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CHANGES OF SURFACE LAYER PROPERTIES IN GEAR TEETH AFTER SHOT PEENING

ZMIANY WŁAŚCIWOŚCI WARSTWY WIERZCHNIEJ ZĘBÓW KOŁA ZĘBATEGO NAGNIATANEGO DYNAMICZNIE

Key words:

shot penning, gears, microhardness

Słowa kluczowe:

nagniatanie dynamiczne, koła zębate, mikrotwardość

Abstract

Considering the phenomenon during teeth cooperation in a toothed gear and produced loads within the macro and micro areas of contact surface, one should be paying attention to the type and condition of the surface layer. Shot peening is often recommended, especially for gears particularly loaded in addition to hardening by heat treatment. Therefore, the study presents hardness changes in tooth surface layers after shot peening, when the surfaces had been previously carburized and quenched. The article presents hardness distribution over the depth of the teeth. Measurements were made on oblique polished and etched

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surface, which allows the identification of the microhardness near the outer surface and through the depth up to the core. Furthermore, based on data analysis obtained from X-ray diffraction, the amount of retained austenite was estimated and changes in the metallographic structure after shot peening were illustrated.

INTRODUCTION

Tribological wear in a direct way leads to changes in the surface layer, both in a quantitative and qualitative way. The surface layer is a thin area of material with a different structure and with different properties than the material in core of the element under consideration. It`s limited by the actual outer surface of the detail and includes some of the material up to core **[L. 1**, **2]**. It should be understood that the surface layer is a set of points contained between the outer surface of the material and the imaginary surface, which is the boundary of any significant changes. These changes depend on the type of the material of the core, its chemical composition, and its physical properties, as well as on external factors, mainly the type and parameters of finishing treatment **[L. 1]**.

Gears are particularly vulnerable to the adverse phenomena causing their wear **[L. 3**, **4]**. From the exploitation point of view, an important property is the fatigue strength. Fatigue strength is closely linked with the state of the surface layer and the geometric structure of the surface of the cooperating components. Improving both the state of the surface layer and its geometrical structure is accomplished during the finishing treatment of the workpieces **[L. 5**, **6]**.

The most important group of materials for gears are steels **[L. 9]**. Steel amply meets the requirements during the design and exploitation of gear wheels. Steel is easy to treatment and at the same time has high strength. To fully exploit the properties of steel intended for gears, it should be subjected to suitable treatment that will enhance its hardness, while maintaining the ductility of the core. These include the methods of thermochemical treatment **[L. 7, 8, 9]**: carburizing, quenching, nitriding, normalizing, annealing, and tempering.

The hardness of steel is determined mainly by the content of the carbon, which in combination with iron forms carbides. In the groups of raw steels, which include steels intended for normalizing and thermal improvement, the carbon content is 0.3 – 0.45%. Instead, in the steels intended for hardening, the carbon content varies from 0.4% to 1.7%, depending on the heat treatment.

After the carburization process, usually quenching is performed (from temperature of carburizing or after cooling to 820°C). After the heat treatment, it`s necessary to carry out the grinding of the teeth **[L. 7, 9]** and it is possible to perform burnishing.

Burnishing consists on mechanical strengthening of the surface layer of a wide variety of materials. It mainly improves the surface roughness, and extends the fatigue strength of the workpiece. Essentially, gear burnishing can be divided into two categories: static and dynamic burnishing. The static method (in which forces affects – during processing – statically, rigidly or elastically) involves the use of a special device consisting of three gear wheels which have quenched and precisely grinded teeth, between which the processing wheel is placed. However, this method is not devoid of disadvantages and it is not frequently used. Instead, dynamic methods (where the forces interact dynamically – periodically changeably – with a workpiece) may be implemented as an impact processes (forced or free). The most frequently used is shot peening, using the stream of ball-shape particles (**Fig. 2**) **[L. 5**, **7, 8]**.

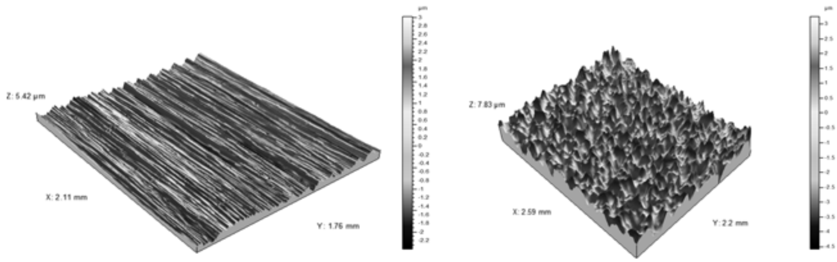

Fig. 1. Tooth surface topography after grinding (on the left) and after shot peening (on the right) [L. 10]
Rys. 1. Topografia powierzchni zęba po szlifowaniu (po lewej) oraz po pneumokulowaniu (po prawej) **[L. 10]**

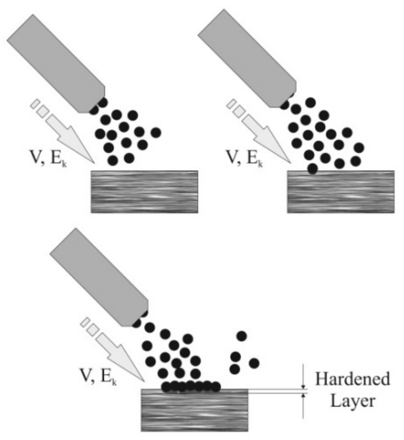

Fig. 2. The concept of the shot peening process [L. 10]
Rys. 2. Idea procesu pneumokulowania **[L. 10]**

Burnishing processes significantly increases the fatigue strength of a workpiece. The increase in fatigue strength is caused by introducing beneficial state of self-stress (compressive – **Figure 3**), and the strengthening of the surface layer and also accomplished by the reduction of micro notches on the surface, by changes in the surface geometrical structure.

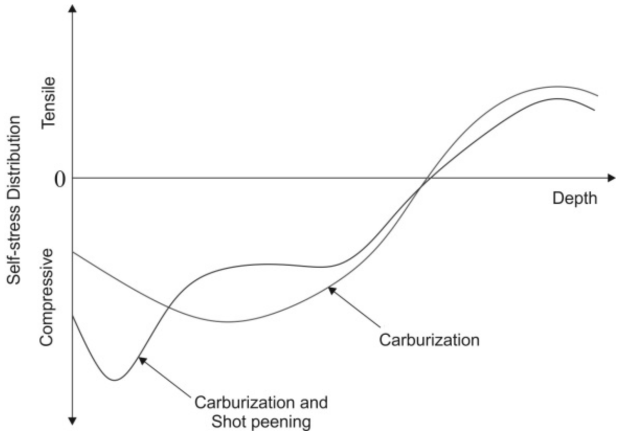

Fig. 3. An example of a stress distribution in surface layer after carburization and after carburization and shot peening [L. 10]

Rys. 3. Przykładowy rozkład naprężeń w warstwie wierzchniej po nawęglaniu oraz po nawęglaniu i naganiataniu dynamicznym **[L. 10]**

Fatigue strength is primarily affected by the following:

- The mechanical properties of the material,
- The distribution of self-stress, and
- The distribution of hardness.

MICROHARDNESS OF SURFACE LAYER AFTER SHOT PEENING

Among the variety of properties of materials used in machinery construction, mechanical properties are very important, i.e. such properties of the material which determine its ability to withstand mechanical loads acting during exploitation. Magnitudes of these properties are determined by a number of different strength tests, the most common are the static compression, shear, torsion tests, and hardness testing, including micro-hardness measurements.

The most popular hardness measurement method is a static pressing of indenter, in which the centred forces acting on the penetrator make a permanent deformation on the tested surface. This indentation made by a strictly defined standard penetrator, which is made from very hard material not subjected to deformations during measurement **[L. 11]**.

According to the standard **[L. 12]**, the scope of microhardness includes all measurements under a load up to 2N on the indenter and with the depth of penetration greater than 0.2μm. Depending on the type of indenter, there are two main methods of measurement:

- Vickers hardness tests, and
- Knoop hardness tests.

The present study used Vickers hardness test (HV) to determine the distribution of the microhardness of the surface layer. In the Vickers method, diamond penetrator should have the shape of an orthogonal pyramid, wherein the angle between the opposite side walls should be in the range of α = 136°±20'. The vertex should be sharply pointed, wherein the permissible length of the edge of the vertex should be equal to 5 μm.

Due to the accuracy of the measurement, the maximum permissible load should be selected in order to obtain a clear indentation, resulting in a significant reduction in the relative error during the linear measurement of the diagonals. If the aim of the research is to determine the average hardness of the metal alloy, the length of the diagonals of an indentation should be much greater than the length of individual grains **[L. 11]**.

Microhardness distribution measurement in a gear surface layer after shot peening

The measurement was performed on gears used in the drivetrain of a coal harvester. Gears after carburizing and quenching were shot peened at "OSK-Kiefer GmbH Oberflächen & Strahltechnik," based in Oppurg, Germany.

Microhardness measurements were performed on the sloped metallographic section (1:10) in order to obtain data about the changes directly on and below the surface of the specimen. Properly prepared samples were mounted in the holder (polished and etched), on the table of the microhardness tester UHL VMH-002VD, so that the tested surface was perpendicular to the axis of the symmetry of the indenter. In order to determine the minimum distance between the individual measuring points, 3 measurements were performed on perpendicular metallographic sections in the core and in the contact surface of the samples. The average micro-hardness of the core was equal to 607 HV, and the designated minimum measurement step was 69.92 μm. The minimum distance of the indentation from the edge of the specimen was 43.70 μm, and the minimum thickness of the specimen was 26.22 μm.

Due to the possibility of a significant scatter of results, a proper test field was designated in order to investigate the distribution of micro-hardness of the surface layer to a depth of 0.6 mm, assuming that the minimum distance between the indentations is equal to 70 microns. In one measurement series at a given depth, the procedure of the study defined the set of 10 measurement points for the assumed confidence interval p = 0.95, a fraction size = 0.7, and a standard error = 0.1. This field comprises a symmetry of an oblique metallographic section and has the shape of a rectangle measuring 770 μm x

3430 μm. At each point, 3 measurements were made in accordance with the cardinality for the average value of an unknown standard deviation n ≥ 2.994.

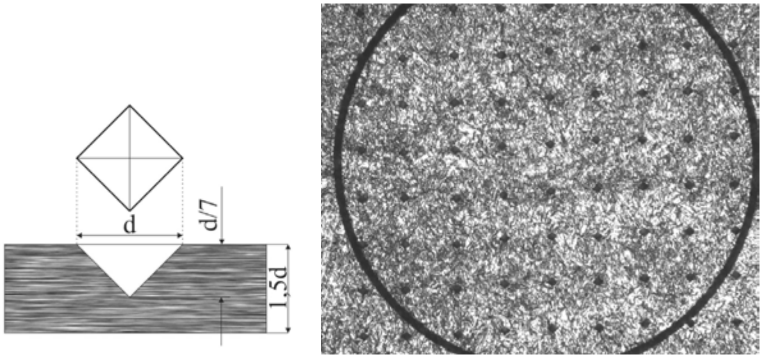

Fig. 4. Geometrical dependencies between penetrator-indentation, and a view of the test field (magnification x100) [L. 10]
Rys. 4. Zależności geometryczne wgłębnik – wgniecenie oraz widok pola pomiarowego (pow. 100x) **[L. 10]**

After obtaining the results from all measuring points (**Fig. 5**), outlier tests were performed to determine whether one of the values in the list is a significant outlier from the rest – Q-Dixon test and T-Grubbs. For the Dixon test with the cardinality n = 10, the critical parameter determining the usefulness of a result in the series with the confidence interval = 0.95 is D> 0.466. The critical parameter for the Grubbs test was G> 2.18. After rejecting outliers and defining N – valid measurements, the mean values of microhardness were calculated along with the errors. A fragment of obtained results are shown in **Table 1** and fully illustrated in **Figure 6**.

Table 1. Fragment of a table of results with statistical parameters of microhardness measurements
Tabela 1. Fragment tabeli wyników i parametrów statystycznych pomiaru mikrotwardości

Depth [mm]	N valid	Avg [HV]	Grubbs test	STD deviation	STD error	Minimum [HV]	Maximum [HV]
0	9	846.3333	1.959427	38.04968	12.68323	792	914
-0.013	9	812.6667	1.809816	34.07345	11.35782	751	850
-0.026	10	857.6000	1.678673	60.52401	19.13937	756	934
-0.039	10	818.3000	1.878675	50.94016	16.10869	731	914
-0.052	10	886.4000	2.028069	92.00870	29.09570	787	1073
-0.065	10	817.3000	1.702139	47.76342	15.10412	736	887
-0.078	9	785.1111	2.119918	47.22405	15.74135	685	832
-0.091	9	790.3333	1.898663	37.74586	12.58195	761	862
-0.104	10	800.7000	1.709610	70.01595	22.14099	681	887
-0.117	10	794.6000	2.149010	58.91086	18.62925	668	868

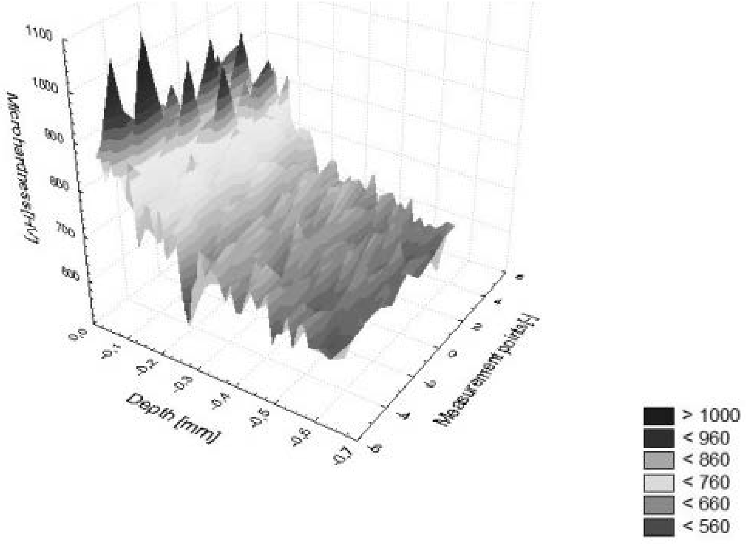

Fig. 5. Distribution of microhardness at a depth below the surface of the sample – raw data
Rys. 5. Rozkład mikrotwardości na głębokości pod powierzchnią próbki – dane surowe

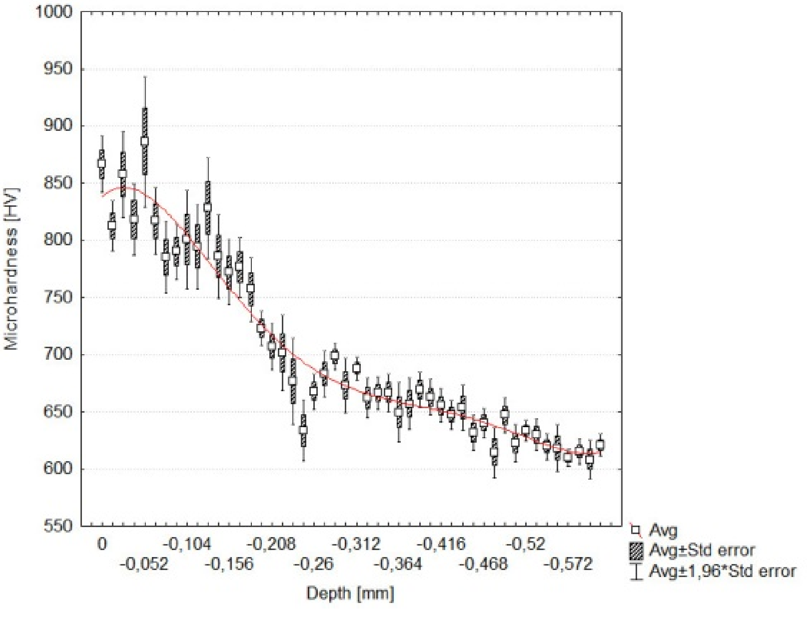

Fig. 6. Distribution of average microhardness determined at the depth of the surface layer after shot peening
Rys. 6. Rozkład średniej mikrotwardość wyznaczonej na głębokości warstwy wierzchniej po nagniataniu dynamicznym

As shown in **Figure 6**, microhardness reaches its highest values in subsurface layers. The highest value is localised under the outer surface at the depth of about 52 µm. At the depth of 130 µm, one can observe the first rapid drop of microhardness. This is the point in which the influence of shot peening fades, and the greatest impact on hardness is taken over by the heat treatment (carburizing and quenching). The stabilization of microhardness begins at the depth of 455 µm, towards the core. Comparing the above distribution of microhardness with the distributions shown in **[L. 13]** for ground and heat-treated samples which were carbonized and hardened (about 715 HV in the subsurface layers), it can be concluded that a more beneficial distribution of microhardness can be found in the subsurface layers. Higher hardness directly under the surface has a positive impact on the exploitation properties of teeth due to increased resistance to contact, fatigue, and tribological effects during exploitation of transmission. A full distribution of microhardness is shown in **Figure 7**.

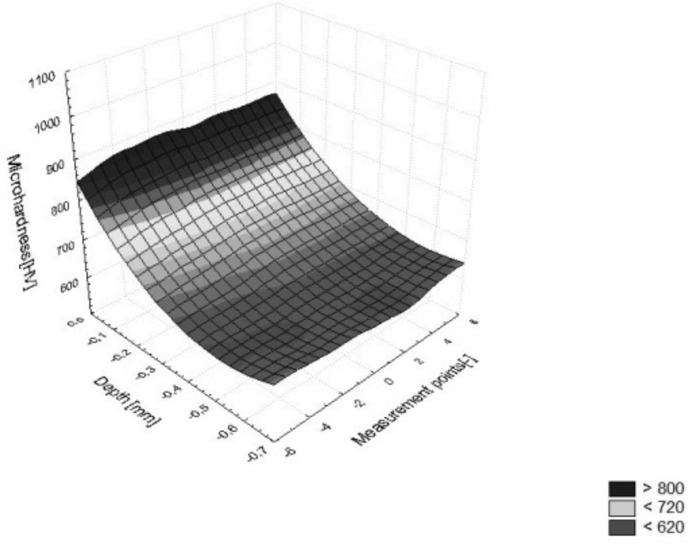

Fig. 7. A full distribution of microhardness on the measurement field
Rys. 7. Pełny rozkład mikrotwardości na polu pomiarowym

MATERIAL STRUCTURE OF GEAR TOOTH SURFACE LAYER AFTER SHOT PEENING

Austenite, which does not change into martensite during quenching, is called retained austenite. It is assumed that the austenite does not transform into martensite under the effect of compressive stresses accompanying the martensitic transformation. Retained austenite is an integral structural component of quenched, carburized layers.

Depending on the chemical composition of the steel, the start and end temperatures of the martensitic transformation and the type of thermo-chemical treatments, the retained austenite content in the steels may vary between 0 – 50%. The content of retained austenite in steels affects the following:

- The dimensional stability of workpiece,
- The wear of the machine parts and components, and
- Impact strength.

In gears, its content should be kept on fairly low levels. The low content of retained austenite and minor austenite grains creates the microstructure of finely dispersed austenite and tempered martensite. This structure prevents the nucleation of fatigue microcracks or significantly delays the initiation of fatigue cracks reaching the surface layer causing devastating stress levels **[L. 14]**.

In the methods of quantitative analysis, the relationship between the intensity of the diffraction lines of the determined phase and its content in the multiphase mixture is used. This relationship is not rectilinear, because, with the same phase content in different mixtures, the intensity of the diffraction lines of such a phase varies depending on the absorption coefficient of the rays in a mixture. Therefore, it is necessary to develop specific methods for individual cases that allow one to find the relationship between the content of the phase, the line intensity, and the absorption coefficient of the mixture, or there is need to use technologies to eliminate the impact of variations in properties of absorption in the mixtures. For the determination of the austenite content, the direct comparison of intensities of reflections was used. This method is used in the cases when the mixture consists of two phases (A and B) and when the mass absorption coefficients of the phases are equal **[L. 10]**.

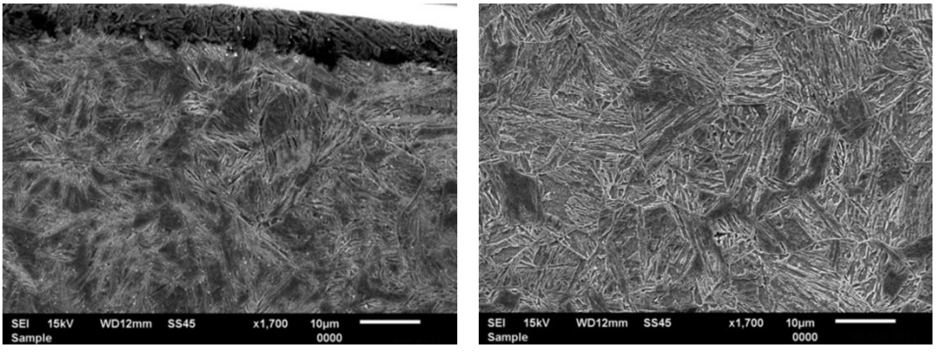

Fig. 8. Metallographic structure on the surface (on the left) and near the core (on the right) – magnification x1700

Rys. 8. Struktura metalograficzna przy powierzchni (po lewej) oraz bliżej rdzenia (po prawej) – powiększenie x1700

Dynamic burnishing treatment significantly changes the content of retained austenite in the surface layer. The change in the contents of retained austenite on the surface of the workpiece is about 7.168% (avg.) – and in the subsurface layers is increased to 8.712% (avg.). **Figure 8** shows the structure of the tooth surface area and at depth, in the direction to the core.

The clearly visible martensite grains are derived from the heat treatment, which is especially produced after quenching. They are characterized by high hardness. The lack of retained austenite can be noticed in **Figure 8**, by paying attention the the blacked out "islands" on the grain boundaries of martensite, which can be places of carbon saturation, under which parts of retained austenite located deeper may hide.

SUMMARY

Through the use of dynamic burnishing as a finishing treatment, a certain state of the surface layer of gear teeth after previous heat treatment (carburization and quenching) can be effectively created.

As a result of the obtained deformation of surface layers, an increase in compressive stress state occurs that increases the surface resistance to exploitation loads. An accretion in hardening emerges in zones located directly below the surface, which microhardness measurements have shown. Application of the method of measurement on oblique metallographic section allowed one to observe a smooth transition from the hardened zone to core hardness zone. This smooth transition is important for increases fatigue resistance, since rapid changes could result in the formation of stress concentration points during exploitation.

Reducing the share of retained austenite on the surface of the workpiece by an average of about 7%, while in the subsurface layers by about 9%, is an additional advantage of shot peening in increasing operational strength.

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Streszczenie

Rozpatrując zjawiska podczas współpracy zębów w przekładni zębatej i wywoływane obciążenia w obrębie mikro- i makroobszarów powierzchni styku, należy zwrócić uwagę na stan i rodzaj warstwy wierzchniej. Coraz częściej dla kół zębatych szczególnie obciążonych zaleca się oprócz utwardzania poprzez obróbkę cieplną lub cieplno-chemiczną nagniatanie dynamiczne jako obróbkę obligatoryjną. Stąd w opracowaniu przedstawiono zmiany utwardzenia warstwy wierzchniej po obróbce nagniataniem dynamicznym zęba koła wcześniej obrobionego poprzez nawęglanie i hartowanie. W opracowaniu przedstawiono rozkład mikrotwardości na głębokości. Pomiary wykonano na zgładach skośnych pozwalających na określenie mikrotwardości jak najbliżej powierzchni. Zobrazowano również na zdjęciach zmiany struktury metalograficznej po nagniataniu dynamicznym. Ponadto na podstawie analizy danych uzyskanych z dyfrakcji rentgenograficznej oszacowano ilości austenitu szczątkowego metodą bezpośredniego porównania natężeń refleksów.