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# Effect of grinding conditions of gears made of 20MnCr5 steel after single-piece flow heat treatment on the condition of the surface layer of the tooth working surface

**W. Stachurski [a,*], J. Janica [a], B. Januszewicz [b], W. Pawłowski [a], J. Sawicki [b]**
[a] Institute of Machine Tools and Production Engineering, Lodz University of Technology,
1/15 Stefanowskiego St., 90-537 Łódź, Poland
[b] Institute of Materials Science and Engineering, Lodz University of Technology,
1/15 Stefanowskiego St., 90-537 Łódź, Poland
* Corresponding e-mail address: wojciech.stachurski@p.lodz.pl
ORCID identifier: https://orcid.org/0000-0003-3936-6846 (W.S.)

## ABSTRACT

**Purpose:** The paper investigated the effect of selected processing conditions during gear grinding on the value and distribution of microhardness and residual stress formed in the technological surface layer of gears after thermochemical treatment (TCT) conducted by a continuous single-piece flow method.

**Design/methodology/approach:** The gears were carburised with LPC at 920°C, then quenched in a 4D Quenching chamber at 7 bar and tempered at 190°C for 3 hours. In the next step, the working surfaces of the gear teeth were ground by supplying grinding fluid (GF) to the grinding zone using the WET method and the MQL method with a minimum amount. Measurements were made on the distribution of microhardness and residual stress formed in the technological surface layer of gears after thermochemical treatment and after the grinding process.

**Findings:** The results of the study showed the influence of workpiece speed $v_w$ and the method of delivery to the grinding zone GF on selected parameters describing the condition of the technological surface layer of the teeth of gears made of 20MnCr5 steel. The grinding process with a white aluminium oxide grinding wheel causes deterioration in the material's residual stress state. For each of the three analysed workpiece speeds $v_w$, smaller changes in microhardness with respect to the microhardness of the material before grinding occur in the surface layer of samples ground with GF fed with the MQL method. Similarly, residual stress values are in the area of favourable compressive stresses.

**Research limitations/implications:** Environmental considerations and the need to comply with increasingly stringent environmental protection and worker safety regulations are pushing researchers and entrepreneurs to completely eliminate or reduce the consumption of grinding fluids in the grinding process. Based on the research and analysis carried out in this study, it was concluded that applying minimum GF by the MQL method could be an alternative to the conventional WET method.

**Practical implications:** In sustainable manufacturing, it is extremely important to produce high-quality items while reducing the cost of manufacturing and taking care of the environment and workers' health. This includes the manufacture of gears, a basic component used in gear transmissions in the automotive industry, for example. The research has established that it is possible to use the MQL method, which reduces the amount of GF used when grinding the working surfaces of gear teeth, as an alternative to the conventional WET method.

**Originality/value:** The conducted research was the first to determine the most favourable conditions, in terms of the obtained residual stresses and microhardness, for grinding the working surface of gear teeth using the MQL method.

**Keywords:** Thermo-chemical treatment, Vacuum carburizing, Single-piece flow method, Gear grinding, Technological surface layer

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MATERIALS MANUFACTURING AND PROCESSING

## 1. Introduction

Gears are widely used in mechanical engineering, mainly as active elements in gears. Most often, steel gears are subjected to a heat treatment process, while in the next stage, the working surfaces of the gear's teeth are ground to compensate for hardening deformations and to give them the required shape and dimensions. It should be noted that the properties of the technological surface layer, which have a direct impact on the functional properties of the workpiece, such as fatigue strength and wear resistance [1], for example, are influenced by both heat treatment and mechanical treatment. In general, among the important parameters describing the state of the technological surface layer are residual stress and microhardness [2-4].

In this context, carburising and quenching are one of the most common types of heat treatment preceding grinding. An analysis of the literature [4-6] indicates that the low-pressure carburization (LPC) variant is superior to conventional carburization in terms of efficiency and provides, among other things, the absence of internal oxidation and greater uniformity of the obtained layers. Among the LPC furnaces, the most noteworthy is the UCM furnace from SECO/WARWICK (Świebodzin, Poland), designed for the heat treatment of gears, among other things. Its innovative design, compared to batch furnaces, allows thermochemical treatment (TCT) of components in a stream system using the "single-piece flow" method [7,8]. In this way, each gear goes through identical positions and process conditions in the furnace. As a result, carburization is characterized by high precision and repeatability with respect to conventional methods [9,10]. After the carburizing process, each gear is individually subjected to high-pressure gas quenching (HPGQ) in a 4D Quenching chamber [7,11,12]. Such a solution allows the cooling curve to be freely shaped and makes it possible to achieve the appropriate microstructure and material properties. In addition, the innovative chamber design features a system of cooling nozzles that surround the component and ensure an even flow of cooling gas from all sides. In addition, a component placed on a rotating table rotates with it, which aids in cooling uniformity (4D). This cooling system solution allows cooling intensity comparable to oil systems without the need for helium (He).

It is worth noting that, in general, conducting thermo-chemical processing in a UCM furnace is beneficial for small quenching deformations and their repeatability [10,13]. This is important given that the grinding process is time-consuming and energy-intensive, which generates high manufacturing costs. Thus, the smaller the dimensional and shape deviations of the parts after the heat treatment process, the smaller the excess to be removed during grinding, resulting in increased production efficiency and reduced manufacturing costs. Such a trend is in line with the general principles of sustainable production. In this context, another important factor is to minimize the negative impact of manufacturing on the environment and increase worker safety by eliminating factors that threaten their health and life [14,15].

Taking the above into account, it should be noted that from the point of view of sustainable manufacturing principles, conventional coolants (GF) supplied to the grinding zone by the WET (Wet Machining) method are considered undesirable factors [16,17]. Efforts are therefore being made to reduce the number of coolants used in the grinding process and introduce alternative lubrication and cooling methods. Noteworthy among them is the method of minimized GF expenditure denoted by the acronym MQL (Minimum Quantity Lubrication) [18-20]. In this method, an air-oil aerosol is continuously produced and fed directly into the grinding zone. The flow of lubricating medium in the form of oil particles is carried out with a stream of compressed air [21], and the oil flow rate is in the order of 10-500 ml/h.

No studies on applying the MQL method in grinding the working surface of gear teeth have been found in the available literature. Conclusions from studies conducted on other variations of the grinding process have shown that using the MQL method with its various modifications (including vegetable oils, nanofluids, and cryogenic cooling) can be an alternative to the WET method with appropriate processing conditions [22]. This includes microhardness and residual stress [4,23]. The authors of this paper researched the application of the MQL method when grinding the flat surfaces of samples after thermochemical treatment in a UCM furnace [24,25]. The microhardness and residual stress results obtained confirmed the validity of the undertaken research. However, it should be noted that due to the specific kinematics of machining, which is different for each variety of grinding process, the conclusions developed should not be generalized.

Accordingly, this paper describes an experimental study to determine the effect of grinding conditions on the working surfaces of gears made of 20MnCr5 steel on the condition of their technological surface layer. The gears were vacuum carburized (LPC) using the single-piece flow method and quenched in high-pressure gas (HPGQ) using an innovative UCM furnace. The gears were then ground using the so-called Niles method by feeding the coolants using the conventional WET method and with minimum GF using the MQL method. Chapter 2 presents the conditions of the experimental research, along with a description of the test sites. The results of the microhardness and residual stress measurements, along with their analysis, are discussed in Chapter 3, while Chapter 4 provides the conclusions.

## 2. Materials and methods

### 2.1. Gear

External spur gears made of 20MnCr5 steel were used in the study. Gears with module $m = 5$ mm, outer diameter $d_a = 160$ mm and face width $b = 20$ mm were used. Table 1 lists a set of geometric parameters describing the tested gears.

Table 1.
Gear parameters

| | |
|---|---|
| Module $m$ | 5 mm |
| Number of teeth $z$ | 30 |
| Outside diameter $d_a$ | 160 mm |
| Pitch diameter $d$ | 150 mm |
| Root diameter $d_f$ | 137.5 mm |
| Face width $b$ | 20 mm |
| Helix angle $\beta$ | 0° |
| Profile shift coefficient $x$ | 0 mm |
| Hole diameter $D$ | ø30 H7 mm |

### 2.2. Thermochemical treatment

The gears were heat-treated in an innovative UCM vacuum furnace from SECO/WARWICK (Świebodzin, Poland), designed for single-piece flow thermal-chemical processing.

The gears in the furnace moved sequentially through three horizontally spaced process chambers (heat-up, low-pressure carburizing LPC, diffusion) located in a common vacuum space with gas-tight separation. Between process chambers, the gears moved in transport chambers (elevators), and external access to the transport chambers was realized through a loading airlock and an unloading airlock. After the carburizing process, each gear was individually subjected to high-pressure gas quenching (HPGQ) in a 4D Quenching chamber.

Table 2 summarizes the thermochemical treatment process conditions used in this study. After carburizing and hardening, the gears were subjected to a tempering process, obtaining an effective thickness of the carburized layer ECD = 0.6 mm.

Table 2.
Conditions of thermochemical treatment

| | | |
|---|---|---|
| Vacuum carburizing | Temperature | 920°C |
| | Boost | 6 s |
| Quenching | Medium | Nitrogen |
| | Pressure | 0.7 MPa (7 bar) |
| | Precooling | 860°C |
| Tempering | Temperature | 190°C |
| | Time | 180 min |

### 2.3. Grinding

Grinding of the working surface of the gear teeth after thermochemical treatment was carried out on a conventional gear grinding machine ZSTZ 315 B (WMW, Germany).

The grinder allows shaping the tooth profile using the generating gear grinding so-called Niles method.

A grinding wheel marked 99A80M8V was used as the cutting tool. It is a grinding wheel made of white aluminium oxide grains and a ceramic bond. Table 3 summarizes the technical parameters of the grinding wheel. It is noteworthy that it is a cylindrical grinding wheel, symmetrically terminated at the periphery with conical surfaces with a total opening angle of 40°.

Table 3.
Grinding wheel parameters

| | |
|---|---|
| Type / Shape | Tapered face straight wheel |
| Abrasive grain | 99A, white aluminium oxide |
| Bond type | V, vitrified bond |
| Hardness grade | M |
| Grain size | 80 |
| Structure | 8 |
| Dimensions $D \times T \times H$ | 340 × 20 × 127 mm |

The gear was ground by removing the machining allowance $a_e = 0.03$ mm on both sides (flanks) of each tooth. In addition, a constant grinding speed $v_s$ = 28.3 m/s was used. Workpiece speed $v_w$ was used as a variable parameter, taking three of its values for testing – 5, 10 and 20 m/min, which simultaneously corresponds to three settings of the stroke frequency of grinding wheel carriage $DH$, respectively: 50, 100 and 200 double-stroke/min. Table 4 summarizes the cutting parameters used during the experimental tests.

Two methods of feeding GF into the machining zone were used during grinding:

1) conventional WET method, in which Polgrind machining oil was fed at a flow rate of $Q_{WET}$ = 3 l/min through two symmetrically spaced nozzles.
2) MQL method, in which Ecolubric E200L rapeseed oil from Accu-Svenska AB was sprayed as an oil mist using an external Ecolubric MQL Booster from Accu-Svenska AB. The oil mist was fed into the grinding zone through three spray nozzles with a total oil output of $Q_{MQL}$ = 100 ml/h.

The grinding wheel was dressed prior to each grinding test, using a two single-grain diamond dresser type M1020. Table 5 lists the variable parameters of grinding conditions put into sets described by individual symbols. The other parameters were constant, according to Table 4.

## 2.4. Residual stress measurement

Residual stress measurements on the working surface of the gear teeth were taken twice, after thermochemical treatment and after grinding. Measurements were performed using the $\sin 2\psi$ X-ray method in ω geometry. For this purpose, PROTO iXRD r (Proto Manufacturing Ltd., LaSalle, ON, Canada) was used, in which the X-ray source is a Cr anode tube emitting radiation with a wavelength of $\lambda$=2.29 A.

Table 4.
Grinding parameters

| Grinding mode | Generating gear grinding by Niles method | | |
|---|---|---|---|
| Grinding wheel rotational speed $n_s$, rev/min | 1590 | | |
| Grinding wheel peripheral speed $v_s$, m/s | 28.3 | | |
| Axial table feed $v_{st}$, mm/min | 165 | | |
| Working engagement / Machining allowance $a_e$, mm | 0.03 | | |
| Grinding wheel stroke length $l_{sk}$, mm | 35 | | |
| Grinding wheel stroke frequency $DH$, double-stroke/min | 50 | 100 | 200 |
| Workpiece speed $v_w$, m/min | 5 | 10 | 20 |

Table 5.
Research plan

| Description | Variable parameters of grinding conditions | |
|---|---|---|
| | Method of coolants (GF) supply | Workpiece speed $v_w$, m/min |
| W5 | WET | 5 |
| W10 | | 10 |
| W20 | | 20 |
| M5 | MQL | 5 |
| M10 | | 10 |
| M20 | | 20 |

The change in the position of the (211) iron reflector, located at an angle of 2θ=156.4°, was studied. X-ray elastic constants ½ S2=5.92 1/TPa and S1=-1.27 1/TPa were used in the calculations. The measurement was carried out for an area bounded by a collimator with a diameter of φ = 2 mm at an exposure time of 1 s. Spot electrochemical etching using PROTO's 8818-V3 electropolymer was used to obtain stress distributions deep into the test substrates. Stress measurements were taken after each etching. Three measurements were taken for each tooth tested, and then the average value was calculated.

### 2.5. Microhardness measurement

As in the case of residual stress measurements, microhardness measurements on the working surface of gear teeth were also made twice, after thermochemical treatment and after grinding. A KB10BVZ-FA microhardness tester (KB Prüftechnik GmbH, Hochdorf-Assenheim, Germany) was used for the measurement. Microhardness was determined on the Vicers scale at a load of 0.9807 N (according to PN-EN ISO 6507). Measurements were taken on a surface perpendicular to the ground surface by spacing the measuring points to a depth of 1 mm. Three microhardness measurements were taken for each tooth tested, and the average measurements obtained were interpolated using cubic B-spline glued functions.

## 3. Results and discussion

### 3.1. Residual stress

Figure 1 shows the results of residual stress *σ*, the average of 3 measurements taken in the material after the thermochemical treatment (TCT) process before grinding. The value of residual stress on the surface of vacuum-carburized samples was -302 MPa. Then, as can be seen in the graph, these stresses increased monotonically with distance from the surface, reaching a value of -395 MPa at a depth of 0.3 mm and then aiming for a value of -96 MPa at a depth of 1.0 mm.

Figure 2 presents the distribution of residual stresses in the surface layer of vacuum-carburized specimens and then ground using GF supplied by the WET method. Similarly, Figure 3 shows the stress distribution of specimens ground with GF feeding using the MQL method. Also plotted on the graphs is a curve representing the residual stresses in the samples after the thermochemical treatment (TCT) process before grinding.

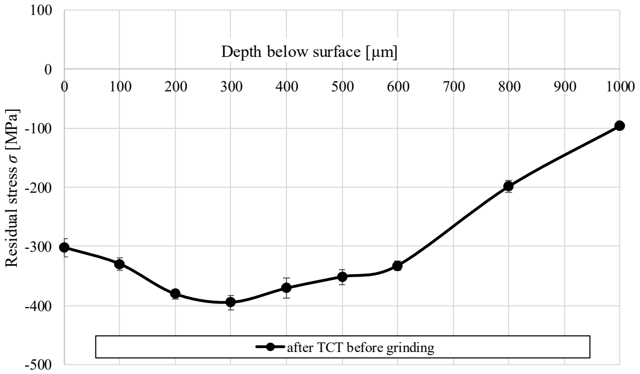

Fig. 1. Residual stresses in teeth after thermochemical treatment, before grinding

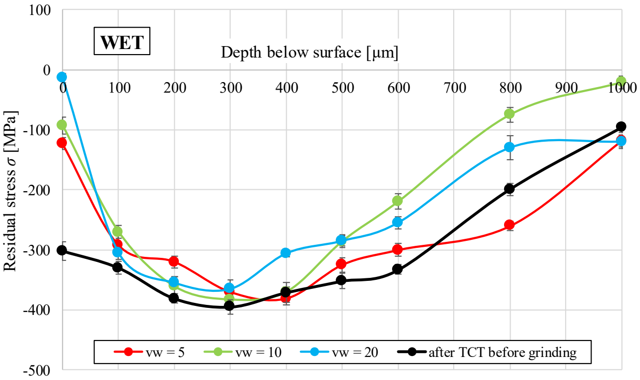

Fig. 2. Residual stresses in ground teeth using the WET method

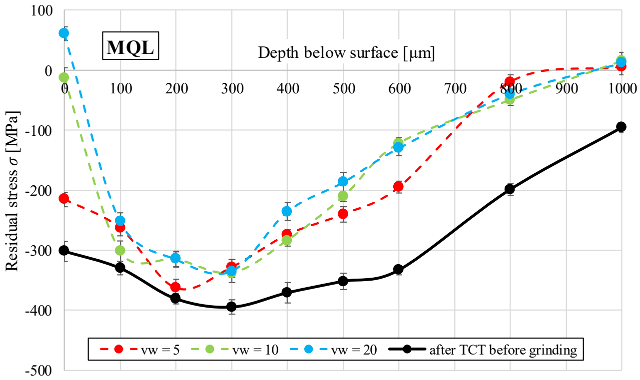

Fig. 3. Residual stresses in ground teeth using the MQL method

As seen from the graphs in Figures 2 and 3, in both cases (WET and MQL), grinding induces a deterioration of the state of residual stress with respect to the base material, that is, after thermochemical treatment and before grinding. This feature can be observed especially on the sample surface. What is noteworthy here is that in the case of both WET and MQL grinding, the smallest difference between the value of the base material surface stress and the surface after grinding was recorded when workpiece speed $v_w$ was the lowest and was 5 m/min. Increasing the value of $v_w$ causes an increase in this difference and shifts the value of residual stress in the direction of unfavourable tensile stresses. This property is probably because increasing the workpiece speed $v_w$ is due to the higher stroke frequency of grinding wheel carriage *DH*, which causes the tooth profile to be shaped by a greater number of generating strokes of the grinding wheel. In each generating stroke, the machining allowance is collected. The phenomena occurring at the contact between the grinding wheel and the workpiece material cause heat generation in the grinding zone. This heat accumulates with each successive stroke of the grinding wheel, causing the temperature to rise. The more generating strokes transitions (*DH* jumps), the higher the temperature in the workpiece material, which adversely affects the condition of the surface layer, causing a change in the distribution of residual stresses.

As can be seen from Figures 2 and 3, in five of the six grinding conditions used, the residual surface stresses remained in the region of favourable compressive stresses. Under grinding conditions at workpiece speed $v_w$ = 20 m/min and applying the MQL method (Fig. 3), the residual stresses on the material surface enter the area of unfavourable tensile stresses. This fact may indicate inadequate cooling and lubrication conditions using the MQL method in this case.

From a practical point of view, related to the subsequent operation of the gearbox, attention should be paid to the distribution of stresses below the surface, deep into the material. As can be seen from both graphs (Fig. 2, Fig. 3), already from a depth of 0.1 mm, the residual stresses in the material after grinding, for all cases, approach by value of the stresses in the base material. This is very advantageous because in the initial stage of operation (known as run-in), the outer surface layer will be removed, and the "exposed" layer will have favourable compressive stresses similar in level to those in the material before grinding.

Figure 4 shows the stress distribution in the material ground at three workpiece speeds $v_w$ [m/min]: 5 (Fig. 4a), 10 (Fig. 4b) and 20 (Fig. 4c). A curve representing the residual stresses in the specimens after the thermochemical treatment (TCT) process, prior to grinding, was also applied to all graphs.

For speed $v_w$ = 5 m/min (Fig. 4a) and $v_w$ = 10 m/min (Fig. 4b), favourable compressive residual stresses were obtained just below the surface of the sample. This property applies to both methods of delivering GF into the grinding zone. Only when using $v_w$ = 20 m/min (Fig. 4a) under minimum lubrication (MQL) conditions do the pressures on the surface enter the area of tensile stresses. In this case, it is probably due to a large amount of heat flowing into the workpiece and the relatively high grinding temperatures causing unfavourable structural changes (including a tempering process in the steel).

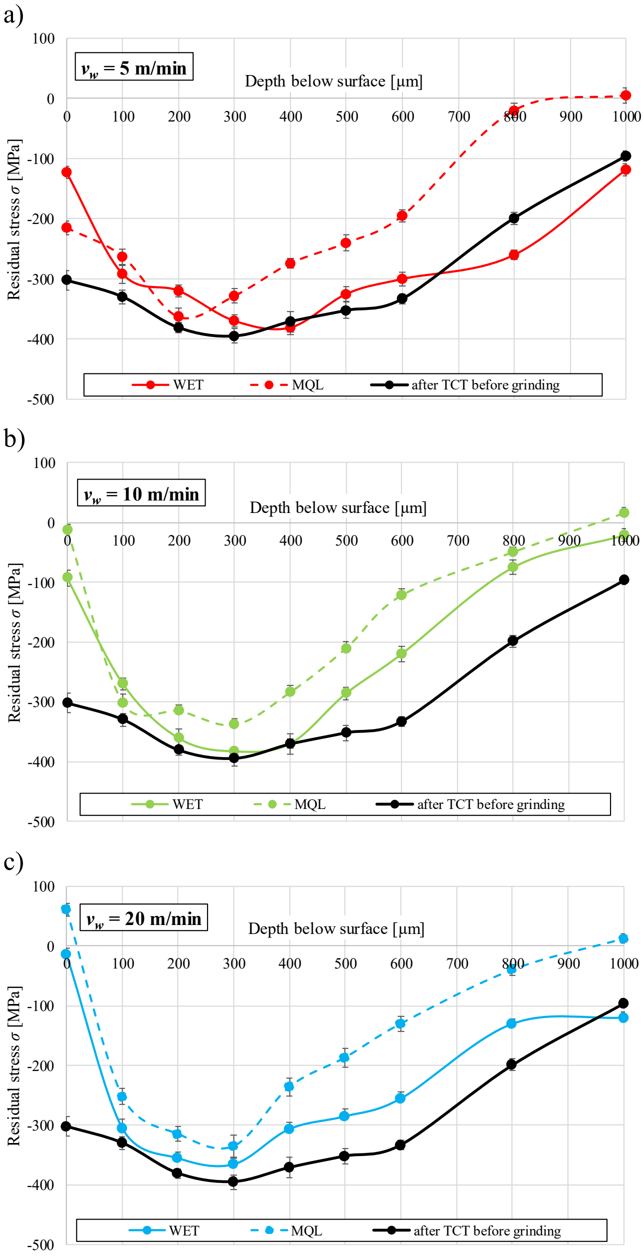

Fig. 4. Residual stresses in teeth ground at workpiece speed $v_w$: a) 5 m/min, b) 10 m/min, c) 20 m/min

Noteworthy is the fact that starting from a depth of 0.01 mm from the surface, the values of residual stresses are similar in all three compared cases, which is favourable from the point of view of the operation of gears as gear elements.

### 3.2. Microhardness

Figure 5 presents the microhardness distribution in the surface layer of vacuum-carburized specimens and then ground using GF supplied by the WET method. Similarly, Figure 6 shows the microhardness distribution in samples ground using GF feeding by MQL. Also plotted on the graphs is a curve representing the microhardness in the samples after thermochemical treatment (TCT) before grinding.

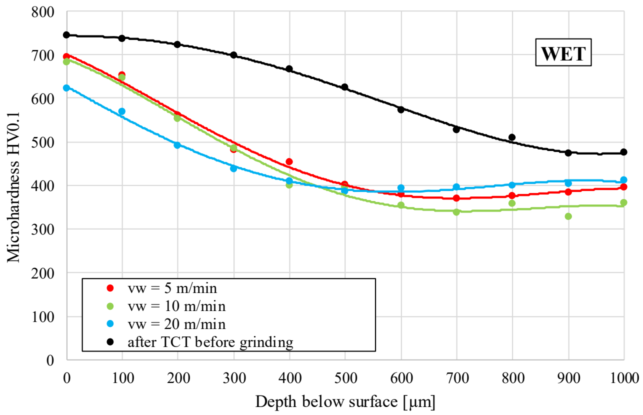

Fig. 5. Microhardness distribution in teeth ground using the WET method

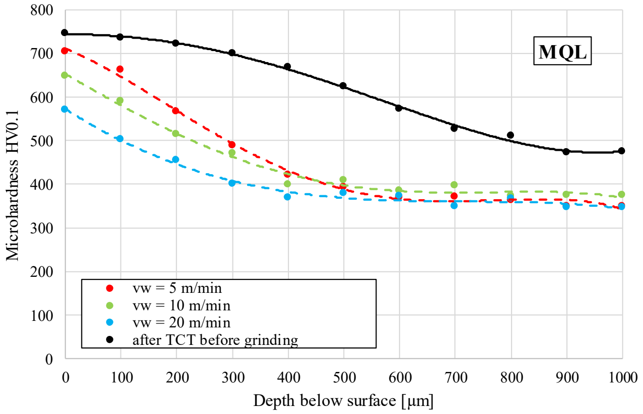

Fig. 6. Microhardness distribution in teeth ground using the MQL method

The graphs above (Fig. 5 and Fig. 6) show that for both GF feeding methods (WET and MQL), grinding causes a reduction in microhardness compared to the material after thermochemical treatment and before grinding. For all cases considered, the microhardness decreases from the surface to a depth of 0.5 mm and then stabilizes at around 350-400 HV.

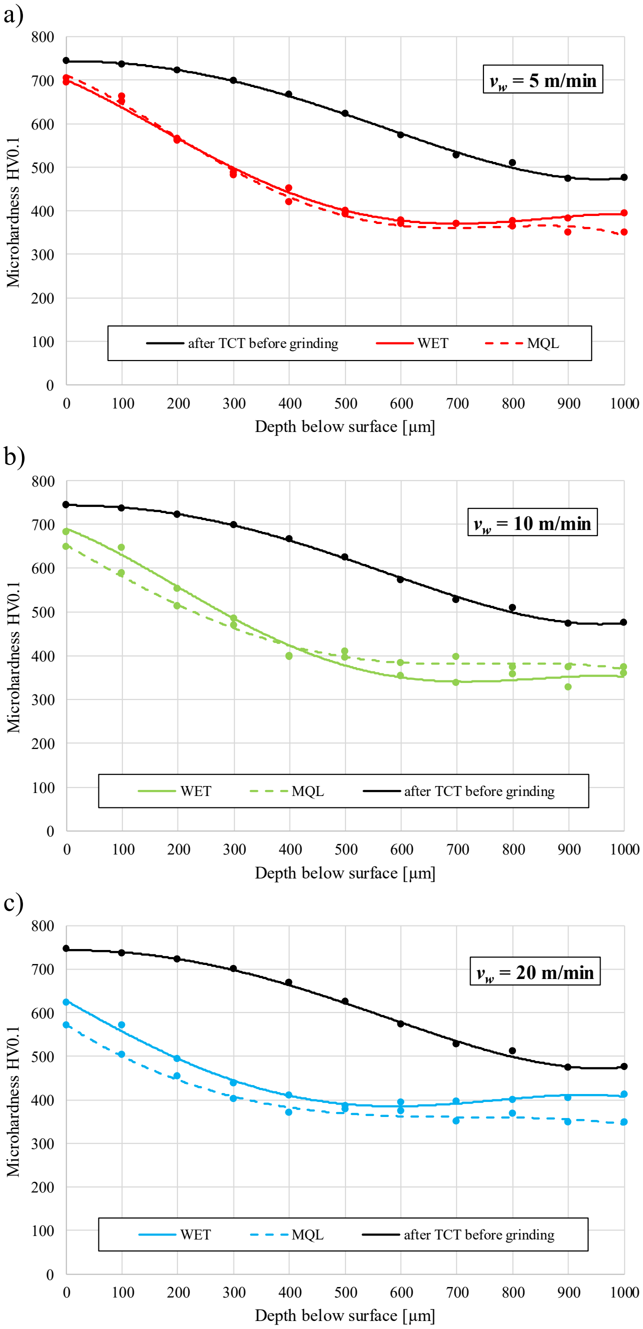

Fig. 7. Microhardness distribution in teeth ground at workpiece speed $v_w$: a) 5 m/min, b) 10 m/min, c) 20 m/min

In both cases of GF feeding, the smallest differences between the microhardness value of the base material and the surface after grinding were recorded when workpiece speed $v_w$ was the lowest and was 5 m/min. Increasing the value of $v_w$ increased this difference.

The above observations confirm the conclusions drawn when analysing the stress diagrams in Figure 2 and Figure 3. Microhardness decreases with increasing workpiece speed $v_w$. At the same time, the stroke frequency of the grinding wheel carriage *DH* indicates the unfavourable effect of the generated heat, which, accumulating with successive generating strokes of the grinding wheel, increases the temperature in the surface layer of the workpiece. Relatively high grinding temperatures cause unfavourable structural changes (including the process of tempering the steel), which translates into a reduction in the microhardness of the material.

Figure 7 shows the distribution of microhardness in the surface layer of material ground at three workpiece speeds $v_w$ [m/min]: 5 (Fig. 7a), 10 (Fig. 7b) and 20 (Fig. 7c). A curve representing the microhardness in the specimens after the thermochemical treatment (TCT) process, prior to grinding, was also applied to all graphs.

Notably, in all three cases illustrated above, a slight difference is apparent between the microhardness distribution obtained for material ground using the WET method and the MQL method. This indicates the provision of comparable lubrication and cooling conditions during processing.

Analysing the microhardness distributions, it should be noted that the smallest, negligibly small difference in microhardness values between the course corresponding to the use of the WET method and the course for the MQL method was recorded for grinding at workpiece speed $v_w = 5$ m/min (Fig. 7a). Similarly, the biggest difference was recorded for samples ground at a speed of $v_w = 20$ m/min (Fig. 7c). However, it should be noted that the difference, in this case, is relatively small, ranging from 8 HV (at a depth of 0.5 mm) to 67 HV (near the surface).

The above observations confirm the conclusions drawn when analysing the stress diagrams in Figure 4.

## 4. Conclusions

The paper describes a novel study to determine the effect of machining conditions during gear grinding on the residual stresses in the technological tooth surface layer. The innovation of the research lies in the delivery of GF to the grinding zone with minimal MQL, which has not been studied before. For comparison, the working surfaces of the teeth were ground using a conventional WET method by feeding machining oil. Workpiece speed was used as a variable grinding parameter $v_w$, which determines the number of generating strokes of the grinding wheel and, thus the accuracy of the tooth contour. In order to better understand the effect of grinding conditions on the state of residual stress, the study was supplemented with microhardness measurements.

Based on the results obtained for the test conditions used, the following conclusions can be drawn:

(1) The vacuum carburizing process carried out by the single-piece flow method makes it possible to obtain favourable compressive residual stresses in the technological surface layer.

(2) In general, the grinding process with an electro-corundum grinding wheel causes a deterioration in the material's residual stress state compared to that of the sample after vacuum carburizing treatment and before grinding. As workpiece speed $v_w$ increases, the stresses on the surface move toward the tensile stress region, but only for the $v_w = 20$ m/min using the MQL method they enter this region.

(3) From a practical point of view, for which the values of the undersurface stresses are decisive, the undersurface stresses have a favourable compressive character in all cases and for both methods of feeding GF (WET and MQL) close to each other.

(4) In the aspect of residual stress, feeding GF by the MQL method can be an alternative to the conventional WET method.

(5) In general, grinding with an electro-corundum grinding wheel results in a reduction of microhardness in the surface layer of the material with respect to the sample before grinding.

(6) For each GF feeding method (WET and MQL), increasing workpiece speed $v_w$ shifts the microhardness waveform toward smaller values. For both methods, the smallest decreases in microhardness compared to the base material were observed for the sample ground at the lowest speed, $v_w = 5$ m/min, while the largest was observed when the $v_w = 20$ m/min was applied.

(7) The smallest, negligibly small difference in microhardness between the waveform corresponding to the use of the WET method and the waveform for the MQL method was recorded when grinding at workpiece speed $v_w = 5$ m/min.

(8) Small, or negligibly small, differences in microhardness waveforms obtained for samples ground using the WET and MQL methods at the same workpiece speed $v_w$ indicate that comparable lubrication and cooling conditions are provided during machining.

In conclusion, it should be said that the analysis of the results of residual stress stress-strain and microhardness measurements showed that the MQL method could be an alternative to conventional GF feeding using the WET method. Therefore, further research work in this area is warranted.

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