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

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Abstract. 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 carburising (LPC) and high-pressure gas quenching (HPGQ) in a 4D Quenching chamber in order to achieve an effective case depth of ECD=0.4 mm. This was followed by grinding the specimens with Quantum and Vortex alumina grinding wheels. Cooling and lubricating fluid were supplied to the grinding zone using the flood (WET) method. The samples were ground in one pass of the grinding wheel using one grinding depth (ae = 0.01 mm). The measurements for each specimen were made twice - after the thermo-chemical treatment and after the grinding. Microhardness and residual stress were measured using the X-ray method sin2Ψ. The final part of the article provides an analysis of the measurement results and presents conclusions and recommendations for further studies.

1. Introduction

The properties of the top layer formed during grinding have a direct impact on functional properties of the item processed such as fatigue strength, resistance to abrasion and corrosion etc. [1]. The important parameters describing the condition of the technological top layer include microhardness and residual stresses. The course of microhardness and residual stresses is influenced by, among other things, the type of heat treatment that precedes grinding and the characteristics of the grinding wheel.

One of the most frequently used methods of surface heat treatment is carburising with subsequent quenching [2]. The low-pressure variety of carburising [3,4] outperforms conventional carburising [5-9] in terms of efficiency and is characterised by a number of advantages such as a lack of internal oxidation and higher uniformity of the layers obtained.

Residual stresses occurring in the heat and chemical treatment procedures exist in both the substrate and the surface layer [10]. The analysis of the condition of residual stresses is of major importance in view of their impact on fatigue strength, tribological wear, corrosion, brittle fracture and contact fatigue [11-14]. In the event of taking mechanical properties into consideration, this impact may be beneficial but may also lead to damage to the item or the whole device, depending on the type of stresses and their superposition with operation stresses origination from external excitations. According to the literature
review, creating compressive stresses in the top layer (TL) that are compensated with tensile stresses in the core may contribute to increased fatigue strength [15-19].

In the case of grinding with the application of grinding wheels with Al₂O₃ abrasive grains, the grinding power is increased as a result of increased efficiency, which leads to an increased grinding temperature in the item processed [1]. Its course is the main cause of changes in microhardness and residual stresses in comparison to the material after heat treatment. The increased heat load of the top layer causes the occurrence of unfavourable residual tensile stresses that reduce the fatigue strength of dynamically loaded parts of machines and also a reduction of microhardness deep in the technological top layer. At the same time, it has to be underlined that the risk of unfavourable heat impact on the top layer is lower in the case of improving the efficiency of the cooling lubricant reaching the zone of contact between the active abrasive grains and the surface ground [20,21].

The objective of the experimental studies described in this article was establishing the impact of changes in grinding conditions, such as the grinding wheel type, on the value and distribution of microhardness and residual stresses occurring in the technological top layer of flat samples made of 20MnCr₅ steel. To this end, the samples were first subjected to low-pressure carburising (LPC) using the single-piece flow method and then to high-pressure gas quenching (HPGQ). Finally, the samples were ground with aloxite grinding wheels of the Quantum and Vortex type. During grinding, the liquid cooling lubricant – in the form of oil emulsion – was supplied to the processing zone using the conventional submersion method.

2. Single-piece flow low-pressure carburising and quenching
For the purposes of conducting heat and chemical treatment, a UCM low-pressure furnace of the SECO/WARWICK Company (Poland), shown in figure 1, was used.

![](image)

**Figure 1.** SECO/WARWICK UCM furnace for low-pressure carburising: a) general view, b) quenching chamber [22].

It is an innovative device in which the heat and chemical treatment is carried out using the single-piece flow method. In this method, each piece passes individually through identical positions and process conditions prevalent in the furnace [22-24]. As a result, carburising of this type is characterised by very high precision and reproducibility in comparison to conventional methods. Additionally, the application of high-pressure gas quenching (HPGQ) – in a quenching chamber of the 4D Quenching type for individual gas – cooling of each piece enables free shaping of the cooling curve and achieving optimal microstructure and properties of steel. An important characteristic of this solution is the application of a system of cooling nozzles surrounding the piece and ensuring a uniform inflow of cooling gas from all directions (3D). At the same time, the uniformity of cooling is supported by a table that rotates together with the piece (4D). Such a cooling system enables the obtainment of a cooling intensity comparable to that of oil systems without having to use helium (He).
For the purposes of experimental studies, four flat samples with dimensions of 100x100x10 made of 20MnCr5 steel were selected. The samples’ dimensions resulted from the structure of parts of the mechanism transporting them within the UCM furnace. The samples were carburised at a temperature of 920°C, achieving the effective layer thickness of ECD=0.4 mm. Next, the samples were quenched in a quenching chamber at the pressure of 7 bar and then tempered at a temperature of 190°C for 3 hours.

3. Grinding

Further examinations of samples previously subject to the heat and chemical treatment process using the single-piece flow method in a UCM furnace were carried out in the process of circumferential grinding of planes. To that end, a type SPD-30B conventional grinder for flat surfaces of the Jotes SA Company (Poland) was used. During the studies, two samples made of 20MnCr5 steel (52±1 HRC) were being ground. Two grinding wheels of the Norton Company (Poland) were used as the tool – 2NQ60JVS3 and IPA60EH20VTX. The 2NQ60JVS3 grinding wheel of the Quantum type is a grinding wheel with a ceramic binder – the volume of which consists of 20% Norton Quantum abrasive grains and 80% aluminum grains. It is a soft grinding wheel (J) with a closed structure. The IPA60EH20VTX grinding wheel is a Vortex type grinding wheel made of aloxite abrasive grains with a ceramic binder (VTX). It is a hard grinding wheel (EH) with an open structure and increased porosity (also referred to as a large-pore grinding wheel). Both grinding wheels feature the same size of abrasive grains, the grain number of which is 60. The grinding wheels were conditioned prior to every test with the use of a single-point diamond dresser of the M1020 type.

The machining allowance was removed in a single work cycle consisting of an overtravel and return travel (the same and opposite rotational direction) using a constant grinding depth of \( a_e = 0.01 \) mm. For the purposes of tests, a constant value of grinding wheel peripheral speed of \( v_s = 25.6 \) m/s and machined item speed of \( v_w = 18 \) m/min were also assumed. Table 1 features a comprehensive summary of the machining conditions applied during grinding.

| Grindino 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 | \( n_r = 1400 \) rpm |
| Grinding wheel peripheral speed | \( v_s = 25.6 \) m/s |
| Workpiece peripheral speed | \( v_w = 18 \) m/min |
| Working engagement | \( a_e = 0.01 \) 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 | \( i_d = 4 \) |
| Conventional grinding fluid (GF) | Emulgol ES-12 in a 5% concentration |
| Conventional GF flow rate | \( Q_{GF} = 4 \) l/min |

The samples were ground with the use of a cooling lubricant supplied using the submersion method. An oil-in-water emulsion employing the Emulgol ES-12 (5%) oil was used as a conventional machining liquid in the submersion method and was supplied to the grinding zone with an expenditure of \( Q_{GF} = 4 \) l/min.
4. Measurements of microhardness and residual stress by the X-ray method

The measurements of sample surface microhardness after grinding were carried out using the KB10BVZ-FA microhardness meter of the KB Prüftechnik GmbH Company (Germany). Microhardness was determined using the Vickers scale at a load of 0.9807 N, in compliance with the PN-EN ISO 6507 standard. The measurements were carried out on cuts perpendicular to the surface ground, down to a depth of 0.3 mm. Three microhardness measurements were performed for each sample. The mean measurement results obtained were subjected to interpolation using cubic B-spline functions.

The measurements of residual stresses in the samples ground were carried out using the sin2ψ X-ray method in ω geometry using a PROTO iXRD apparatus fitted with two position-sensitive semiconductor detectors. The source of X-radiation was a Cr anode tube emitting characteristic X-radiation with a wavelength of λ=2.29 Å. The change in position reflection (211) of iron, positioned at an angle of 2θ=156.4°, was examined. For calculation purposes, there were adopted X-ray elastic constants of ½S2=5.92 1/TPa and S1=1.27 1/TPa. The measurement was carried out for an area limited by a collimator with a diameter of φ=2 mm. The exposure time was 1s. In order to obtain stress distributions deep in the substrates examined, electrochemical point etching by means of an 8818-V3 electropolishing unit of the PROTO Company was used. A stress measurement was performed after each etching.

5. Results and discussion

5.1. Microhardness

The microhardness tests conducted after grinding showed that the smallest changes in it (by about 340 HV near the surface) in comparison to microhardness of the material prior to grinding are obtained during machining with a grinding wheel of the Vortex type (figure 2a). In case of grinding with a Quantum type grinding wheel (figure 2b) the reduction of microhardness at the surface, in comparison to the material prior to grinding, was greater and amounted to approximately 420 HV.

![Figure 2. Distribution of microhardness in 20MnCr5 steel ground with aloxite grinding wheels: a) IPA60EH20VTX (Vortex) b) 2NQ60JVS3 (Quantum).](image)

It is worth noting that, as shown in figure 3, the microhardness at the surface obtained for the sample ground with the Quantum type grinding wheels differs by about 105 HV from the value obtained for the Quantum grinding wheel. Additionally, the comparison of microhardness distributions for samples ground with these two grinding wheels indicates that similar values of microhardness were obtained in a distance of about 0.15 mm from the surface.

5.2. Residual stress

Figure 4 presents the results which are the mean of 3 measurements of residual stresses in samples after the thermo-chemical treatment (TCT) process (prior to grinding). It can be noticed that the value of residual stresses on the surface of samples carburised in low pressure amounted to -257 MPa. These
stresses were increasing monotonically with distance from the surface, achieving a value of -498 MPa at a depth of 0.3 mm.

**Figure 3.** Comparison of microhardness distribution in 20MnCr5 steel ground with aloxite grinding wheels: 2NQ60JVS3 (Quantum) and IPA60EH20VTX (Vortex).

![Microhardness distribution](image1)

**Figure 4.** Residual stresses in 20MnCr5 steel – after TCT, prior to grinding.

Figure 5 presents the distribution of residual stresses for samples carburised in low pressure and then ground with an aloxite grinding wheel of the Vortex type and an aloxite grinding wheel of the Quantum type.

**Figure 5.** Residual stresses in 20MnCr5 steel after grinding with aloxite grinding wheels: 2NQ60JVS3 (Quantum) and IPA60EH20VTX (Vortex).

![Residual stresses](image2)

After comparing figure 4 to figure 5, it is clear that grinding with aloxite grinding wheels results in a worsened condition of residual stresses in comparison to the material after heat and chemical treatment.
(prior to grinding). In both cases, unfavourable tensioning residual stresses were obtained right under the surface. This is caused by a large amount of heat flowing to the item and by relatively high grinding temperatures, which cause unfavourable structural changes (among other things, the steel tempering process).

The most favourable condition of residual stresses was obtained in the sample ground with the IPA60EH20VTX grinding wheel of the Vortex type. In this case, the residual stresses change from tensioning to beneficial compressing ones at about 0.05 mm from the surface, while for the Quantum grinding wheel this distance is about 0.065 mm. It has to be noted that for the Vortex grinding wheel the residual stresses obtained right under the surface were greater than in the case of the Quantum grinding wheel. However, this difference is little and amounts to about 25 HV units. In the opinion of the authors, the above property results from the increased porosity of the grinding wheel structure, characterised by large intergrain spaces in comparison to the Quantum grinding wheel. As a result of that, the zone of contact between the active abrasive grains and the material processed received a larger amount of lubricant, which reduces friction and leads to a reduction in grinding temperature. The reduction in temperature is also caused by a lower number of active abrasive grains in comparison to the Quantum grinding wheel and, in consequence, by lower friction in the grinding zone. As a result, a lower grinding temperature has a more beneficial impact on the condition of stresses caused in the top layer of the steel ground.

6. Conclusion
On the basis of the results obtained within the scope of test conditions applied, it can be stated that:

- the low pressure carburising process conducted using the ‘single-piece flow’ method enables achieving a beneficial (i.e. compressing) distribution of residual stresses in the technological top layer
- the process of grinding with aloxite grinding wheels contributes to worsening of the condition of residual stresses in comparison to the material after low-pressure carburising treatment by causing adverse residual tensioning stresses near the surface in the technological top layer
- the best effect of grinding in relation to the distribution of microhardness and residual stresses are obtained while grinding with open structure grinding wheel characterised by increased porosity (IPA60EH20VTX grinding wheel of the Vortex type)

Further research will focus on the selection of treatment conditions with the aim of increasing its efficiency while retaining the desired properties of the top layer. The authors also plan to expand the research by performing measurements of grinding force and surface roughness.

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