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The influence of workpiece speed on microhardness and residual stresses in vacuum-carburised 20MnCr5 steel using the single-piece flow method

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ABSTRACT

Purpose: To determine the impact of selected conditions of abrasive treatment on the value and distribution of microhardness and residual stresses in layers carburised by a continuous single-piece flow method.

Design/methodology/approach: Reference pieces were low pressure carburised at 920°C and then heat-treated in a 4D Quench heat treatment chamber at a pressure of 7 bar and tempered at 190°C for 3 hours. In the next stage, samples were ground at various v_w piece speeds, introducing grinding fluid into the cutting zone using the WET spraying method or using the MQL method at a minimum flow rate. The distribution of microhardness and residual stresses generated in the technological outer layer of the pieces following heat and chemical treatment and the grinding process was measured.

Findings: Results of the tests indicated that the vw piece speed and method used to supply cooling and lubricating fluid to the grinding zone had an impact on selected parameters of the technological outer layer of flat samples made of 20MnCr5 steel. The process of grinding using an electrocorundum grinding wheel results in a deterioration of residual stresses in the material. For each of the three analysed v_w piece speeds, reduced changes in material microhardness prior to cutting occur in the outer layer of samples ground using GF supplied at a minimum flow rate using the MQL method.

Research limitations/implications: Environmental considerations and having to conform to increasingly stringent regulations related to environmental protection and employee safety motivate researchers and businesses to entirely eliminate or reduce the use of grinding fluids in the grinding process and, therefore, to optimise grinding technology.

Practical implications: Modern manufacturing industry requires the grinding process, which follows heat and chemical treatment, to be performed with the highest possible efficiency. However, retaining high parameters of the technological outer layer in comparison to the sample material following vacuum carburisation (before grinding) is extremely difficult. An optimised configuration of parameters of the grinding process and method of supplying grinding fluids enables meeting the current and future high expectations of the industry in this regard.

Originality/value: The tests have enabled us to determine the impact of the applied vw workpiece speed and method of supplying grinding fluid on microhardness and residual stresses. Generally speaking, grinding with an electrocorundum grinding wheel results in a deterioration of residual stresses. For both methods of supplying GF (WET and MQL), the distribution of microhardness in the material of the samples ground with the highest workpiece speed (18.0 m/min) indicated no significant differences with regard to the distribution of microhardness in the material of the samples following heat and chemical treatment.

Keywords: Surface grinding, Microhardness, Residual stress, Vacuum carburising, Single-piece flow

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Grinding is an abrasive treatment process widely used in finishing treatment operations. Like all mechanical surface treatment processes, grinding also significantly impacts the properties of the technological external layer of workpieces [1,2]. Basic parameters determining the condition of the technological outer layer include microhardness and residual stress. The value of microhardness and residual stress parameters is impacted by factors such as the type of heat treatment that precedes grinding and the abrasive treatment process itself, including grinding parameters and the method used to supply grinding fluid (GF) to the grinding zone [3-5].

The literature indicates [6] that carburisation followed by tempering is one of the most frequently used methods of heat surface treatment. Furthermore, the low-pressure carburisation method [7] is more efficient than conventional carburisation [8-10] and has several other advantages such as the lack of internal oxidisation and greater regularity of layers produced.

Residual stresses produced during thermal and chemical treatment (TCT) are present in both the substrate and outer layer [11]. Analysis of residual stresses is vital due to their impact on properties such as fatigue limit, tribological wear, corrosion, brittle fracture and pitting [12,13]. As regards mechanical properties, the impact may be positive but may also lead to the destruction of the piece or the entire device, depending on the type of stresses and their superimposition with live stresses caused by external inputs. A review of the literature indicates that the generation of compressing stresses in the outer layer compensated with tensile stresses in the core may increase the fatigue limit [14].

It is worth noting that the modern manufacturing industry requires the grinding process following thermal and chemical treatment to be as efficient as possible [15]. Efficiency can be improved by increasing grinding depth, a_e [16], and/or increasing the workpiece speed (v_w). Where grinding is done using grinding wheels with electrocorundum grit, improving efficiency increases grinding power – which leads to an increase of grinding temperature in the workpiece [17]. Changes in temperature are the main cause of changes in microhardness and residual stresses compared to heat treated material [1,18]. The increased heat load of the outer layer generates detrimental residual tensile stresses that reduce the fatigue limit of machine parts subjected to live loads and the microhardness level going downwards into the technological outer layer. Of note here is that the risk of a detrimental effect of temperature on the outer layer is reduced if the grinding fluid can reach the zone of contact between active grit with the ground surface more effectively [19,20].

The flood method (WET) is widely used to supply grinding fluid in the grinding process and involves spraying an oil and water emulsion into the grinding zone. However, to be effective, the WET method requires a high rate of supply of GF to the grinding zone. From a technical perspective, this constitutes a significant drawback of the method because only a small percentage of the emulsion reaches the zone where the grinding wheel contacts the workpiece [21]. Furthermore, having to purchase, clean, regenerate and dispose of grinding fluid significantly increases total costs of production [22,23]. Given the above considerations, efforts are made to fully eliminate or reduce the use of grinding fluids. Environmental considerations and having to conform increasingly stringent regulations related to environmental protection and employee safety are additional incentives in this regard [24-27].

One of the most widely used methods of significantly reducing the amount of grinding fluid supplied to the grinding zone is the use of the minimum quantity lubrication method, abbreviated as MQL [28-30]. MQL involves constantly generating an oil mist and supplying it directly into the grinding zone, usually onto the active surface of the grinding wheel. Synthetic esters or fatty alcohols are most commonly used as lubricants. Plant-based oils have also recently begun to be used as lubricants in the MQL method, primarily due to environmental considerations [31]. The flow of the lubricant is facilitated by a transport medium and a stream of pressurised air which, to a small degree, also acts as a cooling medium [32]. Literature data indicates that in the MQL method, lubricant is supplied at a rate of 10-500 ml/h [31,33,34]. For comparison, the flow rate of oil-water emulsions used in the flooding method exceeds 120,000 ml/h whereas, during grinding, the flow rate can amount to between 300,000 and 1,200,000 ml/h, depending on the variety of the process used.

A review of the literature indicated that opinions on the use of the MQL method during grinding (in the context of the condition of the technological outer layer of the workpieces) vary [10,19,35] – and understandably so, as the varieties of the grinding process and its conditions may significantly differ from each other [36-38].

Given the above considerations, the experimental tests described in this paper were performed to assess the use of the MQL method and various v_w workpiece speeds during the grinding of flat samples made of 20MnCr5 (61±1 HRC) steel. The objective of the study was to determine the impact of selected conditions of abrasive treatment on the value and distribution of microhardness and residual stresses generated in the technological outer layer. First, the samples were low-pressure carburised using the single-piece flow method, quenched in high-pressure gas (HPGQ) and then ground using a Vortex electrocorundum grinding wheel manufactured by Norton. Conventional GF was supplied during grinding using the flooding and MQL methods. Conditions of experimental tests and a description of test stands are described in Chapter 2. Chapter 3 is a discussion and analysis of the results of the test, and Chapter 4 contains the final conclusions.

2. Experimental tests

2.1. Single-piece flow low-pressure carburising and quenching RD analysis

Experimental tests commenced by carburising, heat treating and tempering steel samples made of 20MnCr5 steel. The thermal and chemical treatment was performed using an innovative UCM vacuum furnace manufactured by SECO/WARWICK (Poland) shown in Figure 1. In contrast to the traditional batch method, thermal and chemical treatment in a UCM furnace occurs continuously using the single-piece flow method.

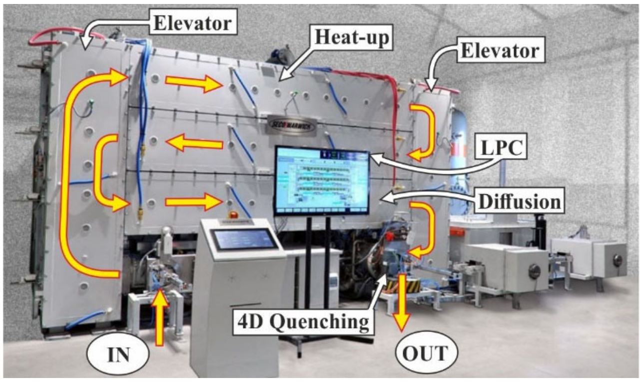

Fig. 1. A SECO/WARWICK UCM furnace for low-pressure carburising – a general view

As shown in Figure 1, the design of the furnace includes three horizontal technological chambers (heat-up, LPC, diffusion) placed parallel to each other in a shared vacuum space with gastight partitions. The chambers are interconnected by lifts equipped with loading and unloading systems that collaborate with each technological chamber. External access to the transport chambers is possible via the loading (IN) and unloading (OUT) bays. As a result, every individual workpiece passes through the same positions and process conditions prevailing in the furnace, ensuring that the carburisation process is characterised by high precision and repeatability in comparison to conventional methods [39-41]. High-pressure gas quenching (HPGQ) in a 4D quench chamber that enables the individual gas cooling of each workpiece is an important part of the process [6,42,43], enabling the cooling curve to be freely shaped and allowing steel with adequate microstructure and properties to be produced. The innovative design of the chamber is equipped with a system of cooling jets that surround the workpiece and ensure an evenly distributed flow of cooling gas from all sites. In addition, the stand rotates together with the workpiece, improving the regular flow of cooling (4D). This cooling system's design enables a cooling efficiency comparable to oil-based systems to be obtained without the use of helium (He).

Experimental tests were performed on six flat ring-shaped samples with an external diameter of 96 mm, an internal diameter of 30 mm and a thickness of 10 mm. The dimensions of the samples were from the design of the components of the mechanism used to transport them inside the UCM furnace. The samples were carburised at a temperature of 920°C, reaching an effective thickness of the

ECD layer of 0.4 mm. Next, the samples were quenched in a quenching chamber at a pressure of 7 bar and tempered at 190ºC for 3 hours. The measurements of the heat and chemical treatment are shown in Table 1. As a result of the heat and chemical treatment, the examined samples were hardened to a value of 61±1 HRC.

Table 1.
Conditions of thermo-chemical treatment (TCT)

Type of treatment	Process parameters and values
Vacuum carburizing	Temperature: 920°C
Quenching	Medium: Nitrogen
	Pressure: 0.7 MPa (7 bar)
	Precooling: 850°C
Tempering	Temperature: 190°C
	Time: 180 min

2.2. Grinding

The next stage of the study involved grinding the flat surface of hardened samples using a conventional SPD-30b flat surface grinding wheel manufactured by Jotes SA (Poland). The test stand is shown in Figure 2. The circumferential grinding was done using a Vortex grinding wheel with the symbol IPA60EH20VTX, manufactured by Norton (Poland). The wheel is a hard grinding wheel with an open structure and increased porosity (large-pore wheel) and is made of electrocorundum grit and ceramic binder.

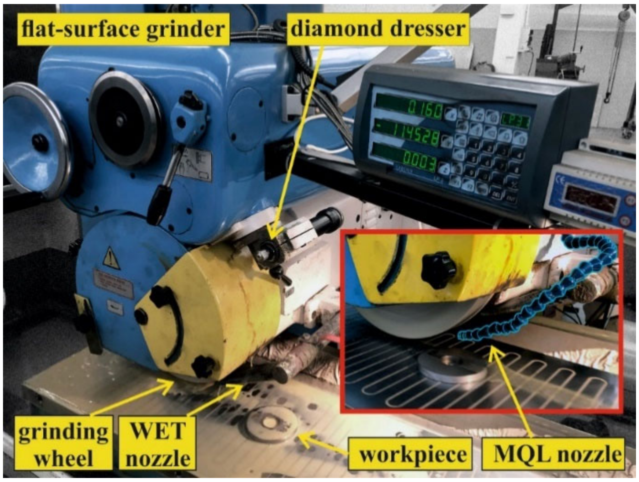

Fig. 2. The experimental test stand with an SPD-30b flat-surface grinder made by Jotes Co. Ltd. (Poland)

During the tests, grinding fluid (GF) was supplied using two methods: (1) at a high flow rate using the flooding method (WET), (2) at a minimum flow rate using the MQL method. In the first case (WET), an oil-water emulsion containing Emulgol ES-12 oil (5%) was used as a grinding fluid. The emulsion was supplied to the grinding zone using a single jet at a Q_{WET} flow rate of 4 l/min. In the second case (MQL), the grinding fluid was supplied in the form of oil mist, where an air jet lifted particles of Ecolubric E200L rapeseed oil [44] at a Q_{MQL} flow rate of 100 ml/h. Oil mist was generated using an external Ecolubric MQL Booster device, manufactured by Accu-Svenska AB (Sweden) [45], equipped with a single spray jet positioned tangentially to the active surface of the grinding wheel.

As previously noted, the flat surfaces of six samples were ground. Before each grinding test, the grinding wheel was conditioned using a single-point M1020 diamond truer. Each sample was ground using individual treatment conditions, choosing one of two methods of supplying grinding fluid (WET and MQL) and one of three v_w workpiece speeds. Table 2 shows the six sets of variable parameters produced in this way. The other grinding parameters were fixed, as shown in Table 3.

Table 2.
Variable grinding conditions applied in the research

Number of samples	Workpiece speed v_w, m/min	Method of coolant-lubricant supply
10-W	10.0	WET
10-M		MQL
14-W	14.0	WET
14-M		MQL
18-W	18.0	WET
18-M		MQL

The grinding parameters used in the tests are typical parameters used during circumferential grinding of flat surfaces. Excess material was removed during a single pass (concurrent direction), using three workpiece speeds: v_{w1} = 10.0 m/s, v_{w2} = 14.0 m/s and v_{w3} = 18.0 m/s. Fixed values of a_e machining depth (0.02 mm) and v_s grinding speed (30.2 m/min) were used.

2.3. Measurement of microhardness and residual stress

The microhardness of the surfaces of the samples (after grinding) was measured using a KB10BVZ-FA micro-hardness tester manufactured by KB Prüftechnik GmbH (Germany). The microhardness was measured using the Vickers scale at a load of 0.9807 N, in accordance with the standard PN-EN ISO 6507. The parameter was measured on sections perpendicular to the ground surface up to a depth of

0.3 mm. Three microhardness measurements were taken for each sample. The average measurements were cubic B-spline interpolated.

Table 3.
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	IPA60EH20VTX (Vortex type)
Grinding wheel rotational speed	n_s = 1650 rpm
Grinding wheel peripheral speed	v_s = 30.2 m/s
Workpiece peripheral speed	v_{w1} = 10 m/min
	v_{w2} = 14 m/min
	v_{w3} = 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 = 0.02 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_{WET} = 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
	A fraction of natural triglycerides, easily biodegradable substances
	Not hazard to human health
MQL flow rate	Q_{MQL} = 100 ml/h
MQL supply air pressure	P = 0.6 MPa

Stresses on the ground rings were measured using the x-ray sin2ψ method in ω geometry using a PROTO iXRD device (Canada) equipped with two position-sensitive semiconductor detectors. X-rays were generated using a lamp with a Cr anode that emitted characteristic x-rays with a λ wavelength of 2.29 A. A displacement of iron reflex (211) positioned at an angle of 2θ=156.4° was examined. ½ x-ray elastic constants of S2=5/92 1/TPa and S1=-1.27 1/TPa were used in calculations. The measurement was taken for an area limited by a collimator with a φ diameter of 2 mm. Exposure time was 1 s. To determine the distribution of stresses deeper in the examined substrates, the spot electrochemical etching technique was applied using an 8818-V3 electropolisher manufactured by PROTO. Stresses were measured after each etching.

3. Results and discussion

3.1. Microhardness

As shown in Figure 3, grinding resulted in a decrease in the microhardness of the material in comparison to its initial microhardness, following TCT, before grinding. Regarding the two methods of supplying GF – WET (Fig. 3a) and MQL (Fig. 3b), the highest drop in microhardness at the surface was recorded following grinding with the lowest v_{w1} workpiece speed of 10 m/min. On the other hand, the highest workpiece speed used (v_{w3} = 18 m/min) resulted in the lowest drop in microhardness at the surface. This may be caused by the differences in grinding temperature depending on grinding efficiency. In the case of grind-resistant materials, increasing the v_w workpiece speed at a constant a_e grinding depth and v_s grinding speed also results in an increase in the volume efficiency of treatment and decrease in temperature.

A comparison of the microhardness of the material, after grinding with initial microhardness, indicates that the lowest changes in this parameter at the surface were recorded in samples ground using grinding fluid supplied at a minimum flow rate using the MQL method (Fig. 3b). In this case, the reduction in microhardness at the surface was 260 HV at v_{w1} with a workpiece speed of 10m/min, 37 HV at v_{w2} with a workpiece speed of 14 m/min and 23 HV at v_{w3} with a workpiece speed of 18 m/min. Correspondingly, where grinding fluid was supplied using the WET method, the reduction in microhardness at the surface was 547 HV at v_{w1} with a workpiece speed of 10 m/min, 93 HV at v_{w2} with a workpiece speed of 14 m/min and 26 HV at v_{w3} with a workpiece speed of 18 m/min (Fig. 3a).

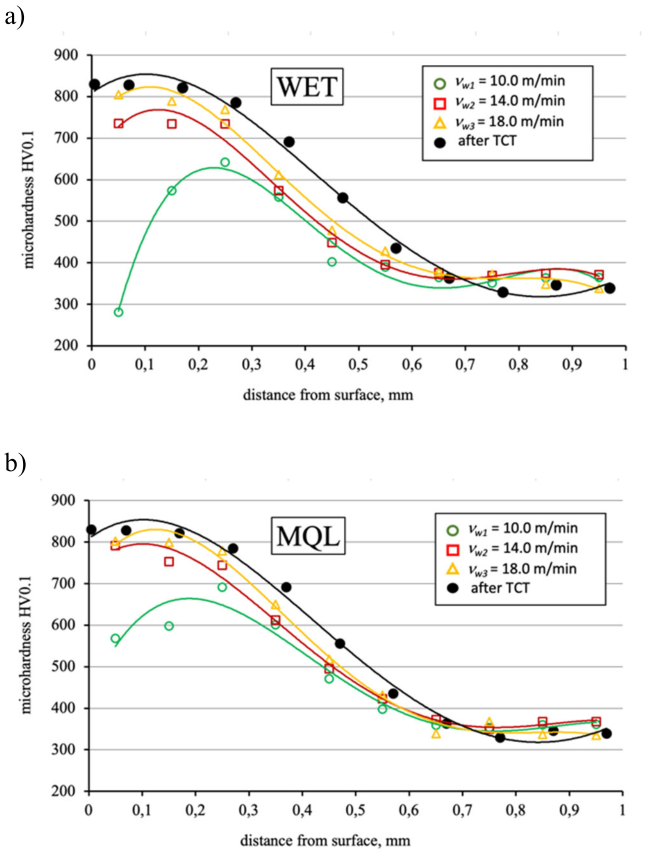

Fig. 3. Distribution of microhardness in 20MnCr5 steel ground using GF supplied using the a) WET, b) MQL method

As previously noted, the greatest changes in microhardness for both the analysed methods of supplying grinding fluid were observed at v_{w1} with a workpiece speed of 10 m/min (Fig. 4c). These changes occurred between the surface and a depth of 0.35 mm, while further down, the values of microhardness for both methods of supplying GF were similar.

The distribution of microhardness obtained for the v_{w3} with a workpiece speed of 18 m/min (Fig. 4c) did not show significant differences in comparison to material following TCT, which may indicate a comparable capability of ensuring adequate grinding conditions, including temperature via the flooding method and MQL method. In the case of the v_{w2} with a workpiece speed of 14 m/min (Fig. 4b), the most significant changes in microhardness were observed on the surface of the sample ground using the WET method. A reduction in microhardness occurs down to a depth of 0.15 mm and amounts to over 80 HV in comparison to material subjected to TCT.

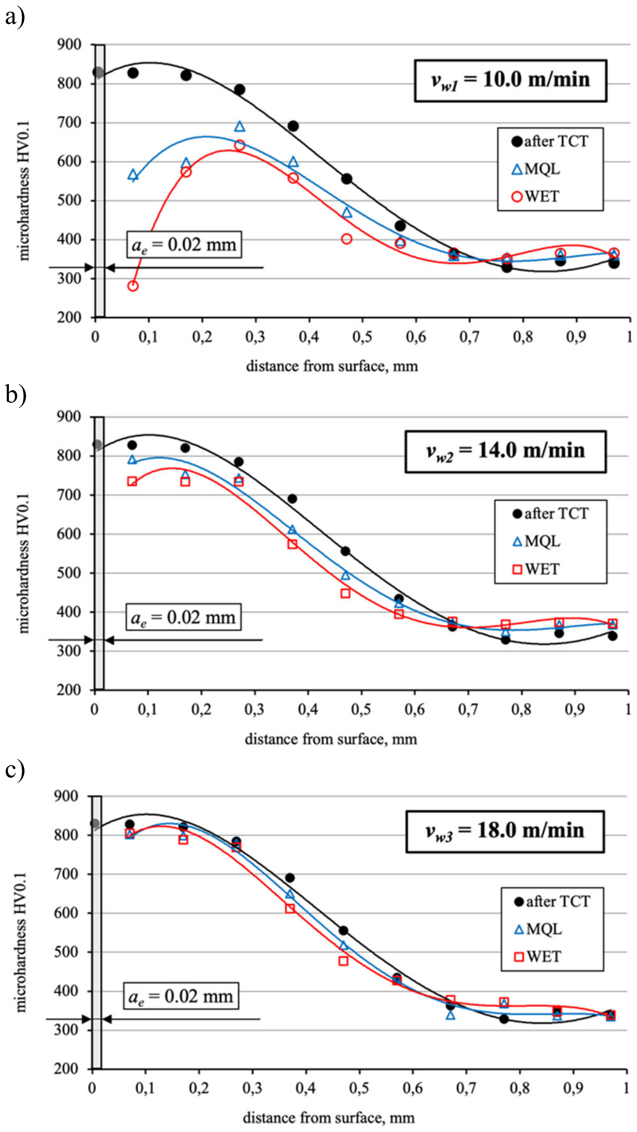

Fig. 4. Distribution of microhardness in 20MnCr5 steel ground using GF supplied using the WET and MQL methods at v_w workpiece speeds of a) 10 m/min, b) 14 m/min, c) 18 m/min

3.2. Residual stress

Figure 5 shows the residual stress values constituting the average of three measurements of samples subjected to heat and chemical treatment (TCT) prior to grinding. The residual stress value on the surface of vacuum-carburised samples was -255 MPa. As seen on the chart, the stresses then increased monotonically with an increase of distance from the surface reaching -445 MPa at a depth of 0.3 mm, and subsequently extending towards -215 MPa at a depth of 0.6 mm.

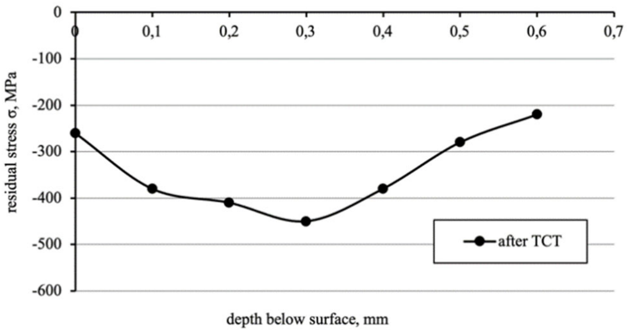

Fig. 5. Residual stresses in 20MnCr5 steel following heat and chemical treatment (TCT); prior to grinding

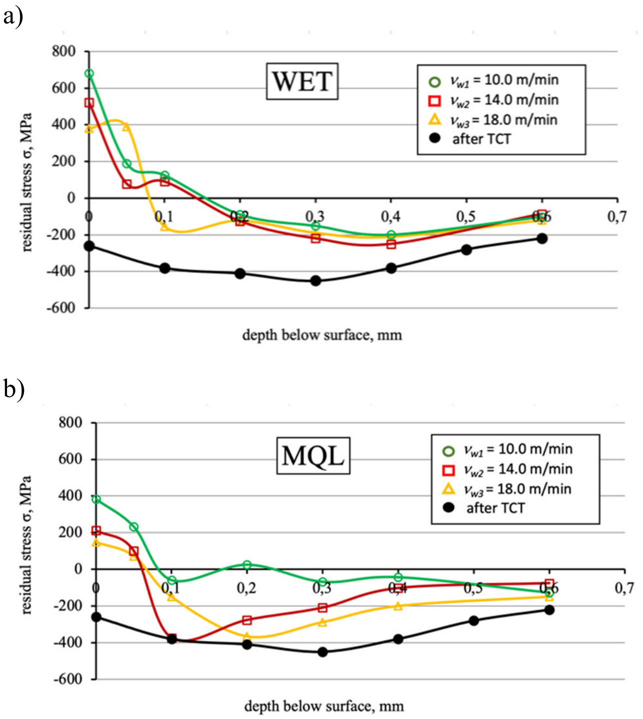

Fig. 6. Residual stresses in 20MnCr5 steel ground using GF supplied using the a) WET, b) MQL method

As shown in Figure 6, grinding in the tested conditions resulted in a deterioration of residual stresses as compared to the material prior to grinding. This observation applies to samples ground using both the WET and the MQL method. In both cases, adverse tensile residual stresses were generated immediately beneath the surface of the samples, which is a result of a large amount of heat flowing into the workpiece and relatively high grinding temperatures causing adverse structural changes (including the tempering of steel).

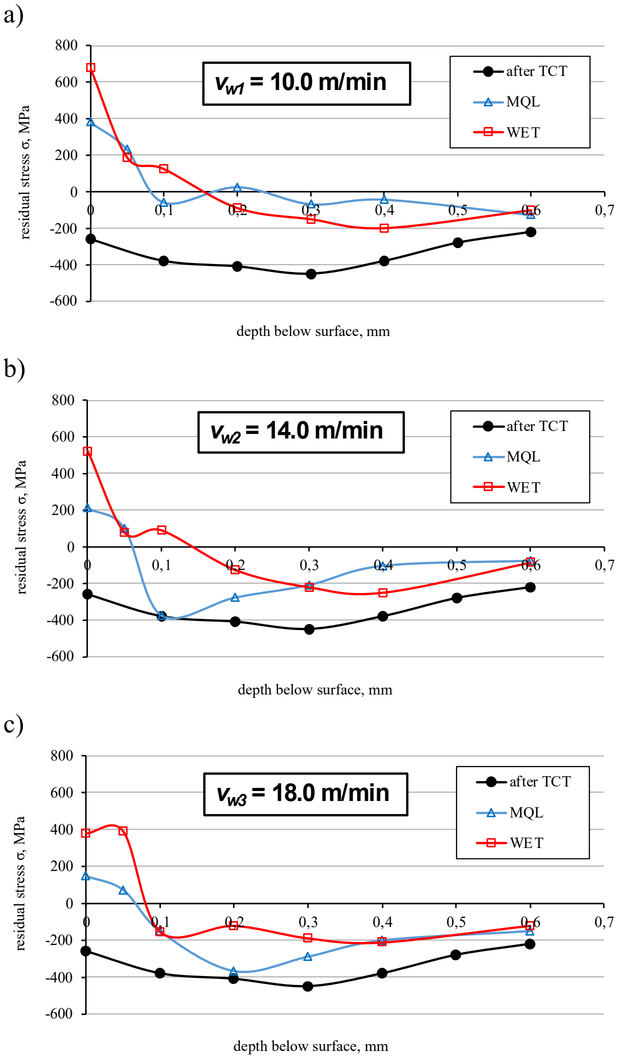

Fig. 7. Residual stresses in 20MnCr5 steel after grinding at v_w workpiece speeds of: a) 10 m/min, b) 14 m/min, c) 18 m/min

As shown in Figure 7, more favourable residual stress values were obtained in samples ground while supplying GF using the MQL method, which indicates that this method has better lubricating qualities than the WET method. In the authors' opinion, the above property is the result of the porosity of the Vortex grinding wheel used in the study, which is characterised by large intergrit spaces and good penetration of this structure by oil sprayed at a high rate by the oil mist producing device in the MQL method. As a result, a large amount of lubricant is supplied to the zone of contact between active grit and the workpiece, reducing friction and grinding temperature. As a result, a reduction of the coefficient of friction between active grits and the ground surface leads to a lower grinding temperature, which significantly impacts the values of residual stresses generated in the technological external layer.

4. Conclusions

The paper describes experimental tests that enable the determination of the impact of the v_w workpiece speed used on selected parameters describing the condition of the technological external layer of samples made of 20MnCr5 steel. The samples were subjected to low-pressure carburising (LPC) using the single-piece flow method and quenched in high-pressure gas (HPGQ) in a 4D quenching chamber. The samples were then ground using a Vortex IPA60EH20VTX electrocorundum grinding wheel. The samples were ground at three workpiece speeds with grinding fluid being supplied to the grinding zone using the flooding method (WET), and at a minimum flow rate using the MQL method. Microhardness and residual stresses were used to describe the condition of the technological external layer.

Based on the results obtained for the test conditions used, we can conclude that:

(1) Low-pressure carburising using the single-piece flow method helps obtain a favourable (i.e., compressing, distribution of residual stresses in the technological external layer).

(2) Generally speaking, grinding with an electrocorundum grinding wheel results in the deterioration of residual stresses in the material compared to the sample after low-pressure carburising and before grinding.

(3) For each of three v_w workpiece speeds, lower (more favourable) changes in microhardness – in comparison to the microhardness of the material prior to grinding – occur in the external layers of samples ground using GF supplied at a minimum flow rate using the MQL method.

(4) For both methods of supplying GF (WET and MQL), the distribution of microhardness in the material of samples ground at the highest workpiece speed (18m/min) indicated no significant differences in comparison to the distribution of microhardness in the material of those samples following TCT.

Acknowledgements

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