Wear Resistance of Electrical Discharge Machined Surfaces

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Abstract

The properties of surfaces can be affected by many factors in Electrical Discharge Machining (EDM). The most efficient working parameters are pulse duration and type of tool electrode and have a tremendous impact on the resultant surface quality. We examined the wear characteristics of EDM'ed austenitic stainless steel, dual phase steel, and plastic mold steel surfaces for two different pulse durations and electrode materials. Wear volumes, rates, and sliding frictions are measured using a reciprocating mode tribometer. Worn surfaces were analyzed by means of Scanning Electron Microscopy (SEM) equipped with an Energy Dispersive Spectrometry (EDS). Finally, samples cut for sectional analysis and etched to reveal the heat affected layers. The results indicated a dependence of surface wear properties regarding the working parameters in EDM, which implies the possibility of producing wear resistant surfaces quickly and efficiently.

Keywords: Electrical Discharge Machining, EDM, Wear, Sliding Friction

Introduction

Electric Discharge Machining (EDM) removes materials due to sequentially applied discharges. Electrical Discharges takes place between electrodes separated by a narrow space occupied by a dielectric fluid. Each of the sequentially used discharges locally melts and evaporates a small fraction of material from both electrode surfaces. All the evaporated and a fraction of melted material removed from the machining region due to the action of circulating dielectric fluid. The remained portion of the melted cavity cooled at an extreme rate and left a small cavity and a re-solidified structure beneath it. The re-solidified structure also mentioned as the recast structure or white layer due to the difficulties confronted during etching. A heat affected zone is lay beneath the re-solidified layer affected by phase transformations in the solid state for allotropic materials.

The aggressive nature of heating and cooling cycles together with the high temperatures attained during the process yields a unique structure and properties of the surface which specific to the used operational conditions. The wide varieties of the process parameters and applications have enormous influences on the properties of the work material such as surface topography,

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subsurface microstructure, hardness and micro cracks. Therefore affects the resultant performance by means of fatigue strength, corrosion and wear resistance.

Not only the thermal energy released but also the dielectric liquid and tool electrode material type dominated the resultant re-solidified microstructure. Examinations of the re-solidified layers indicated interactions with the pyrolysis products from the broken dielectric liquid and migration of materials from the tool electrode [1]. These interactions results in the formation of complex carbides, martensite and retained austenite in the re-solidified structure [2], and their composition vary with respect to the type of the steel machined [3]. Therefore, the resultant re-solidified structure and affected layer represent an overall alteration of the component, mechanical properties, and microstructure. It is much harder than the substrate, under the action of residual stress [4] and may contain surface defects such as cracks and voids [5]. Such large variations in surface properties may result in detraction in service life [6] of a machined component. Studies to understand the defects exposed the complicated nature of the process, and the relevance of the dielectric liquid, tool electrode and the work material [7]. Besides the studies related to the EDM surface integrity, the wear response is not well comprehended in the literature. There a number of studies on the wire EDM of cemented carbides [8] such as WC-Co [9, 10], WC–Ni [11] and a comparison with zirconia-based materials [12].

Although the known variety of operational conditions in EDM and the possible impact on the surface integrity, the information is absent about EDM surface wear responses even for different steel grades in the literature. Therefore, three different steel grades is examined with an experimental set to elaborate the impact of tool electrode on the reciprocating sliding friction wear responses.

1. Materials and Devices

1.1. Samples and tool electrodes

At the beginning of this work, we chose three kind of materials (Table 1) with the different chemical composition, phases and mechanical strengths (Table 2).

Table 1: Chemical composition of the samples

	C	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**
316L	0.03	2.0	0.045	0.030	1.0	16.0-18.0	10.0-14.0	2.0-3.0
1.4442	0.03	2.0	0.035	0.015	1.0	21.0-23.0	4.5-6.5	2.5-3.5
1.2738	0,38	1,50	-	-	0,30	2,00	1.10	0,20

Table 2: Mechanical properties of the samples

	316L	**1.4442**	**1.2738**
Tensile strength (MPa)	515	650	1020
Yield strength, (%0.2) (MPa)	205	450	900

Type 316 is austenitic chromium-nickel corrosion resistance stainless steel with improved strength at elevated temperatures and pitting resistance due to the addition of molybdenum. Type 316L is a modified version of Type 316 with decreased carbon content that minimizes harmful carbide precipitation due to welding. Duplex stainless steel 1.4442 is extremely resistant to corrosion. Chemically, it carries both austenitic and ferritic steels features. 1.4442 is tougher than ferritic stainless steels and two times more resistant to breakage compared to austenitic materials. 1.2738 is pre-hardened plastic mold steel. The hardness value varies between 31 - 35 HRC. It has excellent properties of machining. Because of containing 1% of Ni its hardness change from the surface to the core (especially the blocks of material) arises at a minimum rate and improves polishability. Also, the inclusion of a small amount of sulfur in the structure (S <0.002%) advances the abrasion resistance. Electrolytic copper and graphite are the two different tool electrodes used during EDM.

1.2. Devices

Samples are machined on AJAN EDM CNC 983 brand 4-axis die sinking type electrical discharge machine. The dielectric liquid circulation is disconnected from the machine, and a newly designed one is mounted on the work table. This way, different combinations of dielectric liquid could be used without harming the machine.

Reciprocating wear responses of the EDM surfaces are measured using a TRIBOTECHNIC brand pin-on-disk and oscillating tribometer in oscillating mode. All the functionality and calculations performed via the software supplied by the manufacturer.

The area of the abraded valley and surface roughness of EDM surfaces are measured by TAYLOR HOBSON brand Profilometer. The measured profiles analyzed via the software provided by the manufacturer. The abraded surface diameter of spherical friction partner was measured using STARTLINE STL03200X brand digital microscope.

Machined and abraded surfaces are analyzed using FEI QUANTA 450 brand SEM equipped with an EDS. Samples cut by using METKON MICRACUT 201 brand high-speed precision cutter. Samples molded using METKON METAPREEA 1A brand machine and polished through standard metallographic preparation steps using METKON GRIPO 2V brand polisher equipped with FORCIMAT brand sample holder. Finally, sections are analyzed using METKON 901 brand inverted type metallographic microscope.

2. Method of Experiments

All samples exposed to the same procedure excluding the EDM conditions. Rods of sample material reduced to 10 mm in diameter then cut in 8 mm length intervals. Then, samples are stressed relieved at 600 ºC for 1 hour and slowly cooled for 8 hour in a furnace. Finally, the surfaces are polished to ground prior to EDM.

Total of 12 samples EDM’ed in a parametrical order (Table 3) using two different tool electrodes and pulse-on durations. Moreover, three polished ground samples without EDM are also tested for the purpose of comparison. Then, reciprocating wear responses of all 15 surfaces are measured by the tribometer. The standard load for friction tests is 10 N using 25 mm/s test speed for 1km sliding distance. The stroke length of the oscillating motion was 5 mm. Humidity and temperatures measured before and after the tests by the sensors equipped to the tribometer. All tests conducted at room temperatures 23±2 ºC and a relative humidity of 60±2%. The mating friction partner is an Al_2O_3 ball with 6mm diameter having the young modulus of 380 GPa and Poisson's ratio of 0.28.

Table 3: EDM parameters of the samples

Label	Pulse-on duration (μs)	Pause duration (μs)	Dielectric	Tool Electrode
A*	N.A	N.A	N.A	N.A
B	12	6	Oil	Copper
C	12	6	Oil	Graphite
D	100	50	Oil	Copper
E	100	50	Oil	Graphite

*Polished sample

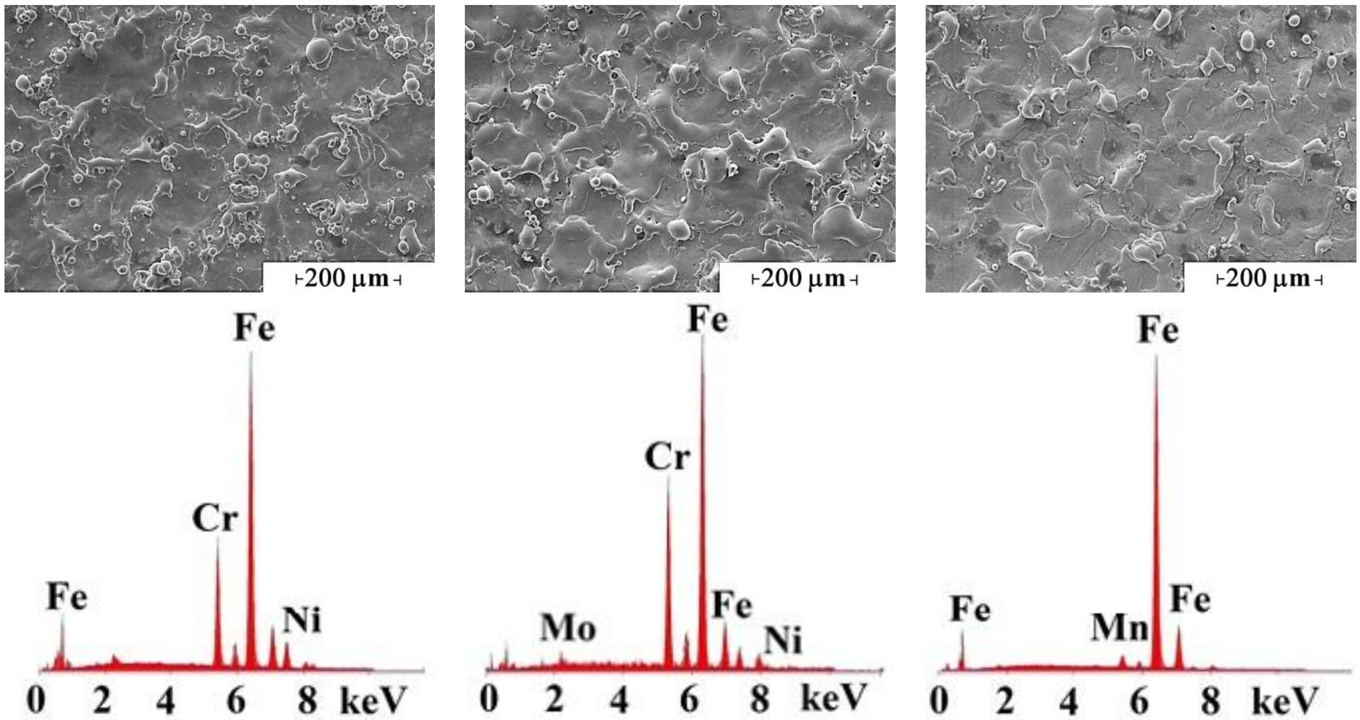
The abraded valley that is formed by tribometer is measured by the profilometer for each sample. The measurement length is 4 mm, and the range is 300 μm for all experiments. Further, the surface roughness of non-abraded region also measured to compromise the results. Then, the diameter of the worn area of the Al_2O_3 ball is measured under the digital microscope. Finally, the wear rates of both the sample and friction partner are calculated via the software based on the Archard model.

The worn valleys and EDM surfaces are analyzed using the Scanning Electron Microscope (SEM). EDS spectrums are taken both from the surface and from several points of the abraded region. Then, the samples are cut precisely from the valleys middle section and molded. Cut samples are polished and etched using the nital for ferrite steel and Carpenters agent for duplex and austenitic steels. Finally, the microstructure of the machined surface, abraded valley and transition regions analyzed under the optical microscope.

3. Results

3.1. Surfaces

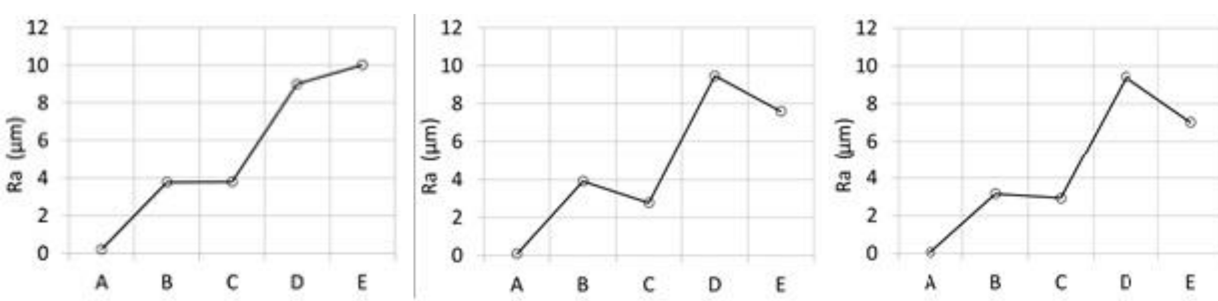
Analyzed EDM'ed surfaces indicated similar characteristic surface topography for three different types of materials. The main difference could be observed around the crater edges which reflect the sudden freezing of the melted cavities process after discharging (Figure 1). Globular type attachments frequently appear over the austenitic steel surface. Such attachments decrease slightly for duplex steel, and a few numbers of randomly micro cracks are developed on the surface. The crater edges are thicker, and small chimney like features occasionally form on the surface when compared to the EDM'ed austenitic steel surfaces. EDM'ed surface of plastic mold steel exhibit similar topographical features, when compared to the duplex steel. Corresponding EDS analysis of the surfaces indicates their characteristic compositions with low-intensity copper peaks from the tool electrodes. Similarly, carbon peak intensity considerably increases when using the graphite tool electrode.



a) b) c)

Figure 1. EDM'ed surfaces. Pulse-on time=12μs, Tool electrode: Copper.
a) 316L b) 1.4442 c) 1.2738

Surface roughnesses are measured at ten different locations, and the average is taken for all analyzed surfaces (Figure 2). Surface roughnesses are around 4 μm irrespective of the type of the used tool electrode when the pulse-on duration is 12 μs during EDM. Increasing the pulse-on duration to 100 μs revealed the effect of the tool electrode. The surface roughness slightly increases for austenitic steel when graphite is used as the tool electrode, however, decrease for duplex and ferritic steel samples.

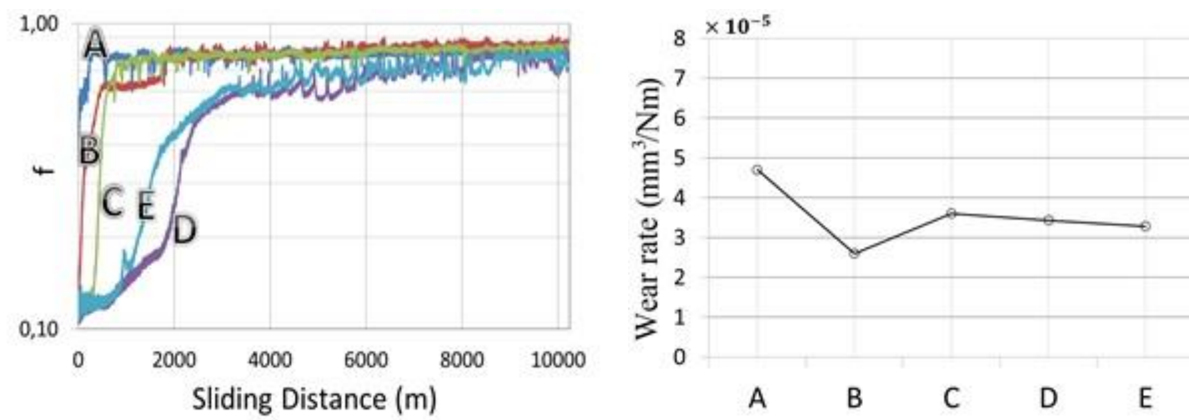


a) b) c)

Figure 2. Surface roughnesses of analyzed samples.
a) 316L b) 1.4442 c) 1.2738

3.2. Friction and wear

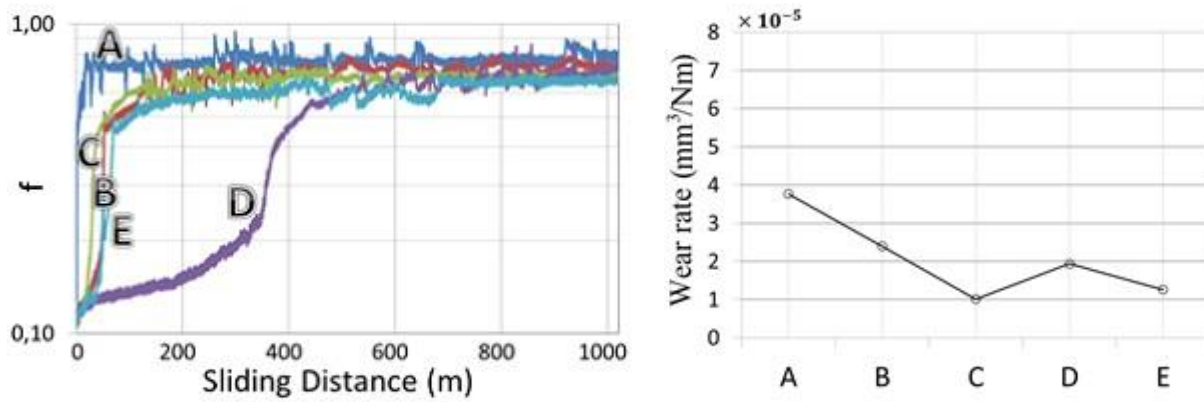
Friction coefficient curves for austenitic stainless steel samples regarding the oscillating sliding distance including the non-machined and polished surface condition are summarized (Figure 3a). The friction coefficient of the material was changing in the range of 0.4–0.8 for the static component depending on the machining conditions. Friction coefficient amplified quickly through the first meters of sliding for the polished sample. After a sliding distance of 500 m, the change in the friction force curve become negligible and stabilized around 0.8. The sliding distance between 400 and 1000 m indicates a steady-state coefficient of friction. However, EDM results in a considerable difference in static friction coefficient. The steady-state sliding distance to reach the steady conditions increased with respect to pulse-on duration and the tool electrode material. Wear rates also designated a gradual decrease indicating a countable contribution to the wear resistance (Figure 3b). The best response is the case when using the copper tool electro under 12μs pulse-on time. However, changing the tool electrode with graphite result in a gradual decrease in wear rate. The main impact of increasing the pulse-on duration is the increase in surface roughness. Therefore, the decrease for high pulse-on durations could be attributed to the increase in surface roughness.



a) b)

Figure 3. Wear rates and friction coefficients for polished and EDM'ed 316L samples.
a) Friction coefficients
b) Wear rates

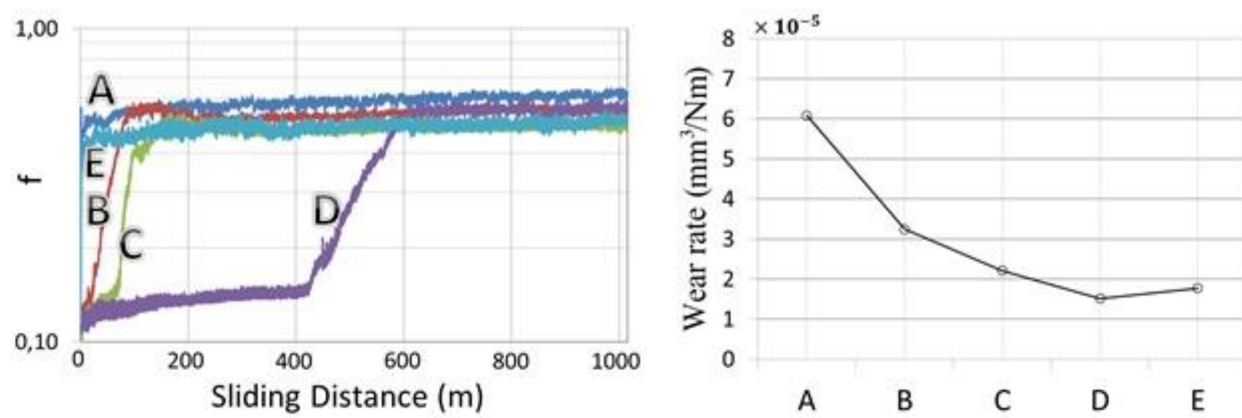
The friction coefficients for duplex steel have approximately indicated similar variations when compared to the austenitic one. Additionally, the effect of the graphite tool electrode on friction response could now more clearly visualized at 100 μs pulse-on time (Figure 4a). Duplex stainless steel has relatively low wear rate if compared to the austenitic steel for the tested tribo-pair. Wear resistance apparently improved with EDM (Figure 4b). The wear resistance gradually increased for the samples using 12 μs pulse-on duration. Changing the tool electrode with graphite further decreased the wear rate. However, increased pulse-on duration do not further the wear response of the surface due to increase in surface roughness.



a) b)

Figure 4. Wear rates and friction coefficients for polished and EDM'ed 1.4442 samples
a) Friction coefficients
b) Wear rates

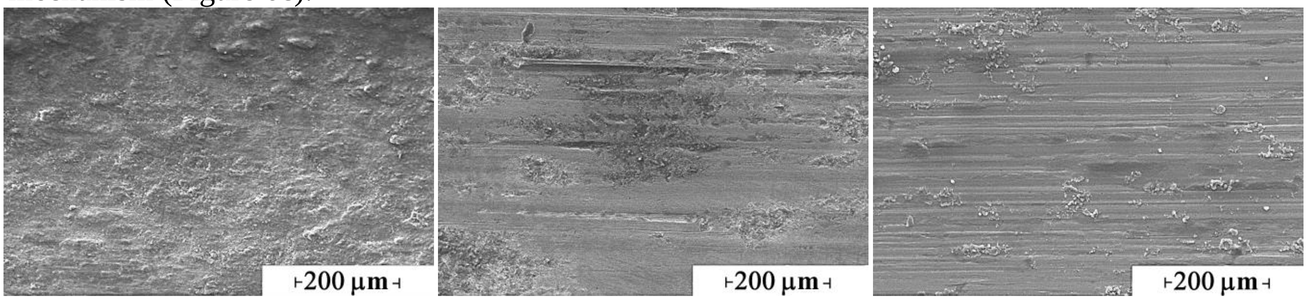
Plastic mold steel samples have ferritic structure and exhibit a well-defined relation with respect to the EDM conditions and the wear response. The friction coefficient of the material was changing in the range of 0.4–0.6 for the static component. Friction coefficient amplified quickly through the first meters of sliding for all the samples excluding D (Figure 5a). After a sliding distance of 100 m, the change in the friction force curve become negligible and stabilized between 0.4 and 0.6. The wear rates continually decreased for both types dielectric liquids used in EDM (Figure 5b). Finally, the results represent saturation of the responses with the increased pulse-on duration of 100 μs.



a) b)

Figure 5. Wear rates and friction coefficients for polished and EDM'ed 1.2738 samples
a) Friction coefficients
b) Wear rates

The worn track SEM images designated the adhesive wear characteristic for the austenitic steel (Figure 6a). A combination of adhesive and abrasive wear is the main response to the duplex steel (Figure 6b).Finally, plastic mold steel surfaces exhibit primarily abrasive nature of the wear mechanism (Figure 6c).

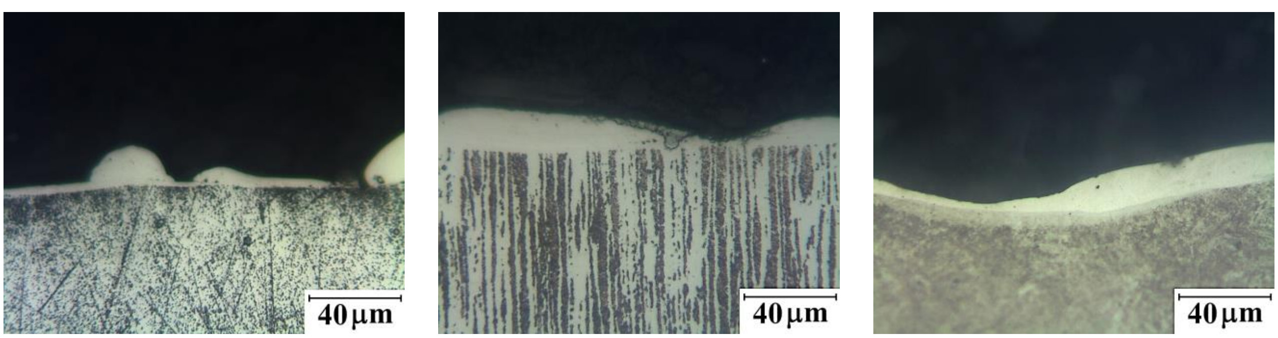


a) b) c)

Figure 6. Weared surfaces.
a) 316L b) 1.4442 c) 1.2738

4. Discussion

The analyzed surfaces indicated different wear responses when using different tool electrodes during EDM. Such a result also reveal the variation in morphological structures beneath the surface. It is well known that EDM'ed surfaces result in a re-solidified layer that is heavily influenced due to the dielectric liquid and the tool electrode. The composition usually defined as retained austenite, martensite, and dissolved carbides where the fractions vary with respect to used materials. Sectional analysis revealed the thicknesses of the re-solidified layer. The layer usually exhibit piled regions when machining austenitic steel (Figure 7a). Hover the structure is more uniformly distributed over the surfaces of duplex (Figure 7b) and plastic mold steel. The chimney-like structures observed on surfaces presumably generated due to trapped gas during the rapid solidification process. The trapped gas suddenly cooled after bubble initiation that is followed by expansion.



a) b) c)

Figure 7. Optical section views of analyzed samples. Pulse-on time=100µs, Tool electrode: Copper .
a) 316L b) 1.4442 c) 1.2738

The main reason for martensite formation is the interstitial atoms that have not enough time duration to diffuse out. Moreover, retained austenite formation can be attributed to the carbon atoms diffused during solidification. The wear responses of the surfaces are become attractive for the austenitic steel. Since, the friction coefficient curves followed the order of experimentations. If the graphite is the tool electrode, the distance between initial and steady-state conditions shifted to a higher range. Increasing the pulse-on duration during EDM, increased the surface roughness, and it expected to get increased wear rates. However, the wear rates continued to decrease. This result is attributed to complex carbide formation in the re-solidified layer. Increasing carbon sources during machining increased dissolved amount of carbides in austenite matrix.

The responses for duplex steel is more resembles the EDM'ed plastic mold steel surfaces. The friction coefficient curves do not follow the order of experimentation. The apparent difference could observed on the samples EDM'ed using a graphite tool electrode and 100 μs pulse-on duration. The static friction coefficient curve quickly reached the steady-state conditions for the both of the work material. On the other hand, using the copper tool electrode change the friction coefficient curve to an elevated distance to steady state conditions. A high fraction of martensite appears in the re-solidified structure and further increase in carbon sources by replacing the tool electrode during machining with graphite result in carbon saturation of the surfaces.

Conclusions

The re-solidified layer of EDM'ed parts reveals a diversity of compositions depends on the operational conditions used during machining. Formation of martensite, austenite and carbides and their fractions significantly contribute to the resultant surface wear response for ferrous alloys. Although, the pronounced surface deficiencies in the literature due to EDM, current results pointed out the possible enhancement of wear responses of EDM surfaces by a proper combination of tool electrode and the electrical parameters.

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