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*Article*

# Micro and Macroscopic Analysis of Fatigue Wear of Gear Wheel Top Layer - An Impact Analysis of Thermochemical Treatment

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**Abstract:** The main purpose of this work was to tests of form and size of fatigue wear of the top layer of oil gear pump wheel (3PW-BPF-24). The object of tests was operated during a determined number of hours at strictly controlled operational and environmental parameters. A microscope of focal differentiation by Alicona InfiniteFocus G4 (with Focus-Variation optical measuring technology) was used for an identification, measurement and description of noticed superficial defects, which resulted from the fatigue process of the top layer and an earlier thermochemical treatment. The work was finished with an analysis of obtained results (based on the analysis of 3D scans) and conclusions concerning about optimization of the thermal treatment. Taking into consideration the presented results (suggestions) in the technology of improving strength properties of gear wheels (of this type oil pumps) may render it possible to obtain an appropriate fatigue endurance of the top layer, i.e. a minimization of observed superficial defects.

**Keywords:** analysis of surface; pitting; thermochemical treatment; residual austenite; gear pump

## 1. Introduction

Gear wheels, being the fundamental components of most drive systems, are crucial in transmitting rotary motion or transporting a medium (e.g., oil) and must meet a series of rigorous technical requirements. The contact between gear teeth (gear wheels), collaborating with each other, is considered one of the most complicated cases of contact interaction in the field of tribology [1]. The design process of gear wheels [2] must take into account the appropriate geometry of the teeth, the correct profile, dimensional tolerances, and material selection [3]. Precision in manufacturing and precise fitting of elements are crucial to ensure optimal system operation. Furthermore, recent research has shown the influence of surface roughness on the fatigue wear behavior of gear wheels. Proper lubrication of collaborating gear wheels is crucial for reducing friction, wear, and failures [4]. Regular maintenance, oil changes, and monitoring of lubrication quality are important activities in maintaining appropriate reliability and durability. Lubrication plays an essential role, particularly when using working fluids that are oil-in-water emulsions or when operating pumps under thermal shock conditions [5,6].

A correct lubrication of collaborating gear wheels has a key significance for a reduction of friction, wear and failures [7,8]. A regular maintenance, an exchange of oil and monitoring of lubrication quality are important activities in maintaining an appropriate reliability and endurance.

In particular a lubrication plays an essential role in the case of using working liquids being an oil-in-water emulsions [9] or an operation of pump in the conditions of thermal shock [10].

The state-of-the-art diagnostic methods such as an analysis of vibrations, thermographics or spectrometry enable to monitor a condition of a gear wheel during its exploitation. They enable to detect early signs of wear, damages or irregularities which renders it possible to undertake appropriate corrective measures before an occurrence of more serious failures. It is possible to find in literature many novel elaborations and suggestions, concerning gear wheels and gear pumps. Tests of new materials, technologies of manufacture, an improvement of teeth geometry and an optimization of lubrication are aimed at increasing endurance, efficiency and reliability of these elements.

In the work [11] the authors presented research results oriented onto testing of efficiency and reliability of different techniques for monitoring damages of gears. Test cases with different kinds of teeth damages in the gear were used. In the result of tests it was stated that the beta kurtosis was a reliable diagnostic technique and a wavelet transform was useful for a visualization of inspection, in particular while using residue signals. In the work [12] the authors concentrated on an identification of future testing possibilities in the scope of diagnostics of damages, using a quality analysis of the tree of damages. In turn, in the work [13] a simple monitoring method of the condition of gears, operated in impulse environments, was presented. The method of synchronous median has turned out to be more resistant to a presence of impulse components of signal which makes it more reliable in an estimation of the state of individual components of the machine. The tests were based both on numerical as well as experimental data. Besides, there are other publications, in which selected diagnostic methods, concerning an assessment of gear wheels condition - a detection of damages during an operation of a pump or of a gear - without any disassembly [14–17], are presented.

In addition to gear wheel diagnostics, it is worth noting that there are diagnostic methods for pump operation based on oil testing. These methods utilize various techniques to analyze the condition of the lubricating oil within the pump system, providing valuable insights into pump health and performance. For instance, oil analysis techniques such as spectroscopy, chromatography, and viscosity measurement can detect contaminants, degradation products, and wear debris in the oil, indicating potential issues within the pump system [18,19]. Moreover, real-time monitoring systems, incorporating sensors and algorithms, enable continuous assessment of oil condition and pump operation, allowing for early detection of abnormalities and predictive maintenance strategies [20]. These diagnostic methods play a crucial role in ensuring the reliability, efficiency, and longevity of pump systems in various industrial applications.

The damaged gear wheels are subject to macroscopic and microscopic tests to obtain even better results. The assessment methods of gear wheels wear after their disassembly, with use of microscopes such as microscopes of focal differentiation made by the Alicona Company [21,22], can deliver detailed information on state of surfaces of gear wheels and the degree of their wear.

During a wear assessment of gear wheels with use of microscopes, specialistic software and high resolution of images a precise geometric measurement of external and internal dimensions of teeth, a profile of tooth, pitches and tolerances [23,24] is carried out. Additionally, the methods of finite elements analysis (FEM) e.g. the ANSYS software enabling to conduct a virtual analysis of load and wear of gear teeth based on a numerical method, are also used. These methods are particularly useful for forecasting a behavior of gear wheels in different operational conditions, an optimization of the project and a diagnosis of problems related to the strength and wear [25–27].

### *1.1. Macroscopic Tests of Gear Pumps*

Macroscopic tests enable an assessment of gear pumps condition, an identification of potential problem areas and an assessment of the remaining life and reliability of these devices. This process can incorporate an analysis of cracks, microcracks, changes of shape and structural damages on the surfaces of teeth, pump frame, shafts and other elements [28–30]. Based on macroscopic observations, it is also possible to elaborate a strategy of maintenance and repair of gear pumps to minimize a risk of failure and to extend their life. The examples of work concerning macroscopic tests of fatigue wear

in gear pumps are e.g. [31–33]. In the work [31] experimental tests of macroscopic fatigue wear in gear pumps, concentrating on an analysis of failure and prevention have been conducted. In the work [32] its authors carried out a macroscopic observation and an analysis of a fatigue damage in gear pumps at different operational conditions. In turn, in the work [33] the test is concentrated on macroscopic characteristics of gear pumps failures in the conditions of high speed and big load. In these tests an essential aspect includes an analysis of so called pitting, i.e. a generation of losses on teeth surfaces of gear wheels. Pitting is one of the main mechanisms of fatigue damage in gear pumps and that is why this phenomenon has a key significance in macroscopic tests concerning an assessment of fatigue wear.

### *1.2. A Consideration of Pitting in a Fatigue Wear Assessment of Gear Wheel Top Layer*

The basic phenomenon of top layer wear of gear wheels operated in the medium such as hydraulic oil, mainly includes pitting. It is a kind of damage which occurs on surfaces of teeth and it is characterized by a generation of micro and macrocracks and electric discharges in the result of high contact stresses.

Pitting can lead to a gradual deterioration of teeth surface quality, causing an erosion and flaking of material. This phenomenon is particularly dangerous because it can lead to serious damages of gear wheels and in consequence to a failure of the whole machine. Tests are concentrated on an identification, measurement and description of pitting to analyze its impact on the output and life of gear pumps in a better way.

Over the years from 2010 to 2022 many interesting tests, concerning pitting and micro-pitting in the context of gear wheels, were concluded. The researchers tried to go deeply into mechanisms of generating these damages and to identify factors which affect them. One of such tests was an elaboration [34], in which the authors concentrated on a generation and evolution of pitting in gear wheels. Analyzing different factors, which affect a generation of this damage, they suggested strategies of minimizing the pitting, aimed at an extension of a gear-box.

Another analysis, which deserves an attention, is presented in [35]. The tests were concentrated on a behaviour of micro-pitting in relation to different conditions of lubrication in gear wheels. Through an analysis of identification and propagation mechanisms of micro-pitting and assessment of lubrication impact on this process, the researchers recognized the processes occurring during this damage. In the work [36] the authors concentrated on an analysis of pitting in worm-and-sector steering gears. Using a semi-terministic method, the researchers attempted to understand processes of damage and to assess an impact of different factors on pitting in the gears of this type.

The tests, conducted by [37] were concentrated on an impact of micro-pitting on fatigue life of teeth surfaces in gears. Using a numerical and experimental analysis, the researchers assessed an impact of micro-pitting on life of gears. All these tests have an essential significance for understanding pitting and micro-pitting in the context of gear wheels. They present different aspects of those damages such as mechanisms of generation, an impact of environmental factors and lubrication and also strategies of minimization and assessment of the impact on gear life.

Besides, operational properties of machine elements such as gear wheels others mainly depend on an application of appropriate manufacturing technologies. In particular, due to life of steel elements, subject to treatment, the heat treatment giving optimum useful properties [38,39] has an essential significance.

A key issue includes a presence of residual austenite in the top layer of gear wheels subject to heat treatment [40]. A significant number of research projects indicates that a presence of residual austenite, apart from a suitable limit value, reduces fatigue strength, hardness and abrasion resistance [41–43].

## **2. Characteristics of Test Object**

The analysis results of fatigue wear form and size of the driven wheel of the prototype, high pressure gear pump (type: 3PW-BPF-24) are presented in this elaboration. The pump was subject to an endurance test (so called labour resource test) [44]. The endurance test is a part of a compulsory



set of tests to be performed before introducing the pump to the mass production. The test, according to the accepted standard, requires a million cycles of loading. The period of one cycle is 2s, during which the pump is loaded with the rated pressure at the half-cycle and afterwards it is unloaded. The pump rotational speed (according to the project assumptions) is determined in the scope from 600 to 6000 rev/min. However, the rotational speed, at which the pump was tested, complies with the rated speed of 1500 rev/min. The pump operational medium was hydraulic oil HL68, having a wide application in medium loaded hydraulic drive and control systems. According to the producer's catalogue card [45] the HL68 oil guarantees a good protection of surfaces of lubricated elements (density: 0.885 g/cm<sup>3</sup> at 15°C, kinematic viscosity: 68 mm<sup>2</sup>/s at 40°C). During the test the oil temperature was maintained on the level of recommended rated value reaching 50°C. However, the maximum temperature limit of operation for this unit is 80°C. The object of tests worked 24 hours, day and night, at controlled rated operational and environmental parameters (i.e. appropriate rotational speed and constant temperature) till one million cycles of loading is reached (about 24 days). After endurance test the hydraulic characteristics for selected rotational speed  $n=800$ ; 1000; 1500; 2000 rev/min were determined. The condition, enabling to approve of the pump design, according to the standard, includes a reduction of efficiency at any working pressure by a value not exceeding 8% in relation to the characteristics obtained directly after a factory run in. After a completion of the labour resource test the experimental unit was disassembled and each of its components was subject to detailed visual inspection and an analysis oriented onto a determination of the wear degree.

A general view of the analyzed pinion after a completion of the labour resource test is presented in Figure 1.

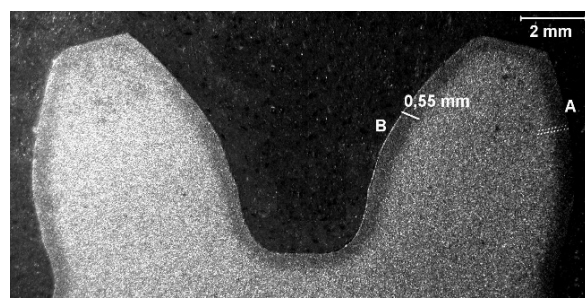


**Figure 1.** General view of gear wheel [46].

The project assumptions required a manufacture of the pinion, subject to tests, of steel for carburization of the 18CrNiMo7-6 grade (acc. to out-of-date standard PN-EN 10084:2002) or 17NiCrMo6-4 acc. to PN-EN ISO 683-2:2022-07) and reaching the following properties due to applying thermochemical treatment:

- the thickness of carburized layer (after mechanical working): 0.5-0.9 mm (marked in Figure 2);
- the core hardness: 29-42 HRC;
- the hardness of top layer of working surfaces: 60-64 HRC.

The values given above were not fully reached due to high contents of residual austenite (which is described in a further part of this elaboration).

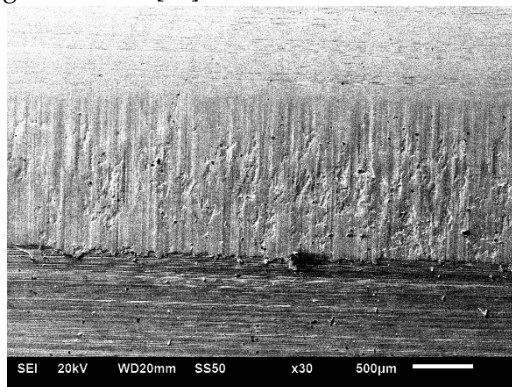


**Figure 2.** Tooth cross-section (visible changes of macrostructure resulting from the applied thermochemical treatment) [46].

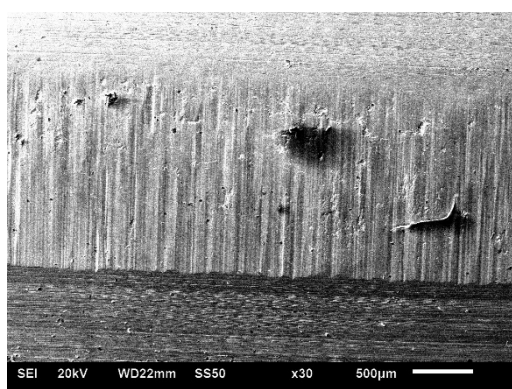
### 3. Macroscopic Tests Results

Macroscopic tests of gear wheel external surfaces were made with naked eye and with use of stereoscopic microscope SMT-800 and a scanning microscope Hitachi S3400N [46].

On the external surface of teeth both sides, the traces of exploitation in a form of chippings and of working surfaces wear - Figure 3 and 4 [46] were seen.



**Figure 3.** Macroscopic view of the tooth surface from the A side (scanning microscope Hitachi S3400N) [46].



**Figure 4.** Macroscopic view of the tooth surface from the B side (scanning microscope Hitachi S3400N) [46].

After cutting off a specimen perpendicularly to the tooth generating line, after its regrinding and pickling with use of the reagent  $Mi11Fe$  acc. to PN-H-04503:1961, some changes of macrostructure resulting from an application of the surface thermochemical treatment to the depth of about 0.55 mm, shown in Figure 2 [46], were noticed. Additionally, the macroscopic analysis of external surfaces of the gear wheel also showed a presence of micropitting, which is a minute kind of superficial damage. Micropitting is caused by contact stress and cyclic loading which leads to a generation of microdamages on the surface of teeth. An occurrence of micropitting may indicate inappropriate operational of constructional parameters of the gear wheel.

### 4. Microscopic and Hardness Test Results

Specimens for microscopic tests were cut off perpendicularly to the tooth generating line. Microscopic tests were conducted at magnification in the scope from 100x to 1000x in the non-pickling condition and after pickling with the reagent  $Mi1Fe$  according to the out-of-date standard PN-H-04503:1961. The metallographic microscope Epiphot 200, coupled with a digital film camera CCD Nikon, was used. The photographic documentation (of characteristic structures), related to the scope of work [46], is only and exclusively presented in the elaboration.

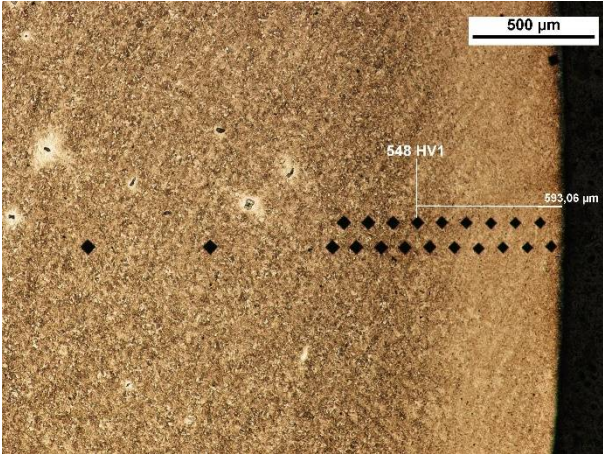
In the non-pickling condition an occurrence of a minor amount of non-metallic inclusions, mainly in a form of oxides spaced pointwise, was noticed. In the close-to-the-surface layer no internal oxidation zone was spotted [46].

After pickling with the reagent Mi1Fe a structure typical for carbonized, heat treated objects was seen. A determination of a conventional depth of hardening after carbonization was carried out by a measurement of hardness at the cross-section along the normal to the carbonized surface, in the direction from the surface to the inside of material according to the standard PN-EN ISO 18203:2022-09. The measurements were taken with use of the Vickers method in the conditions according to PN-EN ISO 6507-1:2018-05. The Zwick 321 hardness tester, the load of 1 kG (9.807 N) acting within the time of 15 s, was applied. An average core hardness from five measurements , made with use of the Vickers method, is 445 +/-3.25HV1 [46]. Table 1 and 2 presents the results and visualizes the hardness analysis from the both sides of the tooth (A and B).

**Table 1.** Determination of the conventional depth of hardening after carburizing by measuring the hardness distribution deep into the material - A side.

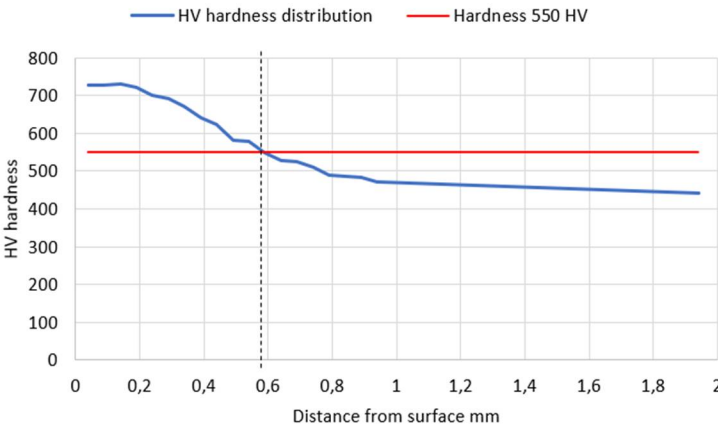
|                       |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Distance from surface | 0.04  | 0.09  | 0.14  | 0.19  | 0.24  | 0.29  | 0.34  | 0.39  | 0.44  | 0.49  | 0.54  |
| HV hardness           | 727.2 | 728.1 | 729.4 | 721.9 | 702.1 | 692.9 | 671.3 | 640.3 | 622.9 | 582.1 | 579.6 |
| Distance from surface | 0.59  | 0.64  | 0.69  | 0.74  | 0.79  | 0.84  | 0.89  | 0.94  | 1.44  | 1.94  |       |
| HV hardness           | 548.9 | 527.6 | 525.5 | 508.8 | 488.2 | 486.9 | 482.4 | 471.7 | 455.4 | 442.5 |       |

The depth of the tooth carbonized zone from side A is about 593 μm - Figure 5. The course of the hardening curve is shown in Figure 6. An occurrence of about 30% residual austenite and then low-temperature tempered, fine acicular martensite of gradually decreasing carbon contents were detected - Figure 7. A cracked, strongly deformed layer of the thickness about 9 μm was seen on the tooth surface - Figure 8 [46].

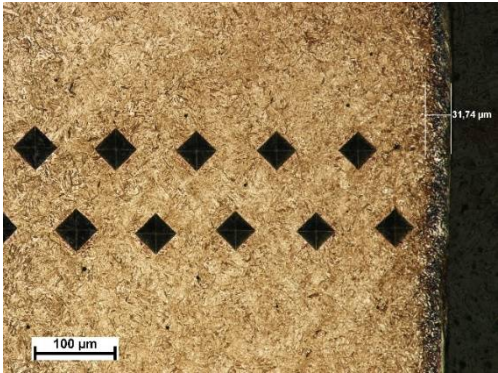


**Figure 5.** View of carbonized and hardened layer on the specimen cross-section from the A side with hardness distribution measurement markers (light microscopy, Mi1Fe pickling) [46].

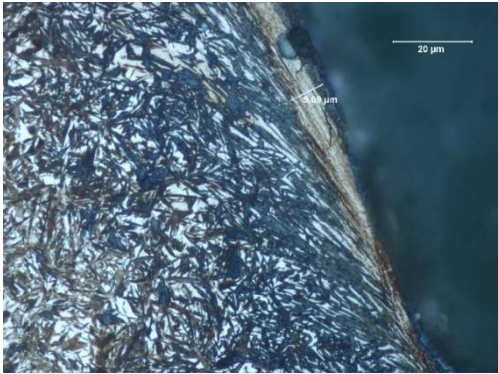




**Figure 6.** Hardness distribution along the normal to the carburized surface - from the A side (in the direction from the tooth surface into the material). Hardness 550 HV occurs to a depth of approximately 0.58 mm.



**Figure 7.** View of carbonized and hardened layer on the specimen cross-section from the A side with indentations of hardness distribution measurements and the layer of residual austenite (light microscopy, Mi1Fe pickling) [46].



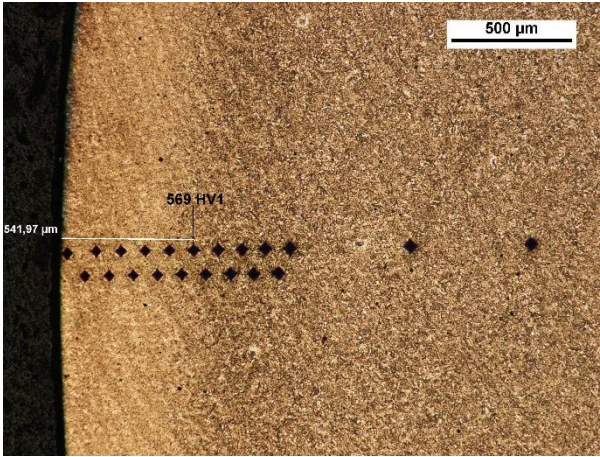
**Figure 8.** View of carbonized and hardened layer on the cross-section of the specimen from the A side - martensite with residual austenite with strongly deformed and cracked layer of the thickness about 9 μm (light microscopy, Mi1Fe pickling) [46].

**Table 2.** Determination of the conventional depth of hardening after carburizing by measuring the hardness distribution deep into the material - B side.

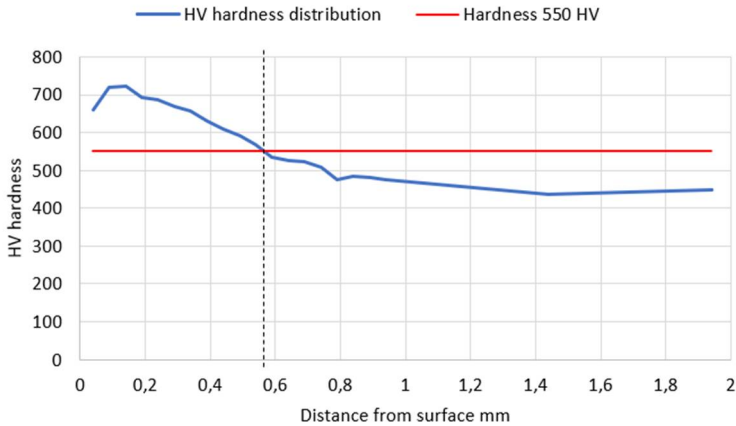
|                       |      |      |      |      |      |      |      |      |      |      |      |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|
| Distance from surface | 0.04 | 0.09 | 0.14 | 0.19 | 0.24 | 0.29 | 0.34 | 0.39 | 0.44 | 0.49 | 0.54 |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|



|                       |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| HV hardness           | 695.9 | 718.2 | 722.1 | 691.3 | 686.0 | 667.9 | 657.9 | 630.7 | 610.5 | 590.4 | 568.9 |
| Distance from surface | 0.59  | 0.64  | 0.69  | 0.74  | 0.79  | 0.84  | 0.89  | 0.94  | 1.44  | 1.94  |       |
| HV hardness           | 534.7 | 525.5 | 523.1 | 509.4 | 474.4 | 485.5 | 482.4 | 475.2 | 436.8 | 447.9 |       |

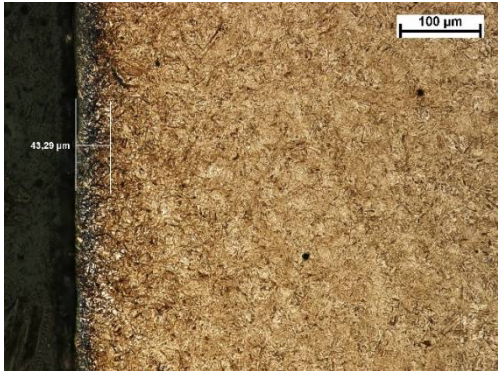


**Figure 9.** View of carbonized and hardened layer on the specimen cross-section from the B side with hardness distribution measurement markers (light microscopy, Mi1Fe pickling) [46].

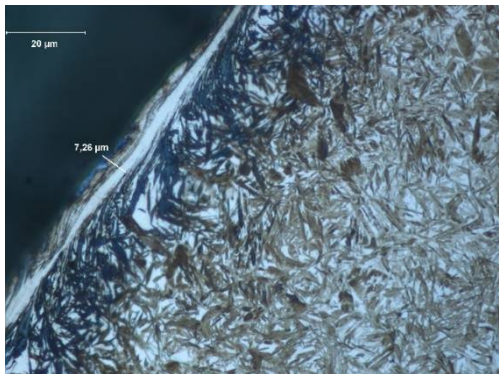


**Figure 10.** Hardness distribution along the normal to the carburized surface - from the B side (in the direction from the tooth surface into the material). Hardness 550 HV occurs to a depth of approximately 0.56 mm.

The depth of the tooth carbonized zone from the B side is about 542  $\mu\text{m}$  - Figure 9. The course of the hardening curve is shown in Figure 10. In the close-to-the-surface zone from the B side to the depth of about 43.29  $\mu\text{m}$  an occurrence of about 30% residual austenite and then low-temperature tempered, fine acicular martensite of gradually decreasing carbon contents were seen - Figure 11. A cracked, strongly deformed layer of the thickness about 7  $\mu\text{m}$  was detected on the tooth surface - Figure 12 [46].



**Figure 11.** View of carbonized and hardened layer on the specimen cross-section from the B side with indentions of the hardness distribution measurements and the layer of residual austenite (light microscopy, Mi1Fe pickling) [46].



**Figure 12.** View of carbonized and hardened layer on the specimen cross-section from the B side-martensite with residual austenite with strongly deformed and cracked layer of the thickness about 7.3 μm (light microscopy, Mi1Fe pickling) [46].

A structure of low carbon martensite after heat treatment typical for steels for carbonization was seen in the specimen core.

5. Analysis of the Material Chemical Composition

An analysis of the chemical composition of the pinion material was performed with the use of the spectral method, applying the PMI Master Pro spectrometer made by the Oxford Instruments Company. The results of the chemical composition of the specimen material are presented in Table 3. The obtained values were listed and compared with the chemical composition of the 18CrNiMo7-6 steel acc. to the out-of-date standard PN-EN 10084:2002.

**Table 3.** Average value (from three measurements) of the specimen chemical composition [46, and the requirements of the standard PN-EN 10084:2002].

| %                        | C         | Mn        | Si        | P      | S      | Cr        | Ni        | Mo        | V      |
|--------------------------|-----------|-----------|-----------|--------|--------|-----------|-----------|-----------|--------|
| Tested material          | 0.2140    | 0.6350    | 0.3510    | 0.0160 | 0.0030 | 1.3300    | 1.6400    | 0.2670    | 0.0060 |
| 18CrNiMo7-6              |           |           |           |        |        |           |           |           |        |
| acc. to PN-EN 10084:2002 | 0.14-0.19 | 0.40-0.70 | 0.17-0.37 | 0.035  | 0.035  | 1.50-1.80 | 1.40-1.70 | 0.25-0.35 | -      |
| %                        | Cu        | Al        | Ti        | Nb     | Co     | As        | B         | Pb        | Zr     |
| Tested material          | 0.1790    | 0.0180    | 0.0030    | 0.0000 | 0.0140 | 0.0210    | 0.0020    | 0.0090    | 0.0030 |

## 6. Methodology of Test - Analysis of Form and Size of Fatigue Wear of the Top Layer of Oil Gear Pump Wheel

Polarization disc for ring

Ring light plug

IF-MeasureSuit 5.1  
Alicona Imaging software

Laboratory measurement device

Sensor head with light source, optic, nosepiece, z-stage

Objectives in the range of 2.5x to 100x

x/y-stage

Passive vibration absorption system

Real 3D rotation unit

IFM G4 control server and IFM G4 electronics

IF-Joystick

Emergency stop button

Specimen

Scans of individual areas of pitting breaches were realized (in relation to the need) with objectives in the 5x or 10x magnification. During digitalizing a polarization diaphragm, which is in particular dedicated to strongly reflexive specimen was used (it was a necessity in the case of applying the Focus-Variation technology). An analysis of the surface topography 3D was carried out according to the recommendations PN-EN ISO 25178-600:2019-05 Standard.

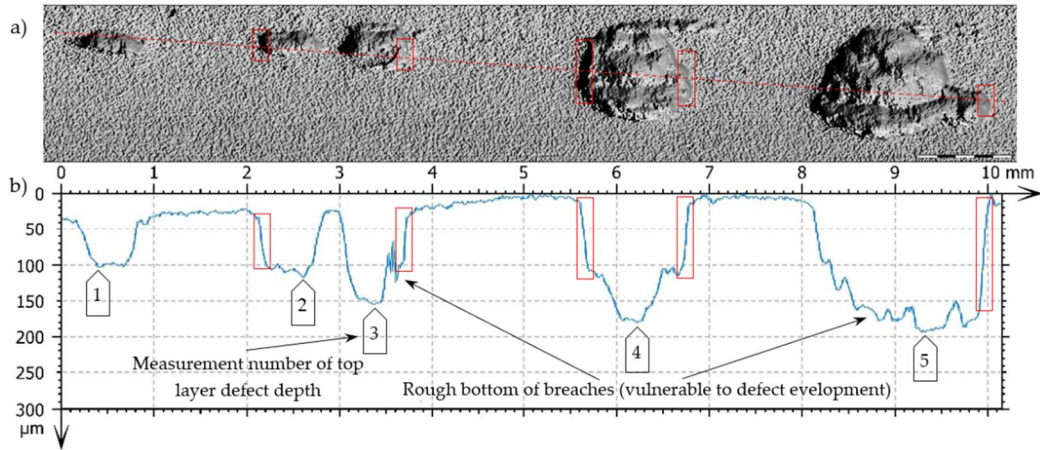
Additionally, during the microscopic analysis with use of the microscope of focal differentiation Alicona InfiniteFocus G4, advanced algorithms of image processing, enabling an identification and measurement of micro - pitting depth, were applied. Due to that it was possible to obtain detailed



information concerning the depth and dimensions of these defects which is essential for an assessment of their impact on the strength and functionality of a gear wheel.

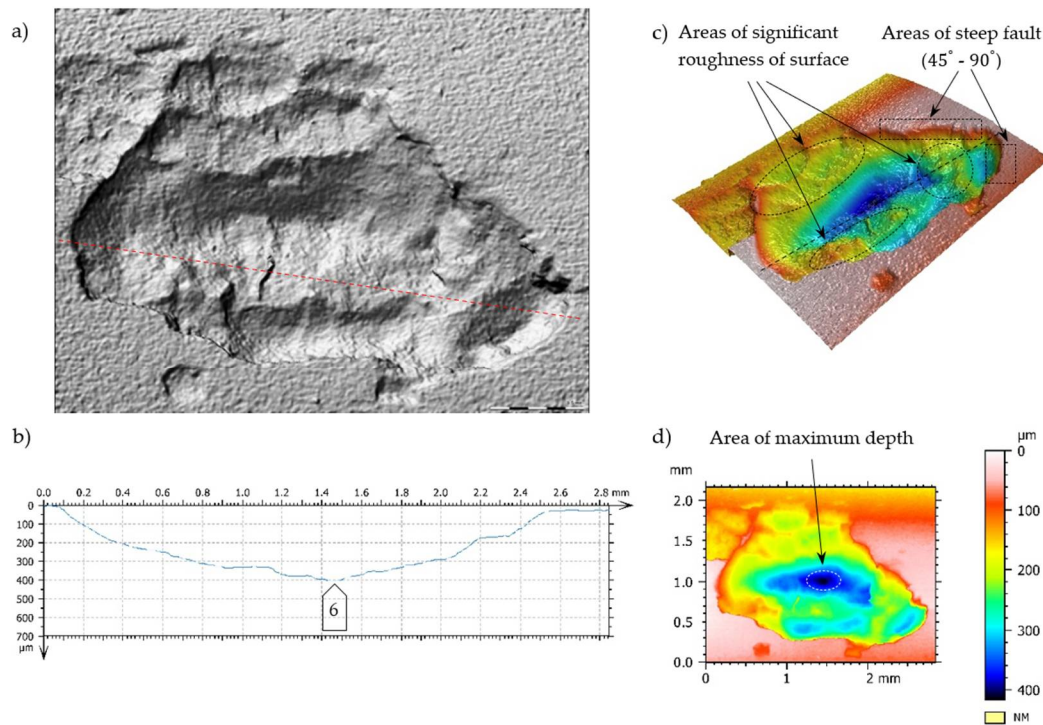
6.1. Wear Assessment of Top Layer Working Surfaces of the Pinion

In the result of taking superficial scans 3D superficial fatigue damages (characterized by breaches of oval shapes and sharp edges, inclined perpendicularly to the surface of the teeth under analysis) - Figure 14, were diagnosed.



**Figure 14.** Fatigue pits (pitting) on the tooth working surface - magnification 5x; a) photo simulation, b) profile curve, ---- - line of cross - section, □ - indication of breaches edges inclined to the surfaces, subject to analysis at the angle close to 90° on the cross-section.

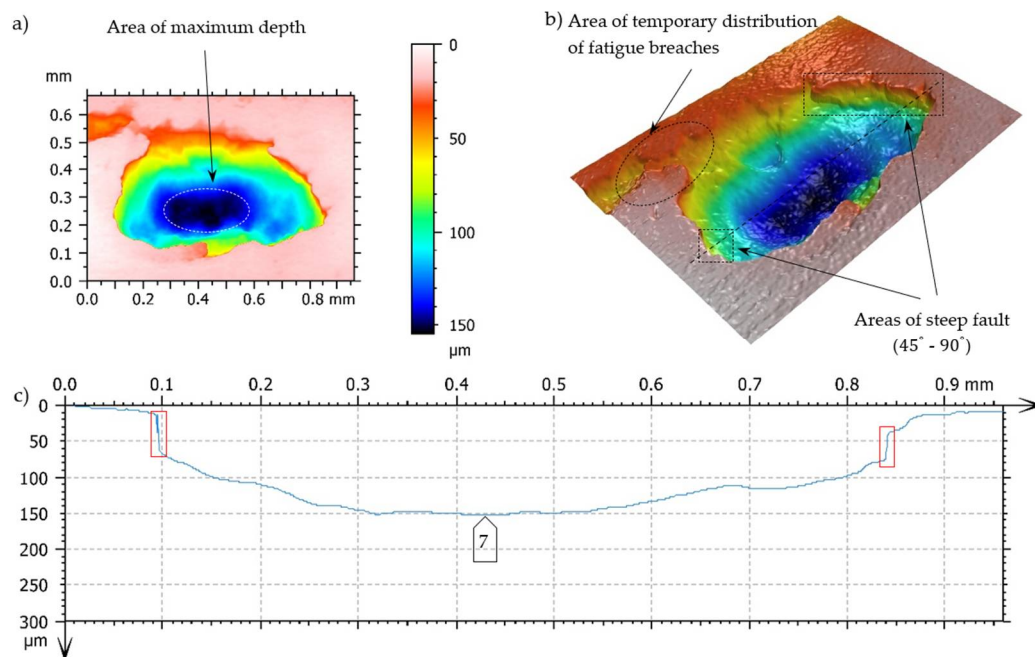
The observed breaches, generated in the result of the material chipping, have different dimensions, rough bottom and they occur locally or on a much smaller scale but on a bigger tooth surface (micropitting) - in particular below the pitch diameter of pinion. A linear arrangement of described defects was observed in some places - Figure 15.





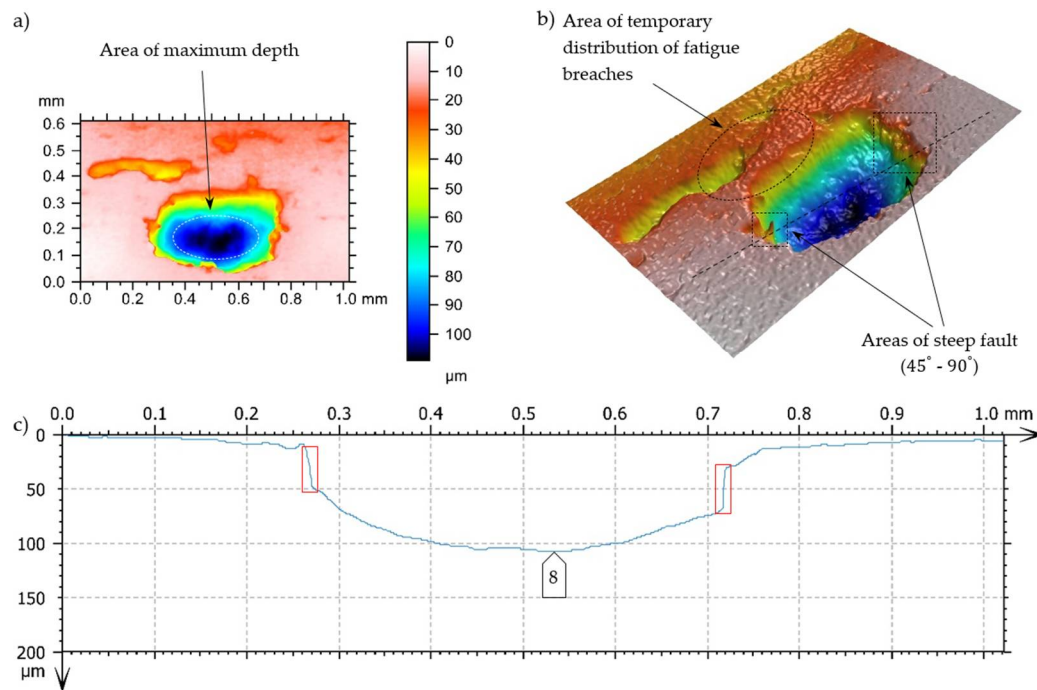
**Figure 15.** Fatigue pit (pitting) on the tooth working surface - magnitude 5x. a) photo simulation, b) profile curve, c) and d) 3D superficial view - pseudocolour of surface with the depth visualization, ---, ----- lines of cross-section.

An advancing chipping of the material particles, which is presented in Figure 15 can lead, in extreme conditions, to a reduction of the teeth working surface to a degree which will make a further transmission of loads (in the case of gears) impossible. In some situations teeth of carbonized wheels can change their shape to the degree leading to their significant wear or even fracture in the result of pitting. Carbonized and hardened teeth of wheels, which were subject to pitting in the area of the tooth root connected with a significant wear, are vulnerable to fracture. The reason is an initiation and a development of fatigue cracks in the pits generated where the crumbled away material was. A significant noise accompanies an operation of gear wheels with considerable pitting [47].



**Figure 16.** Fatigue pit (pitting) on the tooth working surface - magnitude 10x a) and b) superficial 3D view - pseudocolour of surface with visualization of depth, c) profile curve,----- cross-section line, □ - indication of breaches edges, inclined at the angle close to 90° to the surfaces under analysis, on the cross-section.

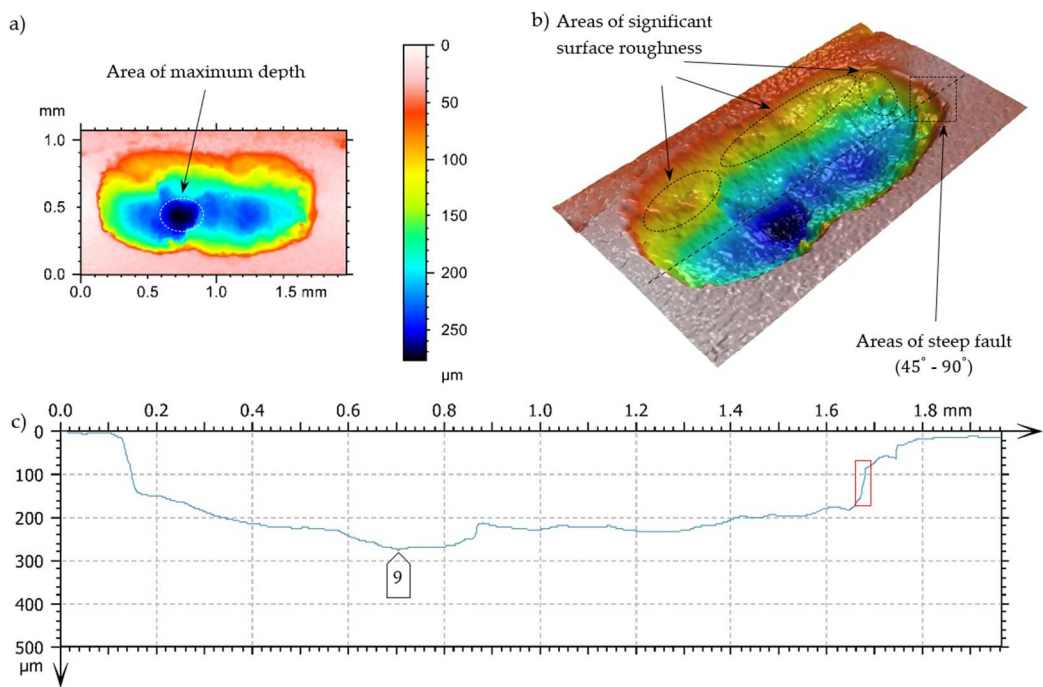
A surface increase of pitting cavities is caused very often by their mutual connecting. In Figure 16 and 17 the limiting state before a connection of two fatigue breaches is presented.



**Figure 17.** Fatigue pit (pitting) on the tooth working surface - magnitude 10x a) and b) superficial view 3D - pseudocolour of surface with visualization of depth, c) profile curve, ---- - line of cross-section, □ - indication of breaches edges, inclined at the angle close to 90° to the surfaces under analysis, on the cross - section.

The main reason of generating this type of breaches includes exceeding of limiting contact stresses of the teeth collaborating surfaces. The degree of tolerating this kind of defects (their number, size and arrangements) depends mainly on the application area. In this case (at an assumption of the forecasted pump life due to a degradation development of the top layer of collaborating teeth), it does not have any big significance. Pitting breaches in the scope of dimensions 0.1-1.5 mm (Figure 14) and even to 2.5 mm (Figure 15) do not exclude the pinion from its further (but temporary) exploitation. It should be borne in mind that correct filtration should be ensured. In this case a high pressure filter of exact purification should be installed directly after the pump to prevent against a failure of valves and receivers situated in the hydraulic line between the pump and the tank, caused by solid impurities.

Additionally, it should be taken into an account that a breach of 1 mm dia. close to the fillet of the tooth heat treated or superficially hardened, may begin a crack, which can finally lead to a tooth break; and that is why in some cases this kind of breach should be treated as inadmissible (e.g. in air applications) [47].



**Figure 18.** Fatigue pit (pitting) on the tooth working surface - magnitude 10x a) and b) superficial view 3D - pseudocolour of surface with visualization of depth, c) profile curve, ---- - line of cross - section, □ - indication of breaches edges, inclined at the angle close to 90° to the surfaces under analysis, on the cross-section.

Destructive pitting develops naturally from non - destructive pitting, micropitting and that one in turn from a dull finish of surface and imperfections in the top layer of collaborating teeth. An essential issue also concerns a characteristic of chipping (Figure 14, 15, 16, 17 and 18) as well as a relationship between its depth and thickness of the top layer, subject to heat treatment, thermochemical treatment. The present measurement technologies (optical metrology) enable to check a real depth of this type defects.

To determine the essence of top layer wear of the pinion selected working surfaces under testing, a short geometric analysis of individual chippings was performed. In Table 4 basic measurement values, characterizing geometries of defects, are presented, i.e. maximum depths of pitting chippings are compared in relation to the changes in the macrostructure resulting from the applied thermochemical treatment.

**Table 4.** Geometric characteristics of chippings and an analysis of selected values in relation to the depth changes of macrostructure resulting from the applied superficial thermochemical treatment.

| I | II  | III |
|---|-----|-----|
|   | μm  | μm  |
| 1 | 550 | 100 |
| 2 | 550 | 120 |
| 3 | 550 | 160 |
| 4 | 550 | 180 |
| 5 | 550 | 190 |
| 6 | 550 | 400 |
| 7 | 550 | 150 |



|   |     |     |
|---|-----|-----|
| 8 | 550 | 110 |
| 9 | 550 | 270 |

I - no. of defect, II - depth of changed macrostructure resulting from the applied thermochemical treatment, III - maximum depth of chipping measured in relation to the local flank pitch line surface in the defect vicinity (+/- 5 μm).

In the cases under analysis the defect depth of the top layer did not exceed the depth of layer subject to thermochemical treatment. A location of all the chippings is enclosed in the scope of the zone, having the structure of low-temperature tempering, fine-acicular martensite of comparatively decreasing carbon contents. The measurement data from Table 4 are graphically presented in Figure 19.

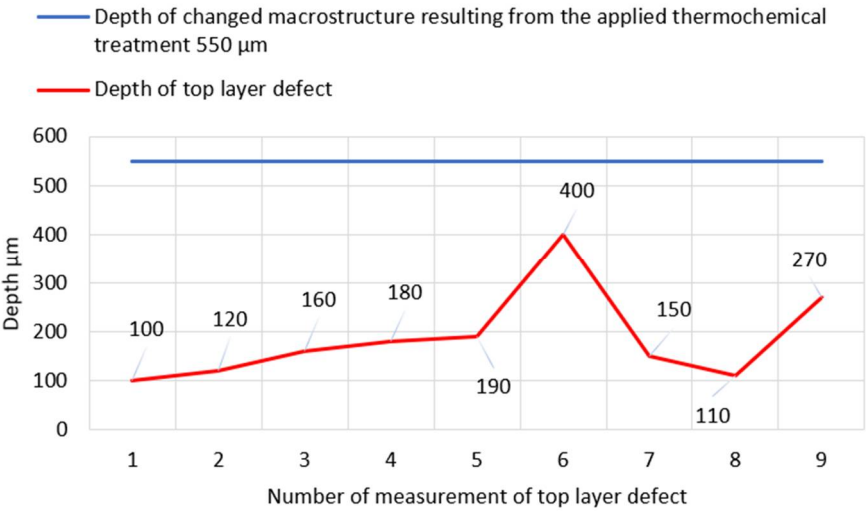


Figure 19. Graphical presentation of the data from Table 4.

Table 5. Relationship between maximum dimension of analyzed chippings and corresponding to their depth values.

| I | II<br>mm | III<br>μm |
|---|----------|-----------|
| 1 | 0.8      | 100       |
| 2 | 0.7      | 120       |
| 3 | 0.8      | 160       |
| 4 | 1.3      | 180       |
| 5 | 1.95     | 190       |
| 6 | 2.5      | 400       |
| 7 | 0.75     | 150       |
| 8 | 0.5      | 110       |
| 9 | 0.85     | 270       |

I - no. of defect, II - maximum dimension of chipping measured in parallel to the tooth flank pitch line (+/- 0.05mm), III - maximum depth of chipping measured in relation to the local flank pitch line surface in the defect vicinity (+/- 5 μm).

In most cases - Figure 20, the correlation between an increase of the maximum dimensional value of the defect (measured at the level of the surface layer) and the adequate deeper chipping was confirmed.

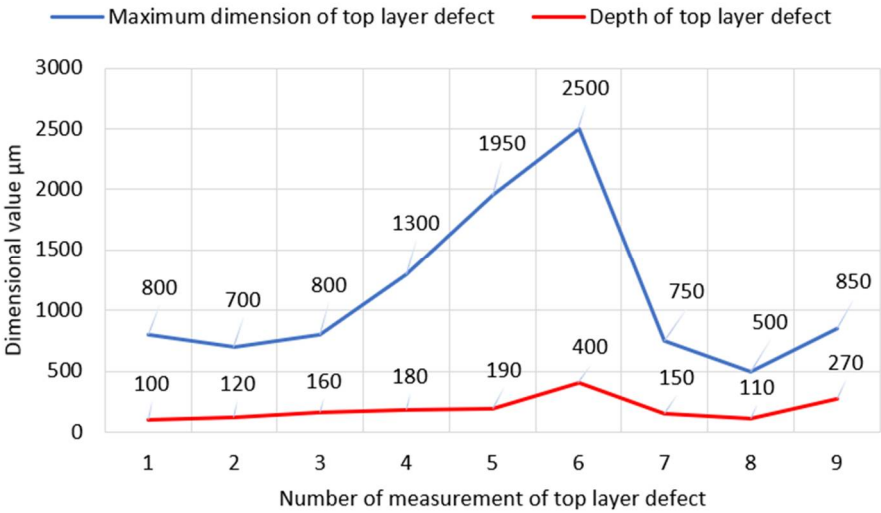


Figure 20. Graphical presentation of the data from Table 5.

7. Conclusions

The macroscopic analysis by using the Focus-Variation technology (in this case with additional microscopic examinations) was aimed at a quick and proper assessment of the degree of wear of the surface layer of the pinion subjected to thermo-chemical treatment with established technological parameters. In all tested cases, the pitting depth doesn't exceed the depth of the heat-chemically treated pinion surface layer.

Based on the microscopic research results it was stated that the conducted thermochemical treatment only partly met the project assumptions (in the sense of obtaining appropriate changes in the macrostructure inside the material).

The obtained results of the assessment of 3D scans of selected defects enable quick verification of the quality of the applied thermo-chemical treatment (fulfillment of the requirements in relation to technical assumptions). The following parameters were taken into account: the profile of the defect, depth, bottom roughness and the nature of the fault (steep, gentle).

In addition, a high content (up to 30%) of residual austenite in the volume of hardened surface enables to formulate a hypothetical conclusion concerning non-optimum parameters of a thermochemical process in relation to the chemical composition of the pinion under analysis.

An occurrence of residual austenite causes a reduction of the tooth surface hardness, an initiation of brittle fractures, a rapid reduction of fatigue strength and an increase of brittleness, in particular it can indicate a trend of generating fractures of the superficial layer during an exploitation [46].

Additionally, in the result of conducted analysis of chemical composition with use of spectral method, it can be stated that in the scope of the elements under analysis the material of the specimen, subject to tests, does not have its direct equivalent in the group of alloy, machine steels for carbonization according to the standard PN-EN ISO 683:2022-07. An application of steel grade, dedicated by the standards in power, enables to avoid a presence of other elements, which can affect properties of the material. A maintenance of a correct chemical composition will ensure required strength, hardness and other mechanical parameters which play a key role in ensuring correct useful properties.

Besides, to extend life of gear wheels, pinions their heat treatment should be selected properly. In the case of heavily loaded gear wheels it is recommended to use sub-zero treatment enabling a very efficient minimization of residual austenite contents and thus an improvement of hardness and a dimensional stabilization.

Additional information concerning recommendations and advantages resulting from heat treatment is as follows:

- the microstructure of the specimen, after the present heat treatment, subject to tests, indicates a partial meeting of project assumptions, but with a presence of residual austenite;
- a high content of residual austenite in the hardened surface volume suggests non-optimum parameters of heat treatment process in relation to the chemical composition of pinion subject to tests.

Advantages resulting from heat treatment:

- a life extension of gear wheel parts through a minimization of residual austenite contents;
- an improvement of tooth surface hardness and dimensional stabilization;
- a reduction of initiations of brittle fractures, an improvement of fatigue strength and a reduction of brittleness;
- a protection against a generation of fractures in the top layer during an exploitation.

In relation to the information given above, it is recommended to apply additional heat treatment, in a form of sub-zero treatment which will enable an efficient minimization of the residual austenite contents, an improvement of hardness and a dimensional stabilization which will contribute towards an extension of the pinion life and an improvement of its useful properties.

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