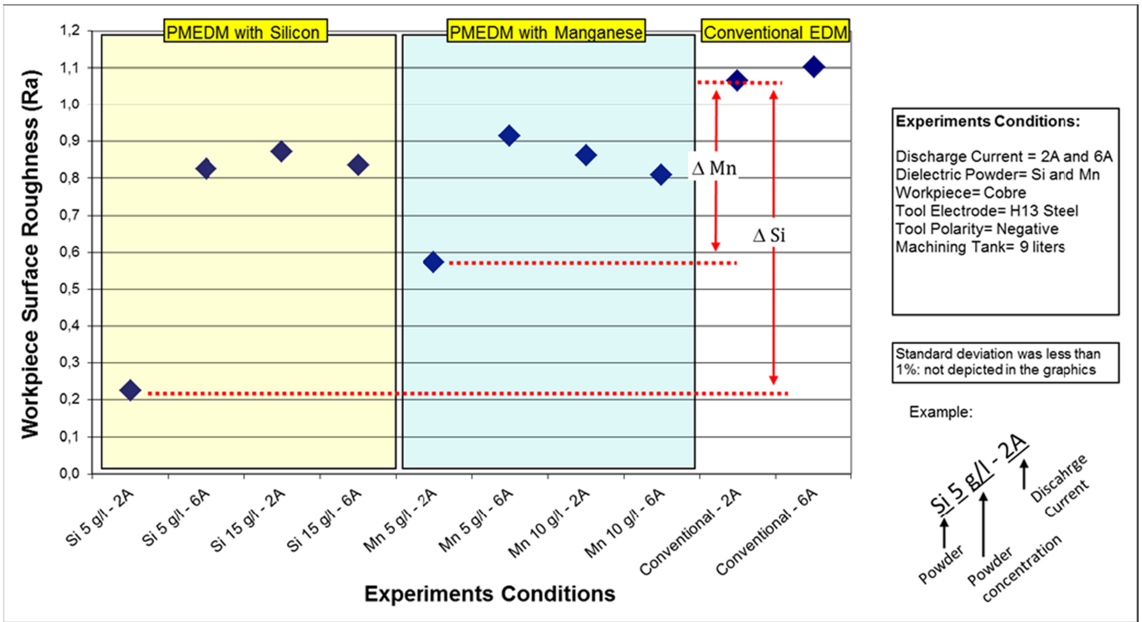


Fig. 3 Average surface roughness measurements of the evaluated samples

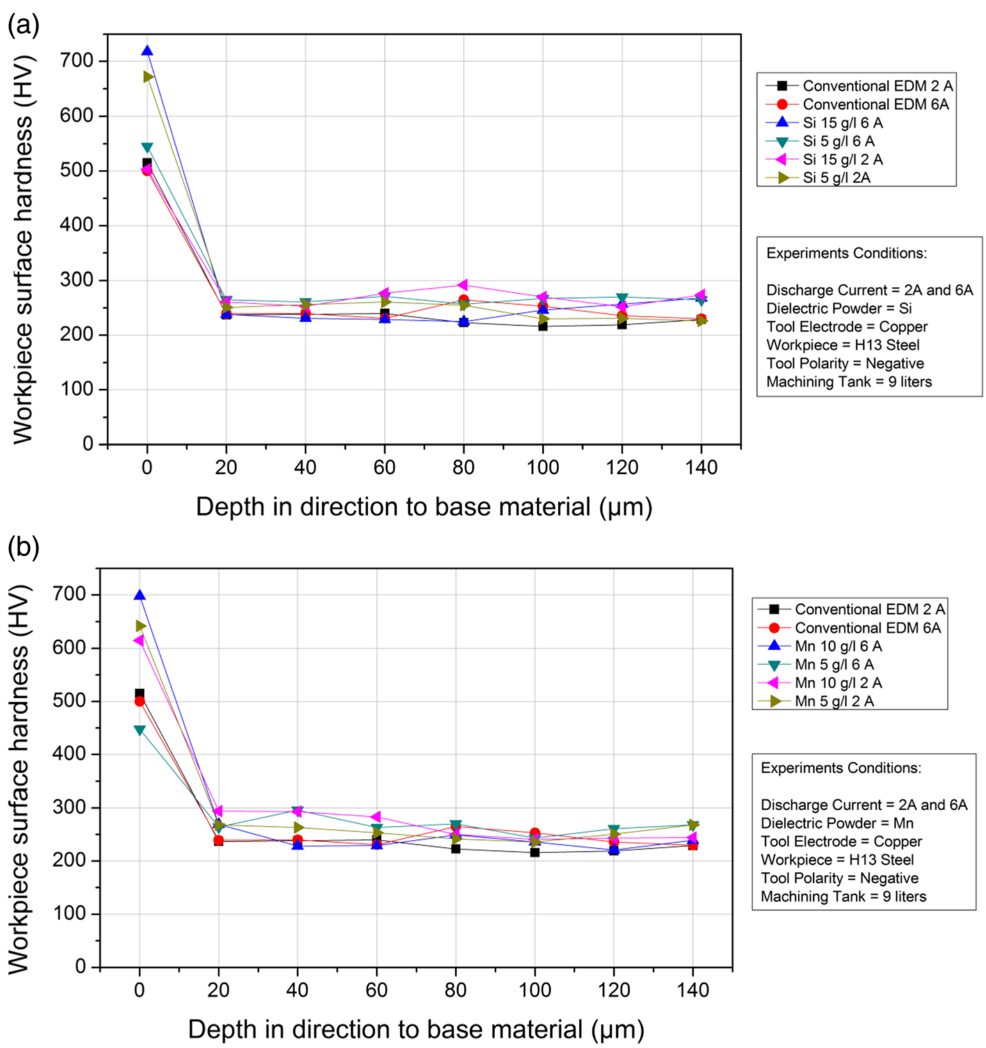
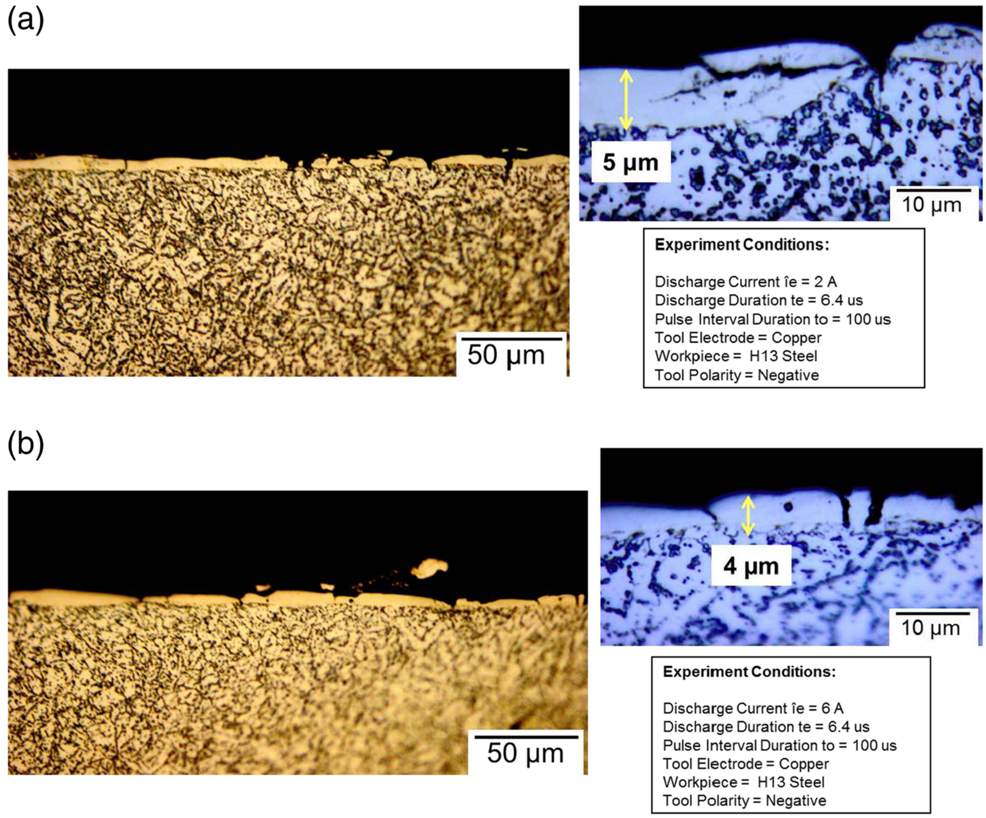


Fig. 4 Vickers hardness (HV) profile of the samples transversal section when EDM machined with **a** silicon powder and **b** manganese powder

Fig. 5 Cross-section micrographs of the workpiece samples machined with conventional EDM: **a** Discharge current 2 A. **b** Discharge current 6 A



2 Experimental methodology

Figure 1 depicts the experimental methodology used to conduct this research. It starts with the definition of independent parameters, aiming to evaluate their effect on the surface integrity of the samples. Then, it is followed by the experiments execution, which is carried out with both the absence of powder in the dielectric and also addition of powder. The samples are then investigated in regards to their surface integrity, focusing on the main characteristics of the surface like surface roughness, resolidified layer thickness and presence of micro-cracks, chemical and phase composition and hardness.

To carry out the experiments, the following materials, equipment, and methods were used:

i. EDM: A Charmilles ROBOFORM 30 CNC machine equipped with an isoenergetic generator, allowing to set the discharge energy W_e supplied to the working gap during a spark ($W_e = u_e . i_e . t_e$ [mJ]).

ii. Tool electrodes: 20 mm diameter cylindrical electrolytic copper electrodes were applied. During the EDM experiments, the electrodes were set up to work rotating at a constant speed of 20 rpm, so that the powder suspended in working gap was more uniformly dispersed.

iii. Workpiece electrodes: AISI H13 tool steel samples (42× 42×15 mm) were used. The workpiece surfaces were grinded (R_a=0.4 μm) in order to ensure parallel surfaces between the tool and workpiece electrodes, avoiding problems such as non-uniform wear of the tool electrode and process instability in the form of short circuits and arc discharges.

iv. Machining tank: In order to keep the suspended powder in a smaller volume and to prevent the particle settling, a 9 L machining tank was designed and built. It is placed inside the main machine tank as shown in Fig. 2. A stirring system composed of a high flow pump (2 m^3/h) and dielectric orienting pipes was used to properly circulate the dielectric fluid inside the machining tank.

v. Suspended powders: Two different powders were used, silicon (Si) and manganese (Mn) powders; their main characteristics are presented in Tab. 1 according to Merelex Corporation, CA, USA.

vi. EDM process parameters: In order to establish a comparison between conventional EDM and PMEDM, experiments using the above described powders as well as with no powder were conducted. Table 2 shows the main process parameters applied. The focus was to investigate the effect of different powder concentrations (5 and 15 g/L for Si powder; 5 and 10 g/L for Mn powder) as well as the influence of the discharge current i_e, where finishing machining values of 2 and 6 A were applied for all experiment configurations. Discharge duration of 6.4 μs and pulse interval time of

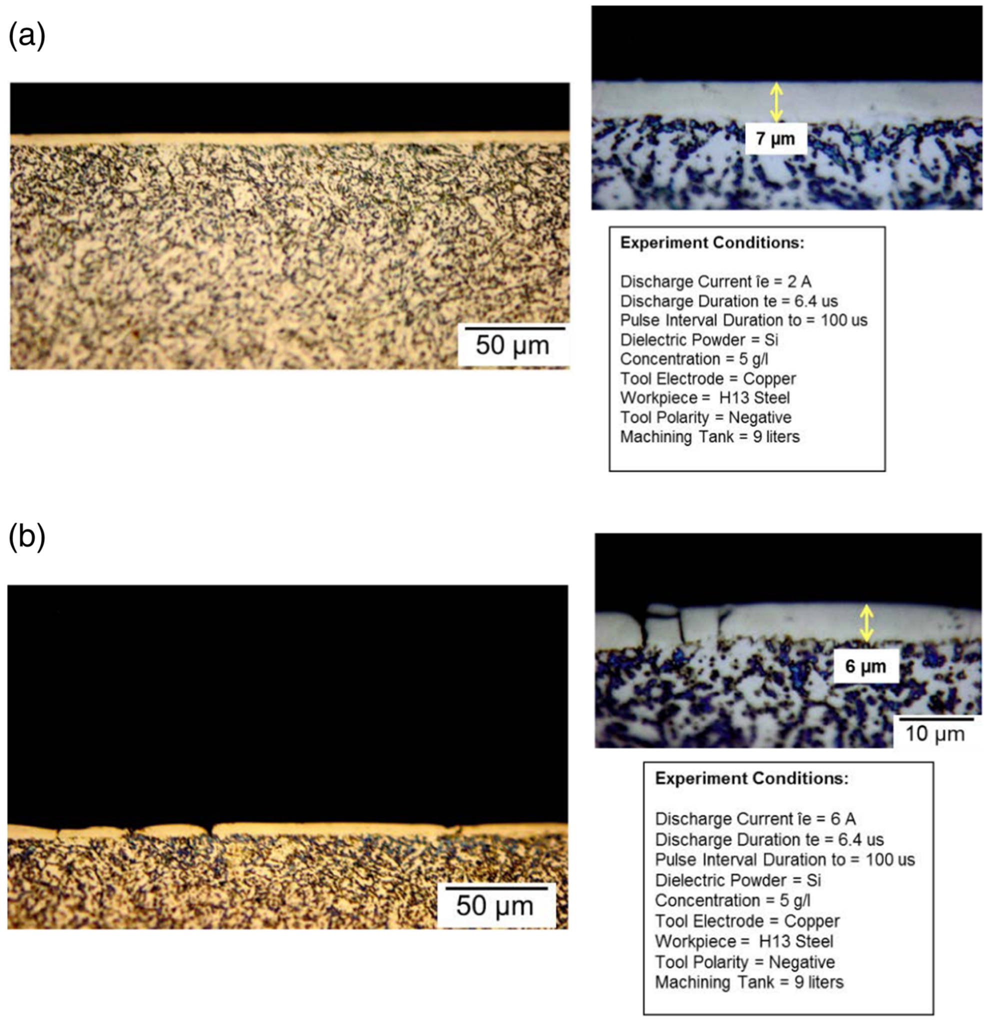


Fig. 6 Cross-section micrographs of the workpiece samples machined with silicon PMEDM with a concentration of 5 g/L: **b** Discharge current 2 A. **b** Discharge current 6 A

100 μs were applied for all experiments. Negative tool electrode polarity was used. The machining time of 4 h was applied to all the experiments. These low values of i_e and t_e were chosen because alloying with powder suspended in the dielectric requires low discharge energy $W_e = u_e . i_e . t_e$ [mJ], once the use of higher values of i_e and t_e would induce the removal of the small amount of material that was incorporated on the surface, when a subsequent discharge occurs at the same place. Long pulse interval time t_0 was applied to resolidify the molten material already during the occurrence of the discharge. The negative tool electrode polarity (cathode) was used because it causes lower discharge density on the workpiece (anode), due to the enlargement of plasma channel diameter, and then generates shallower craters which increase the amount of molten material resolidified on the workpiece surface.

vii. Surface integrity characterization: After conducting the PMEDM experiments, the samples surfaces were characterized in order to evaluate their surface integrity. The following aspects were considered:

- Surface roughness: To measure surface roughness, a Taylsurf Series 250 equipment was used with the following parameters: measure length L=4 mm, cut-off=0.8 mm. The average of three measurements of Ra (in μm) was used.
- Hardness: Vickers hardness was measured on the upper surface of the workpiece and down 140 μm to the base material in fixed intervals of 20 μm using a micro-indentation tester (Shimadzu Micro Hardness Testers HMV) with a 10 g load applied for 15 s.
- Micro-structure: The samples surface microstructures were evaluated by both optical and scanning electron microscopy. Optical microscope Olympus Bx60 was used to observe the transversal sections of the micrographs. Scanning electron microscope (SEM, Jeol JSM-6360LV) was used to measure the resolidified layer

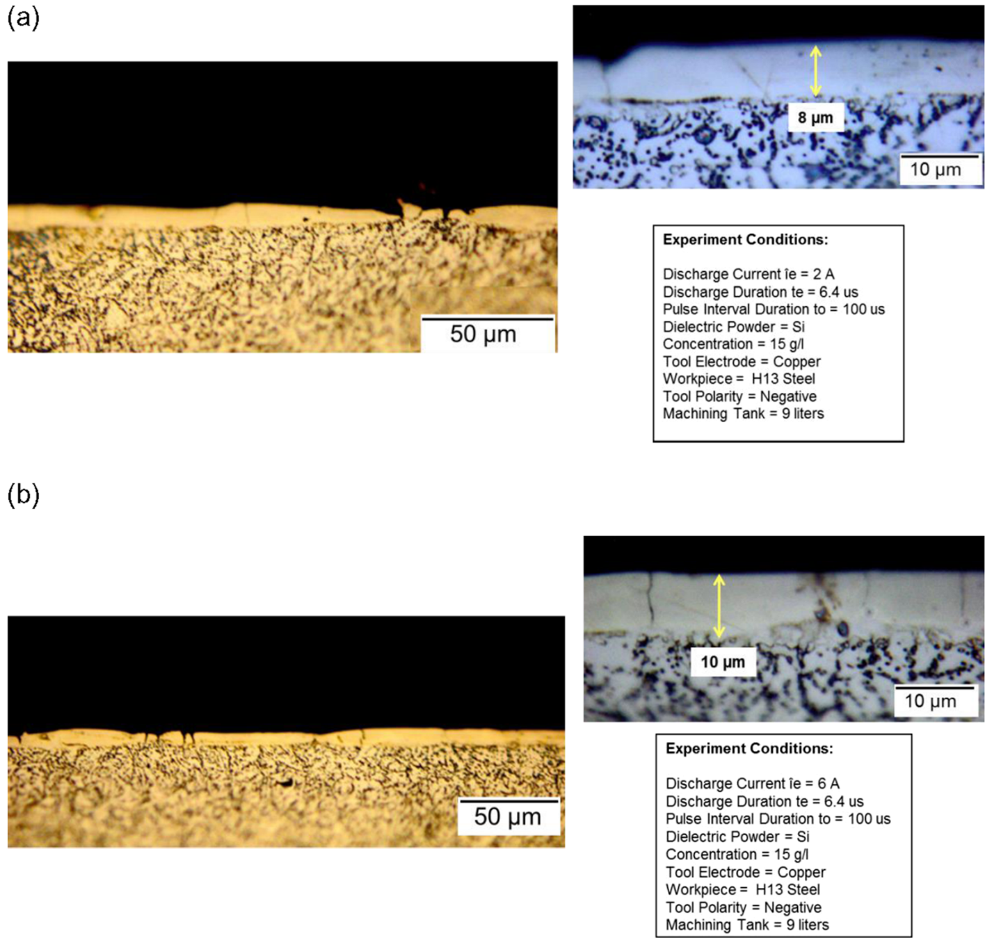


Fig. 7 Cross-section micrographs of the workpiece samples machined with silicon PMEDM with a concentration of 15 g/L: **a** Discharge current 2 A. **b** Discharge current 6 A

thickness for some samples as well as to measure the average particle size of the silicon and manganese powders used in the experiments and the chemical composition of the white layer using energy dispersive spectroscopy (EDS).

- Crystalline phase identification: X-ray diffraction analysis (XRD) using a Shimadzu XRD-7000 with Cu K_α 40 kV was used to identify the crystalline phases present in the resolidified layer.

3 Results and discussion

This section presents the main results obtained using the experimental approach discussed above. The presentation follows the surface integrity characterization presented in section 2, starting with surface roughness and micro-hardness results, followed by micro-structure analysis and at last chemical and phase characterization.

3.1 Surface roughness

Surface roughness measurements of the experiments with silicon and manganese powder as well as without powder are depicted in Fig. 3, where the values are the average of three measurements done (n=3) for each experiment conditions. The standard deviation is not depicted in the graphics because it was too small (less than 1 %) and would not be seen in the graphics. PMEDM with silicon powder at a concentration of 5 g/L and discharge current of 2 A resulted in five times better surface finish when compared to conventional EDM (ΔSi). Increasing both the discharge current and silicon powder concentration resulted in a worse surface roughness but still better than with conventional EDM. This behavior can also be noticed when EDM machining with manganese powder. Higher discharge currents are associated to higher discharge energies, which results in larger and deeper craters formation on the workpiece, worsening the surface finish.

The use of manganese at a concentration of 5 g/L and discharge current of 2 A promoted two times better surface finish than conventional EDM (ΔMn). When comparing PMEDM results with silicon and manganese, clearly, silicon

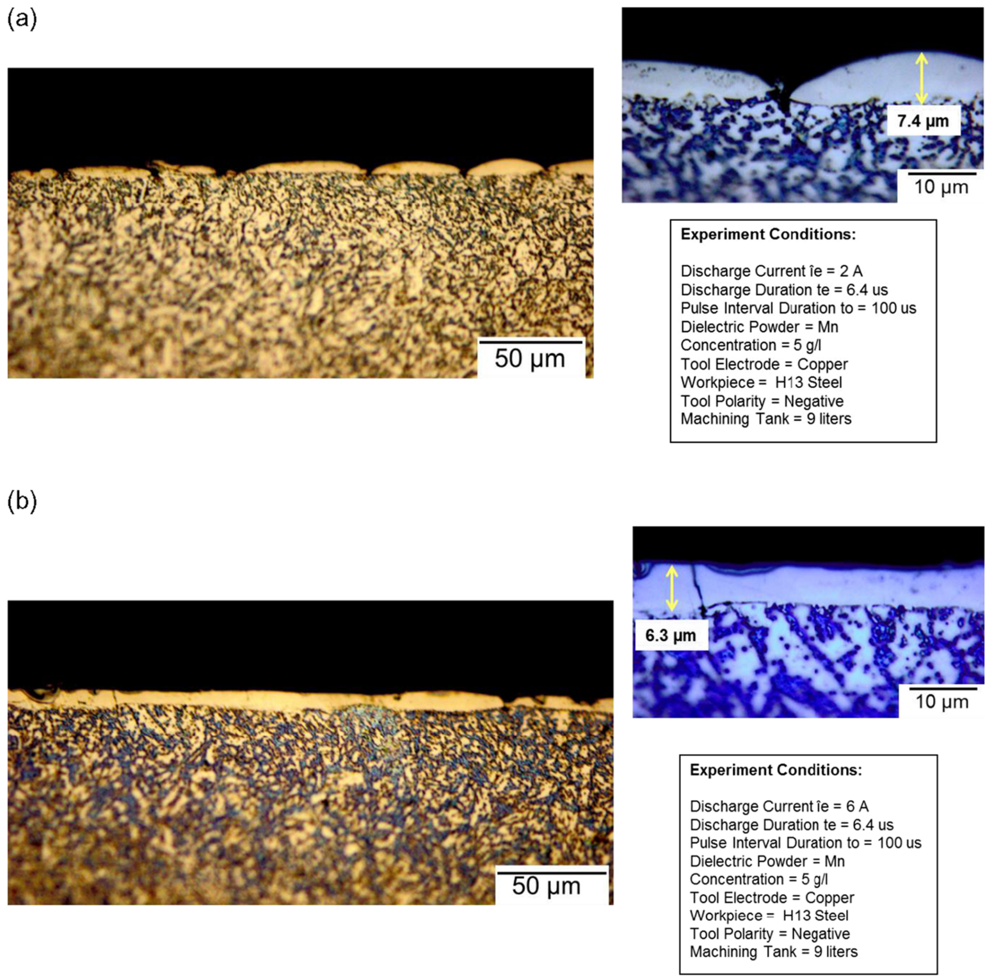


Fig. 8 Cross-section micrographs of the workpiece samples machined with manganese PMEDM with a concentration of 5 g/L: **a** Discharge current 2 A. **b** Discharge current 6 A

reaches the best surface roughness levels, achieving a near mirror surface finish. This behavior is also confirmed in the literature with other workpiece materials [14].

3.2 Hardness

The micro-hardness profile of the cross-section of the EDM machined tool steel AISI H13 samples is presented in Figs. 4a, b, for silicon and manganese powder, respectively. It can be observed from the graphic that the hardness of the samples immediately below the resolidified layer slightly varied from 210 up to 300 HV. The difference in the hardness can be seen in the resolidified layer. For silicon powder, the micro-hardness was higher for low discharge currents and low powder concentration (672 HV) as well as high current and high powder concentration (718 HV). For a concentration of 5 g/L, increasing the discharge current to 6 A leads to a decrease in the surface hardness (545 HV). On the other hand, at a higher powder concentration, the discharge current of 6 A results in a 40 % harder surface. In Fig. 4, the hardness measurements are the results of a single measurement ($n=1$) done at various positions, starting from surface of the resolidified layer surface in direction to the base material. This result is the hardness profile of the resolidified layer and is considered representative to evaluate the difference between the powders tested during PMEDM.

PMEDM with manganese showed best hardness results for a concentration of 5 g/L and discharge current of 2 A (642 HV) as well as for 10 g/L and 6 A (698 HV). Again, when increasing the discharge current for lower powder concentrations, a 30 % worse surface hardness is found. At a concentration of 10 g/L, increasing the discharge current from 2 to 6 A brings to an improvement of 13 % on the surface hardness.

When comparing the surface hardness of the workpieces machined with PMEDM and conventional machining, the improvement in the hardness of the workpieces machined with suspended powder is clearly noticed. This can be credited to two main factors, the formation of a uniform and free of micro-cracks layer and the formation of phases in the

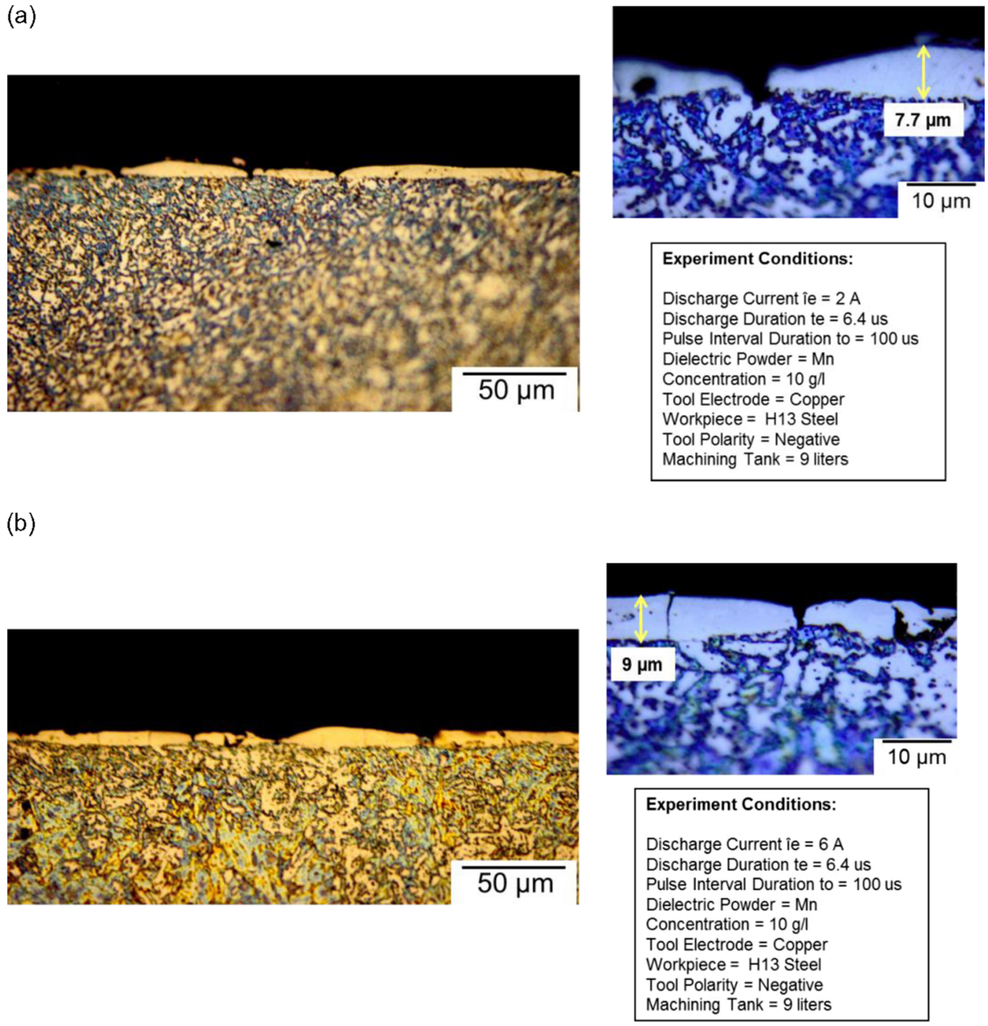


Fig. 9 Cross-section micrographs of the workpiece samples machined with manganese PMEDM with a concentration of 10 g/L: **a** Discharge current 2 A. **b** Discharge current 6 A

resolidified layer which benefit the surface hardness. These aspects can be better investigated by means of a surface characterization, discussed below.

3.3 Micro-structure of the resolidified layer

Figure 5a, b shows the micrograph of the cross-section of the workpiece samples machined without powder suspension. These images are taken as a reference to evaluate the influence of the powder suspension in the dielectric. The resolidified layer is visible in both micrographs and can be characterized by the high concentration of micro-cracks, pores, and irregular formation. The layer achieved a thickness of 5 μm for 2 A and 4 μm for 6 A.

The micro-structure of the samples EDM machined with silicon powder at a concentration of 5 g/L and discharge currents of 2 A and 6 A are depicted in Fig. 6a, b, respectively. The use of 2 A resulted in a smooth and uniform resolidified layer surface, noticeable by the absence of micro-cracks and pores. The layer thickness achieved here is in the order of 7 μm. Increasing the discharge current to 6 A results in a non-uniform layer, and the presence of micro-cracks is visible throughout the micrograph. The resolidified layer reached a thickness of up to 6 μm, less than in the former conditions. The poorer surface quality achieved here can be related to the increased discharge energy delivered to the workpiece, which negatively affecting the resolidification of material on its surface.

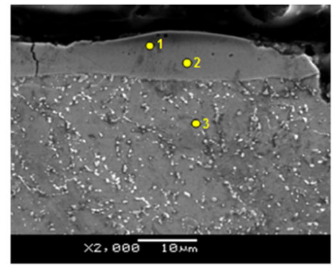
The micrographs from Fig. 7a, b show the cross-section of the workpiece samples machined with 15 g/L silicon powder concentration and 2 A (Fig. 7a) and 6 A (Fig. 7b) of discharge current. For both cases, the resolidified layer presents micro-cracks and is not uniform along the workpiece surface. On the other hand, thicker layers are found for this higher concentration, reaching 8 μm for 2 A and 10 μm for 6 A .

When higher powder concentrations are used in PMEDM, there is a higher chance of contamination of the working gap by powder settling and debris, making the process unstable by the presence of unwanted short circuits.

The microstructures of the workpieces EDM machined with manganese powder in a concentration of 5 g/L are shown

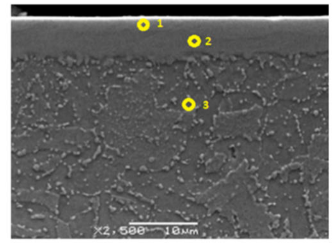
(a)

	Atomic Weight (%)				
	Si-K	*V-K*	*Cr-K*	*Fe-K*	*Mo-L*
Point 1	0.98	0.93	4.97	92.09	1.03
Point 2	1.09	1.19	5.43	92.14	0.15
Point 3	0.87	0.72	4.14	94.09	0.18



(b)

	Atomic Weight (%)				
	Si-K	*V-K*	*Cr-K*	*Fe-K*	*Mo-L*
Point 1	2.43	1.83	6.71	87.90	1.12
Point 2	1.93	0.93	4.79	92.35	
Point 3	0.76	1.27	4.30	93.67	



(c)

	Atomic Weight (%)				
	V-K	*Cr-K*	*Fe-K*	*Cu-K*	*Mo-L*
Point 1	2.10	6.61	91.30		
Point 2	1.86	5.53	88.80	1.80	0.94
Point 3	0.97	6.46	92.57		
Point 4	1.45	8.61	89.94		

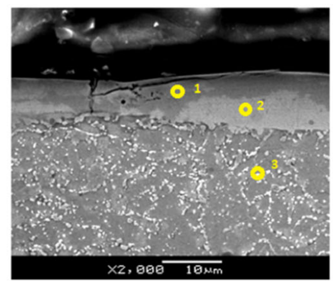


Fig. 10 SEM images and chemical composition analysis of the workpiece samples machined: **a** Without powder. **b** Silicon powder at 5 g/L and i_e=2 A. **c** Manganese powder at 5 g/L and i_e=6 A

in Fig. 8a, b, for discharge current of 2 A (Fig. 8a) and 6 A (Fig. 8b). Two distinct scenarios are seen. For low discharge current, the resolidified is irregular, showing an undulated pattern, but it is free of micro-cracks. Maximum layer thickness found here is 7.4 μm. Using a discharge current of 6 A leads to a more uniform layer, but as a counter back, the density of micro-cracks is also more prominent. The layer thickness achieved here is 6.3 μm.

The cross-section micrographs of the workpiece samples EDM machined with a powder concentration of 10 g/L are presented in Fig. 9a, b. The increase of the powder does not bring any benefit to the machined surface; on the contrary, it resulted in a more irregular resolidified layer with more micro-cracks. The thickness of the layer also increases, reaching a maximum of 7.7 μm for 2 A and 9 μm for 6 A.

The micro-structure shows that better results are found for lower powder concentration, regardless the material powder used. As mentioned before, higher powder concentrations promote the concentration of the working gap with particle settling and debris, generating process instabilities. The best results when using manganese powder in terms of resolidified layer uniformity were achieved for the higher discharge current of 6 A, whereas silicon powder resulted in a better surface quality for lower discharge current of 2 A. The better surface quality of workpieces machined with silicon powder in comparison to manganese powder can be associated to their differences of specific mass. Silicon has a specific mass of 2.33 g/cm^3, whereas manganese has more than three times this value (7.47 g/cm^3). This property has a direct influence on the capacity of the powder to be suspended in the dielectric. Manganese, having a higher specific mass, could not easily be suspended in the dielectric, resulting in a non-uniform concentration of the powder in the working gap and negatively influencing the formation of a uniform and free of cracks resolidified layer.

The best results for recast layer thickness occur at higher discharge current to Mn and at lower discharge current for Si. It is probably related simultaneously to two aspects, one is the specific mass of both powders—where for Si it is 2.33 g/cm^3 and for Manganese three time higher (7.47 g/cm^3)—and the second is the behavior of plasma channel collapse when higher discharge energies are applied. For Mn at increased discharge current values, the higher energy released during the plasma collapse causes a greater turbulence level of the dielectric fluid, improving the capacity of the heavier Mn powder to be suspended in the dielectric and promoting thicker recast layer. For the Si, such high energy expels away the material when the plasma channel collapses, generating a thinner recast layer.

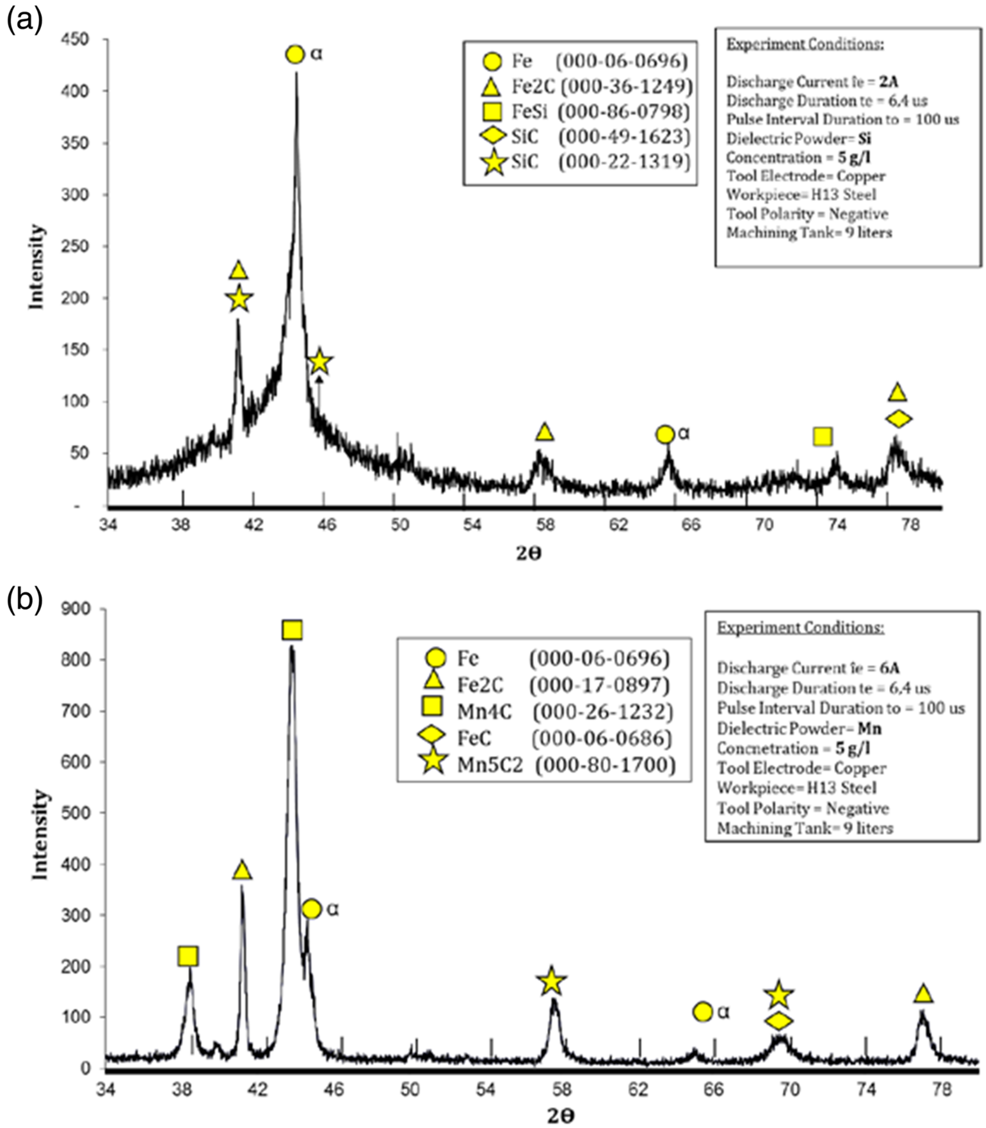


Fig. 11 XRD spectrum analysis of the workpiece samples machined: **a** Silicon powder at 5 g/L and t_e=2 A. **b** Manganese powder at 5 g/L and t_e=6 A

3.4 Chemical composition of the resolidified layer

Figure 10 shows the SEM images and chemical composition of the samples EDM machined without any powder and a discharge current of 2 A (Fig. 10a), with silicon powder at a concentration of 5 g/L and discharge current of 2 A (Fig. 10b) and with manganese powder at a concentration of 5 g/L and discharge current of 6 A (Fig.10c)

The resolidified layer formed during EDM without powder (Fig 10a) shows no significant variation of silicon through the direction into the base material (0.98 % at resolidified layer to 0.87 % at the base material). The other elements presented are related to the standard composition of the H13 tool steel. On the other hand, as shown in Fig 10b, when PMEDM with silicon powder at a concentration of 5 g/L and discharge current of 2 A, the silicon mass percentage at position 1 increased significantly to 2.43 %, showing that silicon was adhered in the resolidified layer during the process.

As presented in Fig.10c, using manganese powder at a concentration of 5 g/L and a discharge current of 6 A also contributed to the formation of a resolidified layer rich in manganese. Even though the table of Fig. 10c shows no presence of manganese, Mn peaks were revealed by the EDS spectrum and also by the XRD analysis.

3.5 Phase composition of the resolidified layer

The X-ray diffraction spectrum of the samples machined with silicon and manganese powder at a concentration of 5 g/L and discharge currents of 2 and 6 A, respectively, is depicted in Fig. 11a and b. It is clearly seen the effect that the powders had in the phase composition of the resolidified layer. The use of silicon powder at 5 g/L resulted in the formation of two distinct phases containing silicon, SiC and FeSi. The formation of SiC can be associated to the chemical interaction between the suspended powder and the carbon dissociated from the dielectric fluid. The formation of manganese carbides (Mn_4C, Mn_4C_2), when PMEDM with manganese, could also be based on this interaction with the dielectric fluid.

Silicon carbide presents a hardness of near 2800 HV, whereas the hardness measured at the resolidified region reached a maximum of 718 HV. This difference is explained by the fact that these carbides are dispersed in the iron matrix of the resolidified layer, acting to improve the surface hardness but not reaching the hardness of the pure silicon carbide. An analogous analogy can be applied to manganese, which reached a hardness of 700 HV.

4 Conclusions

This work aimed to investigate the use of silicon and manganese powders with fine particle sizes suspended in the dielectric fluid during EDM machining of AISI H13 tool steel. The influence of different powder concentrations and discharge currents on the characteristics of the resolidified layer was evaluated. From the results and discussions presented in this work, the following conclusions can be drawn:

1. The addition of Si and Mn to the dielectric fluid promoted a more uniform resolidified layer when compared to EDM process without the use of powder suspended in the dielectric.
2. Surface roughness of the workpieces improved significantly when PMEDM with silicon and manganese powders. Si powder improved the average surface roughness by a factor of five, whereas Mn improved two times the same parameter.
3. The use of PMEDM generated a resolidified layer free of micro-cracks and pores and resulted in a hardness increase of roughly 40 % when compared to a resolidified layer machined without powder addition.
4. EDS analysis of the resolidified layers confirmed the idea that the powder suspended in the dielectric adhered to the workpiece surface, playing a main role in the surface quality improvement.
5. Phase analysis with XRD revealed the presence of silicon and manganese carbides in the resolidified layer, showing that the EDM with powder suspension, negative polarity, and low discharge current can be used to modify the surface properties of workpieces.

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