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INFLUENCE OF THE SURFACE ROUGHNESS, LUBRICATION AND GRINDING ON TRIBOLOGICAL PROPERTIES OF THE C35 STEEL SHOT-PEENED SURFACES

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Abstract:
The roughness and lubrication of the contact surfaces play a major role in determining the contact forces and the coefficient of friction during contact between the two parts. The objective of the research, the results of which are presented in this paper, was to establish what, in fact, is the influence of those two important parameters on the surface properties of the shot-peened C35 steel specimens. Another important aspect that was considered was the influence of the post-treatment of the shot-peened specimen surfaces, the fine grinding. The experimental work included verification of the steel's chemical composition (as compared to the standard values), the heat treatment, evaluation of the material's microstructure, measurement of the mechanical properties, the shot-peening treatment and evaluation of the magnitude of the compressive residual stresses, measurement of the surface roughness profiles and the friction tests. An effect of the surface roughness and lubricant on the coefficient of friction (CoF) was established. The CoF values of the dry shot-peened steel surface after the fine grinding, as compared to the unground surface, decreased from about 30% to 39%. The application of lubricant caused the CoF to decrease by 66% and 43% for the ground and unground surfaces, respectively.

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1. INTRODUCTION

The high-quality, heat-treated steels are an important group of structural materials used in transport engineering. These steels are heat-treated by quenching and tempering at high temperatures (usually above 400°C). The objective of the heat treatment is to obtain the higher strength properties of the material while keeping the relatively high toughness. Those steels are characterized by a medium or high carbon content and alloying elements, such us Cr, Mn, Si, Ni, V, Mo. Those alloying elements primarily contribute to increased hardenability and improved mechanical properties. These steels are in operation subjected to high requirements regarding reliability, safety, and durability while simultaneously respecting economic and environmental aspects [1-2].

In transport, the most common material degradation mechanisms are fatigue and wear. Those usually arise on the surface or at a small depth below the surface of components and structures. To increase the material's resistance to mechanisms of fatigue and wear, the surface layers' mechanical properties must be enhanced.

Methods for improving the mechanical properties of the surface layers, i.e., their strengthening, can be static and dynamic. The static methods include static pressure on the tool,

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static pressure combined with sliding on a surface, rolling off the strengthening tool on the surface-roller, burnishing, static shot-peening, etc. The dynamic methods include shot-peening, ultrasonic shot-peening, hydro tumbling, hardening by explosion, etc. Other methods can be applied, as well, like surface hardening and thermo-chemical treatments, such as carburizing and nitriding, etc. [3-4].

Shot-peening (SP) and severe shot-peening (SSP) are processes in which the surface layer of material is subjected to cold plastic deformation due to the high-velocity impacts of hard particles. The result is the strengthening of the material surface, which means an increase of both surface strength and hardness, as well as the creation of the surface roughness and compressive residual stress field in the sub-surface layer. When considering the material's fatigue, it is known that the compressive residual stresses extend the fatigue life, which also results in the fatigue limit increase, usually up to 20% [5-7]. However, it ought to be emphasized that the shot-peening parameters must be very carefully selected and defined since the incorrectly selected shot-peening or severe shot-peening parameters, not corresponding to the material parameters, can cause a reduction of the fatigue strength [8].

Shot-peening and severe shot-peening technologies can be applied to increase the resistance of materials to wear. The peening process creates a typical surface texture characterized by visible surface dimples and the creation of high rims on their circumferences. Those changes in the surface roughness influence friction [9-10]. Given the importance of wear as an undesirable material degradation mechanism, attention must be paid to the effect of the compressive residual stresses created by the shot-peening or severe shot-peening on wear. The opinions on that effect are different, often even contradictory. Authors of [11] stated that the shot-peening has a positive effect on tribological characteristics of investigated steels, 36CrNiMo4 and 36NiCrMo16. The shot-peening produced a lowering of the friction coefficient, as well as wear rate, in comparison to the ground surface in both dry and lubricated sliding and for both materials. However, the shot-peening did not improve the wear of austempered ductile iron [12]. Yan et al. 2022 [13] researched the effect of shot-peening on the surface properties and wear behavior of heavy-duty axle gear steels. In the case of samples treated with a coverage of 1000%, the average wear volume can be decreased by 52.26% and the friction coefficient by 7.69%. The friction wear behavior of shot-peened 7075-T651 aluminum alloy was studied in [14]. From the results obtained, it was shown that the average coefficient of friction increased for the shot-peened specimen when compared to the un-peened one. The higher friction coefficient was explained by the high surface roughness created during the shot-peening process. Bhavar et al. 2017 [15] reported the results of the shot-peening influence on DIN 1.2714 Hot Work Tool Steel. Both the coefficient of friction and wear rate increased with an increase in the shot size and peening intensity. This might be caused by an increase in the shot size, since the peening intensity increase results in the higher surface roughness values, which adversely affect the wear performance. A similar statement, i.e., the higher friction as a result of the higher surface roughness after the shot-peening by ceramic and steel shots, is made by authors of [16]. Authors of [17] concluded that the shot-peening has the potential to improve the wear behavior of an aluminum alloy. The improved behavior of shot-peened specimens was mainly attributed to the surface hardening induced by the treatment and again, the surface roughness played an important role, as well.

The use of lubricants plays an important role in contact friction. In the work [18], the AA7075-T6 aluminum alloy samples were shot-peened at various shot-peening pressures to study their mechanical and tribological properties under dry and mineral oil lubrication conditions.

When the samples, previously shot-peened, are subjected to tests in lubricated conditions (lubricant being the mineral oil), they exhibit lower wear when the shot-peening pressures are higher. That is the result of the synergistic effect of the samples' higher resistance and better bearing surfaces. This points to the conclusion that lubricating by the mineral oil during the sliding definitely decreases wear of the previously shot-peened surfaces of samples.

Kameyama et al. 2014 [19] have considered the influence of fine particle peening (FPP) on the tribological properties of stainless steel using carbon-black/steel hybridized particles. They concluded that specimens treated by the FPP have shown a low friction coefficient and low wear due to the presence of carbon block on the contact surface between the specimen and the reciprocating ball, thus actually having the role of a lubricant. On the other hand, Komori and Ubehara

(2016) have analyzed the tribological effects of surface asperity geometry of the diamond-like carbon coatings (DLC) deposited on the micro-shot peened rough surface substrates [20]. Those surfaces exhibited low friction coefficients and no significant wear in comparison to the DLCs coated on the usually polished substrates. The conclusion was that the surface structuring can have positive effects on the lubricated contact regime. In the study [21], the oil-lubricated friction and wear tests of both commercial and experimental coatings and surface treatment (including the shot-peening) for titanium alloy Ti-6Al-4V were conducted to determine which one would be the most appropriate for applications in diesel engines.

The surface engineering methods significantly improved the wear performance of Ti-6Al-4V alloys, but their relative rankings varied significantly between the oil-lubricated and non-lubricated conditions. Authors of [22] investigated the tribological properties of high-strength screws of a connecting rod (upon the bolt fastening), exposed to surface peening treatment and deep rolling. The authors concluded that the shot-peening produced a beneficial lowering of the bearing friction coefficient in the lubricated conditions, up to 25%, while, on the other hand, the deep rolling produced no such effect. The 3D surface morphology and performance, including the roughness, microhardness and tribological performance of TC17, processed by the high energy shot-peening (HESP), were investigated in detail, and results are presented in [23]. The better wear resistance-lubrication performance synergy was obtained at an air pressure of 0.45 MPa and a peening duration of 30 minutes. The increase of the surface roughness was suppressed by an increase in microhardness that could cause the worsening of the surface flatness. That resulted in changes in the wear resistance and lubrication performance. In the paper [24], the study has been reported on the sliding wear behavior of the surface mechanical attrition (SMA) treated AISI 304 stainless steel by spherical shot-peening, for both under the lubricated and unlubricated conditions, subjected to various contact loads. The steel treated by the SMA has exhibited much higher wear resistance in the lubricated conditions than the steel that was not subjected to that treatment, which was valid for a wide range of the contact load.

The objective of the study presented in this article was to experimentally verify the influence of roughness and lubricant on CoF (Coefficient of Friction) of C35 shot-peened steel, as well as to investigate the influence of the post-treatment grinding on the most important tribological properties of the shot-peened specimens.

2. EXPERIMENTAL ANALYSIS

The experimental work was focused on determining the influence of roughness and lubricant on CoF of C35 shot-peened (SP) steel. Verification of the chemical composition of the experimental material (quantitative chemical analysis) was performed using spark optical emission spectroscopy on a SPECTROMAXx device. The experimental material was subsequently heat treated according to the following regime: austenitization was performed at 830°C ± 5°C for 40 minutes, followed by quenching in the Durixol V70 oil at 20°C ± 5°C, and tempering at 520°C ± 5°C for 120 minutes, with cooling in air. After the heat treatment, the specimens for the tensile and tribology tests were machined. For the tensile tests, the round cross-section specimens of a diameter d = 10 mm were used and prepared according to the EN 10002-1 standard. Three specimens were used for the tensile tests, which were carried out on a ZWICK Z050 testing machine at an ambient temperature of T = 20 ± 5°C, with the load within the range of F = 0 to 20 kN and at a strain rate of $\varepsilon_m = 10^{-3}\ s^{-1}$. The HV1 hardness was measured on an INNOVATEST hardness tester, with the average value from five measurements given. The shape and dimensions of a specimen for the experimental determination of CoF are shown in Fig. 1. The finishing operation on specimens was grinding. The grinding was carried out on a Struers metallographic grinder (Tegramin-30), using the SiC sandpaper (P1000) with a grain size of 18 µm. The surface roughness of specimens was measured three times on an Infinite Focus device of Alicona.

The shot peening technological process of specimens (Fig. 1) was carried out by Peen Service Company, Bologna, Italy, with parameters corresponding to the properties of C35 steel and according to [5-7]. After the technological process of shot peening and possibly grinding, the CoF was determined experimentally without and with the presence of a lubricant. There were four types of specimens, notation of which is given in Table 1.

Table 1. Notation of the Shot-peened specimens

Mark	Specimen type
SP	Shot-peened without lubrication
SPL	Shot-peened with lubrication
SPG	Shot-peened and ground without lubrication
SPGL	Shot-peened and ground with lubrication

However, an accompanying sign of shot peening is also an increase in the surface roughness of the blasted parts' surfaces, which, of course, affects the tribological processes. From the point of tribology, there are contact processes, processes of friction, wear and lubrication. Due to the fact that the condition of the surface and its roughness are decisive factors, methods are recommended to reduce the roughness, such as grinding, polishing, etc. As a result of mechanisms for reducing the surface roughness, the tribological properties of metal parts are closer to optimal.

The coefficient of friction was determined on a linear tribometer by the Ball-on-Flat test method (Fig. 2), by performing 15000 cycles of rectilinear reciprocating motion of the SiC ball over the surface at a sliding speed of 0.1 m/s. The sliding distance used for the reciprocating tribo-test was 50 mm. The test was terminated after approximately 125 minutes. During the tribological tests, the SiC ball was loaded by a normal force F_N = 10 N. The experimental data, obtained from the three measurements by the linear tribometer, were processed by the NI DIADEM software. The Mobil SHC Gear Oil was used as a lubricant. That oil is a high-performance gear oil of the highest quality, intended primarily for closed gears and sliding and rolling bearings. It retains excellent performance even in the demanding operating conditions of high and low temperatures.

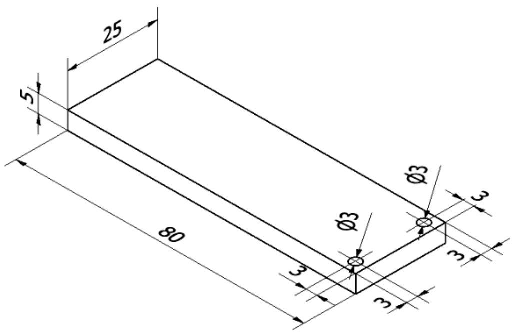


Fig. 1. Shape and dimensions of specimens for determination of the CoF

The residual stress state after the application of shot-peening was evaluated by the X-ray diffraction measurement on the ProtoiXRD device, using the CrKα radiation with an irradiated area of 1 mm^2. The diffraction signal from {222}α planes was collected at 2θ = 156.9°. The measurements were carried out using the $\sin^2\psi$ method, with nine inclinations between + 39° and - 39°; the measurements were carried out in axial (ϕ = 0 °) direction. The shot-peening parameters are given in Table 2.

Table 2. Shot peening parameters

Parameter	Value
Almen intensity	12 A
Coverage	1000%
Shots diameter	0.42 mm
Incidence angle with respect to the specimen's surface	90°

To obtain the depth profile of the residual stress distribution, the surface was gradually removed by electrolytic polishing. The depths at which the residual stress was detected were measured using a micrometer.

3. RESULTS AND DISCUSSION

The chemical composition of the experimental material – medium carbon C35 steel – (verified by the OES – Optical Emission Spectroscopy vs. the material standard), is shown in Table 3. At the same time, its mechanical properties are given in Table 4.

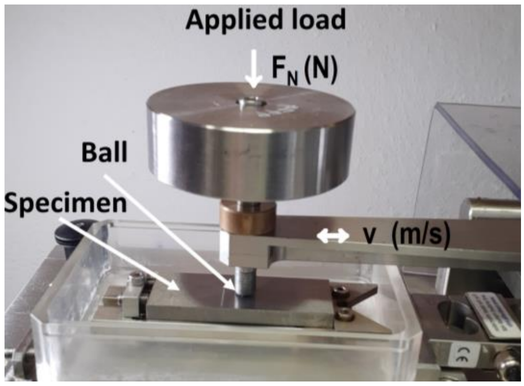


Fig. 2. Testing equipment, method Ball-on-Flat

Table 3. Chemical composition (wt. %) of the experimental material

Steel grade	Elements				
	C	Si	Mn	P	S
Experimental material	0.35	0.242	0.616	0.023	0.009
Standard	0.32 – 0.40	0.17 – 0.37	0.50 – 0.80	max. 0.040	max. 0.040

Results of the test confirmed that the experimental material composition and properties are in accordance with the material standard (ISO 683-1, C35, W.Nr. 1.1181, STN 41 2040). This steel is characterized by higher Si content, which increases the ultimate tensile strength and mainly yield strength, and Mn, which increases the hardenability [1, 2].

Table 4. Mechanical properties of the experimental material

Steel grade	Property			
	Yield point (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	HV1
Experimental material	490	730	18	227
Standard	min. 430	630 – 780	min. 17	-

The microstructure after the heat treatment (quenching and high tempering) was sorbitic formed by a ferritic matrix and globular cementite (Fig. 3) in accordance with [25].

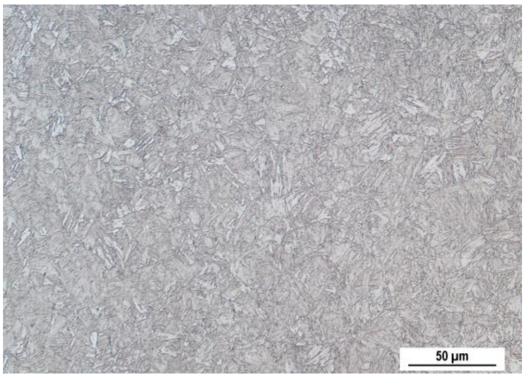


Fig. 3. Microstructure of C35 steel after the heat treatment, etch 3% Nital

The surface layers of the experimental material after the shot-peening are characterized by the appearance of the compressive residual stresses (Fig. 4). With the increase in the measurement depth, the value slowly increases and at a depth of 0.07 mm, reaches the maximum value of approximately - 441 ± 14.6 MPa.

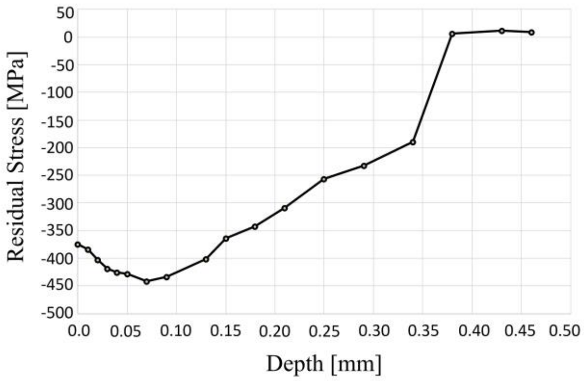


Fig. 4. Compressive residual stresses in the experimental material after application of SP

Beyond this point, the compressive residual stress values are decreasing, and they reach values close to zero at a depth of approximately 0.38 mm under the surface. The above facts are in agreement with the results presented in [4, 5-7]. The authors of those articles stated that by applying the shot-peening, one can obtain compressive residual stresses up to the magnitude of the yield stress. In the presented case, the ratio of measured stress and the yield stress was approximately 0.9.

The hardness results of the two specimens, obtained after the shot-peening, are presented in Fig. 5. It can be noticed that hardness is increased at the surface (values are 278 and 283 HV1). The hardness for the not-shot-peened material is the same under-shot-peened layer, 227 HV1.

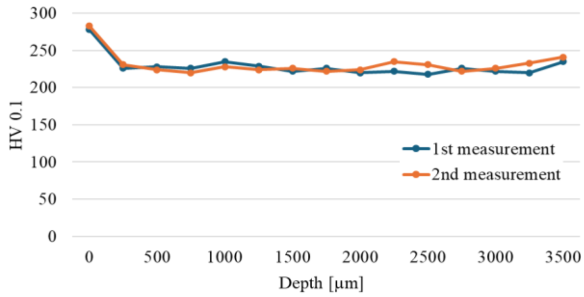


Fig. 5. Hardness values for the shot-peened specimens

In the surface layer of the material, the shape and dimensions of the grains, which are among the most important microstructural factors, change during the cold plastic deformation. The hardening of the work, besides the introduction of the residual stresses, causes the grain refining of the surface and sub-surface layers, as well. It was proven in [26] that the change in the grain size of the bulk material increases the yield point, ultimate tensile strength and hardness. However, the localization of the grain refinement only in the surface layers does not improve the total mechanical properties of the bulk material and difference is observed only in degradation mechanisms, which are surface-related.

The change in surface topography is an accompanying effect of the shot-peening process. Substantial changes in the surface features can have favorable effects on the functionality of the structural components. Therefore, it can be confirmed that surface roughness has an important role [4]. The values of the roughness profile parameters and roughness selected area parameters, including tribological (wear) trace in the transversal section for the SP and SPG specimens, are given in Table 5 (with respect to ISO 4287 and ISO 25178 standards) and in Figs. 6 – 8. The calculated average values of wear areas and wear volumes, respecting the sliding distance of 50 mm, for all the specimens' types (SP, SPG, SPL, SPGL) are given in Table 6.

Table 5. Roughness parameters of specimens [μm]

	Ra	Rz	Rq	Sa	Sz	Sq
SP	5.78	28.36	7.32	6.31	97.45	8.00
SPG	2.40	10.19	3.14	2.57	50.33	3.40

Here is applied the usual notation: for the roughness profile parameters: *Ra* – average roughness, *Rz* – average distance between the highest peak and lowest valley and *Rq* – root-mean-square roughness profile); as well as for the roughness selected area parameters: *Sa* – average height of selected area, *Sz* – maximum height of selected area and *Sq* – root-mean-square height of selected area. A significant decrease in the *Ra*, *Rz* and *Rq*, as well as in *Sa*, *Sz* and *Sq* parameters for the SPG specimens was registered, as compared to the corresponding values for the SP specimens. The grinding led to a decrease in coefficient of friction values for the SPG vs. the SP specimens for about 30% to 39% (the resulting CoF value, after stabilization, for SP was 0.39 and for SPG was 0.23). The measured results of the CoF are graphically illustrated and compared, shown in Fig. 9. From the figure, it can be seen that when the surface is stressed by friction, the initial starting roughness changes to the operating roughness (up to approximately 2250 s), which is constantly restored during the entire functional operation and shows considerable stability. This observation was noted, above all, during the dry friction [27]. The shot-peening changed the topography and surface roughness by the creation of dimples, i.e., peaks and valleys were formed. Those dimples influence friction. The sliding contact is, therefore, localized on the roughness peaks, creating very high contact pressure. In the case of reduced roughness, after the fine grinding of SP specimens, i.e., for the SPG specimens, there was a decrease in peaks and, subsequently, a decrease in the contact pressures [3, 14-17].

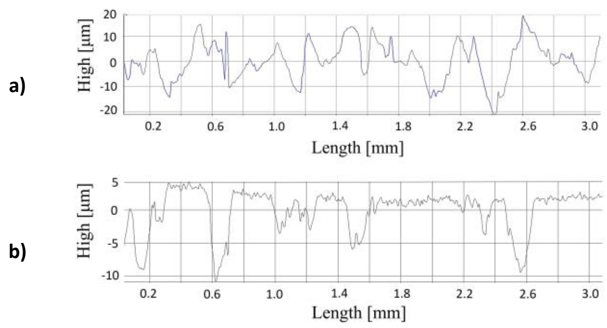


Fig. 6. Roughness profiles of specimens, a) SP, b) SPG

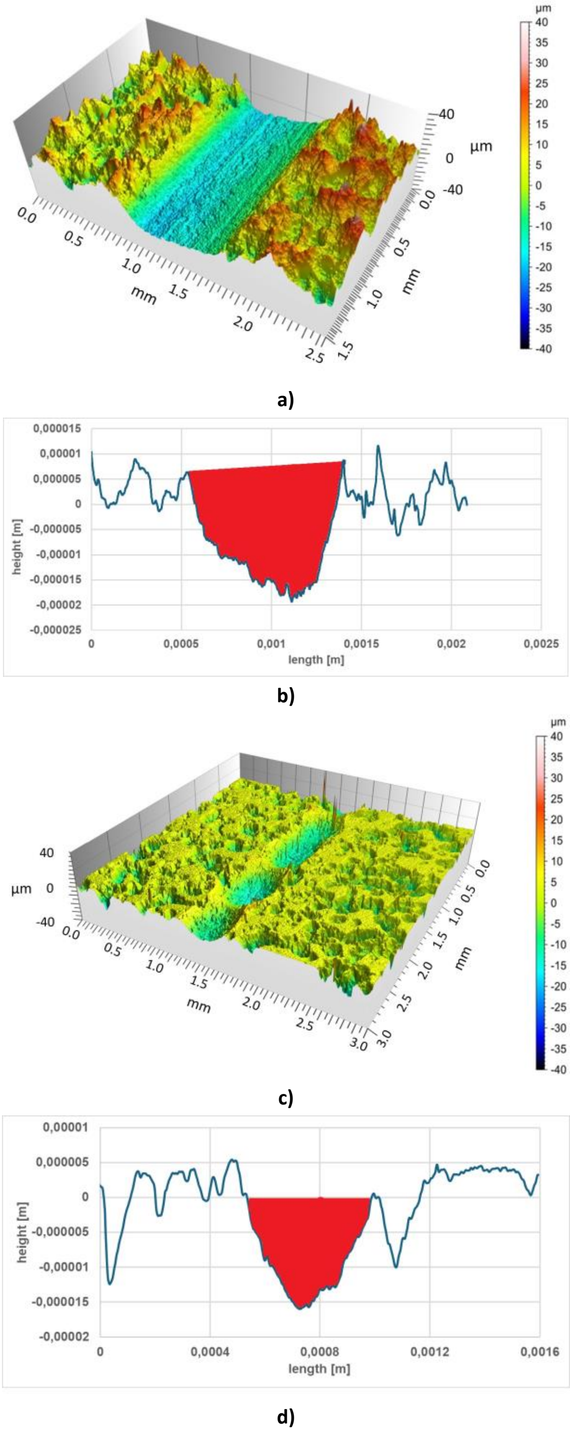
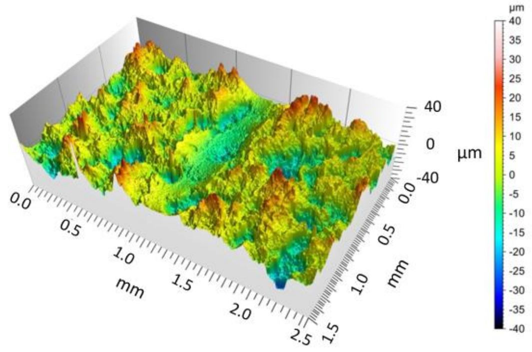


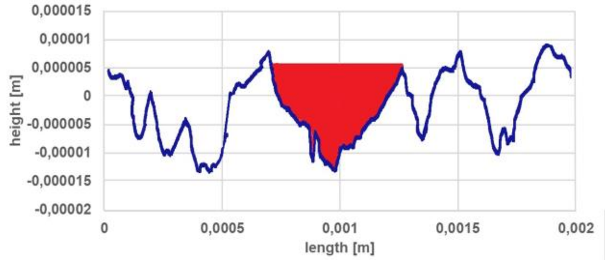
Fig. 7. 3D topographies of shot-peening surface including the tribological trace in transversal section after the dry tribology test, load F_N = 10 N; a, b) SP, c, d) SPG

Table 6. Values of wear areas and wear volumes for the specimens (SP, SPG, SPL, SPGL)

Specimens	Wear area [m^2]	Wear volume [m^3]
SP	9.585x10^{-9}	4.793x10^{-10}
SPG	4.692x10^{-10}	2.346x10^{-11}
SPL	3.856x10^{-10}	1.928x10^{-11}
SPGL	3.124x10^{-11}	1.562x10^{-12}



a)



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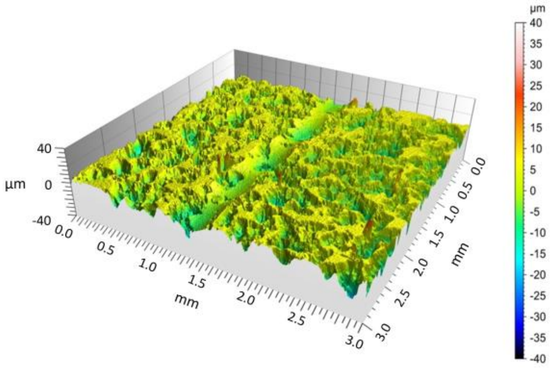

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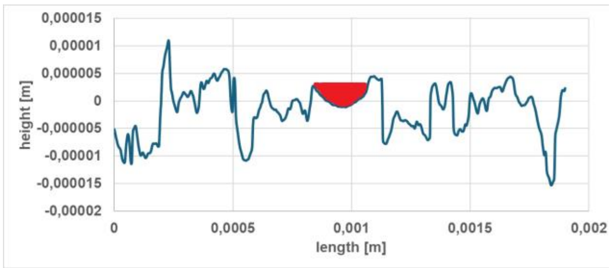

d)

Fig. 8. 3D topographies of shot-peening surface including the tribological trace in the transversal section after lubricated tribology test, load F_N = 10 N; a, b) SPL, c, d) SPGL

The coefficient of friction depends on the roughness of the surface, elastic properties of materials, specific loading, and parameters that characterize the mutual molecular interactions at the point of contact, [28].

The lubricants play an important role in friction. Lubrication is an effective means for reducing friction and limiting or almost completely suppressing the signs of wear of rigid friction bodies. The effect of surface roughness is thus suppressed [28]. The lubricant can reduce friction drastically [29]. These facts are confirmed by results for the coefficient of friction, Fig. 9.

The experimentally determined coefficient of friction results for the SPL and SPGL specimens are approximately 0.13 and are practically the same. The viscosity of the used lubricant increases due to the high pressure, and with a sufficient sliding speed, a carrier film is formed between the friction bodies. The effect of surface roughness is thus suppressed [28]. The decrease in coefficient of friction values (SPL vs. SP), namely (SPGL vs. SPG), is 66% and 43%, respectively. The coefficient of friction using the lubrication is typically of the order 0.03 to 0.2 [30]. The used oil lubricant during the sliding apparently decreased the coefficient of friction of the SPL and SPGL specimens [17, 18-23]. The minute pockets produced on the rough surface can also act as oil reservoirs, thus resulting in longer lubricant retention [11].

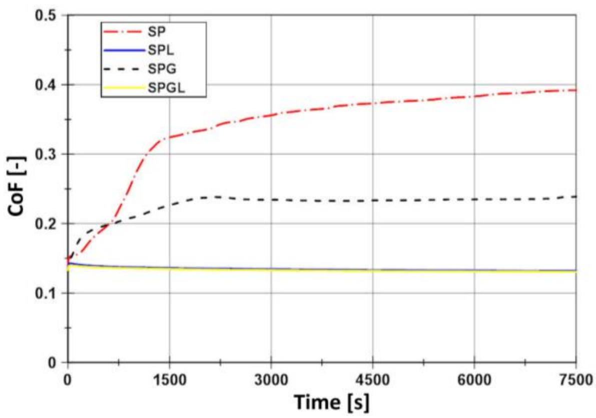

Fig. 9. Comparison of the CoF values for the SP, SPL, SPG and SPGL specimens

4. CONCLUSIONS

With regard to the obtained results on the influence of roughness, lubricant and grinding on the coefficient of friction, the following conclusions on the tribological properties of the C35 shot-peened steel can be drawn:

- Compressive residual stresses were obtained by the shot-peening with a maximum value of -441 ± 14.6 MPa.

- An increase of the surface roughness due to the shot-peening process was observed.

- The surfaces of the shot-peened fine ground specimens exhibited the lower coefficient of friction (CoF) values as compared to surfaces of the unground specimens; the stabilized CoF values were 0.39 and 0.23, for the unground and ground specimen surfaces, respectively, which are the reduction of about 39%.

- The wear areas were reduced for the ground specimens, regardless of the lubricant application (see Table 5), over 20 times for the unlubricated specimens and 12.3 times for the lubricated specimens; consequently, the wear volume was also drastically reduced for the ground specimens' surfaces.

- It should be emphasized that the grinding of the shot-peened steel reduces both its friction and wear. After removing the shot-peened induced surface roughness by grinding, the work-hardening effect became even more apparent at 3M. Thus, the increased surface hardness causes a decrease in friction (by reducing the contact between the two rubbing surfaces) and simultaneously reduces the wear due to increased abrasive wear resistance. It is also expected that the compressive residual stresses (a result of shot-peening) would increase the fatigue wear resistance in the course of time.

- The use of lubrication during the sliding significantly reduced the coefficient of friction both in the case of shot-peened finely ground specimens and in the case of unground specimens' surfaces; the decrease in coefficient of friction values for SPL vs. SP specimens was 66 %, and for SPGL vs. SPG specimens it was 43 %.

Thus, one can state that the surface roughness and lubricants play an important role in the component surface friction after the shot-peening applications.

The grinding, as the post-treatment after the shot-peening process, appeared to be extremely important for improving the tribological properties of the shot-peened surfaces, resulting in a decrease of values of the coefficient of friction, as well as of wear area and wear volume of the tested specimens.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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