The influence of grinding conditions on surface roughness parameters of 20MnCr5 steel vacuum-carburised by single-piece flow method

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Abstract. The purpose of the experimental tests described in the article was to determine the effect of selected abrasive machining conditions on the value of surface roughness of 20MnCr5 steel samples. The samples were subjected to vacuum carburising (LPC) using the 'single-piece flow' method and high-pressure gas quenching (HPGQ) in a 4D Quenching chamber to obtain an effective case depth (ECD) of 0.4 mm. Next, the samples were ground with a Norton Vortex corundum grinding wheel. Cooling and lubricating fluid was delivered to the grinding zone using the flooding method (WET) and with the minimum quantity lubrication method (MQL). The samples were ground in one pass of the grinding wheel using two grinding depths – \( a_e = 0.01 \) mm and \( a_e = 0.02 \) mm. For each grinding test, surface roughness measurements were made using a stationary laboratory profilometer T8000 from Hommel Werke. These measurements enabled the determination of the 2D and 3D roughness parameters. Analysis of the measurement results showed that for the adopted test conditions, the use of the MQL method resulted in a decrease in surface roughness compared to the surface ground using the WET method. This property applies to both tested grinding depths.

1. Introduction
An important factor that has an impact on the resulting parameters of the grinding process is the grinding temperature. The most efficient method of lowering it is by applying a liquid cooling lubricant (GF) [1,2]. From among many methods of supplying it to the grinding zone, the most popular is the submersion method (WET) employing oil-in-water emulsions [3,4]. This method is still considered the most effective way of reducing high temperature in the grinding zone by reducing friction as a result of lubricating and cooling the zone of contact between the grinding wheel and the material processed. Another advantage of this method is flushing the shavings from the grinding zone as well as wetting and cleaning the grinding wheel.

The main downside of the submersion method is the high expenditures of cooling lubricant (GF) and the fact that only a small portion of its volume reaches the zone of contact between the grinding wheel and the material processed. It is estimated [5,6] that the cost of applying cooling lubricants constitutes up to 17% of the total production costs and are markedly higher than the tool costs (2-4%). Thus, endeavours are made to reduce cooling lubricant (GF) expenditure or eliminate it totally due to economic reasons. Additionally, such limiting is also motivated by environmental issues and the...
The application of conventional cooling lubricants applied using the submersion method, attempts are made at eliminating them by applying alternative methods of lubrication and cooling.

An important aspect of the application of the MQL method during grinding is the method of positioning of the oil mist spraying nozzle, which has an impact on the effectiveness of this method. It has to be underlined here that a similar relationship exists with regard to the positioning of the nozzle in the submersion method (WET) [13]. The best results, similar to those provided by the submersion method, were achieved when the nozzle was positioned as close as possible to the zone of contact between the grinding wheel and the item processed [14]. However, the method of angular positioning of the nozzle in relation to the grinding wheel should be considered individually for each case of grinding [8].

The aim of the experimental studies described in this article was to establish the impact of the employed method of supplying cooling lubricant to the grinding zone on the value of surface roughness after grinding. Two methods were selected for comparison – the submersion method (WET) and the minimum quantity lubrication (MQL) method. Two machining depths were used during the research. The samples ground were previously subjected to low-pressure carburising (LPC) using the single-piece flow method and then to high-pressure gas quenching (HPGQ). It is necessary to underline here that carburising with subsequent quenching is one of the most frequently used methods of surface heat treatment [15]. The low-pressure variety of carburising [16,17] outperforms conventional carburising [11,18-21] in terms of efficiency and is characterised by a number of advantages such as, among other things, a lack of internal oxidation and higher uniformity of the layers obtained.

2. Single-piece flow low-pressure carburising and quenching
For the purposes of conducting heat and chemical treatment, a UCM low-pressure furnace from the SECO/WARWICK Company (Poland) was used [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 [15,23-25]. 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 a cooling intensity comparable to that of oil systems to be obtained 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 a pressure of 7 bar and then tempered at a temperature of 190°C for 3 hours. Table 1 summarises the parameter of heat and chemical treatment.

| Number of samples | Parameters of treatment |
|-------------------|-------------------------|
| V.WET-1           | Vacuum carburizing at 920°C |
| V.WET-2           | Quenching in nitrogen at 7 bar and at a temperature of 850 ºC |
| V.MQL-1           | Tempering at 190 ºC for 180 min |
| V.MQL-2           |                         |

3. Grinding

Further examinations of samples previously subjected 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 from the Jotes SA Company (Poland) was used. During the studies, four samples made of 20MnCr5 steel (52±1 HRC) were ground. An IPA60EH20VTX grinding wheel from the Norton Company (Poland) was used as the tool. The IPA60EH20VTX grinding wheel is a Vortex type of grinding wheel made of aloxite abrasive grains with a ceramic binder (VTX). It is a hard grinding wheel (EH) with an open structure, increased porosity (also referred to as large-pore grinding wheel) and abrasive grain granulation with a grain size number of 60. The grinding wheel was conditioned prior to every test with the use of a single-point diamond dresser of the M1020 type.

The machining allowance was removed in ten work cycles. A single work cycle consisted of an overtravel and return travel. Two grinding depths were used for removing the material during overtravel: \( a_e1 = 0.01 \text{ mm} \) and \( a_e2 = 0.02 \text{ mm} \). For the purposes of tests, a constant value of grinding wheel peripheral speed of \( v_s = 25.6 \text{ m/s} \) and machined item speed of \( v_w = 18 \text{ m/min} \) were also assumed. Table 2 features a comprehensive summary of the machining conditions applied during grinding.

| Grinding mode                     | 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   | \( n_s = 1400 \text{ rpm} \) |
| Grinding wheel peripheral speed   | \( v_s = 25.6 \text{ m/s} \) |
| Workpiece peripheral speed        | \( v_w = 18 \text{ m/min} \) |
| Working engagement                | \( a_e1 = 0.01 \text{ mm}; a_e2 = 0.02 \text{ mm} \) |
| Dresser                           | Single grain diamond dresser type M1020 (2.0 kt) |
| Dressing allowance                | \( a_d = 0.01 \text{ mm} \) |
| Environments                      | WET – conventional fluid |
| Conventional grinding fluid (GF)  | Emulgol ES-12 in a 5% concentration |
| Conventional GF flow rate         | \( Q_{GF} = 4 \text{ l/min} \) |
| 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                     | \( Q_{MQL} = 100 \text{ ml/h} \) |
| MQL supply air pressure           | \( P = 0.6 \text{ MPa} \) |
The samples were ground with the use of a cooling lubricant supplied using the submersion method (WET) and the minimum quantity lubrication (MQL) 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 $Q_{GF} = 4 \, \text{l/min}$. For creating the oil mist in the MQL method, an external Ecolubric MQL Booster device from the Accu-Svenska AB Company (Sweden) was used. Ecolubric E200L rapeseed oil supplied at an expenditure rate of $Q_{MQL} = 100 \, \text{ml/h}$ was used as the cooling lubricant in the MQL method. During the studies, a single spray nozzle positioned tangentially in relation to the active grinding wheel surface was used.

Table 3 shows the set of variable processing conditions employed in the studies described.

| Number of samples | Environments | Working engagement |
|-------------------|--------------|--------------------|
| V_WET-1           | WET          | $a_{e1} = 0.01 \, \text{mm}$ |
| V_MQL-1           | MQL          |                    |
| V_WET-2           | WET          | $a_{e2} = 0.02 \, \text{mm}$ |

4. Surface roughness measurements

The sample surface roughness measurements after grinding were carried out using a Hommel Tester T8000 profilometer from the Hommelwerke Company (Germany). The measurement conditions were established on the basis of PN-EN ISO 3274:2011E and PN-EN ISO 4288:2011E standards and summarised in Table 4. A 2D parameter, determined from the roughness profile, and a 3D parameter – obtained as a result of surface topography measurements – were used for describing the roughness of the surface ground. The value of the maximum height of roughness profile $R_z$ was employed as a 2D parameter (according to PN-EN ISO 4287:1999). The roughness of the surface of a single sample was determined as an arithmetic mean from three measurements. The amplitude parameter $S_z$ was used as a 3D parameter.

| Table 4. Surface roughness – measuring conditions. |
|--------------------------------------------------|
| Profilometer | Hommel Tester T8000 by Hommelwerke company (Germany) |
| Stylus type | TKU 300 |
| Stylus tip radius | $r_{tip} = 2 \, \text{μm}$ |
| Traverse width | $l = 4 \, \text{mm}$ |
| Traverse length | $l_T = 4.8 \, \text{mm}$ |
| Evaluation length | $l_n = 4.0 \, \text{mm}$ |
| Sampling length | $l_r = 0.8 \, \text{mm}$ |
| Traverse speed | $v_t = 0.05 \, \text{mm/s}$ |
| Cut-off | $λ_c = 0.8 \, \text{mm}$ |
| Measuring ranges | ±80 μm |

5. Results and discussion

Figure 1 presents the results of surface roughness measurements for samples after grinding with the use of two different liquid cooling lubricant supply methods – WET and MQL.

On the basis of $R_z$ and $S_z$ roughness parameter graphs presented in figure 1, it can be stated that, for both methods of cooling and lubricating, the roughness increases together with increasing grinding depth, which results from the geometrical correlation between the size of a single abrasive grain and the grinding depth.

The lowest values of the $R_z$ parameter (figure 1a) were measured on the surface of the sample ground with Emulgol ES-12 emulsion supplied using the submersion method (WET) at the grinding
depth of $a_{e1} = 0.01$ mm. In the case of the application of the MQL method, the surface roughness obtained for the same grinding depth was higher by about 7% in comparison to the WET method. A similar dependence between the $R_z$ parameter value and the liquid cooling lubricant supply method was noticed for the grinding depth of $a_{e2} = 0.02$ mm. In this case, the value of $R_z$ for the sample ground using the MQL method is only about 5% higher in comparison to that obtained for the submersion method (WET).

![Figure 1](image)

**Figure 1.** Surface roughness parameters: a) $R_z$, b) $S_z$.

The above observations can be explained by the worse efficiency of the liquid cooling lubricant supply to the grinding zone in the MQL method. The increased friction in the grinding zone, combined with insufficient cooling thereof characteristic for the MQL method, resulted in a temperature in the top layer of the item processed, resulting from heat accumulated in the item processed after subsequent passes of the grinding wheel, tempering the surface of that item. As a result, the phenomenon of fissure formation, the appearance of side burrs with significant height and rubbing of the tempered surface with grinding products that were not removed from the grinding zone. An additional probable cause of an increase in surface roughness could be the appearance of the grinding wheel agglutination phenomenon. Additionally, due to technical limitations in spray nozzle positioning in the MQL method, the oil mist stream does not enable the correct removal of shavings and other products of grinding from the processing zone. Shavings stick to the surface tempered, which leads to surface rubbing that increases the roughness of the ground sample surface. It is also necessary to remember that the effectiveness of lubrication depends, to a large extent on – among other things – the distance of the MQL nozzle from the item processed. As a result of the nozzle position applied, a part of the air-oil aerosol stream could undergo dispersion and end beyond the zone of contact between the grinding wheel and the material processed thus reducing lubrication effectiveness, which leads to increased friction in the grinding zone and worsening the shavings removal effectiveness. It has to be underlined here that the outlet of the MQL nozzle was located as close as possible to the grinding zone and further reduction of this distance was impossible due to technical considerations.

Regarding the $S_z$ parameter (figure 1b), which due to lack of vulnerability to impact of individual accidental elevations and cavities has high generalising capabilities, its lowest value was noticed, similarly to the case of the $R_z$ parameter, for the surface ground with the use of submersion method (WET) of supplying liquid cooling lubricant during grinding. In the case of grinding a sample to the depth of $a_{e1} = 0.01$ mm and with the use of the MQL method, the $S_z$ value was 36% higher in comparison to the WET method. For the depth of $a_{e1} = 0.01$ mm this difference amounted to 23%.

When comparing the values of $R_z$ and $S_z$ parameters, it is noticeable that the values of the $S_z$ parameter for all the four surfaces ground using various methods of cooling lubricant supply are several times greater than the values of the $R_z$ parameter. The cause of such a situation can be found in differing methods of determining the value of individual parameters. In the case of the $R_z$ parameter, it is described as the sum of the height of the highest-profile elevation and the depth of the deepest cavity of the profile inside the elementary section whereas the $S_z$ parameter is the mean value of absolute height of five largest elevations and five deepest cavities within the sampling area. Another cause of the
occurrence of differences in values of the $R_z$ and $S_z$ parameters can be the different reference bases in relation to which the individual parameters are calculated. For the profile, it is the mean line and, for the 3D measurements, the surface. Additionally, the value of the surface topography parameters is influenced by issues related to, for example, maintaining an accurate height reference basis between passages or maintaining accurate sampling spacing on each track in relation to other ones.

6. Conclusion

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

- Within the scope of each of the grinding depths considered, the surface roughness obtained during grinding using the MQL method is similar to the value obtained for the submersion method (WET).
- The minor differences in the $R_z$ parameter between results obtained for the MQL and WET methods most likely result from the temperature difference between individual tests. The higher temperature taking place during grinding with the application of the minimum quantity lubrication (MQL) method may result from insufficient lubrication and cooling of the grinding zone in comparison to the submersion method (WET). As a result of the impact of higher temperature, in the tempered and softer material, the plastic deformations increase when the blade is cutting in, manifesting in the formation of side burrs of significant height and occurrence of the fissuring phenomenon. This results in increased roughness of the surface ground.
- Another cause of increased roughness expressed by the $R_z$ parameter in case of grinding with the use of the MQL method may be the fact that the stream of oil mist does not enable the appropriate removal of shavings and other products of grinding from the processing zone. As a result of this, the shavings stick to the surface tempered, leading to surface rubbing that increases the roughness of the ground sample surface.

Further research will focus on the selection of treatment conditions with the aim of lowering the surfaces’ roughness obtained after grinding. The authors plan to conduct studies on improving the effectiveness of supplying oil mist to the grinding zone through: 1) changes in the positioning of the spraying nozzle, 2) increasing oil expenditure as a result of using additional nozzles spraying the oil most. Additionally, the authors plan to conduct measurements of the grinding temperature.

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