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Research Paper

Investigation of Parameters Affecting Surface Integrity and Material Removal during Electrical Discharge Machining of HARDOX-400 Steel

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Abstract

Hardox-400 with an extra-high yield strength of ~1000 MPa and excellent abrasion resistance is a good candidate for several industrial applications including automotive parts, working tools, barges, loaders, etc. Due to high dimensional precision and to avoid mechanical abrasion of the work-piece, electrical discharge machining (EDM) is a proper machining technique for such steel. The influences of important process parameters, i.e. discharge current and spark pulse cycle on the electrode wear, material removal, surface roughness, and integrity of the machined material is investigated. It was observed in this work that as the discharge current increased, the electrode wear also increased but this occurred with a gradually decreasing rate. On the other hand, increasing the ratio of pulse-on to pulse-off time decreased material removal. Furthermore, it was observed that increasing both the discharge current and the pulse-on time led to a thicker solidified so-called white layer which is more susceptible to cracking and thus is detrimental to the material integrity.

Keywords

Hardox, Discharge Machining, Roughness, Surface Integrity, Pulse Time

1. Introduction

Due to their superior strength and hardness, various categories of high strength steels (HSS) are nowadays used in different industries. As ultra-high-strength steel, Hardox-400 (manufactured by SSAB) shows a yield strength as high as ~1000 MPa and ultimate tensile strength of ~1200 MPa[1]. The extremely high strength and abrasion resistance of this steel are due to its very high hardenability and thus its high martensite content[2]. The steel has wide industrial applications, including dump trucks, front loaders, barges, and buckets[3].

Conventional machining/cutting of such high strength martensitic steel is very difficult. Instead, modern machining techniques avoiding mechanical abrasion of the work-piece can be potentially good alternatives. It has been shown that very good mechanical properties (particularly fatigue behavior) can be obtained in Hardox-400 when it is machined by techniques like water jet and laser cutting[4]. From a metallurgical point of view, the influence of different advanced cutting techniques including plasma, laser, wire erosion, and abrasive water jet was studied by Dahil et al.[5]. It was concluded that the water jet technique introduces the least change in the microstructure of Hardox-500 steel.

Chamarthi et al. [6]studied the plasma arc cutting (PAC) of Hardox-400 and investigated the effects of arc voltage, cutting speed, and plasma flow rate on the cut surface quality. Prajapati et al. [7]studied the effective parameters of Co2 laser cutting on Hardox-400. It was found that the surface roughness was much influenced by cutting speed and plate thickness than other parameters such as laser power and gas pressure. The same method has been widely used for cutting soft materials as well. For instance, Hashemzadeh and Mohammadi have recently studied the effect of laser power and cutting speed on the material removal rate of polycarbonate sheets[8].

Among the modern machining techniques, electrical discharge machining (EDM) and its subcategory, i.e. wire electrical discharge machining (WEDM) are well known for dimensional accuracy of the work-piece and fine surface finish[9, 10]. In the EDM technique, the electrically conductive material is removed using repetitive spark discharges usually occurring in a dielectric liquid, although variations such as the dry version[11], the ultrasonic-assisted [12] and magnetic field-assisted methods [13] have also been proposed and used. Furthermore, researches have been conducted on the influence of adding surfactants to the dielectric liquid[14]. Che Haron et al. [15] compared to copper and graphite electrodes performance for EDM of XW42 tool steel. It was found that in the case of the copper electrode, a relatively higher MRR and lower electrode wear rate are encountered. In a similar work, Younis et al. [16]studied the effect of electrode material on the induced residual stresses and surface roughness in EDM of two plates of steel. It was seen that the Dura graphite electrode resulted in a higher surface roughness compared to DIN 1.2080 steel electrode. Ghrib et al. [17]investigated the evolution of the thermal properties of a 36NiCrMo16 steel during EDM. Cao et al. [18]studied the surface integrity of two plates of steel (S390 and SKD11) multi-cut by WEDM. They showed that as the cutting pass increased, the surface roughness, white layer thickness, and surface residual stress decreased.

Several studies have been also focused on the optimization of EDM for different materials. Chamarthi et al. [19]optimized the parameters cutting speed, plasma gas, and arc voltage using the ANOVA technique to improve the evenness of Hardox-400 processed by plasma arc cutting (PAC). Bobbili et al. [20] utilized the Buckingham pi theorem to model the influences of process and material properties on material removal rate (MRR) and surface roughness (SR) of aluminum alloy 7017 and rolled homogeneous armour steel. Similarly, Guu et al. [21]proposed empirical formulae for surface roughness, the thickness of the recast layer, residual stress, and EDM damage at various machining conditions in case of the AISI D2 tool steel. It was shown that the increase of pulse-on time could improve the MRR and surface finish in the case of both materials. Also, the optimal process parameters for EDM of AISI 202 stainless steel were determined through a grey relational analysis with the Taguchi method[22]. The well-known Neural network and genetic algorithms have been also utilized to optimize the EDM on DIN1.2080 alloy[23]. Furthermore, optimization techniques have been also applied on powder metallurgy electrodes to achieve maximal material removal rates with minimal tool wear[24].

The EDM of different tool steels has been extensively studied by many researchers, some of which were mentioned above. However, a review of the available literature on EDM of steels shows that very little research work is done on Hardox steels. Regarding the attractive mechanical properties of these steels and thus their potential for various industrial applications, the effects of different process parameters on EDM of these alloys still needs further investigation. In the present work, the influences of two important process parameters, i.e. current density and pulse-on time on the electrode wear, material removal rate and surface roughness were studied in EDM of Hardox-400 steel. Furthermore, the evolutions of surface and sub-surface layers of the material at various process parameters were investigated by light optical and scanning electron microscopy (LOM and SEM).

2. Materials and Methods

A Pishraneh-511-63 spark machine was used for EDM processes. Considering the results obtained by Che Haron et al.[15], cylindrical electrodes of 20 mm diameter and 30-50 mm length were fabricated from pure copper. Work-pieces with dimensions of ~50×50×10 mm were machined out of a Hardox-400 steel plate. The chemical composition of the experimental steel is mentioned in Table 1.

Table 1. Chemical composition of the experimental Hardox-400 steel (wt%)

C	Mn	Ni	Cr	Si
0.19	1.71	0.30	0.55	0.68
Mo	P	S	B	Fe
0.25	0.025	0.018	0.003	Bal.

All of the EDM experiments were conducted at the condition of positive electrode polarity. Three different currents of 5, 10, and 15 A were tested in the experiments. Two groups of pulse-on and off times were chosen. The first group consisted of 50-12, 100-25, and 200-50 μs as on-off times in which the pulse-on time was 80% of the whole cycle. In the second group, the pulse-on time was 67% of the cycle which comprised 50-25, 100-50, and 200-100 μs as on-off times, respectively. Thus, 18 different sets of process parameters were chosen, each of which was tested at least twice. The total EDM time for each test was 20 min. The surface roughness of the samples after EDM was determined by a Time TR100 surface roughness tester.

The EDM specimens (specimens machined by the electrical discharge machining) were also studied by LOM and SEM. In order to survey the cross-section of the samples, they were wire-cut and consequently ground and polished as shown in Figure 1. Nital 2% agent was used as the etchant.

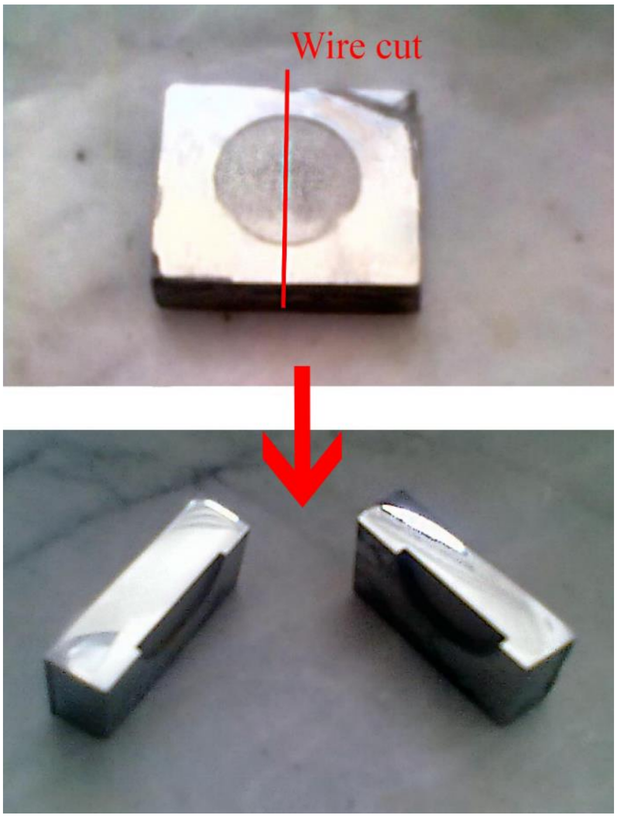


Figure 1. Cutting and preparation of the samples for microscopy

Finally, micro-hardness tests were carried out at different points in the white layer, heat affected (HA) layer, and base metal zone. In each zone, at least three readings were done, the average of which is reported.

3. Results and Discussion

3.1 Wear of Electrodes and Material Removal

The weight of the electrodes and specimens were measured before and after EDM. Thus, the wear of the electrodes and the removal of specimens were determined for each set of process parameters. The averaged values for different discharge currents and pulse times are shown in Figure 2.

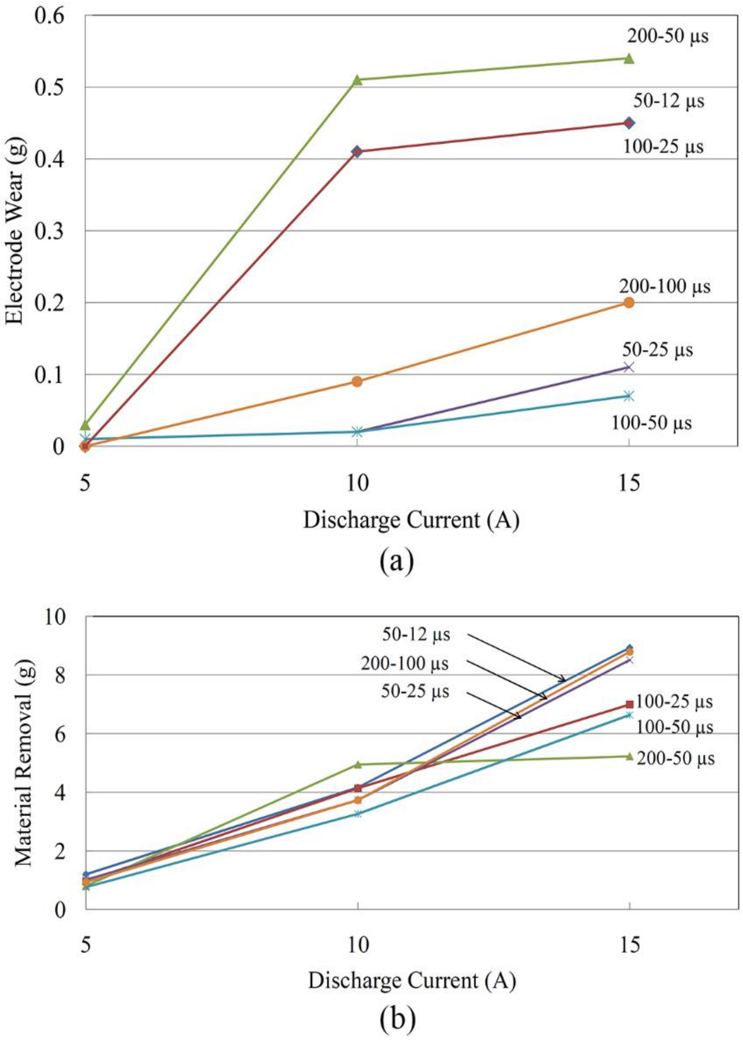
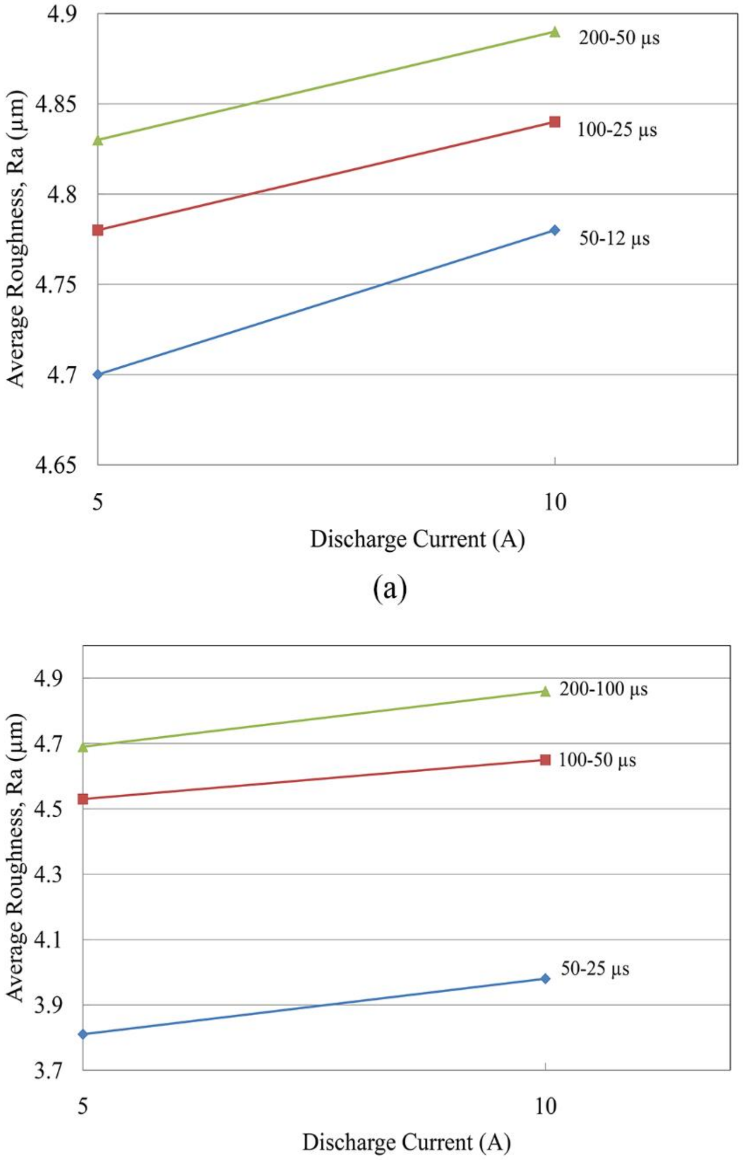


Figure 2. Average values of (a) electrode wear and (b) material removal during 20 min of EDM at different currents and pulse times

Firstly, it should be noted that the amounts of material removal are much more than the electrode wear and this indicates that the correct polarity has been chosen for the electrode and the material. The electrodes wear was higher in the tests with higher pulse-on time and/or higher discharge current. But, increasing the discharge current from 10 to 15 A, did not much affect the electrode wear. On the other hand, material removal was increased as the current increased. However, material removal also depends on both the on-time and off-time. In other words, the material which is melted in the on-time must be flushed by the dielectric during the off-time. Consistently, in the test with 200-50 µs on-off time, the relatively high amount of material which melted during 200 µs on-time, had a relatively shorter time (50 µs) to flush away from the surface leading to relatively low material removal. But, although there was an equal duty factor in the test with 50-12 µs on-off time, a much higher removal occurred in this test. Thus, it can be concluded that at a constant on/off time ratio, higher material removal occurs in the process with shorter on-time. This may be ascribed to the existence of incubation time for the initiation of the melting of the material. In other words, as the on-time decreases, the amount of molten material decreases more, and consequently, a shorter off-time will be sufficient for the removal of the molten material.

3.2. Surface Roughness

The average roughness (Ra) of the EDM specimens was determined by a Time TR100 roughness tester. The results are depicted in Figure 3. The roughness test results were also verified by loupe images (Figure 4).



(a)

(b)

Figure 3. Average roughness of the samples EDMed with different discharge currents and (a) 80% pulse-on time, (b) 67% pulse-on time

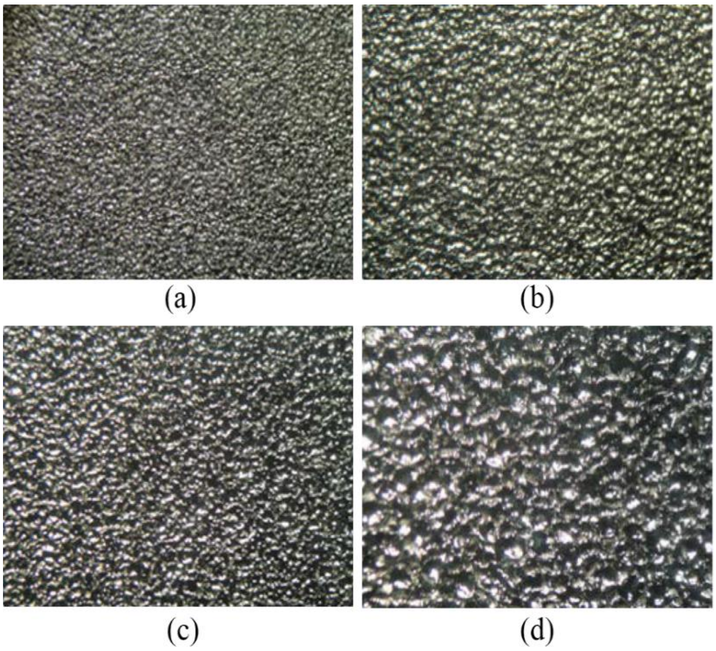


Figure 4. Loupe images of EDMed specimens, (a) 50-12 μs and 5A, (b) 50-12 μs and 10A, (c) 200-50 μs and 5A, (d) 200-50 μs and 10A

In all cases, increasing the discharge current led to increased surface roughness. Furthermore, both in tests with 67% and 80% pulse-on times, as the pulse-on time increased, the average roughness of the specimens increased as well. This can be related to the influence of pulse-on time on the width of the discharge area. Increasing the pulse-on time leads to an expanded plasma channel between the electrode and the material's surface. Thus, with each spark, a wider discharge area forms on the surface and this decreases the impact of the spark for material removal. As a result, a smaller fraction of each molten particle of the material is flushed away to the dielectric. Instead, most of the molten material sticks to the surface in the form of small drops which solidify on the surface and increase its roughness.

3.3. Microstructural Investigations

Frequent melting and solidification of the surface material occur during the EDM process. In each spark pulse, once the pulse-off time is initiated, a major fraction of the molten material solidifies on the surface. The surface micrographs of specimens EDMed with different discharge currents and pulse-on/off times are shown in Figure 5. Both the discharge current and the pulse-on time have an increasing effect on the size of the molten resolidified areas.

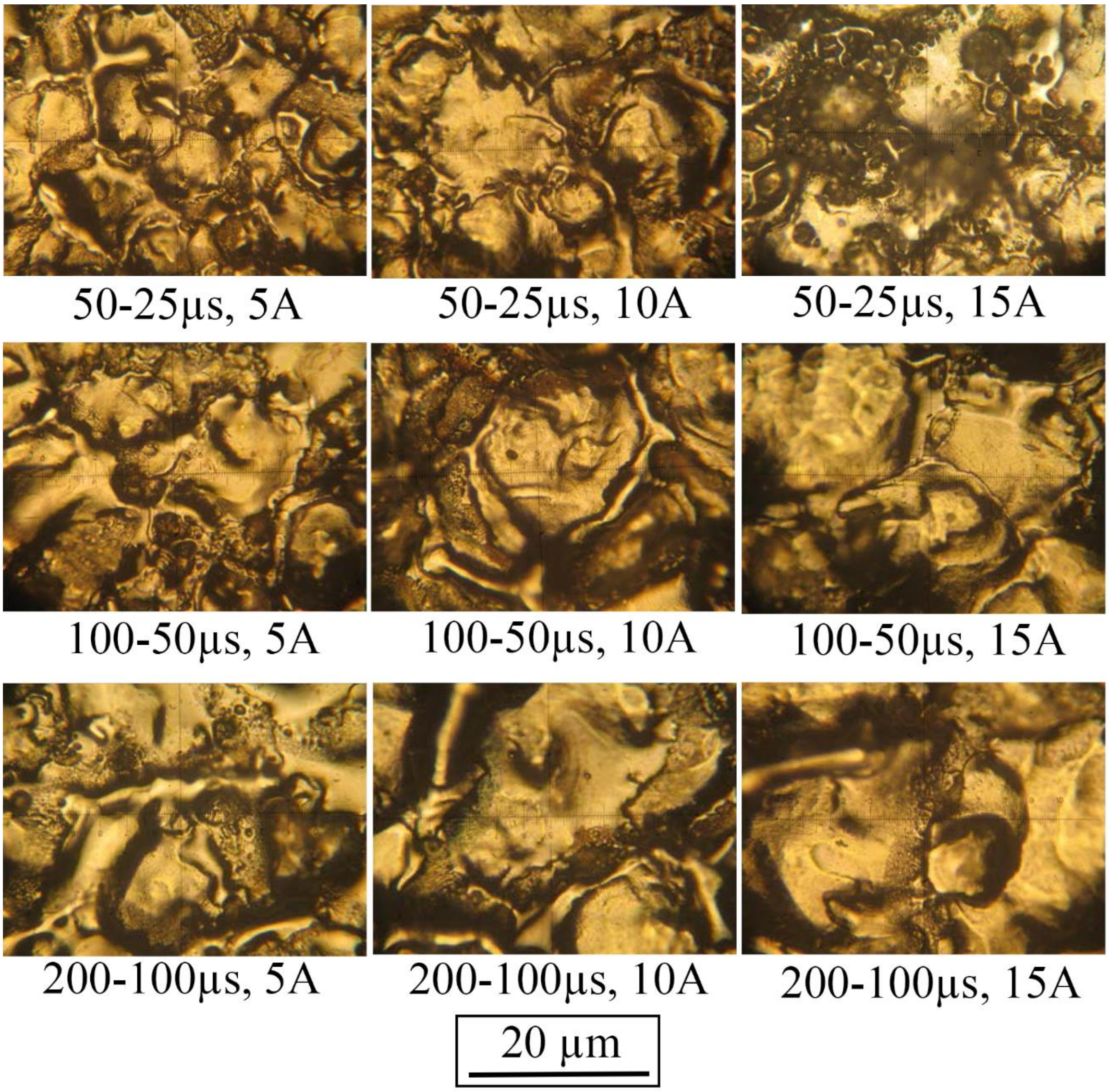


Figure 5. Optical micrographs from the surfaces of specimens EDMed at different discharge currents and pulse-on and off times

Due to the contact between the molten material and the dielectric medium, usually, a rapid non-equilibrium solidification occurs in the surface layer (called white layer). Also, the sub-surface layer of the work-piece (heat affected zone, HAZ) cools down in a non-equilibrium condition. This leads to the formation of more martensite laths in surface and sub-surface layers. As a result, these layers of the EDMed work-piece acquire quite higher hardness compared to the base metal. Furthermore, non-equilibrium cooling of the material also induces stresses in the microstructure which contributes to increased hardness of the white and HAZ layers. On the other hand, Muthuramalingam et al. [25]showed that the polarity of the electrode highly affects the amount of electrode material that melts and solidifies on the EDM surface. Thus, the surface hardness of the EDMed work-piece may also depend on the electrode material. In the present work, it was shown that proper selection of the polarity led to considerably small erosion of the electrode (Figure 2). Thus, the contribution of the electrode material in the surface hardness is negligible. Micro-hardness examinations on the specimen which was EDMed with a discharge current of 10 A and pulse on-off times of 200-100 µs, showed average hardness numbers of 664, 493, and 396 HV for white layer, HAZ and base metal, respectively.

The optical micrographs of the sectioned surfaces of EDMed specimens and the corresponding SEM images of the EDM surfaces for two discharge currents of 5 and 10 A and constant pulse time of 200-100 µs are shown in Figure 6.

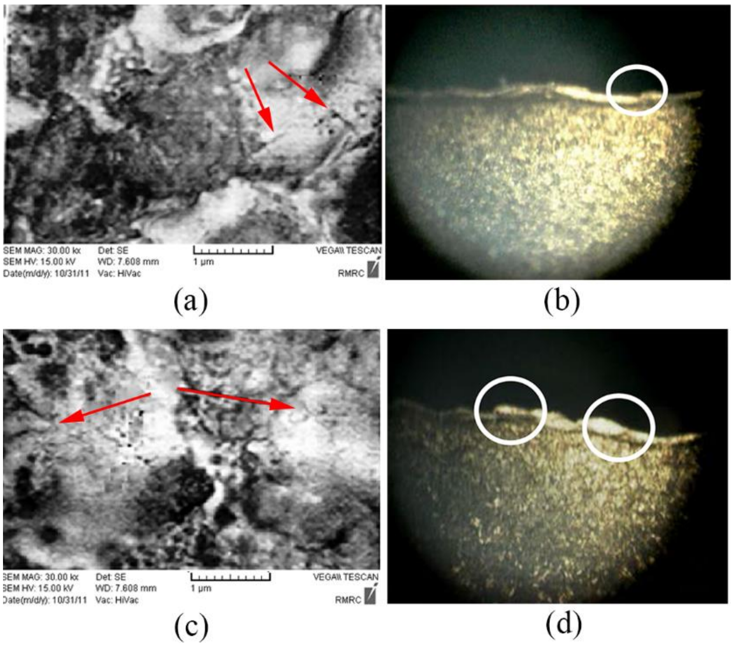
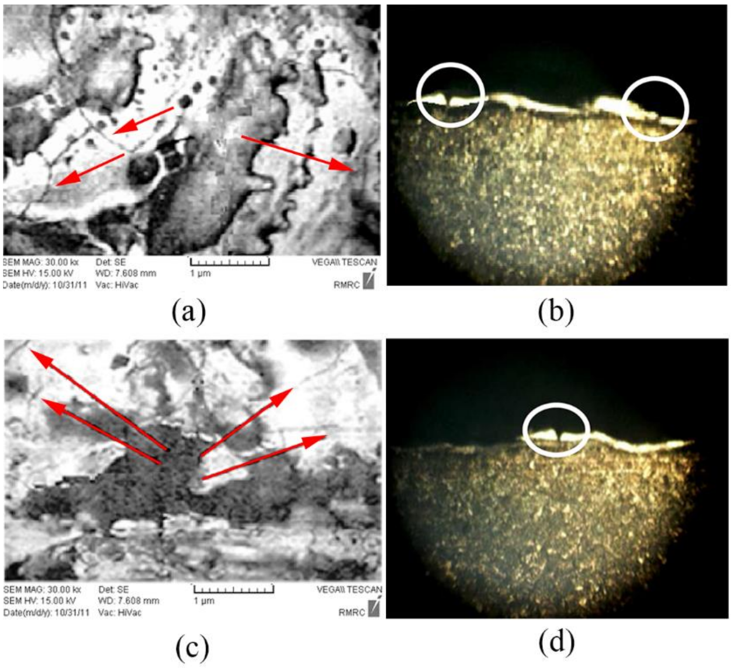


Figure 6. EDM surface and section micrographs of specimens machined with a discharge current of 5A (a,b) and 10A (c,d) and a constant pulse time of 200-100 µs

Also, the optical and corresponding SEM images for specimens which are EDMed with different pulse on-off times of 200-100 and 100-50 µs at a constant discharge current of 15 A are shown in Figure 7. Due to the high hardness and brittleness of the surface layer, the stresses which are induced at the surface layer of the EDMed specimen led to the formation of cracks in the white layer (marked on the figures). The cracks did not propagate into the sub-layers which are relatively softer. But, as the thickness of the white layer increased, it was more susceptible for the cracking. The influencing process parameters being discharge current and pulse-on time increased the thickness of the white layer. Comparison of Figures 6 and 7 shows that the pulse-on time is more effective than the discharge current. It was previously stated that increasing the pulse-on time, widens the plasma channel, and reduces the amount of molten material that is flushed to the dielectric. Thus, the amount of heat that remains in the work-piece increases and this leads to the increased thickness of the white layer.



(a) (b)

(c) (d)

Figure 7. EDM surface and section micrographs of specimens machined with pulse on-off times of 200-100µs (a,b) and 100-50µs (c,d) and constant discharge current of 15A

4. Conclusions

The influence of important EDM process parameters, i.e. discharge current and pulse-on/off time on the electrode wear and the quality of the machined surface was investigated. The following main conclusion could be drawn:

- As the discharge current increased, the electrode wears increased but this occurred with a decreasing rate. Only slight changes were observed with increasing the current from 10 to 15A.
- Increasing the ratio of pulse-on to pulse-off time decreased the material removal rate. At a constant on/off ratio, a higher removal rate occurred when the shorter pulse-on time was used.
- Increasing the discharge current and/or the pulse-on time led to an increased surface roughness of the EDMed work-piece.
- Increasing the discharge current and/or pulse-on time increased the thickness of the resolidified surface layer and its susceptibility for the formation of cracks. In this case, the pulse-on time was more effective than the discharge current.

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