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INFLUENCE OF SHOT PEENING ON ABRASION WEAR IN REAL CONDITIONS OF Ni -Cu-AUSFERRITIC DUCTILE IRON

The paper presents results of the wear tests of chain wheels made of austempered ductile iron with various content of residual austenite. The aim of this study was to demonstrate the impact of the dynamic surface treatment (shot peening) on wear properties of surface layers of the chain wheels tested that were subjected to the action of quartz abrasive. Apart from determining the value of the abrasive wear, examinations of the magnetic phase content in the microstructure were carried out and plots of hardness of the surface layer as a function of the distance from the surface and microstructure of the materials were prepared. Based on the results, the following was found: an increase in the abrasive wear and a reduction in the hardness of the surface layer of chain wheels subjected to shot peening, as well as reduction of susceptibility to negative action of the shot for cast irons with the structure of upper ausferrite.

Keywords: ADI, shot peening, wear, abrasion,

1. Introduction

Materials that optimally combine good operating properties with economy of the manufacturing process have been sought for many years [1,2,3,4]. When analysing the materials and technologies used in the terms of cost-effectiveness, it has been found that toothed elements made of austempered ductile iron (ADI) and manufactured with the use of the sand casting method are characterised by a very favourable ratio of the operating properties to the production price. As a result of an appropriate heat treatment, ADIs obtain an austempered structure characterized by favourable performance characteristics.

The main aim of the studies presented in this paper was to find whether it is possible to reduce the wear of mating elements through the preliminary strengthening of the surface due to the transition of the residual austenite into martensite under the influence of a shot stream. The practical significance of these studies is considerable, because they may allow obtaining appropriate wear properties of the surface layer as early as at the stage of production. The results of the tests presented in this paper are continuation of the studies [5,6] which concerned the impact of the dynamic surface treatment on the wear resistance.

ADI cast iron, since the development of the technology of its production in the 1970s, has been used in elements working in difficult conditions as well as in parts that require a combination of good strength and wear parameters [7,8,9,10]. Despite good performance characteristics of austempered cast irons, methods for improving their capabilities are continuously being sought for. Shot peening is a process that sets high expectations.

It has been used for many years to increase the durability of machine elements exposed to the action of a construction notch or to compensate for adverse effects of other processes making up the production technology of a specific detail. An example of this type of elements are toothed elements [11,12,13] used in highly loaded industrial gears or in gears used in transport systems. The dynamic action of shot during the shot-peening process [14] substantially modifies the stress distribution in the surface layer, increases the surface hardness, and leads to the transition of residual austenite into martensite under the influence of stresses. As a result of the plastic deformation of the surface, compressive stresses occur in the surface layer of the materials treated, the value of which depends on the properties of the metal treated and on the shot peening parameters.

In the case of ADIs, there was also found an increase in the surface hardness that resulted from shot peening as well as a favourable influence of compressive internal stresses on their performance characteristics, but an increase in the roughness associated with the dynamic surface treatment process was also observed at the same time. Zammit et al. [15] examined the fatigue strength of ADI containing Cu and Ni that was austempered at the temperature of 360°C. The samples subjected to shot peening had the strength by approx. 60% higher than the ground samples. The authors explained that the properties had been improved due to an increase in the value of compressive stresses which inhibited the formation and propagation of cracks in the surface zone. Benam et al. [16] also examined the fatigue strength of three variants of ADI austempered at a temperature ranging from 320 to 400°C and they found that the strength had increased by 27.3–48.4%. Mhaede et al. [17] obtained similar results. However, Myszka et al. [18] found that in order to start a deformation-induced transformation of austenite into martensite, the stresses caused by shot peening must have adequate values dependent on the type of cast iron. Thus, identical process parameters may have

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different effect on the microstructure in the case of different types of cast iron.

Ohba et al. [19] conducted comparative wear tests under conditions of rolling movement with lubrication for ADI subjected and non-subjected to shot peening. They found no significant differences between the wear for both variants of surface treatment. They explained that such a result had been obtained due to fact that the negative impact of the increase in the roughness had been compensated by a favourable increase in the surface hardness and the introduction of additional compressive stresses. Sharma [20] found that in the case of shot-peened ADI containing Ni and Mo, the fatigue strength had dropped by 35-45% as compared with carburized steel. The author explains that such a result was obtained due to greater roughness of the ADI's surface and its lower hardness as compared with the carburized steel. Zammit et al [21] examined the fatigue strength of shot-peened and not shot-peened lubricated surfaces of ADI containing Ni and Cu. Surfaces in both variants differed significantly in terms of roughness. Based on the cone/three balls wear tests carried out in the presence of the lubricating oil, it has been found that the resistance to pitting for the shot-peened variant increased by 72% due to a negative impact of the higher surface roughness and the damage to graphite nodules caused by shot hits. Similar results of comparative tests for the surface resistance to pitting of ADIs subjected and not subjected to shot peening were presented by Vrbka et al. [22].

2. Experimental details

2.1. Characteristics of the wear tests

The tests of wear properties of alloy cast iron were carried out on an especially designed test rig that allows reproducing the real operating conditions of chain wheels. The test rig is presented in Fig. 1A, while [1] describes in detail the methodology and the test rig itself. The abrasive wear of the chain wheels was obtained by filling the test box with quartz abrasive, which resulted in its continuous presence between the chain wheels tested and the chain surface. A set of chain wheels made of ADI subjected to shot peening was used for the wear tests. Depending on the austempering temperature, the chain wheels had the following designations: ADI_240_SP, ADI_270_SP, ADI_310_SP and ADI_360_SP. The results obtained for a set of not shot-peened chain wheels were used as the reference level (designations of the set of wheels: ADI_240, ADI_270, ADI_310 and ADI_360) as a part of study [4].

The chain wheels, in the area of the contact between a wheel and the chain (Fig. 1B), were subjected to a dynamic treatment (shot peening) with the Almen intensity of 0.32% mmA and the coverage of 2x100%. Shot peening was conducted with the use of cut and rounded shot with the diameter of 0.6 mm and the hardness of approx. 54 HRC. The main wear tests were carried out in the presence of loose quartz abrasive for 200 hours, 100 hours for each rotation direction of the motors. The tangential velocity of the chain wheels was v = 0.7 m/s, while the energy consumed by each of the motors was PM1= PM2 = 7.5 kW. The surface pressures determined between the surface of the wheel and the chain were at the level of 48.9 MPa, while the maximum equivalent stresses at the tooth base were at the level of 2.18 MPa.

2.2. Characteristics of ADI

The input material for the production of the ADI was EN-GJS-600-3 (PN-EN 1563) ductile iron with the compositions presented in Table 1.

The ductile iron castings had a pearlitic-ferritic structure with the graphite nodule count of 200 per 1 mm^2, while the spheroidization of graphite was greater than 90%. After the final material removal processing the ductile iron castings were subjected to a heat treatment in order to obtain an austempered structure typical of ADI. The parameters of heat treatment in a salt bath used for the wheels under consideration are shown in Table 2, while the mechanical properties obtained – in Table 3.

TABLE 1
Chemical composition of ductile iron EN-GJS-600 [mass%]

C	*Si*	*Mn*	*S*	*P*
3,50	2,54	0,16	0,013	0,041
Mg	***Cr***	***Cu***	***Ni***	***Mo***
0,047	0,026	0,50	1,40	0,24

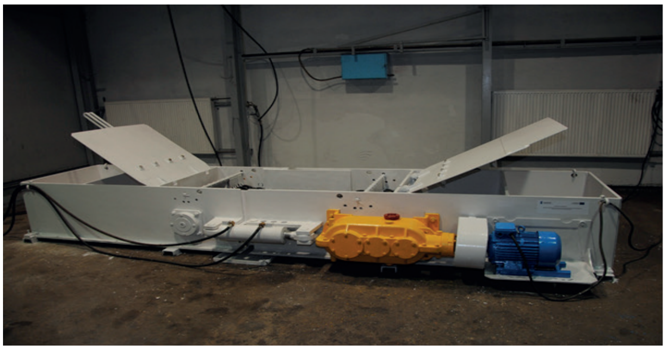
TABLE 2
List of the process parameters used in the production of the chain wheels tested

Heat treatment parameters	ADI_240	ADI_270	ADI_310	ADI_360
Austenitising temperature,ºC	950			
Austenitising time, min	180			
Austempering temperature,ºC	240	270	310	360
Austempering time, min	150			

3. Results

3.1. Results of the wear tests

When performing the wear tests in the presence of quartz abrasive, the mating surfaces of the wheel and the plain link chain were subject to cutting, scratching and ridging by the quartz abrasive. Damages to the area of mating between the chain and the chain wheel had a form of shallow pits formed due to the action of hard quartz abrasive (Fig. 2). Table 4 presents the values of the abrasive wear δ_{AVR_MAX} determined for the chain wheels tested in the presence of the abrasive, as well as the measures of dispersion.



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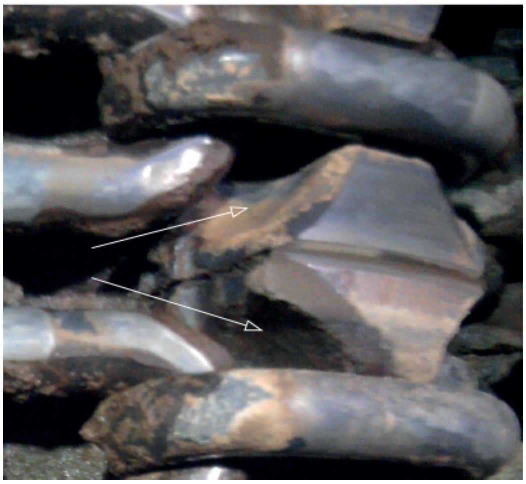

B

Fig. 1. Test rig, A – general view, B – view of the zones of contact of the chain with the chain wheel subjected to shot peening (indicated by arrows)

TABLE 3

Mechanical properties of the ADIs tested

Mechanical Properties	*ADI_240*	*ADI_270*	*ADI_310*	*ADI_360*
Tensile Strength TS, MPa	1507	1372	1132	1028
Yield Strength YS, MPa	1072	936	804	652
Impact Toughness K, J	54	72	84	124
Elongation A5, %	3	4	5	10

3.2. Results of the hardness tests

On surfaces of the toothed elements (before and after shot peening) Brinell hardness was measured and the difference between both these values was determined: $\Delta HB = HB_{After\ SP} - HB_{Before\ SP}$ (Table 5). Along with an increase in the austempering temperature, the degree of hardness (described by ΔHB parameter) becomes higher.

After the wear tests, the chain wheels were cut in the area of mating between the teeth and the chain, and then this surface was ground. After that, Vickers hardness HV0.1 was measured as a function of the distance from the surface and the hardness distributions were determined.

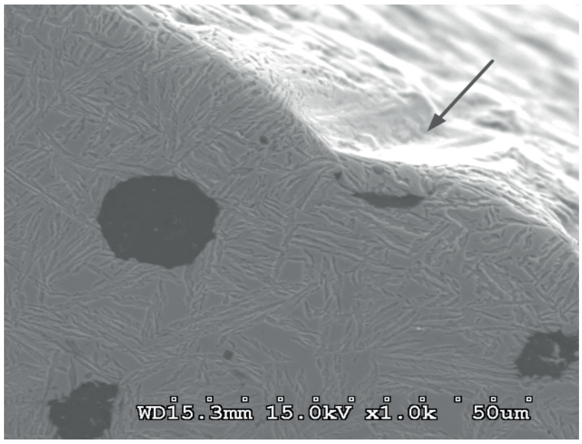

Fig. 2. View of the area of mating between the ADI_360_SP chain wheel and the chain (SEM); the arrow indicates a microscratch resulting from the action of the abrasive

TABLE 4

The determined parameters characterizing the abrasive wear

Designation of sample	δ_{AVR_MAX}, *mm*	S_δ, *mm*	$S_{\delta x}$, *mm*
ADI_360	0,930	0,28	0,057
ADI_310	0,920	0,24	0,05
ADI_270	0,800	0,18	0,037
ADI_240	0,710	0,18	0,037
ADI_360_SP	1,017	0,17	0,035
ADI_310_SP	0,962	0,32	0,066
ADI_270_SP	0,920	0,27	0,056
ADI_240_SP	0,887	0,28	0,099

TABLE 5

Comparison of values of Brinell hardness HB before and after shot peening and the difference in hardness ΔHB caused by shot peening

Designation	$HB_{Before\ SP}$	$HB_{After\ SP}$	ΔHB
ADI_240_SP	387,2±17	394,8±20,1	7,6
ADI_270_SP	382,0±6,8	390,0±8,3	8,0
ADI_310_SP	335±8,9	350,4±10,0	15,4
ADI_360_SP	283,6±3,9	316,8±9,3	33,2

Fig. 3 shows a comparison of plots of hardness as a function of the distance from the surface, determined for both variants. The plots obtained are characterized by considerable variability of the Vickers hardness in the range from 0 to 0.2 mm. It can be easily seen that the maximum hardness of wheel surfaces increases along with a decrease in the austempering temperature, and thus a reduction in the content of austenite. A reduction of hardness HV0.1 in the superficial zone for the shot-peened variant as compared with not shot-peened variant of the chain wheels can be seen in this figure.

3.3. Macro- and microscopic observations

The observations were done using Zeiss AXIO Observer optical microscope. On the surface of all the ADIs subjected to shot peening, plastic deformations with the shape of spherical cavities can be observed. They were caused by the dynamic action of the shot and a quite large number of shallow superficial line cracks.

After the wear tests, samples for metallographic examinations were cut out from the area of mating between the chain wheel and the chain. Then the samples were ground, polished and etched with 2% Nital solution.

The microstructure of the ADI_360_SP matrix (Fig. 4) consists of upper ausferrite with the austenite content of 40%. The matrix of ADI_310_D consisted of upper ausferrite with the austenite content of approx. 27%. The microstructure of the ADI_270_SP matrix consisted of lower ausferrite with the austenite content of approx. 20%. The microstructure of the ADI_240_SP matrix also consisted of lower ausferrite (Fig. 5) with the austenite content of approx. 12%.

3.4. Examinations of the magnetic phase content

The content of magnetic phases was measured with the use of the Fisher MP 30 feritscope in the area of mating between the chain wheels and the chain before and after shot peening of the chain wheels (Table 6). The uncertainty of the magnetic phase measurement determined for the confidence level of 0.95 was less than 5%.

TABLE 6

The determined magnetic phase contents in the chain wheels tested

Designation	*Before Shot peening*	*After Shot peening*
ADI_360_SP	46,2%±2,1	53,9%±2,3
ADI_310_SP	44,0%±2,0	57,1%±2,5
ADI_270_SP	50,1%±2,4	59,2%±2,4
ADI_240_SP	42,0%±1,9	60,0%±2,7

The share of the magnetic phases of chain wheels after shot peening was higher by 8–18 % as compared with the not shot-peened wheels. So it appears that in all the chain wheels subjected to shot peening the number of paramagnetic phases was reduced in favour of ferromagnetic phases (ferrite and martensite).

No growth of ferrite takes place as a result of deformation (as it was found by Garin and Mannheim [23]), so it can be concluded that the martensite content increases as a result of the phase transition caused by the action of the shot.

4. Discussion

Fig. 6 presents a comparison of the plots of the wear of chain wheels determined for the shot-peened and not shot-peened variants as a function of the austenite content in the ADI matrix.

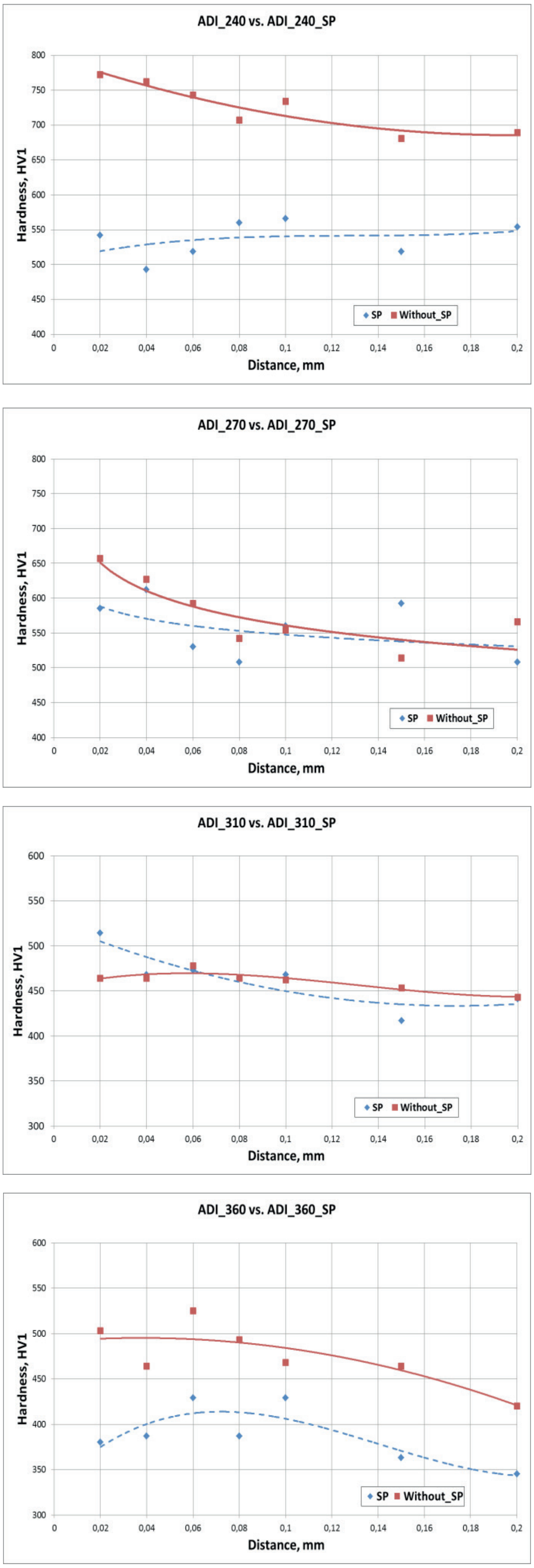

Fig. 3 Comparison of plots of hardness HV0.1 for the shot-peened chain wheels (SP) and not shot-peened wheels (Without_SP)

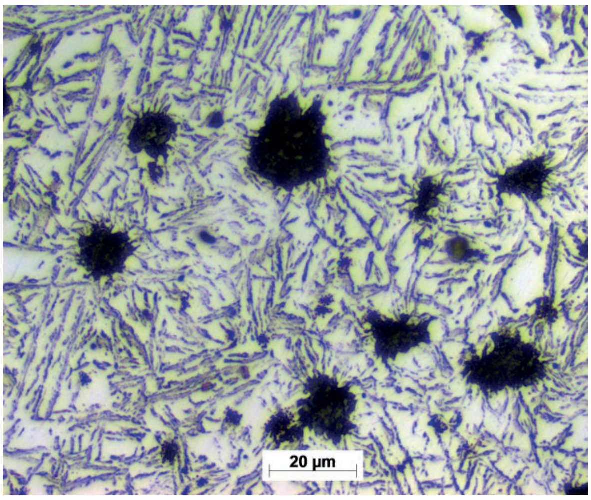

Fig. 4. Microstructure of ADI_360_SP

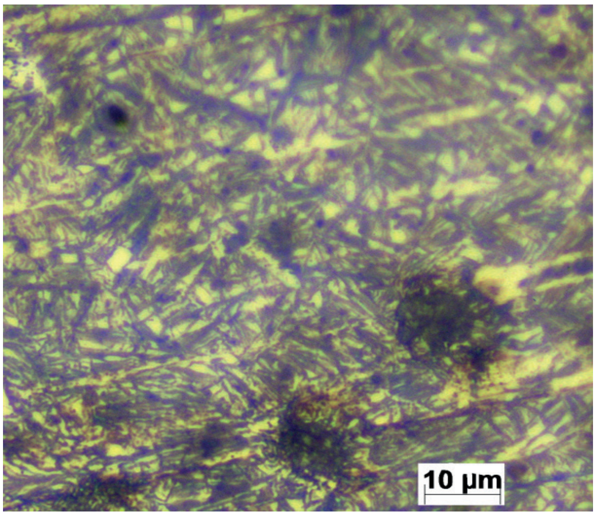

Fig. 5. Microstructure of ADI_240_SP

The following can easily be seen in this figure:

- a linear dependence of the wear on the content of austenite is observed for the shot-peened and not shot-peened wheels,
- higher values of the wear of chain wheel surfaces were found for the shot-peened variant as compared with the not shot-peened variant.

When expressed in percentage, the use of shot peening caused an increase in the wear of chain wheels by 4.1%–25,5% as compared with the not shot-peened variant (Fig. 7). Higher values of the difference in the wear between the shot-peened and not shot-peened variants are observed for ADIs austempered at lower temperatures (240°C and 270°C). These ADI are characterized by higher mechanical strength, but worse plastic properties (Tab. 3).

When analysing the results, it can be concluded that giving initially more favourable characteristics to castings of the chain wheels through the process of dynamic surface treatment did not translate into more favourable operating properties. Such favourable characteristics of castings include higher initial surface hardness (for the cast iron with the highest content of austenite the increase in the hardness was approx. 11%, while for the cast iron with the lowest content of austenite – approx. 2%) and the growth of the ferromagnetic phase which proves the phase transition of the residual austenite into martensite. Based on the results of studies [15 to 22], it should also be assumed with a high probability that compressive stresses occurred in the surface layer.

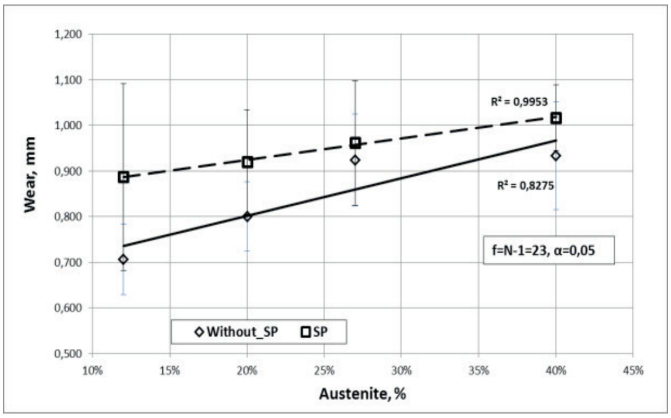

Fig. 6. Comparison of the wear in the presence of abrasive for the shot-peened (SP) and not shot-peened (Without_SP) chain wheels

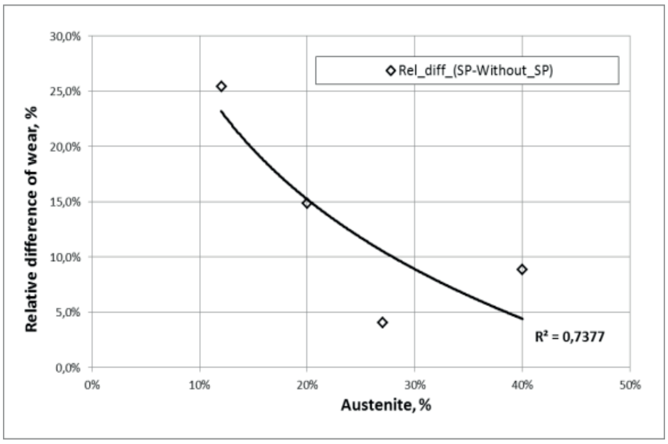

Fig.7. The relative difference in the wear of the shot-peened and not shot-peened chain wheels as a function of the content of austenite

However, as a result of the action of the shot at a high pressure, there occur not only more favourable phase transitions in the cast iron, but also graphite is removed from the surface of the element as well as some deformed areas occur, which can initiate surface cracking of the matrix and may deform the graphite located deeper under the surface. The initiated changes may facilitate the action of the abrasive grains on the surface of the chain wheels in the form of cutting, scratching or ridging of the surface layer (Fig. 2 shows a microscratch caused by the action of hard abrasive; below this groove, a small, significantly deformed graphite spheroid can be seen).

A decrease in the energy required to loosen the material of a toothed element with the use of abrasive grains is associated with the growth in the deformed area (in a measurable way this effect manifests itself by an increase in the roughness) caused by the shot peening process. This may reduce the intensity of the process of phase transition of residual austenite into martensite. The martensite formed on the surface of ADI as a result of the action of the shot is initially removed by the abrasive, but increased susceptibility to the penetration by abrasive grains may reduce the stresses in the surface layer and thus the amount of the residual austenite transformed into martensite can be lower as compared with the situation where the zone of surface deformations does not exist. This is confirmed by Fig. 3, in which it is easy to notice a reduction in hardness measured for the shot-peened variant as compared with the not shot-peened variant.

The last issue to be discussed is a reduction in the susceptibility to adverse impact of shot peening and thereby an increased surface roughness of ADI austempered at higher temperatures (360°C and 310°C), for which the least deterioration in the wear resistance caused by the shot peening process was found. The ADI tested have different impact resistance (Tab. 3) which depends on the content of residual austenite [24–26]. A relatively high content of block austenite in the structure of upper ausferrite enables a phase transition into martensite, but also causes that not entire austenite will be transformed, which ensure that a satisfactory level of plastic properties will be achieved. The possibility of deformation of the structure probably prevents the development of cracks along the austenite-ferrite phase interface in the surface layer of cast irons [27].

5. Conclusions

1. Based on the wear test reproducing the real operating conditions of chain wheels, it has been found in this study that shot peening of the area of mating with the chain caused an increase in the abrasive wear.
2. The favourable effects of shot peening, the increase in the hardness and the transformation of austenite into martensite did not compensate the adverse effects of the increased surface roughness and the initiation of damage to graphite which could be a source of crack propagation along the austenite-ferrite phase interface in the matrix.
3. A reduction in the hardness of the surface layer of the chain wheels submitted to shot peening was found in this study. This was probably caused by a reduction of the stresses associated with the action of abrasive grains on the surface layer.
4. The reduction in the susceptibility to the negative impact of shot peening observed for cast irons with the structure of upper ausferrite is associated with plastic properties of residual austenite.

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