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Surface Characteristics and Wear Resistance of 316L Stainless Steel after Different Shot Peening Parameters

Mariusz Walczak[1]

[1] Department of Materials Engineering, Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 36D, 20-618 Lublin, Poland

E-mail: m.walczak@pollub.pl

ABSTRACT

The study was conducted to evaluate the effect of ZrO_2-based ceramic beads shot peening on the performance properties of AISI 316L austenitic steel. The results obtained in the roughness and microhardness measurements, the state of the surface layer, and the tribological properties (ball-on-disc) of the specimens after the peening process were compared to the results obtained for the reference specimen. The tests were carried out with varying parameters of pressure (0.3 MPa, 0.4 MPa) and time (30 s, 60 s). The lowest values of COF (μ = 0.576) and wear factor (K = $3.95\cdot10^{-4}$ $mm^3\cdot N^{-1}\cdot m^{-1}$) were observed for the surface peened using parameters: 0.4 MPa and 60 s. By increasing the time twice, a much lower wear factor can be achieved unlike when increasing the shot peening by 0.1 MPa. Observations of wear traces indicate that abrasive wear is predominant and the transfer of specimen material by countersample is also observed.

Keywords: wear mechanism, 316L, stainless steel, shot peening

INTRODUCTION

For many years, researchers [1-4] in the field of surface engineering have been concerned with modifying the surface layer in order to increase its resistance to fatigue wear, abrasive wear and corrosion. These procedures usually focus on mechanical, heat and also thermo-chemical treatment [5, 6]. As the requirements for the quality of the surface layer increase, so does the need to minimize the costs. However, it is important to properly plan the modifications and select materials for specific applications to obtain a component with the best possible properties at the lowest possible cost [7-9].

Austenitic steel is a material that is used in a variety of technical fields [10]. Its availability, price and favorable properties have firmly anchored its position in the market. A wide selection of corrosion-resistant steel, which have unique mechanical and anti-corrosive properties, makes it possible to select a material that ensures the structure's long-lasting performance. Proper selection of surface layer finishing allows to extend the product's service time [11]. The wear resistance of machinery and equipment depends on the properties of the surface layer, the structure of its surface, hardness and the state of internal stress. [5, 12].

The article focuses on the steel grade AISI 316L (1.4404), which is widely used in the food, chemical, aerospace and, most importantly, medical industries [5, 11]. Medical apparatuses related to the manufacture of implants or medical devices require the material to have high resistance to abrasive wear in addition to high corrosion resistance, so they are subjected to special surface treatments [9, 12]. Due to the inability of the 316L grade to undergo conventional strengthening heat treatment, other methods are being sought to increase abrasive wear resistance while maintaining its high corrosion resistance [5, 13].

There are many reports in the literature regarding surface modification studies carried out to improve the tribological [12-14] and anti-corrosion properties [5, 10, 15]. Frequently, the use of certain methods is constrained by the high cost of instrumentation and specialized equipment, long processing times and availability. Methods that at the same time provide the highest possible increase in properties at a low cost are constantly being sought and refined. One of such methods is a shot peening process [13]. The simplicity and versatility of the process have made shot peening a popular method of strengthening in the industry. A wide range of options for changing the processing parameters such as time, pressure, type and material of the shot, angle of incidence, and distance of the peening nozzle from the surface enable this process to be applied to different types of materials. Many authors have addressed the topic of shot peening: steel [4, 5], titanium alloys [9, 16] magnesium [17, 18] and aluminum [19]. The favorable properties imparted to the material as a result of the processing have made the process a popular method of modifying alloys for many applications, particularly in medical ones [9, 14, 16].

In the literature, most of the work on peened 316L steels for medical applications focuses on changes in properties related to fatigue strength and corrosion resistance, and the topic of wear resistance is somewhat neglected [5, 11, 13]. In addition, also most of the work is on pressing stainless steel balls [5, 11]. In contrast, this study focuses on bio neutral ceramic medium which seems a more rational approach especially in the context of later medical applications.

Hence, the article evaluates the possibility of using this method to increase the technological quality related to the state of the surface layer and wear resistance of components made of austenitic 316L steel. The purpose of this study was to examine and compare the properties of 316L steel after peening treatment with ZrO_2-based beads, taking into account the variation of technological parameters of the process, i.e. the time and the pressure of peening.

EXPERIMENTAL PROCEDURES

Specimens preparation and treatments

The object of the study was stainless steel grade AISI 316L. The material was subjected to a chemical composition control analysis on a Magellan Q8 spark emission spectrometer (Bruker, Germany), and the results are shown in Table 1. The average percentages of the elements are in accordance with the requirements of the EN standard 100088-2-2014. For the tests, disc-shaped specimens of ø20 mm and 6 mm thickness cut from the bar in the delivery state were used. The surfaces of the steel discs were subjected to grinding on water-based abrasive papers with gradations: 300, 600, 800 and 1200 on a metallographic grinder-polishing machine with a polishing head made by Buehler - Beta model. The final surface treatment was a peening process with ceramic beads with an average size of 125–250 µm. The characteristics of the shots are included in Table 2. The specimens were peened using two kinds of pressure: 0.3 and 0.4 MPa, and two duration periods: 30s and 60s. The peening process was carried out perpendicularly to the surface until the surface was completely covered, with the distance of the nozzle from the face of the treated surface at approximately 20 mm. The specimens not treated with shot peening process in the study constituted the reference surfaces. The study used 3 specimens for each type of surface.

Table 1. Chemical composition of the tested AISI 316L* (1.4404) stainless steel (mas. %)

C	Cr	Ni	Mo	Mn	Cu	Si	P	S	N	Fe
0.015	17.33	10.85	1.85	1.47	0.42	0.354	0.043	0.001	0.023	bal.

Note: * Results of spectrometer analysis.

Table 2. Parameters of shot for shot peening according to the manufacturer - Kuhmichel Abrasiv GmbH.

Shot	Typical chemical composition (%)		Average grain size (µm)	Grain shape	Hardness
Ceramic beads	ZrO_2	61.98	125-250	spherical	approx. 7-7.5 Mohs
	SiO_2	27.77			
	Al_2O_3	4.57			
	CaO	3.47			
	TiO_2	0.34			
	Fe_2O_3	0.14			

Surface characterization

Analysis of the surface after shot peening tests was performed on a Phenom ProX SEM microscope (Phenom-World, Waltham, MA, USA) in topographic mode using a magnification of 500x.

The surface roughness of the modified surfaces was analyzed on the Dektak 150 contact profilometer (Veeco Instruments, USA). The measurements were taken on a measuring section of 5 mm by randomly taking 6 measurements on each specimen surface. The following roughness parameters were used for the stereometric condition of the surface: arithmetic average roughness *Ra*, quadratic mean deviation *Rq*, maximum profile valley depth of the roughness profile *Rv* and maximum profile peak height of the roughness profile *Rp*.

Hardness measurements

Vickers hardness test was performed on the modified surfaces using a FM-700 micro hardness tester equipped with an ARS 900 automatic system (Future-Tech Corp., Japan). The measurements were performed at a low loading force of 1,961 N (HV0.2) with a dwell time of 10s. For each specimen, 15 indentations were made.

Wear testing and post wear test characterization

The wear tests were performed under technically dry friction conditions (at room temperature of 22°C) on a ball-on-disc tribometer (CSM Instruments, Switzerland). Calibrated 6 mm diameter balls made of WC-Co (hardness 1900HV0.5) were used as a counter sample (ball). The tests were carried out under a load of 10N with a linear speed of 10 cm/s at a radius of 7 mm. There were 3 repetitions of the tests. The total test distance was 300 m, during which the change in COF (coefficient of friction) was recorded. In tribological tests for ball-on-disc tribological pairs, the degree of wear is determined according to the wear factor *K* which was calculated using Archard equation (Eq. 1):

$$K = \frac{Wear\ volume}{Applied\ force \times sliding\ distance}[mm^3N^{-1}m^{-1}] \quad (1)$$

The wear volume of the specimen was determined from the wipe trace using a Dektak 150 contact profilometer (Veeco Instruments, United States) taking 12 measurements per circumference each [20]. After that, the surface of the wear tracks of the tested materials in order to identify the wear mechanisms were analyzed using a scanning electron microscope Phenom ProX with EDS (Energy Dispersive X-ray Spectroscopy) detector.

RESULTS AND DISCUSSION

Surface morphology

Austenitic steel AISI 316L is one of the materials with high plasticity and a tendency to strengthen by crushing. SEM analysis of the specimens after surface treatment with ceramic beads (Fig. 1) showed plastic deformation and spherical craters. Spherical imprints are the result of the impact of ceramic beads with small diameters especially 20–30 µm. The shot peening process carried out at low pressures (i.e., 0.3 MPa) provides a more homogeneous surface compared to surfaces treated at 0.4 MPa. It is also observed that the shot fragments are embedded in the surface. According to the model of phenomena occurring in the surface layer as presented in the work of Kameyama and Komotori [21], the shots hitting the material break off and remain on the treated surface. With each successive shot hitting the surface, the remaining fragments in the surface become more firmly "jammed" into the surface layer of the material. Generally, dents can be divided into two types in terms of their features as "ploughed dent" and "indented dent.". The first type of indentation is associated with the heap of piledup material at its edge, and the second is formed when a shot penetrates the surface without ploughing. In addition, SEM analysis of the tested surfaces indicates that the most significant changes in the surface topography are observed for the specimen which was peened at the highest pressure and the shortest peening time - i.e. 316L/0.4/30. The above observations of the surface are in agreement with the results of roughness (see Fig. 2). The evaluation of the roughness of shot peening treated surfaces is most often based by the authors of works [14, 17, 19, 21] on the parameter Ra as the most representative one. The treatment of the surface with steel shot resulted in an increase in surface roughness at both 0.3 and 0.4 MPa (an average increase in 10–14 times vs. the reference surface). At the same time, greater changes in roughness are detected when peening pressure is increased rather than when treatment time is increased. Similar behavior was witnessed for AISI 304 steel when treated with CrNi steel shot [10], yet AISI 304 and AISI 316L grades are similar in terms of their properties. Additionally, it was observed that during the use of a pressing pressure of 0.4 MPa, increasing the pressing time from 30 s to 60 s it does not result in statistically significant changes relative to the 316L/0.4/30 surface. Then similar values of the Ra parameter are obtained with a relatively smaller Rv. This could indicate that at a pressure of 0.4 MPa, increasing the time removes the effect of deep impact indentations. Analyzing the parameters of Rp and Rv it becomes apparent that there are greater differences in the valley depth of the roughness, with little change in the peak height of the roughness (see the standard deviation of the parameter Rp – Fig. 2c) of the surfaces tested. Such surface topography can have a key effect on the tribological characteristics of the specimens under study. In addition, also literature data [22-24] confirm that increasing pressure peening leads to an increase in roughness.

Surface hardness

Vikers hardness measurements (Fig. 3) showed an increase in average hardness values for all treated surfaces (from 70% to 102% on average) compared to untreated specimens. The research shows that the longer the pressing time and the higher the peening pressure, the greater the strengthening of the modified material is achieved. At the same time, higher values of average hardness are obtained when the peening time is increased from 30 s to 60 s (a change of about 7.9÷13.5%) rather than when the pressure is increased from 0.3 MPa to 0.4 MPa (a change of about 5÷10.5%). Also, a similar trend in hardness measurements was obtained for AISI steel [10]. The increase in the surface hardness of the treated surfaces is related to the fact that as a result of the percussive impacts of the ceramic beads, the dislocation density increases and the remnants of the hard ceramic shot penetrate the surface according to the mentioned Kameyama and Komotori model [21]. A nanocrystalline structure is then formed. [14, 25]. The thickness of the deformed region is a function of the size of the beads and treatment time and, for instance, for AISI steel, it may reach from 59 μm to 150 μm [26].

Wear and morphology of worn surfaces

The results of the recorded average COF values and the characteristics of COF changes over time are rearranged in Fig. 4. The comparative analysis of COF showed that the lowest values (while very close) of the friction coefficient were recorded for the surfaces with the longest pressing time and the highest value of pressure peening. The roughness of the surface (parameter Rp) of the peened surfaces can affect the operating values, and as its value increases, the friction coefficient value decreases. This is because there is abrasion of higher roughness profiles. However, the mean COF changes are relatively small - they are in the range of $\mu = 0.576 \div 0.603$ and, taking into account the standard deviation, it can be concluded that the differences are not statistically significant. Analyzing the average shape of changes in the COF course, for all surfaces, elevated COF values were noted in the initial stage of the test when the lapping phase occurs, as indicated by the shapes of the graphs of friction coefficient against time. The next stage (after about 500 s) is an increase in COF caused by an increase in

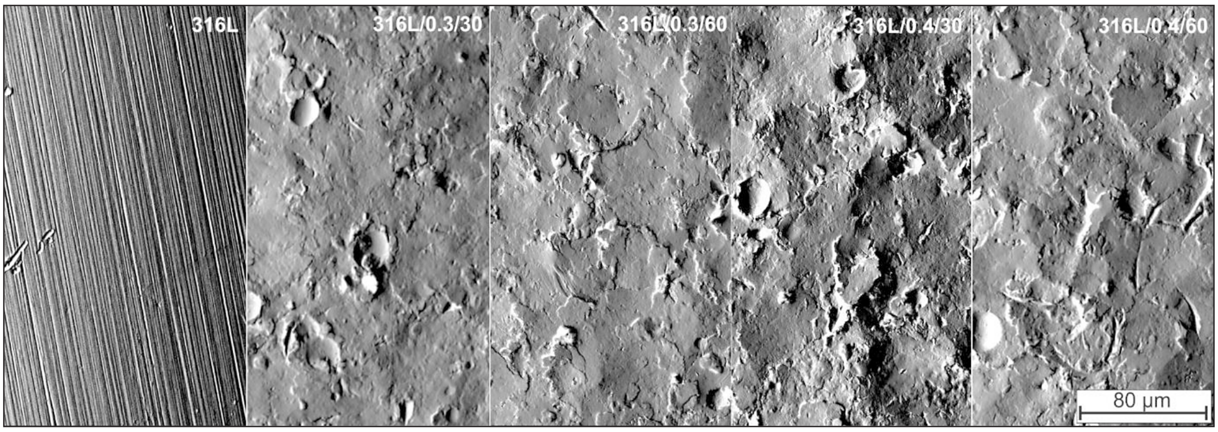


Fig. 1. SEM images of the surface of the specimens in the untreated and shot peened cases

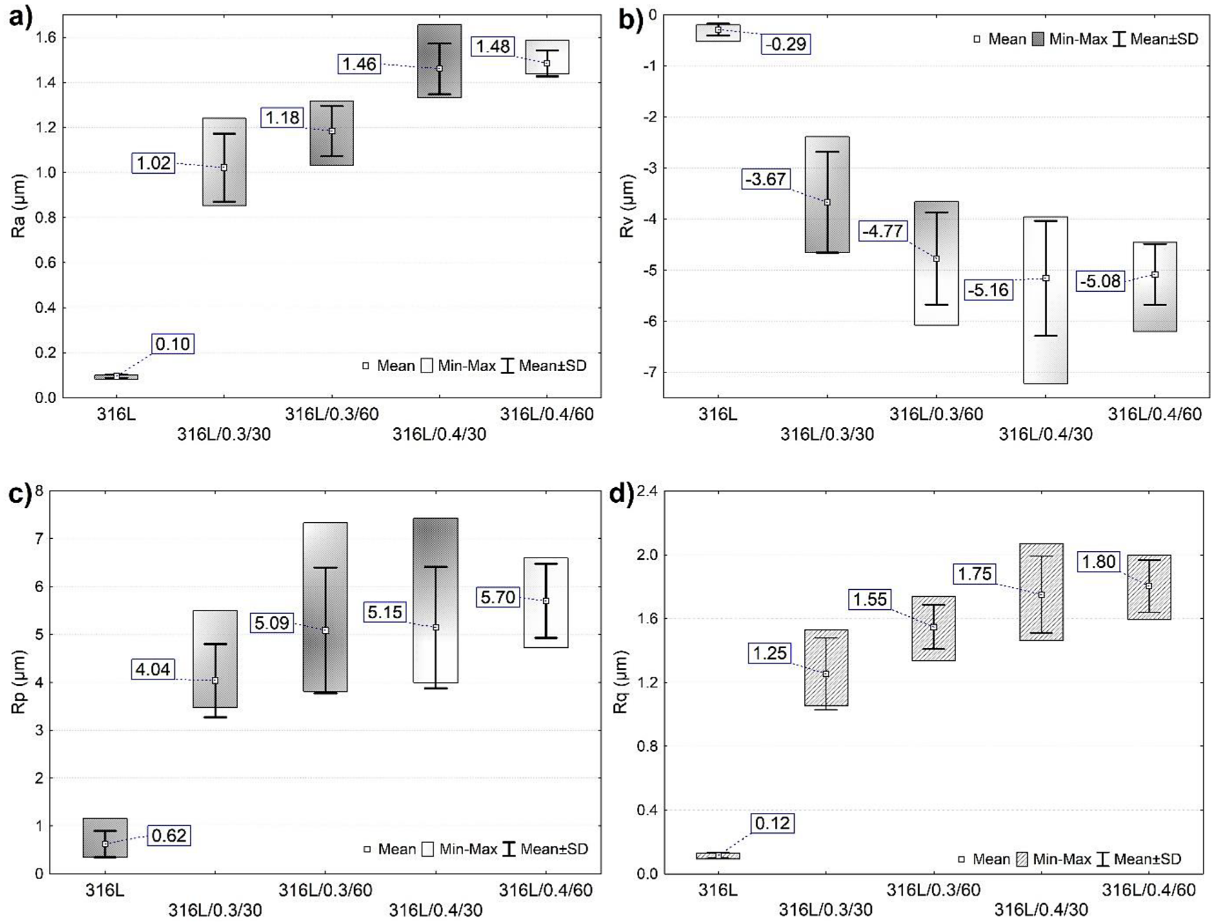


Fig. 2. Roughness parameters: a) Ra, b) Rv, c) Rp and d) Rq of untreated (marked as 316L) and shot peened surfaces

the contact area between the test material and the WC-Co counter sample. In further stages of the process, a slight increasing tendency is observed.

Figure 5 shows the results of the wear coefficient of the treated surfaces. For all modified surfaces, an increase in wear resistance was observed with an increase in the treatment time and

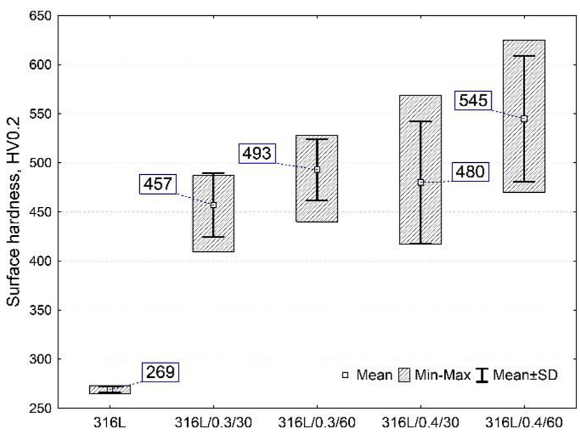


Fig. 3. Surface hardness of untreated and shot peened 316L

with an increase in peening pressure. The highest wear resistance under conditions of technically dry friction was recorded for surfaces using the highest values of processing parameters - i.e. 316L/0.4/60. At the same time, it can be observed that the increase in twice the processing time allows to obtain lower values of wear factor than when increasing by 0.1 MPa shot peening. In addition, in the case of surfaces modified with ceramic beads, a strong relationship can be observed between hardness and the value of the wear coefficient. A lower average surface hardness leads to a higher K factor value when evaluating the wear resistance of low carbon steel after shot peening. Wang et al. [27] indicate the increase in hardness associated with the fine-grained surface layer of low carbon steel after shot peening reduces the depth of penetration of the countersample. This behavior, in turn, translates into minimizing ploughing and micro-cutting. Similar arguments can be found in works [14, 28], where the lower wear of stainless steel after shot peening is attributed to, among other

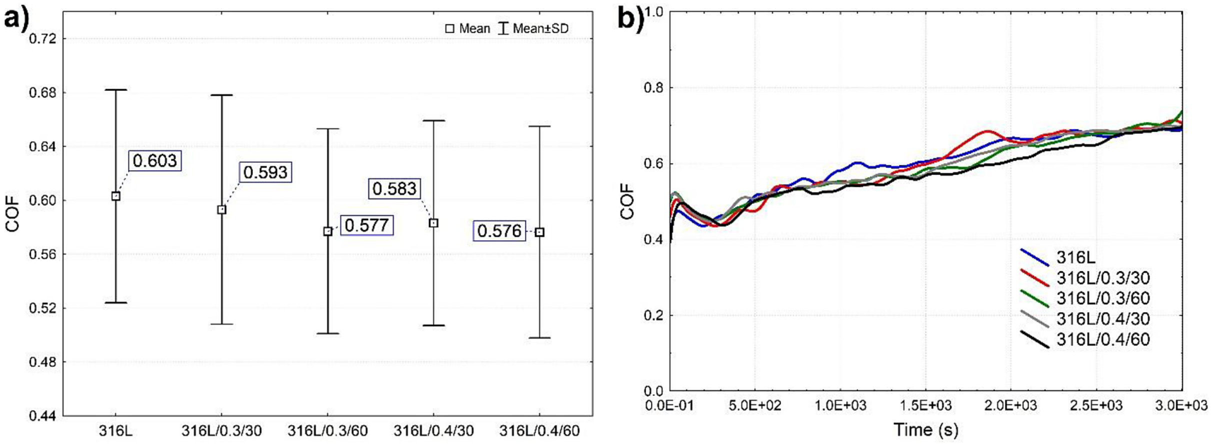


Fig. 4. Coefficient of friction a) mean value ± standard deviation, b) with regard to time.

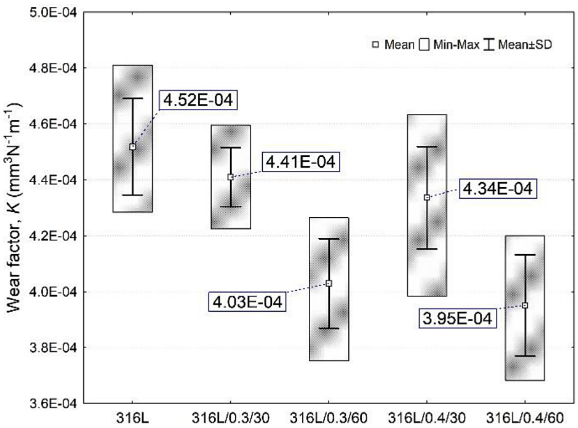


Fig. 5. Result of the wear factor

things, elevated grain-refinement effect and severe plastic deformation.

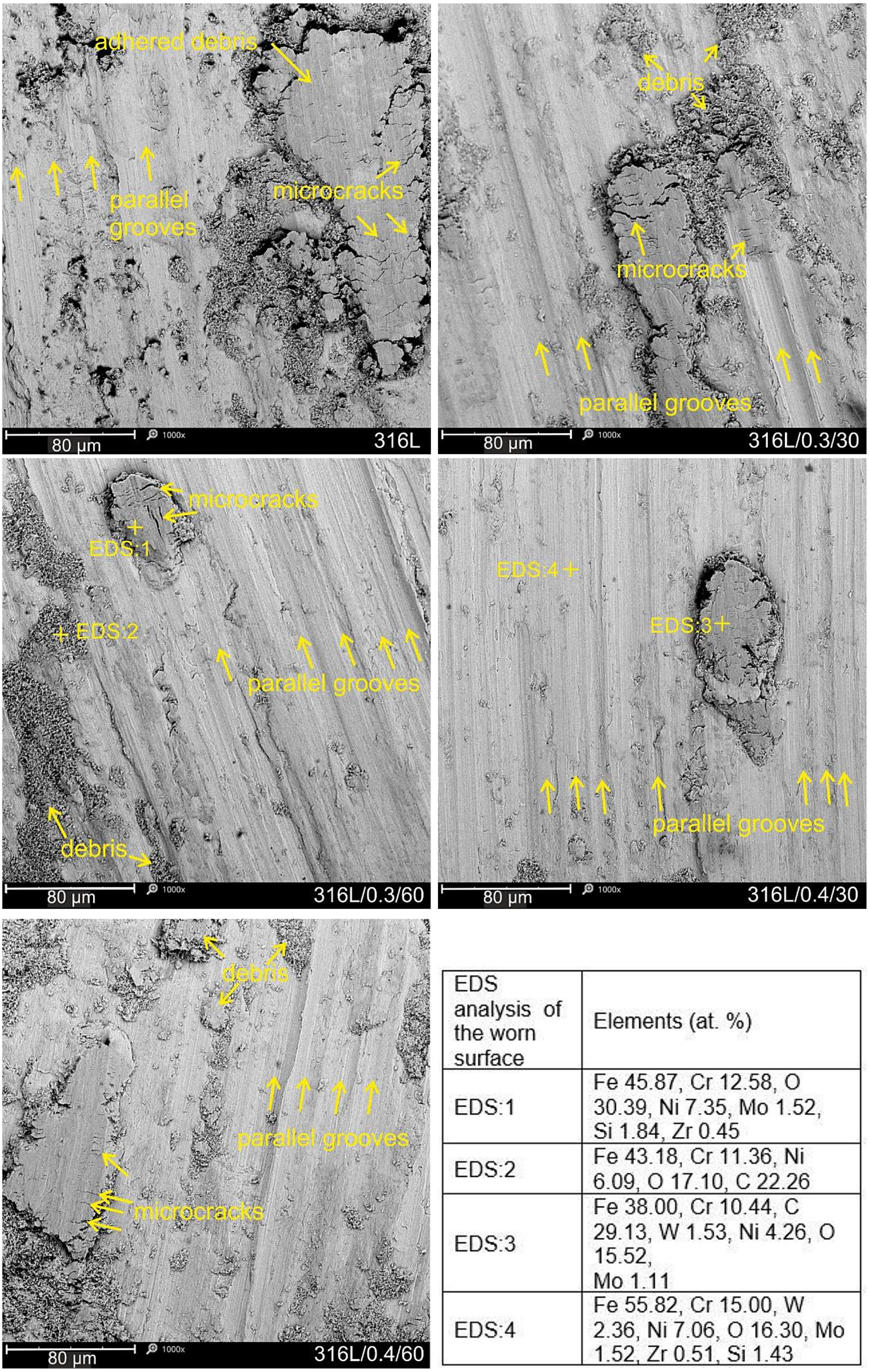
The surface of the wear tracks was subjected to SEM and EDS analysis (Fig. 6) to identify wear mechanisms. All analyzed wear surfaces are dominated by the abrasive wear mechanism in the form of paraller grooves (along the direction of movement of the counter-sample) and microcracks associated with the fatigue mechanism. The latter mechanism is associated with repeated bulking of the same volume of material by the WC-Co counter sample. Consequently, this results in the formation of microcracks propagating perpendicular to the direction of motion of the counter sample. Furthermore, sticking of fragments of bonded materials was also observed in the wear paths, with the phenomenon of transfer of secondary wear products by the counter sample (Fig. 7). In addition, EDS analysis in selected areas indicates that oxidation may be occurring, as evidenced by the elevated oxygen levels in the debris. Oxygen and Si and Zr-type elements may also represent residual of ceramic shots in the surface layer. Fragments of hard ceramic shots may represent a natural hindrance to countersample [14].

Wang et al. [27] found that wear tests performed with loads below 4 N are dominated by a typically abrasive wear mechanism resulting in micro-cutting and parallel grooving. In contrast, at higher loads (6 and 8 N), the abrasive wear mechanism transitions to fatigue surface cracking. A similar phenomenon was also reported by Brinckmann and Dehm [29]. On the other hand, Yang et al. [30] found that an increase in load from 1 N to 5 N reduced this difference and that slippage was the main wear mechanism at low loads, while fatigue cracks is the dominant wear mechanism at high loads. Also, Sanjeev et al. [31] in their tests observe two dominant wear mechanisms: abrasion grooves and smearing.

CONCLUSIONS

The article analyzed the effect of shot peening treatment on the surface layer properties and tribological characteristics of 316L steel. On the basis of the conducted research, it was found that:

Surface roughness measurements of the ceramic-treated specimens showed that there is an increase in surface development as the working pressure increases. In addition, SEM analysis of the surface and roughness measurements revealed that increasing the peening time from 30s to 60s at a pressure of 0.4 MPa, does not result in statistically significant changes relative to the 316L/0.4/30 surface (similar Ra values with relatively lower Rv). In addition, with a pressure of



EDS analysis of the worn surface	Elements (at. %)
EDS:1	Fe 45.87, Cr 12.58, O 30.39, Ni 7.35, Mo 1.52, Si 1.84, Zr 0.45
EDS:2	Fe 43.18, Cr 11.36, Ni 6.09, O 17.10, C 22.26
EDS:3	Fe 38.00, Cr 10.44, C 29.13, W 1.53, Ni 4.26, O 15.52, Mo 1.11
EDS:4	Fe 55.82, Cr 15.00, W 2.36, Ni 7.06, O 16.30, Mo 1.52, Zr 0.51, Si 1.43

Fig. 6. SEM microphotographs with EDS analyses of the worn surfaces

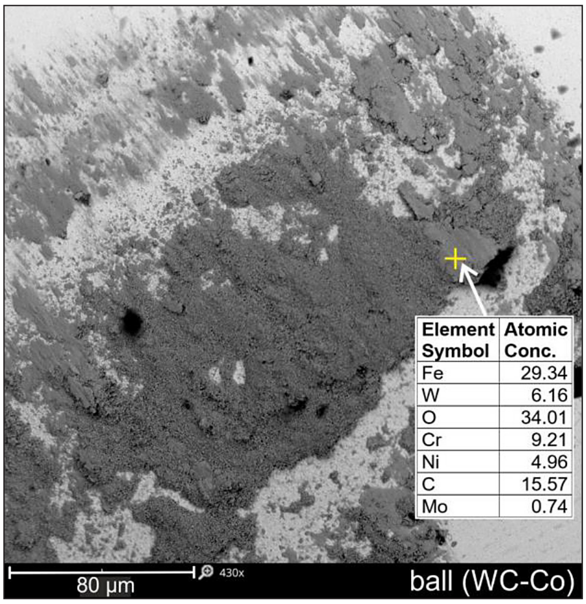


Fig. 7. Typical worn surface of counter sample after wear test

0.4MPa, the increase in time removes the effect of deep impact indentations (decrease in Rv).

Shot peening resulted in an increase in the micro hardness of the surface of 316L steel ranging from 70% to 102% – for the highest pressure and longest processing time. At the same time, higher average hardness values are obtained when the peening time is increased from 30 to 60s than when the pressure is increased from 0.3 to 0.4 MPa.

The lowest COF (μ = 0.576) and wear factor ($K = 3.95 \cdot 10^{-4}$ $mm^3 \cdot N^{-1} \cdot m^{-1}$) values were recorded for the surfaces with the longest pressing time and the highest pressure peening value. In addition, it was found that increasing the treatment time by two times produced significantly more favorable results in terms of wear resistance than increasing the pressure peening by 0.1 MPa. A relation between hardness and the value of the wear coefficient was also observed (lower hardness results in higher K-factor value).

SEM analysis of the wear tracks showed that the dominant wear mechanism is abrasive wear in the form of paraller grooves and fatigue wear that resulted in the observed microcracks. In addition, there is an observed transfer of secondary wear products through the countersample, and EDS analysis in selected areas indicates elevated oxide content.

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