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AN EFFECT OF GRINDING ON MICROHARDNESS AND RESIDUAL STRESS IN 20MnCr5 FOLLOWING SINGLE-PIECE FLOW LOW-PRESSURE CARBURIZING

The aim of the experiment described in the paper was to determine the effect of selected conditions of abrasive machining on the size and distribution of microhardness and residual stresses developed in the technological surface layer of flat specimens made of 20MnCr5 steel. The specimens were subjected to single-piece flow low-pressure carburizing (LPC) and high-pressure gas quenching (HPGQ) in a 4D Quenching chamber, in order to achieve the effective case depth of ECD=0.4 mm. This was followed by grinding the specimens with Quantum and Vortex alumina grinding wheels made by Norton. Cooling and lubricating liquid were supplied to the grinding zone in both cases by the flood (WET) method and by the minimum quantity lubrication (MQL) method. The measurements for each specimen were made twice - after the thermo-chemical treatment and after the grinding. Microhardness and residual stress was measured by the X-ray method $\sin^2\Psi$. The final part of the article provides an analysis of the measurement results and presents conclusions and recommendations for further studies.

1. INTRODUCTION

Grinding is one of the most common machining methods used in technological processes for finishing hard materials. Thus, the properties of the surface layer formed by grinding have a direct impact on the functional properties of a workpiece, such as fatigue strength, abrasion and corrosion resistance, etc. [1]. The important parameters which determine the state of the technological surface layer include microhardness and residual stresses. The distribution of microhardness and residual stresses is affected, among other things, by the type of thermal treatment preceding the grinding process and the characteristics of the grinding wheel, in particular the type of the abrasive material.

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Carburizing followed by quenching is one of the most frequently used methods of thermal surface treatment. It is widely used in the automotive industry [2]. The low-pressure version of the carburization process [3, 4] outperforms conventional carburization [5–9] in terms of efficiency and it has a number of advantages: no internal oxidation, greater uniformity of the obtained layers, energy efficiency and environmental friendliness.

Residual stresses in thermo-chemical treatment (TCT) processes exist both in the substrate and in the top layer. Analyzing the state of residual stress is important due to its effect on, among other things, fatigue strength, tribological wear, corrosion, brittle cracking, contact fatigue [10–13]. When considering the mechanical properties, this effect may be beneficial, but it may also lead to damage to a component or an entire unit, depending on the type of stress (compression/elongation) and its superposition with operating stresses from external forces. It is believed that the generation of compressive stress in the layer compensated for by tensile stress in the core can contribute to an increase in the fatigue strength [14–18]. When grinding is carried out with grinding wheels with Al_2O_3 grit, an increase in productivity results in the grinding power increase, which leads to an increase in the grinding temperature of the workpiece [1]. It is the main cause of changes in microhardness and residual stresses as compared with the material following thermal treatment. Increased heat load on the surface layer results in unfavorable residual tensile stresses, which decrease the fatigue strength of dynamically loaded machine parts, as well as in a decrease in microhardness deep in the technological surface layer. It should be noted that the risk of adverse thermal effects on the surface layer is lower if the coolant-lubricant reaches more effectively the contact zone of the active abrasive grit with the surface being ground. To this end, oil mist can be introduced into the grinding zone by the MQL method [19].

The paper [20, 21] presents the experiment conducted during the grinding of ABNT 4340 (60 HRC) steel with a grinding wheel made of aluminum oxide (Al_2O_3). In the course of the experiment, coolant-lubricant was supplied by the MQL method and by the flooding method, and moreover grinding was carried out with no coolant-lubricant. The results have shown that application of the MQL method resulted in favorable residual compressive stresses, with values lower than those obtained in the other processing conditions. According to the authors of the study, this is due to better lubricating properties of the MQL method, lower friction between the active abrasive grit and the workpiece, and – in consequence – lower temperature in the grinding zone. The results of microhardness measurements have also shown the beneficial effect of the MQL method in grinding on the state of the technological surface layer.

This paper [9] describes the tests carried out during plunge grinding of external cylindrical surfaces with an alumina grinding wheel and a CBN grinding wheel. The results show that the use of an Al_2O_3 grit wheel results in a significant deterioration of the residual stress compared with the use of a CBN grit wheel. In addition, residual stress in specimens ground with the use of the MQL method was higher than in specimens ground with the flood method.

Shao et al. [22] proposed a physical model for predicting the residual stress in the surface layer of a material being ground with minimum quantity lubrication (MQL).

The proposed model was validated by experimental tests, during which steel specimens (AISI 1018) were ground with an alumina grinding wheel. Test results indicate that the residual stress profile obtained by MQL grinding can be significantly different from that obtained by grinding with the use of the flood method. It was found that higher temperature generated while grinding with the use of the MQL method shifted the residual stress profile towards tensile stress.

The aim of the experiment studies described in this paper was to determine the effect of selected conditions of abrasive machining on the size and distribution of microhardness and residual stresses developed in the technological surface layer of flat specimens made of 20MnCr5 steel. To this end, first, the specimens were subjected to single-piece flow low-pressure carburizing (LPC) and high-pressure gas quenching (HPGQ) in a 4D Quenching chamber, in order to achieve the effective case depth of ECD=0.4 mm, and subsequently, they were ground with Quantum and Vortex alumina grinding wheels manufactured by Norton. Coolant-lubricant was supplied to the grinding zone by the flood method and by minimum quantity lubrication (MQL) method. The experiment results are discussed in Chapter 2. Chapter 3 provides an analysis of the results of microhardness and residual stress measurements for the specimens after the thermo-chemical treatment and after the grinding process. Chapter 4 contains conclusions and recommendations for further research.

2. EXPERIMENTS

2.1. SINGLE-PIECE FLOW LOW-PRESSURE CARBURIZING AND QUENCHING

The thermo-chemical treatment was carried out in an innovative vacuum UCM furnace (Fig. 1) manufactured by SECO/WARWICK (Poland). This unit differs from other vacuum furnaces by the thermo-chemical treatment being conducted by the single-piece flow method, which has not been applied in the batch method so far. In the single-piece flow method, each individual component passes individually through identical process positions and conditions in the furnace [23–25]. As a result, this type of carburization is more precise and repeatable compared with conventional methods. In addition, the use of high-pressure gas (HPGQ) quenching in a 4D Quenching chamber (Fig. 1) for individual gas cooling of each element allows for the free shaping of the cooling curve and for achieving the optimal steel microstructure and properties. An important feature of this solution is the use of a system of cooling nozzles surrounding the element and ensuring an even flow of cooling gas from all sides (3D). At the same time, the table rotating together with the workpiece helps to achieve the cooling evenness. This cooling system allows for achieving a cooling intensity comparable to that of oil systems, without the need to use helium (He).

Four flat specimens, made of 20MnCr5 steel, with the dimensions of 100×100×10 each, were selected for the experiment. The specimens dimensions resulted from the construction of the transporting mechanism inside the UCM furnace. The specimens were carburized at the temperature of 920°C, which resulted in the effective case depth of ECD=0.4 mm and total case depth of TCD=0.7 mm. Subsequently, the specimens were quenched in the quenching atmosphere at a pressure of 7 bar, and then tempered at 190ºC for 3 hours. The TCT process parameters are given in Table 1.

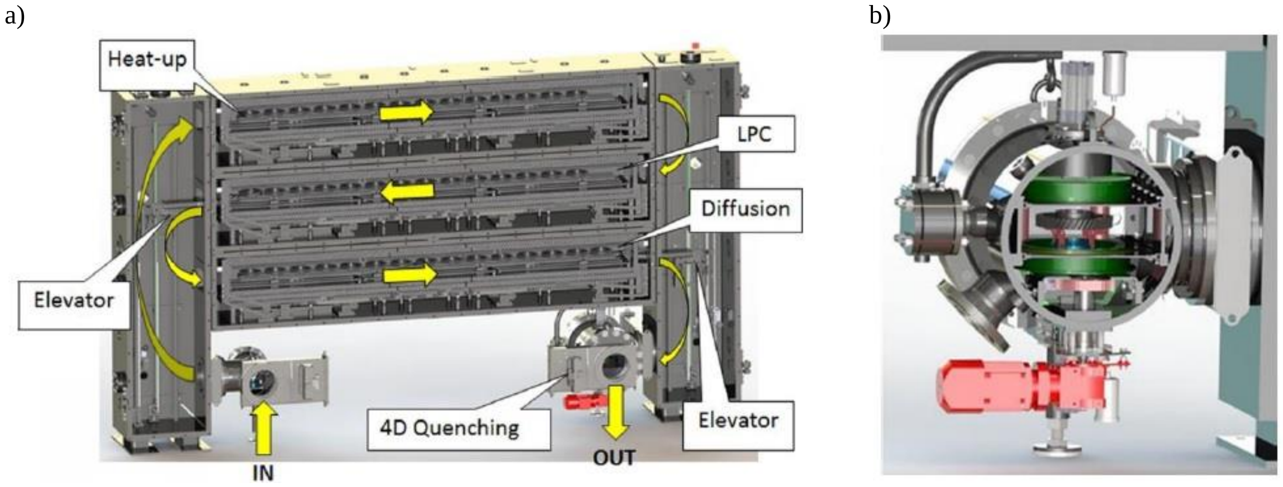

Fig. 1. A SECO/WARWICK UCM furnace for low-pressure carburizing: a) general view, b) quenching chamber [23]

Table 1. Thermo-chemical treatment (TCT) parameters

Number of samples	Parameters of treatment		
Q_WET	Vacuum carburizing at 920 ºC	Quenching in nitrogen at 7 bar and at a temperature of 850 ºC	Tempering at 190 ºC for 180 min
Q_MQL			
V_WET			
V_MQL			

2.2. GRINDING

Experimental tests of grinding flat surfaces were aimed at determining the effect of changes in the grinding conditions, such as the type of a grinding wheel and the method of supplying coolant-lubricant on the output parameters of the process, such as microhardness and residual stresses generated in the surface layer of the ground surface. Four specimens were ground; they had been subjected to thermo-chemical treatment (TCT) described in the preceding chapter.

The tests were conducted in the course of longitudinal circumferential surface grinding with a conventional SPD-30B grinder for flat surfaces manufactured by Jotes SA (Poland). Two grinding wheel, manufactured by Norton (Poland) - 2NQ60JVS3 and IPA60EH20VTX - were used in the experiment. The 2NQ60JVS3 Quantum type grinding wheel is a ceramic bonded wheel which consists of 20% Norton Quantum abrasive grit and 80% of alumina. It is a soft grinding wheel (J) of a closed structure. IPA60EH20VTX is a Vortex type grinding wheel, made of ceramic-bonded alumina abrasive grit (VTX). It is an open-structure hard grinding wheel, with increased porosity (so called large-pore grinding wheel).

The grit size distribution is identical in both grinding wheels, with grit number 60. The grinding wheels were conditioned before each trial with a single grain diamond dresser.

Table 2 shows the conditions in which grinding was conducted during the tests. The grinding parameters used in experimental research are typical parameters used in flat surface grinding. The machining allowance was removed in one work cycle which consisted of the work run and return (synchronous and asynchronous direction), at a constant grinding depth of a_e=0.02 mm. The constant perimeter speed of v_s=25.6 m/s and the workpiece speed of v_w=18 m/min were used in the experiment.

Table 2. Grinding conditions

Grinding mode	Single-pass longitudinal circumferential surface grinding
Grinding machine	Flat-surface grinder SPD-30B by Jotes Co. Ltd. (Poland)
Workpiece material	20MnCr5, carburized and hardened with 61±1 HRC
Grinding wheels	2NQ60JVS3 and IPA60EH20VTX
Grinding wheel rotational speed	n_s = 1400 rpm
Grinding wheel peripheral speed	v_s = 25.6 m/s
Workpiece peripheral speed	v_w = 18 m/min
Working engagement (machining allowance)	a_e = 0.02 mm
Dresser	Single grain diamond dresser type M1020
Dresser weight	Q_d = 2.0 kt
Grinding wheel peripheral speed while dressing	v_{sd} = 10 m/s
Dressing allowance	a_d = 0.01 mm
Axial table feed speed while dressing	v_{fd} = 5.0 mm/min
Number of dressing passes	i_d = 4
Environments	WET – conventional fluid MQL – minimum quantity lubrication
Conventional grinding fluid (GF)	Emulgol ES-12 in a 5% concentration
Conventional GF flow rate	Q_{GF} = 4 l/min
MQL system	Ecolubric MQL Booster - oil-mist generator with single external nozzle
MQL fluid	Ecolubric E200L – cold-pressed rapeseed oil without additives
MQL flow rate	Q_{MQL} = 100 ml/h
MQL supply air pressure	P = 0.6 MPa

The specimens were ground with the use of coolant-lubricant supplied by the flood method (WET) and by minimum quantity lubrication (MQL) method. Aqueous oil emulsion with Emulgol ES-12 oil (5%) was used as conventional processing liquid. Oil mist in the MQL method was generated with an external device Ecolubric MQL Booster (Fig. 2) made by Accu-Svenska AB (Sweden) [26]. The individually controlled pump supplies an adjustable quantity of lubricant to the nozzle. Through a concentric outer tube, compressed-air is lead towards the end of the capillary tube so that the lubricant is atomized and applied to the grinding zone.

A single spray nozzle tangential to the active surface of the grinding wheel (GWAS) was used in the tests. Figure 3 shows a test stand equipped with a grinder, as well as the position of the MQL nozzle in relation to the GWAS.

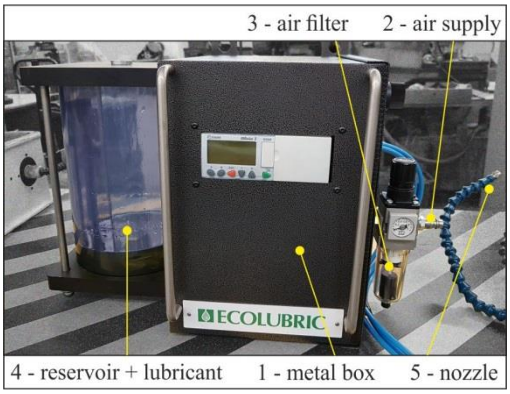

Fig. 2. Components of Ecolubric MQL Booster applicator by Accu-Svenska AB (Sweden): 1 – metal box containing: actuator, air flow valve, frequency generator, 2 – air supply, 3 – air filter, 4 – reservoir with lubricant, 5 – nozzle

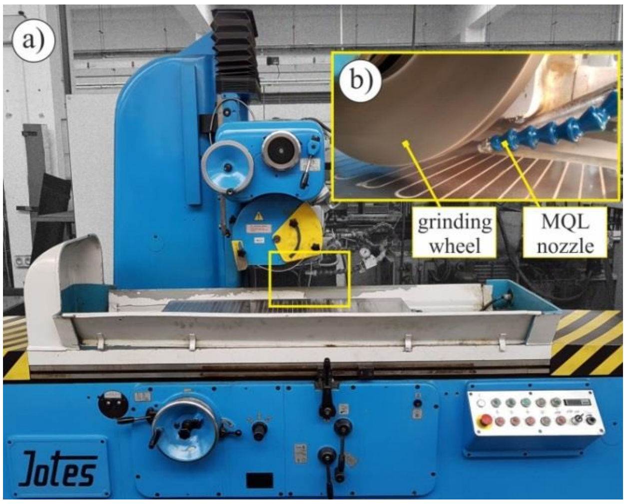

Fig. 3. The test stand with an SPD-30B flat-surface grinder made by Jotes SA: a) general view, b) a view on the grinding zone

Ecolubric E200L rapeseed oil [27], supplied by the device manufacturer, was used as the coolant-lubricant in the MQL method. The information about rapeseed oil is shown in Table 3.

Table 3. Characteristics of Ecolubric E200L rapeseed oil applied in the research [27]

Properties	Description
Chemical description	A fraction of natural triglycerides, easily biodegradable substances
Health hazard	Not hazard to human health
Flash point	325 °C
Ignition point	365 °C
Density at 0°C	0.9273 g/cm^3
Dynamic viscosity at 0°C	2.881 N s/m^2
Partition coefficient	<3%

Table 4 shows the set of variable machining conditions applied in the tests described above.

Table 4. Variable grinding conditions applied in the research

Number of samples	Grinding wheel	Method of coolant-lubricant supply
Q_W	2NQ60JVS3 (Quantum)	WET
Q_M		MQL
V_W	IPA60EH20VTX (Vortex)	WET
V_M		MQL

2.3. MICROHARDNESS MEASUREMENTS

The microhardness of the specimens surface after grinding was measured with a KB10BVZ-FA microhardness meter made by KB Prüftechnik GmbH (Germany). Microhardness was determined in the Vickers scale at the load of 0.9807 N. The loading time was 15 seconds (according to PN-EN ISO 6507 standard). The measurements were carried out on metallographic sections perpendicular to the ground surface to the depth of 0.3 mm Three microhardness measurements were carried out on each specimen. The obtained average measurement results were interpolated with cubic B-spline functions.

2.4. MEASUREMENT OF RESIDUAL STRESS BY THE X-RAY METHOD

Stress measurements on the ground samples were carried out using the sin2ψ X-ray method in ω geometry with a PROTO iXRD device equipped with two position-sensitive diode detectors. The X-rays source was a Cr anode lamp emitting characteristic X-rays of a wavelength of λ = 2.29 A. The change of position of the reflex (211) of iron, at an angle of 2θ = 156.4°, was measured. X-ray elasticity constants of ½ S2 = 5.92 1/TPa and S1 = -1.27 1/TPa were taken for calculations. The measurement was conducted on an area delineated by a collimator with a diameter of φ = 2 mm. The exposure time was 1 s. The voltage of x-ray tube source was 20 kV, work current 4 mA. In order to determine the stress distributions inside the tested substrates, spot electrochemical etching was carried out with a 8818-V3 electropolishing device made by PROTO. Solution containing 70% $HClO_4$ with flow rate of 5 l/min was used as the etching agent. The substrates were etched successively at the depth of 0.05, 0.1, 0.15 and 0.2 mm. The stresses were measured after each etching. The voltage during the etching process was 60 V, current intensity 0.5 A.

3. RESULTS AND DISCUSSION

3.1. MICROHARDNESS

The microhardness tests carried out after grinding showed that the smallest changes (about 240 HV at the surface), compared with the microhardness of the material before grinding, occurred when a Vortex type grinding wheel was used with the coolant-lubricant supplied by the MQL method (Fig. 4a). Testing a specimen ground with the same wheel, but with the coolant-lubricant supplied by the flood method (WET) showed a microhardness decrease at the surface by approx. 510 HV. At the same time, as the microhardness distributions for the two above mentioned specimens show (Fig. 4a), similar microhardness values were observed at a distance of about 0.2 mm from the surface.

When a Quantum grinding wheel was used (Fig. 4b), the smallest changes in microhardness at the surface, compared with the material prior to grinding, were also obtained by grinding with the use of the MQL method. It decreased by approx. 370 HV (with 240 HV when grinding was carried out with a Vortex wheel). For the same grinding wheel, the microhardness at the surface of a specimen ground with the use of the flood method (WET) is lower by approximately 470 HV compared with the original material. It is noteworthy that the microhardness at the surface obtained for the two above mentioned Quantum grinding wheels differs by about 100 HV, while the difference for the Vortex wheel was about 270 HV. Moreover, the microhardness distributions for the two specimens ground with a Quantum wheel show (Fig. 4b) that similar microhardness developed at a distance of about 0.26 mm from the surface.

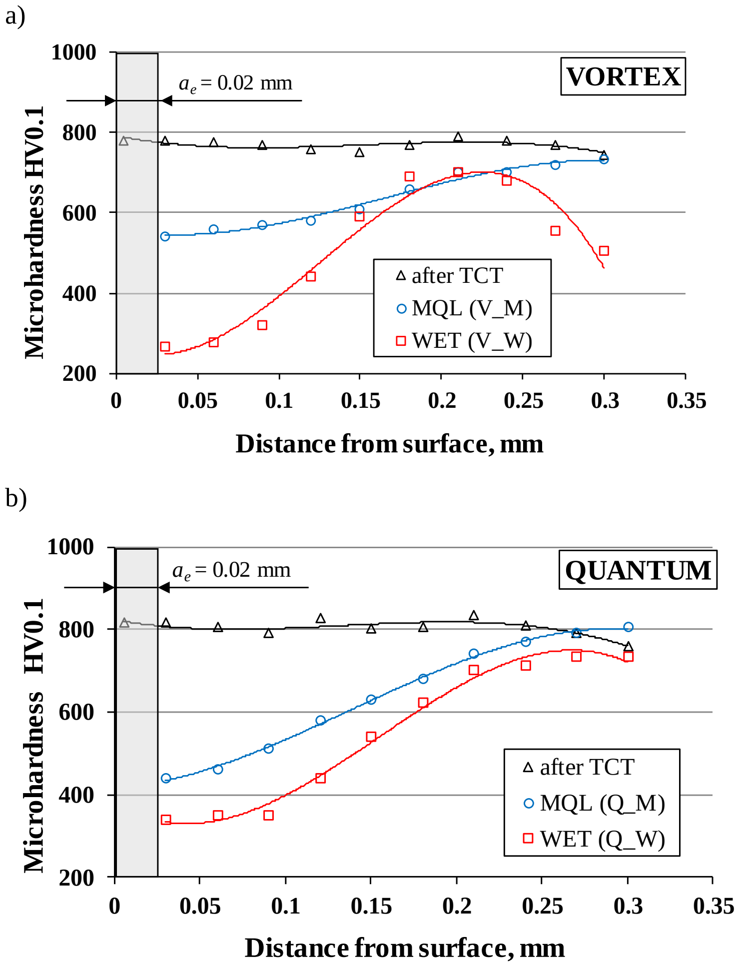

Fig. 4. Distribution of microhardness in 20MnCr5 steel ground with alumina grinding wheels: a) IPA60EH20VTX (Vortex), b) 2NQ60JVS3 (Quantum)

3.2. RESIDUAL STRESS

Figure 5 shows the results – an average of 3 measurements of residual stress in specimens following the TCT process (before grinding). It shows that the residual stress on the surface of specimens after low-pressure carburizing was −248 MPa. The stress increased monotonically with the distance from the surface, reaching −492 MPa at the depth of approx. 0.3 mm.

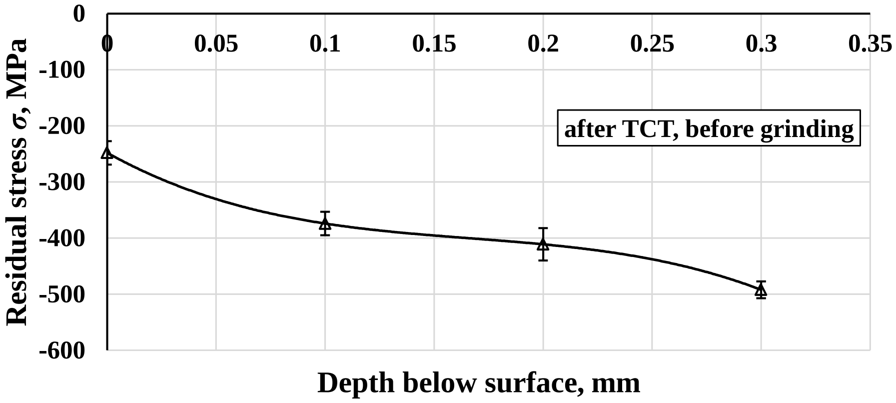

Fig. 5. Surface residual stress profile – after TCT, before grinding

Figure 6 shows a distribution of residual stress for specimens after low-pressure carburizing followed by grinding with an alumina Vortex grinding wheel (Fig. 6a) and an alumina Quantum grinding wheel (Fig. 6b). Moreover, the graphs show the effect of the type of coolant-lubricant supply method (MQL, WET) applied while grinding on the stress distribution in the top layer.

A comparison between Figures 5 and 6 shows that grinding with an alumina grinding wheel brings about a deterioration of the residual stress compared with the material after the thermal treatment (before grinding). In each case, unfavorable residual tensile stress was observed just below the surface. This general relationship applies both to the two types of grinding wheels used and to the two methods of supplying the coolant-lubricant to the grinding zone. This is caused by a large amount of heat which flows to the item and relatively high temperatures of grinding, which result in adverse structural changes (among others, the process of steel tempering).

As shown in Figure 6, the value of the residual stresses produced was more favorable for the specimens ground using the MQL method when both Vortex and Quantum grinding wheels were used. This indicates a better lubrication capacity of this method than of the flood method (WET). As shown in [28], the high air pressure in the MQL method induces high velocity of oil particles, which penetrate more efficiently the interface between grinding wheel and the workpiece. In effect, the reduction of the friction coefficient between the active abrasive grit and the surface being ground leads to a lower grinding temperature, which has a significant effect on the residual stresses generated in the technological surface layer. Despite the MQL method's advantages related to its good lubricating properties, its apparent disadvantage is a lack of sufficient cooling properties in a wide range of changes of grinding process parameters as compared with the traditional WET method [29]. This results mainly from the relatively low heat storage capacity of the oil and air and from the small amount of the coolant delivered into the grinding zone [30].

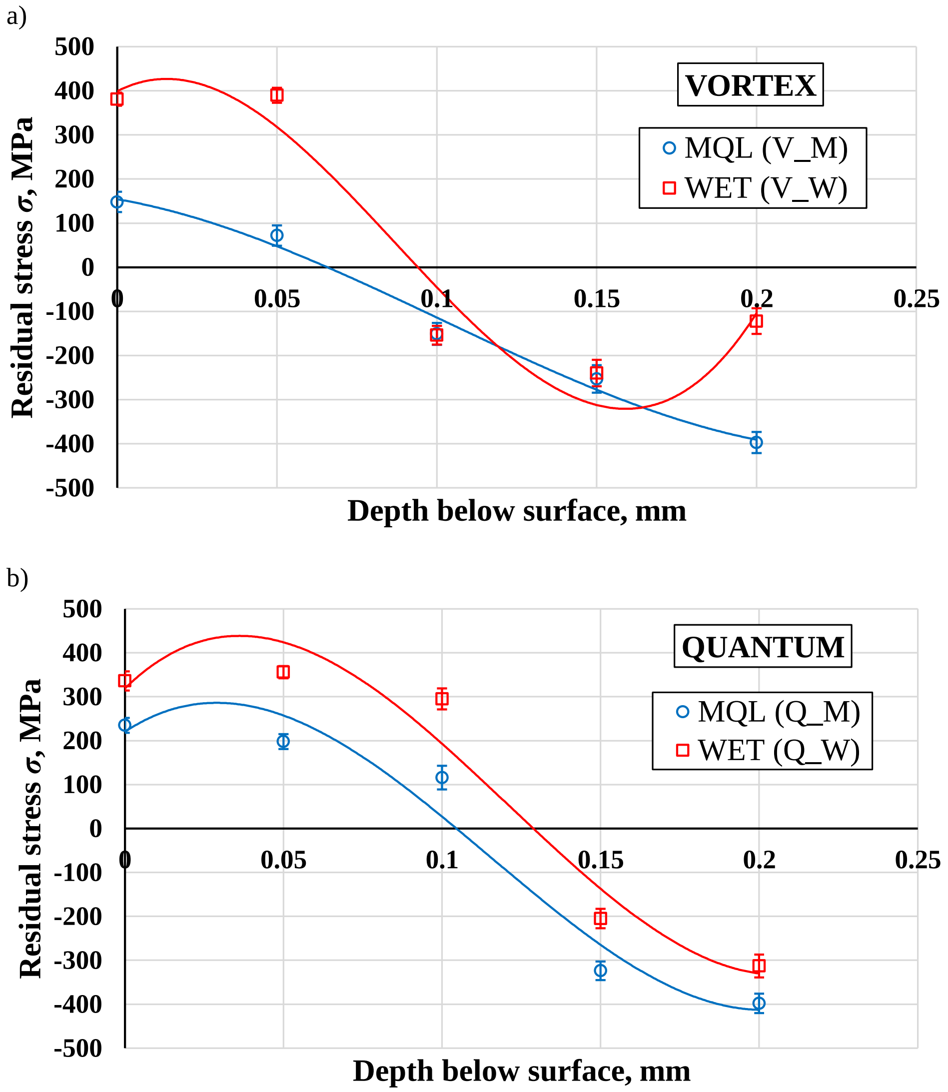

Fig. 6. Surface residual stress profile – longitudinal residual stress vs. depth below surface: a) Vortex grinding wheel, b) Quantum grinding wheel

It should be noted that the most favorable residual stress was obtained in the specimen ground with the IPA60EH20VTX type Vortex grinding wheel with the use of minimum quantity lubrication (MQL). According to the authors, this property results from the increased porosity of the grinding wheel, compared with the Quantum one, which is characterized by large intergranular spaces. As a result, more lubricant enters the contact zone of the active abrasive grit with the workpiece, which reduces friction and lowers the grinding temperature. The temperature decrease is also caused by a lower number of active abrasive grits compared with the Quantum grinding wheel and the consequent lower friction in the grinding zone. In both cases, a lower grinding temperature has a more positive effect on the stress created in the surface layer of the steel being ground.

4. CONCLUSIONS

The results of the experiment has shown that:

- the “single-piece flow” carburization produces a favorable, i.e. compressive distribution of residual stress in the technological surface layer,
- grinding with alumina grinding wheels results in deterioration of the residual stress compared with the material after low-pressure carburizing, producing adverse tensile stress in the technological surface layer close to the surface,
- the best results of grinding, in terms of the distribution of microhardness and residual stress, are obtained when grinding with an open structure grinding wheel with increased porosity (IPA60EH20VTX, Vortex type) and supplying coolant-lubricant by the minimum quantity lubrication (MQL) method.

Further research is going to focus on the selection of the processing conditions to increase its productivity while maintaining the desired surface properties. The authors also plan to expand the research to include measurements of grinding force and surface roughness.

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