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Influence of Shot Peening on the Wear Behaviour of Medium Carbon Steel

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Abstract
Influence of shot peening on the wear behaviour of medium carbon, C55 steel was experimentally verified. Experimental work included determination of the chemical composition, heat treatment, microstructure evaluation, mechanical properties measurement, shot peening treatment, the magnitude of the compressive residual stresses was evaluated, roughness profiles measurement and finally the friction tests. The results evidence the significant role played by the applied shot peening on wear behaviour of medium carbon steel. An important effect of surface roughness has been demonstrated. The coefficient of friction after shot peening compared to ground surface increased, 1.44 – 1.85 times.

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1. Introduction

The steels recommended for use in transport engineering are one of the most important groups of structural materials. Special position in the given field of engineering have medium carbon steels. These steels are heat treated by quenching and tempering to high temperatures (usually above 400 °C). The goal of the heat treatment is to achieve higher strength properties with relatively high toughness. They are characterized by a medium or high carbon content and alloys such us Cr, Mn, Si, Ni, V, Mo. Regarding their use, these steels are subject to high requirements in terms of reliability, safety, durability in real operation while respecting economic and environmental aspects (Steels, 1980; Skočovský et al., 2000).

In transport, the most common degradation mechanisms are fatigue and wear. These usually arise on the surface or at a small depth below the surface of components and structures. To increase the resistance to these mechanisms, improvements the mechanical properties of the surface layers is required. Methods of the improving the mechanical properties of the surface layers, strengthening can be static (static pressure of the tool, static pressure combined with sliding on a surface, rolling of the strengthening tool on the surface-roller burnishing, static shot peening) or dynamic (shot peening, ultrasonic shot peening, hydro tumbling, hardening by explosion and so on). The methods of surface hardening, thermo chemical treatments such as carburizing and nitriding are also used (Moravčík and Hazlinger, 2017; Moravčík et al., 2021; Bílik and Baca 2004).

Shot peening or severe shot peening are processes in which the surface layer of material is subjected to cold plastic deformation by high velocity impacts of hard particles. The result is strengthening of the material surface and creation of compressive residual stress field in the sub-surface material's layer. In the field of fatigue, the compressive residual stresses are prolonging fatigue life and result in fatigue limit increase usually up to 20 % (Bokůvka et al., 2014; Baiker et al., 2012; Miková et al., 2013; Trško et al., 2014; Lago et al., 2019; Ulewicz and Mazur, 2013; Vasko et al., 2017). However, it should be noted that incorrectly selected shot peening or severe shot peening parameters vs. material parameters can cause a reduction on fatigue strength (Holzman and Klesnil, 1972; Nový et al., 2008). Shot peening or severe shot peening technologies can be also used in the field of increasing the resistance of materials to wear. The peening process creates a typical surface texture characterized by visible surface dimples accompanied with creation of high rims on their circumference. These changes in the surface roughness influence friction (Bagherifard et al. 2019, Bagherifard et al. 2021, Wu et al. 2020). Given the importance of wear as an undesirable degradation mechanism, attention is paid to the effect of compressive residual stresses, shot peening or severe shot peening on wear. The opinions on the effect of shot peening or severe shot peening on wear are different, often contradictory. Mitrovic et al. 2014 stated that shot peening has a positive effect on tribological characteristics of investigated 36CrNiMo4 and 36NiCrMo16 steels. Shot peening produced lowering of the friction coefficient, as well as wear rate, in comparison with ground surface, in both dry and lubricated sliding and for both materials. The shot peening did not improve the wear of austempered ductile iron (Zammit et al., 2013). Yan et al., 2022 researched the effect of shot peening on the surface properties and wear behavior of heavy-duty axle gear steels. In the case of the samples treated with the coverage of 1000 % the average wear volume can be decreased by 52.26 % and the friction coefficient can be decreased by 7.69 %. Friction wear behavior of shot peened 7075-T651 aluminum alloy was studied by in (Abens et al., 2019). From the obtained results it was clear that the average coefficient of friction increased for shot peened specimen when compared to the un-peened specimen. The higher friction coefficient was measured due to the high surface roughness created during the shot peening process. Bhavar et al., 2017 in work report the results of influence of shot peening on DIN 1.2714 Hot Work Tool Steel. Both coefficient of friction and wear rate increase with increase in shot size and peening intensity. This may be because, increase in shot size and peening intensity results in higher surface roughness values which adversely affect wear performance. A similar statement, higher friction as a result of higher surface roughness after shot peening by ceramic and steel shot, is made in the work (Gangopadlhyay, 2008). Authors Palacios et al., 2014 and Trško et al., 2015 concluded that the shot peening has the potential to improve the wear behaviour of an aluminum alloy and the improved behavior of shot peening specimens was mainly attributed to the surface hardening induced by the treatment and again, also surface roughness played an important role.

The objective of this study was to experimentally verify the influence of shot peening on the wear behaviour of medium carbon, C55 steel.

2. Experimental analysis

The experimental works were focused on determining the influence of shot peening (SP) on the wear behaviour of medium carbon, C55 steel. Verification of the chemical composition of the experimental material (quantitative chemical analysis), was performed by the spark optical emission spectroscopy on a SPECROMAXx device. The experimental material was subsequently heat treated as following: austenitizaion at 820°C ± 5°C, 30 minutes, cooling in the Durixol V70 oil at 20°C ± 5°C, tempering at 450°C ± 5°C, 120 minutes with cooling on air. After the heat treatment, the specimens for tensile tests and tribology test were machined. For the tensile tests, round cross-section specimens with diameter d = 10 mm per EN 10002-1 were used. The tensile tests were carried out on a ZWICK Z050 testing machine at an ambient temperature of T = 20 ± 5°C, with the loading range in interval of F = 0 – 20 kN and the strain rate $\varepsilon_m = 10^{-3}\ s^{-1}$. The HRC hardness was measured on an RR-1DAQ hardness tester, average value from five measurements is given. Shape and dimensions of specimens for the tribological tests are shown in Fig. 1. The finishing operation on the specimens was grinding. Specimens were divided into two groups and one of them was subsequently treated by SP with parameters chosen according to works Bokůvka et al., 2014; Baiker et al., 2012; Miková et al., 2013; Trško et al., 2014; Lago et al. 2019. The SP parameters were as follows: Almen intensity 12A, coverage 100%. Cast steel shots with diameter 0.42 mm were used for the treatment, and they were shot at the incidence angle close to 90° with respect to the specimen's surface. The residual stress state was evaluated by the X-ray diffraction measurement. The ProtoiXRD device was used for the measurements, using the CrKα radiation with an irradiated area of 1 mm2. The diffraction signal from {222}α planes was collected at 2θ = 156.9°. The measurements were carried out using sin2ψ method, with nine inclinations between ± 39°. The measurements were carried out in axial (φ = 0°) and tangential (φ = 90°) direction. To obtain the depth profile of the residual stress distribution, the surface was gradually removed by electrolytic polishing. The surface roughness of specimens in the initial (ground) state and after applying of shot peening was measured on an Infinite Focus G5 device from Alicona. The friction tests were conducted in atmospheric conditions without presence of a lubricant (dry wear). The dry coefficient of friction was determined on a linear tribometer by Ball-on-Flat test method. After performing 5000 cycles of rectilinear reciprocating motion of the SiC ball over the surface at the sliding speed of 0.1 m·s^{-1}, the test was terminated after approximately 42 minutes. During the tribological tests, the SiC ball was loaded by a normal force F_N = 2 N, F_N = 5 N and F_N = 10 N. The experimental data, obtained by linear tribometer, were processed by NI DIADEM software.

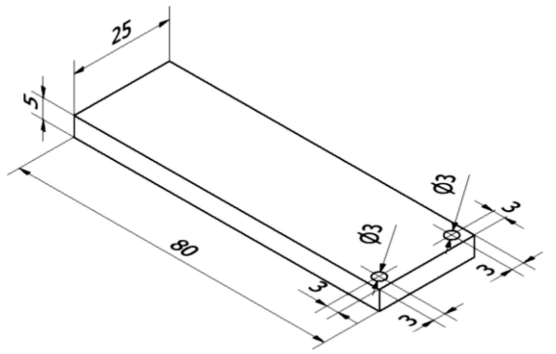


Fig. 1. Shape and dimensions of specimens for tribology tests

3. Results and discussion

The chemical composition and mechanical properties of experimental material, medium carbon, C55 steel (demonstrated by OES measurement vs. material standard) is shown in Tab. 1 and Tab. 2. The experimental material was in accordance with the material standard (ISO 683-1). This experimental material, steel is characterized by higher Si content, which increases the ultimate tensile strength and mainly yield strength, Mn, which increases the hardenability and Cr which increase the hardenability and inhibits tempering processes (Steels, 1980; Skočovský et al., 2000).

The microstructure after the heat treatment (quenching and high tempering) was sorbitic formed by a ferritic matrix and globular cementite in accordance with the work Jech, 1983.

Table 1. Chemical composition of the experimental material (in wt.%)

Steel grade	Chemical composition									
	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Fe
Experimental material	0.597	0.398	0.860	0.037	0.014	0.345	0.033	0.193	-	Bal.
Standard	0.50 – 0.60	0.30 – 0.50	0.70 – 1.0	max. 0.040	max. 0.040	0.30 – 0.50	-	max. 0.40	max. 0.30	Bal.

Table 2. Mechanical properties of the experimental material

Steel grade	Yield point [MPa]	Ultimate tensile strength [MPa]	Elongation [%]	Hardness HRC
Experimental material	1150	1316	8	43
Standard	min. 883	1128 - 1324	min. 8	37 - 44

The surface layers of the experimental material after SP are characterized by compressive residual stresses (Fig. 2). With increase of measurement depth, the value slowly increases and at a depth of 0.02 mm reaches a maximal value of approx. – 600 MPa. Beyond this point the compressive residual stresses values decrease and they reach values close to zero in depth approx. 0.2 mm under the surface. The compressive residual stresses levels are in the axial direction (φ = 0°) and in the tangencial direction (φ = 90°) practically the same. The above facts are in agreement with the works Moravčík et al., 2021; Bokůvka et al., 2014; Baiker et al., 2012; Miková et al., 2013; Trško et al., 2014; Lago et al., 2019. The authors of these works state that the application of SP can achieve values of compressive residual stresses up to the size of the yield point.

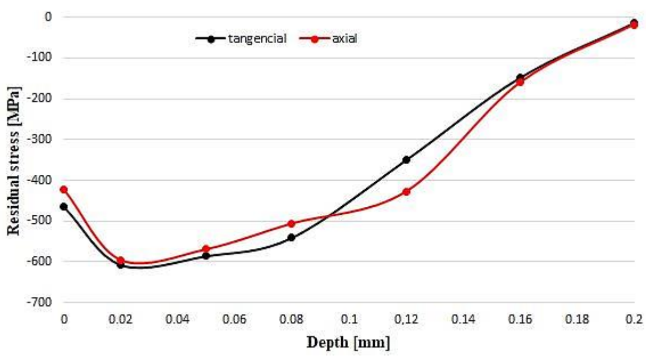
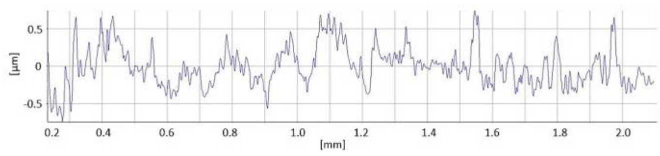
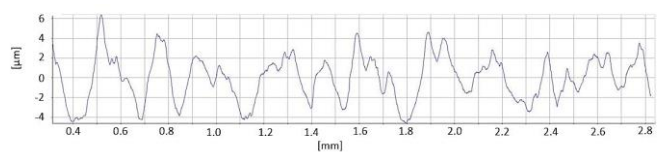


Fig. 2. Compressive residual stresses in the experimental material after application of shot peening

In the surface layer of the material, the shape and dimensions of the grains change during cold plastic deformation, which are among the most important microstructural factors. Work hardening besides the introduction residual stresses causes also grain refining of the surface and sub-surface layers. It was proven in Skočovský et al., 2015 and Höppel et al., 2010, that change of the grain size of the bulk material increases yield point, ultimate tensile strength and hardness. However, localization of the grain refinement only in 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 surface roughness of specimens in the initial state, substrate (S) and after applying of SP was measured on an Infinite Focus G5 device from Alicona. The roughness parameters (Ra, average roughness, Rq, root-mean-square roughness profile and Rz, average distance between the highest peak and lowest valley) with respect to ISO 4287 and ISO 25178 standard and 3D topographies are given in Table 3, in Fig. 3 and Fig. 4. There was a significant increase in the Ra, Rq and Rz parameters after SP compared to the S specimens.

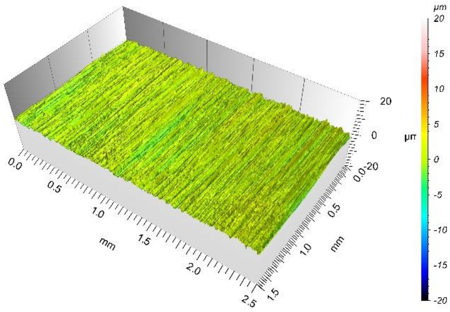


a)



b)

Fig. 3, Roughness profiles of S a) and SP b) specimens



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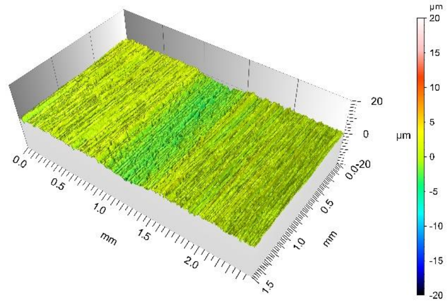

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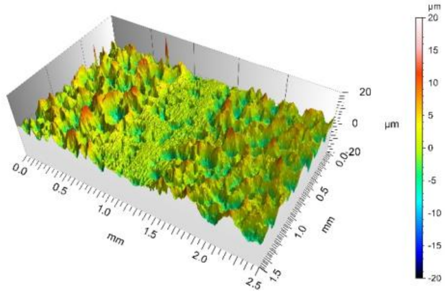

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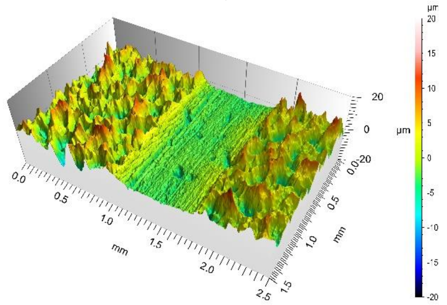

d)

Fig. 4. 3D topographies after tribology test of S, F_N = 2 N a), F_N = 10 N b) and SP, F_N = 2 N c), F_N = 10 N d)

Table 3. Roughness parameters (µm), S and SP

specimen	Ra	Rq	Rz
S	0.21	0.29	1.20
SP	1.96	2.39	8.17

The results of friction of the tested tribological pair, S vs. SP are shown in Fig. 5. The resulting values of coefficient of friction (COF) are the average values of the three measurements made for each load. From the obtained results it is clear, that the average COF is increased for SP specimens in contrast to the ground surface finishing.

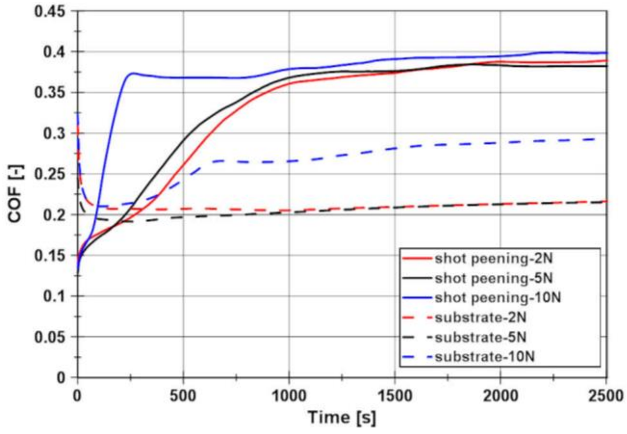

Fig. 5. Comparison of the coefficient of friction, S vs. SP at loads F_N = 2, 5, 10 N

COF after stabilization was in the case of loading F_N = 2 N, F_N = 5 N approx. 1.85 times higher, in the case of loading F_N = 10 N approx. 1.44 times higher. The SP change the topography and surface roughness by creation of dimples that is peaks and valley are formed. These dimples formed by shot peening influence friction. The sliding contact is therefore localized on the roughness peaks creating very high contact pressured - Fig. 3, Fig. 4 and Table 3. During repeating sliding, these surface peaks are worn down what results in enlargement of the contact area and decrease of the contact pressure. This is the reason why it takes approx. 1000 seconds to saturate the COF behaviour on the shot peened surfaces. Results of the higher COF were in agreement with Moravčík and Hazlinger, 2017; Abens et al., 2019; Bhavar, et al., 2017; Gangopadlhyay, 2008; Palacios et al., 2014; Trško et al., 2015 due to higher surface roughness. Shot peening generates higher roughness compared to ground surface, meaning that it highly increases contact points of asperities, or real contact area between two materials in contact (Mitrovic at al., 2014).

4. Conclusion

Based on the experimental analysis performed on ground and shot peened medium carbon, C55 steel, the following conclusion can be drawn:

- compressive residual stresses were achieved by the shot peening,
- increase of the surface roughness due to peening process was observed,
- in comparison to ground material, the coefficient of friction of shot peened steel was increased after performing of shot peening from 1.44 to 1.85 times.

In this study, reduction of COF was not achieved by the shot peening process. Testing of other peening process parameters such as, different intensities, shot geometry and coverage needs to be further investigated.

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喷丸强化对中碳钢磨损行为的影响

關鍵詞
钢
喷丸强化
磨损行为

摘要

实验验证了喷丸强化对中碳C55钢磨损行为的影响。实验工作包括确定化学成分、热处理、微观结构评估、 机械性能测量、 喷丸处理、 评估压缩残余应力的大小、粗糙度轮廓测量以及最后的摩擦测试。 结果证明了喷丸强化对中碳钢磨损行为的重要作用。已经证明了表面粗糙度的重要影响。 喷丸后的摩擦系数与地面相比增加了 1.44 - 1.85 倍。