



Wear behavior of wire electric discharge machined surface of 316L stainless steel

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Abstract

This study presents the wear behavior of 316L stainless steel material machined with wire electric discharge machine (EDM) at different machining conditions by varying the machining parameters pulse on time (T_{ON}), peak current (IP), servo voltage (SV) and wire tension (WT). Sliding wear tests are conducted on the cylindrical specimens using pin on disc apparatus and the worn morphology of the specimens are analyzed by SEM and XRD. The experimental investigation revealed that the wear resistance is highly influenced by the wire EDM parameters. T_{ON} and IP are identified to be the most influencing factors effecting wear resistance. At similar values of the product of T_{ON} and IP, the wear resistance remained constant and the wear resistance increased with decrease in the product of T_{ON} and IP. The obtained parameters setting can be used in die making industries where wear behavior is of importance.

Keywords Wire EDM · Microhardness · Wear resistance · Discharge energy

1 Introduction

Wire EDM process is considered as the best among the machining process available for machining hard materials and complex shapes. In wire EDM, the material removal process does not involve contact between the tool and the work material but is done by series of sparks. The electrical discharge takes place between the two electrodes in the presence of dielectric fluid by a narrow margin. The work material is cathode while wire electrode acts as anode. Depending upon intensity of spark, the work material heats, melts and cools in the dielectric fluid and thus cutting action takes place. Along with the high temperature gradient thermal energy, wire electrode material and dielectric fluid also shows effect on the machined surface causing phase changes and deposition of wire material. This type of material removal process effects the surface properties of the machined surface such as roughness, hardness, wear resistance, corrosion and so on. The

machining parameters of wire EDM are more and the control of these parameters is important. The main drawback is that the improper combination of parameters cause voids, craters, micro cracks and heat effected zone which in turn shows the negative effect on machined surface.

As T_{ON} and IP is increased, the surface roughness and the thickness of the white layer also increased. Hardness of the machined surface is found to be higher because of copper deposition from anode and formation of oxides and carbides [1]. The surface roughness is observed to be low at high values of T_{ON} and IP [2]. The most influencing electrical pulse parameters are T_{ON} and IP show significant impact on machining performance of wire EDM as the values of their product is proportional to discharge energy which in turn effects the melting and vaporization of the material during machining [3]. Increase in carbon content on the machined surface is observed on electric discharge machining on 316L stainless steel led to the increase in microhardness. Also the surface modifications

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are observed with formations of chromium carbides along with rough surface resulting in decrease in corrosion resistance [4]. Investigation by Han et al. [5] revealed that, at constant pulse energy/discharge, surface roughness obtained is also constant but with variation in cutting rate and surface morphology.

Few works related to hardness and wear behavior of surfaces are presented. ZrO₂-WC composites were machined with EDM and their machinability was studied under rough cut and fine cut EDM surface. The specimens are subjected to wear test on cemented carbide plate. Results showed that the rough cut surfaces exhibit better wear resistance, lower hardness and at high cutting speed with recast layer consisting of resolidified droplets of molten material with voids [6]. The effect of wear behavior of cryotreated D2 steel was investigated and the study revealed that there is an enhancement in wear resistance because of fine and secondary carbides formation [7]. The wear resistance of tungsten carbide and zirconium oxide composites subjected to different machining process wire EDM, grinding and polishing are analyzed. The wire EDMed samples have shown less wear resistance when compared to others machining process and is due to the decrease in the flexural strength of the wire EDMed sample. Also the micro structural changes have shown cracking, delamination, loss of surface binder and wear debris spalling [8]. Effect of wear resistance of cemented carbide coatings was analyzed. Test results shown that the proper combination of coarse and nanoparticles of cemented carbide enhanced the hardness and wear resistance. Decrease of de carburization is seen in coarse articles inclusion and nano particles prevent penetration of debris [9]. According to Boujelbene et al. [10], the hardness of wire EDM specimens are high. Low levels of T_{ON} and IP leads to the formation of a thin white layer with low hardened surface. Deposition of carbon is the main reason for increase in hardness. Influence of EDM on duplex and ferritic materials with hydrocarbon-based dielectric liquid shown decrease in surface wear rate due to martensite and carbides formation in resolidified layer. Graphite wire electrode material is sensitive to water as die electric fluid showing the cavity formation due to release of carbon gas from the molten pool resulting in wear resistance decrease [11]. Wire EDM parameters highly effects the formation of surface oxides which results in change of surface properties from metallurgical view [12]. Enhancement of wear resistance and hardness was observed for EDMed shape memory alloys using titanium as wire electrode and die electric fluid as

nitrogen gas [13]. According to author's previous study, the wire EDM parameters show significant effect on the corrosion behavior of machined surface of 316L SS. At the low values of the product of pulse on time and peak current, corrosion resistance is found to be high with good surface finish [14]. According to Adik et al. [15] machining of shape memory alloy with wire EDM yielded good surface finish compared to traditional machining process when machining at high T_{ON} the surface finish was observed to be rough with crack, craters and blow holes. According to Tushar et al. [16] T_{ON} is identified as the significant factor showing effect on material removal rate and surface finish. Higher the T_{ON}, more is the surface roughness and material removal rate. Adaptive network based fuzzy inference system (ANFIS) model was developed by Sandeep et al. [17] for multi objective optimization of surface roughness and material removal rate for machining titanium alloy with wire EDM and observed that T_{ON} and IP are the most influencing parameters affecting the responses.

Most of the researchers identified various parameters which influence the corrosion, surface roughness and damping [18]. However, there is a dearth of information available concerning the changes in wear resistance of wire EDMed surface. So an experimental investigation on the wire EDM parameters affecting the microhardness and wear behavior of wire EDMed surface of 316L stainless steel (SS) is carried out and presented in this paper.

The specimens are machined with wire EDM under varying input parameters and then subjected to micro hardness tests and wear tests. The worn morphology was studied using scanning electron microscope and phase analysis from XRD.

2 Materials and methods

316L SS is used as the working material whose elemental composition is demonstrated in Table 1.

2.1 Wire electric discharge machining

Japax LDM50 wire EDM shown in Fig. 1 [14] is used in the present investigation for machining the specimens. Based on the previous studies, the wire EDM parameters that are considered for experimentation are T_{ON}, IP, SV and WT [19, 20]. Brass wire is electrode and distilled water is the dielectric liquid. Specimens of size 10 mm diameter and 35 mm length are machined according to Taguchi L8 orthogonal

Table 1 Elemental composition of 316L SS

S	C	P	Si	Mn	Mo	Ni	Cr	Fe
0.001	0.017	0.025	0.56	1.21	2.16	11.1	17.6	Bal



Fig. 1 Japax LDM50 wire EDM

array with four parameters and two levels and are shown in Fig. 2. Table 2 shows the corresponding machining conditions. All the eight conditions of machining are designated as MC1 to MC8 and are presented in Table 3.

2.2 Microhardness testing

Microhardness tests are conducted according to ASTM standards. Microhardness test used for the measurement in this work is Vickers hardness tester. Shimadzu N20 is used for conducting microhardness tests. 1 kg load is applied for 15 s duration on each sample and three indentations are taken and the average of the three readings is considered as hardness of the sample.

2.3 Wear test

Figure 3 shows pin on disc apparatus used for conducting wear tests for wire EDMed specimens at different machining conditions. Specimens of size 10 mm diameter and



Fig. 2 Machined specimens

Table 2 Machining conditions as per L8 orthogonal array

Machining condition	Pulse on time (μ s)	Peak current (A)	Servo voltage (V)	Wire tension (kg-f)
MC1	15	9	5	5
MC2	15	9	15	12
MC3	15	12	5	12
MC4	15	12	15	5
MC5	25	9	5	12
MC6	25	9	15	5
MC7	25	12	5	5
MC8	25	12	15	12

35 mm length were machined at different machining conditions. D2 steel is used as the disc material. A load of 5 kg was applied for a sliding distance of 1000, 1500 and 2000 m respectively. All the specimens are subjected to wear test at the same load and sliding distance and at a speed of 750 rpm. For the worn out surface of the cylindrical specimens, the SEM images are captured and the wear surface were analyzed.

3 Results and discussions

3.1 XRD analysis

Patterns of XRD obtained for the specimens machined at different conditions are presented in Fig. 4 [14]. The presence of copper is seen on the machined surface which indicates the transfer of wire electrode material. High temperatures resulted during machining led to the formation of various oxides can be observed. At high temperatures, the formation of chromium carbides and chromium oxides are observed. This shows the depletion of chromium from the parent material. This shows the occurrence of metallurgical modifications.

3.2 Wear behavior

Figure 5a demonstrates the weight loss variation with sliding distance at different machining conditions and Fig. 5b represents the variation of weight loss with different machining conditions at different sliding distances. It was noted that the weight loss increases with the increase in the sliding distance for all the cases. It is also identified that the weight loss at machining condition MC1 and MC2 are close to each other. The same similarities of closeness of weight loss are observed between the machining conditions MC3 and MC4, MC5 and MC6 and also between MC7 and MC8. The maximum weight loss was reported for as received material. The corresponding wear test results are

Table 3 Microhardness and wear values

Machining condition	Pulse on time (μ s)	Peak current (A)	Servo voltage (V)	Wire tension (kg-f)	Cutting speed (mm/min)	Weight loss (g) at a sliding distance of			Vickers hardness number (VH)
						1000 m	1500 m	2000 m	
MC1	15	9	5	5	1.41	0.003	0.005	0.007	351
MC2	15	9	15	12	1.23	0.004	0.004	0.006	354
MC3	15	12	5	12	1.36	0.021	0.053	0.068	337
MC4	15	12	15	5	1.29	0.034	0.06	0.071	339
MC5	25	9	5	12	1.52	0.108	0.138	0.194	314
MC6	25	9	15	5	1.78	0.093	0.129	0.185	311
MC7	25	12	5	5	2.2	0.212	0.296	0.313	282
MC8	25	12	15	12	2.32	0.2	0.288	0.292	286
As received material						0.198	0.216	0.316	280



Fig. 3 Pin on disc apparatus

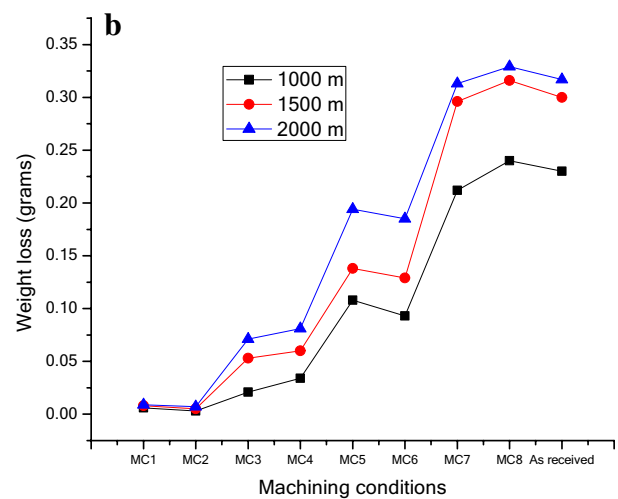
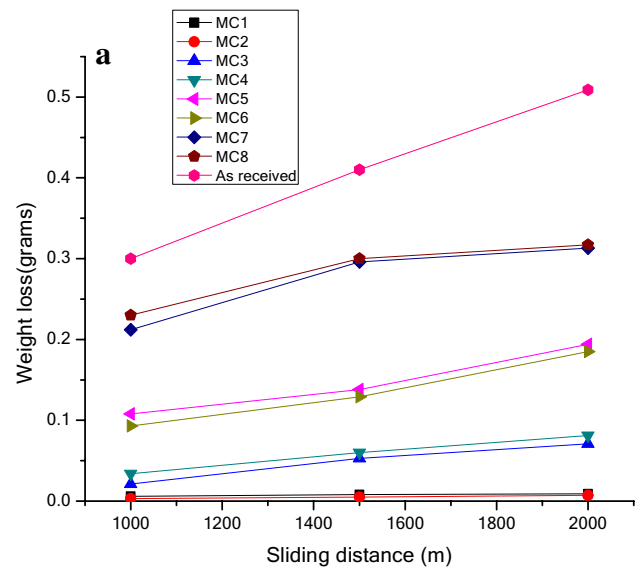


Fig. 5 Variation of weight loss w.r.t. **a** sliding distances **b** machining conditions

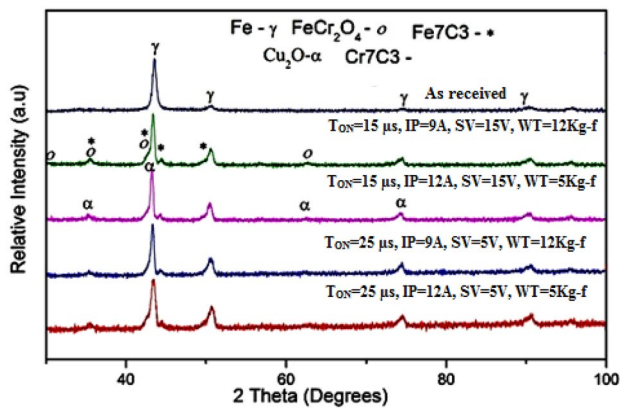


Fig. 4 XRD pattern of the specimens

presented and tabulated in Table 3. At similar values of product of T_{ON} and IP (proportional to discharge energy), the weight loss is almost the same and the other parameters, servo voltage and wire tension are showing least impact, hence only four cases were considered one from each set taking low cutting speed as criteria. All combinations of discharge energy levels are covered in the selected machining conditions MC2, MC4, MC5 and MC7 which are considered as case-A, case-B, case-C and case-D respectively in the subsequent paragraphs.

3.3 Microhardness

The microhardness values of the specimens are shown in Table 3. The Vickers microhardness value for the as received material is observed to be 280 VH and found to be high for all specimens machined with wire EDM. It is noticed that at lower discharge energy level, hardness was found to be high and then declined with increase of discharge energy. A high value of 354 VH was observed for case-A and a least value of 282 VH was reported for case-D and the hardness for case-B and case-C were found to be 339 and 311 VH respectively. The high hardness for case-A resulted because of hard thin layer comprising of Cu, $FeCr_2O_4$, Cu_2O , Fe_7C_3 and Cr_7C_3 from the wire electrode, which is evident from XRD shown in Fig. 4. For case-D, low hardness was reported because of chromium depletion.

3.4 Worn morphology

Figure 6a, b shows the SEM micrograph of worn morphology of the as received 316L SS material at a sliding distance of 1000 m and 2000 m respectively. From Fig. 6a it could be observed that the surface consists of smooth and

rough patches. This rough patch consists of rippled surface which shows predominant wear. This feature is more significant as the sliding distance increases. As the sliding distance increase the smooth patch vanishes and the size of the rough patch increases and this rough patch consists of deep grooves, debris and rippled surface showing abrasive wear. This feature is demonstrated in Fig. 6b. The wear behavior of wire EDM specimens for four above mentioned machining conditions are presented below.

3.4.1 Case-A

Figure 7a–d indicates the worn surface of wire EDMed surface for the four cases at 2000 m of sliding distance. Figure 7a represents the morphology of worn surface for case-A. From the figure it was noticed that the surface is covered with smooth area without evidence of loss of material which represents high resistance to wear. The high wear resistance at this machining condition was probably due to the following reason.

Due to availability of low discharge energy at this machining condition, a thin protective hard white layer consisting of oxides and carbides is formed on the surface along with copper compounds which is due to deposition from the wire electrode resulting in harder surface which eventually decreases the wear of the surface. Figure 8 [14] shows the thin protective hard white layer formed during the machining process. This white layer consists of $FeCr_2O_4$, Cu_2O , Fe_7C_3 and Cr_7C_3 and is evident from the XRD. Also the hardness at this machining condition is 321 VH which was the highest value reported among all the specimens machined at different conditions. As the hardness is directly proportional to wear resistance, the

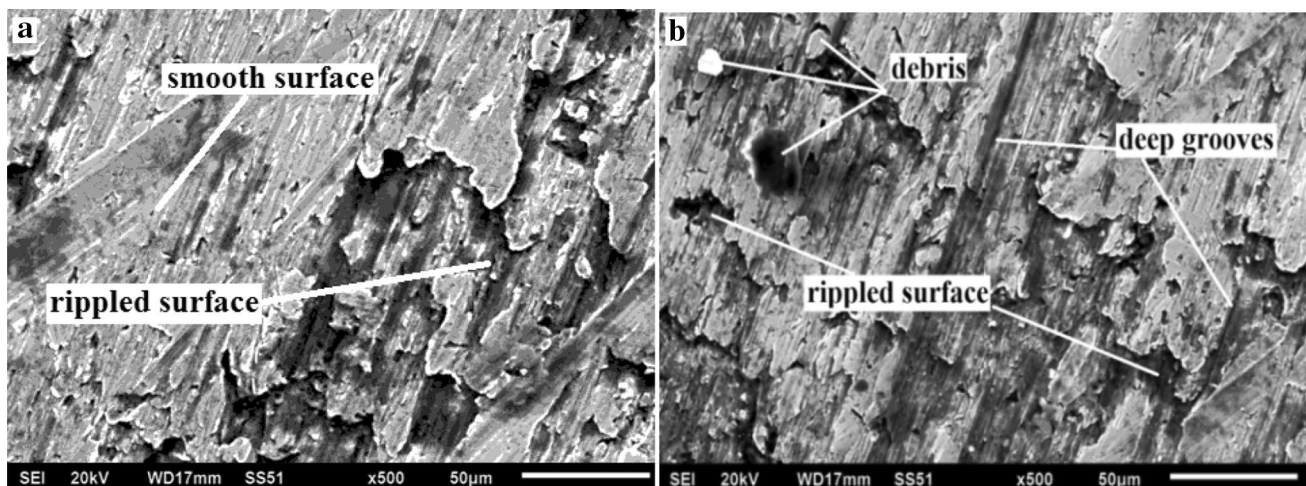


Fig. 6 SEM image of as received 316L SS material **a** at 1000 m **b** 2000 m

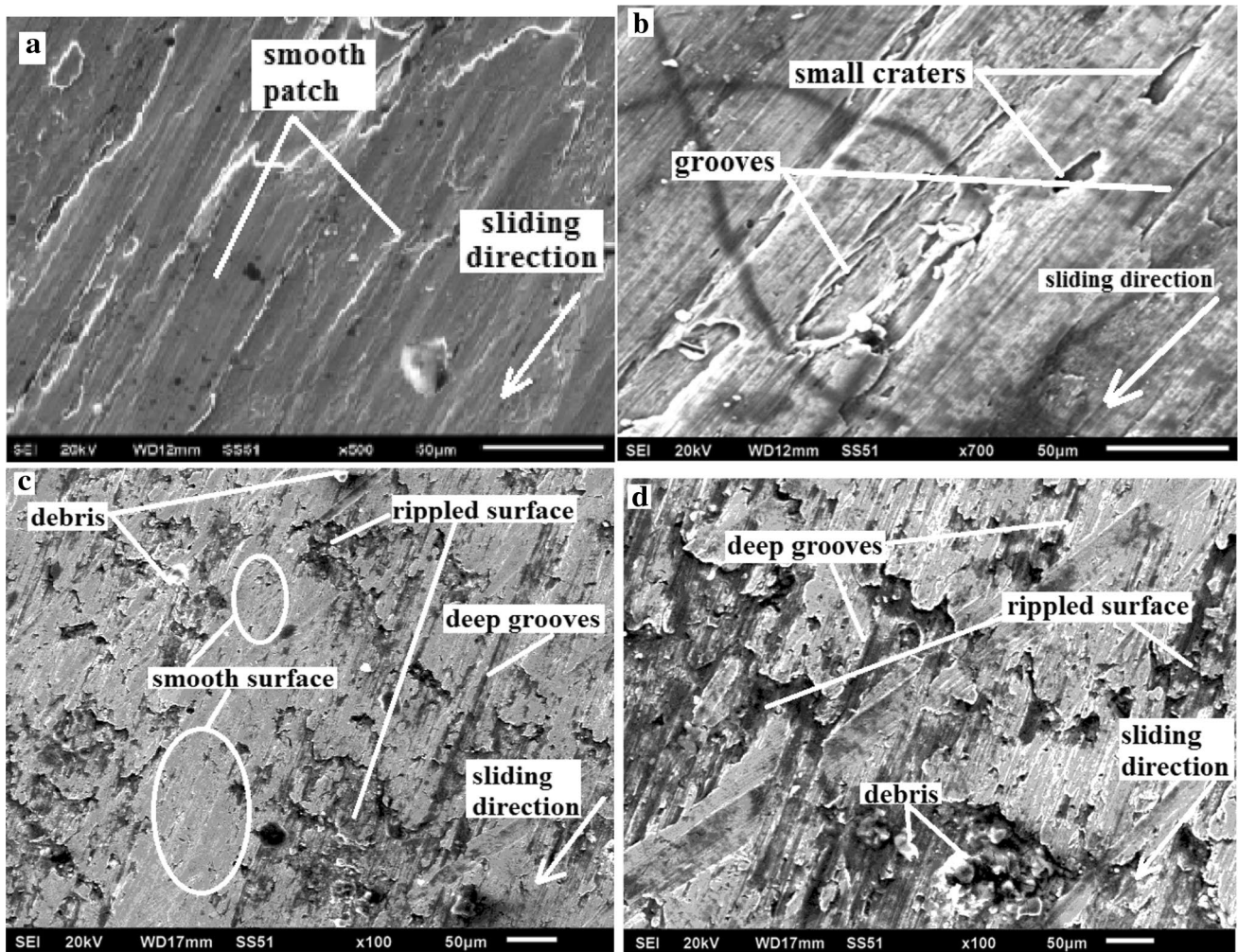


Fig. 7 Worn morphology of wire EDMed specimens at **a** case-A **b** case-B **c** case-C **d** case-D

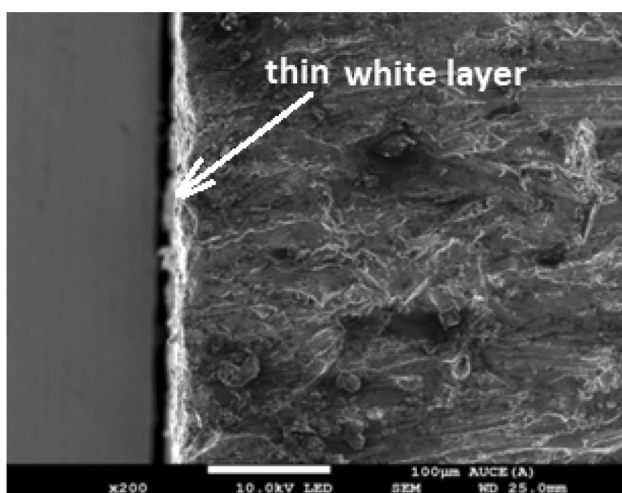


Fig. 8 Cross sectional SEM image of white layer formation for case-A

increase in hardness was also one on the reason for the high wear resistance.

3.4.2 Case-B

The worn morphology for case-B is represented in Fig. 7b. The surface consists of thin grooves in the sliding direction along with small craters. Also the hardness at this condition is observed to be 311 HV which is less when compared to case-A. Hence, at this machining condition weight loss is marginal.

3.4.3 Case-C

The SEM image showing worn morphology for case-C is presented in Fig. 7c. For this case, increase in rough surface was observed with grooves, debris and rippled surface. The wear was observed to be high in comparison with case-B. At this machining condition, there is still increase

in the discharge energy generating high temperatures and the molten material solidifies quickly and small portion is flushed away by the dielectric fluid creating rough surface with pores and oxides formation. Also depletion of chromium from the parent metal is observed causing high amount of wear. Also the hardness value of 311 HV was observed showing reduction in hardness. Hence wear resistance is observed to be lower than case-B.

3.4.4 Case-D

Figure 7d demonstrates the SEM image for case-D. The surface consists of deep grooves running in the direction of sliding with large rough patches with the presence of debris showing predominant wear at this condition. The hardness at this condition is observed to be 282 HV, which is low among other machining conditions. This low hardness resulted in high amount of weight loss of the material. As the availability of discharge energy increases, more amounts of material melts causing deposition of FeCr_2O_4 , Cu_2O , Fe_7C_3 and Cr_7C_3 as thick white layer and is shown in Fig. 9 [14]. During the process of oxidation the depletion of high amounts of chromium from the material occurs resulting in low hardness. The increasing amount of discharge energy leads to increase in the oxidation of wire EDMed surface which leads to the decrease in the hardness of the surface [21–24]. Also, during cooling of the high amount of molten material may not properly solidify thus forming craters and rough porous surface. SEM micrograph on the surface at this machining condition shows this feature and presented in Fig. 10. Due to the presence of more oxidized and porous layer on the machined surface, the specimen subjected

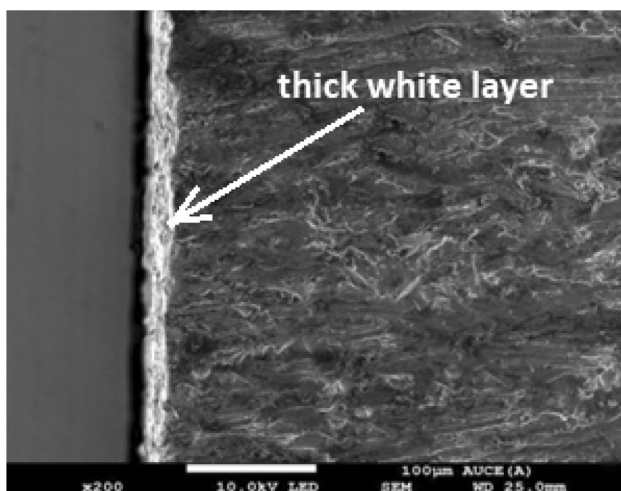


Fig. 9 Cross sectional SEM image of white layer formation for case-D

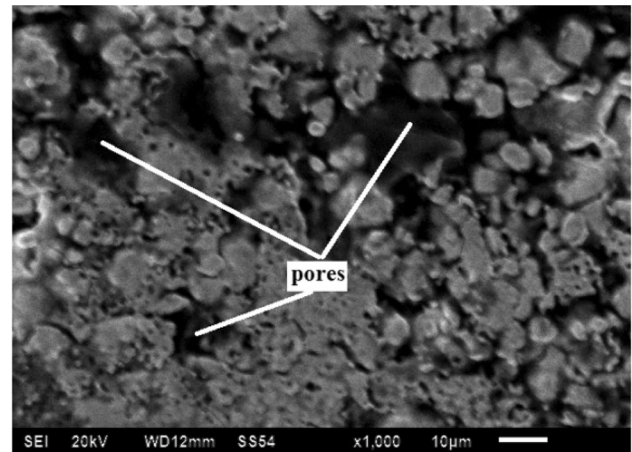


Fig. 10 SEM image of white layer on the machined surface for case-D

to wear test wore at a faster rate showing rough oxidized areas with scratches along the sliding direction.

4 Conclusions

Wear and microhardness of wire EDMed surface of 316L SS is investigated. The parameters T_{ON} and IP showed significant impact on microhardness and wear behavior. Study revealed that the weight loss and microhardness of the specimens are similar for the same values of the product of T_{ON} and IP values. At low levels of this, the microhardness and wear resistance is found to be high when compared to other machining conditions and as received 316L SS material. This is probably due to thin protective hard layer formation on the wire EDMed surface and also due to the presence of copper deposition from the wire electrode. The microhardness and wear resistance is found to decrease with increase of product of T_{ON} and IP values. With increase in the amount of discharge energy, the more material melts and due to sudden cooling in the dielectric medium, the molten material may not properly solidify and more amount of oxides are getting deposited on the machined surface with thick white layer containing pores, craters and cracks causing low wear resistance and microhardness.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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