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Effects of thermo-chemical treatment and grinding process of external cylindrical surfaces on residual stresses in 13CrMo4-5 steel

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ABSTRACT

Purpose: This paper presents a study aimed at determining the effect of the carburizing treatment process and the subsequent grinding process on the residual stresses occurring in ring-shaped specimens made of 13CrMo4-5 steel.

Design/methodology/approach: During the tests, vacuum carburizing was used, achieving an effective case depth ECD = 0.5 mm. Subsequently, the cylindrical outer surfaces of the samples were ground by conventional plunge grinding and with innovative kinematics using a test stand based on a conventional flat-surface grinding machine. As part of the study, microhardness and residual stresses were measured before and after grinding. Measurements were carried out to a depth of 1 mm. The main component of the stand is an original special device that allows the cylindrical specimen to be clamped. Then the angle between its axis of rotation and the axis of rotation of the grinding wheel is set with respect to the plane of the grinding machine's magnetic table. In the described tests, the axis of rotation of the cylindrical specimen was deviated from its original position by 15° and set at an angle of 75° to the axis of rotation of the grinding wheel. The specimens were ground with a grinding wheel of noble electro-corundum marked 38A60K8V. In both kinematic cases of the grinding process, a machining allowance of 0.01 mm was removed.

Findings: Grinding using innovative kinematics did not cause any significant changes in the microhardness distribution, either for vacuum or conventional carburizing. In addition, residual stress measurements using the Dawidenkov-Sachs method showed that innovative grinding enables a more favourable distribution than those obtained after conventional plunge grinding.

Research limitations/implications: Further research will focus on, among others, selecting the angular settings of the workpiece axes relative to the grinding wheel axes depending on their dimensions. Grinding guidelines should include coverage ratio, infeed value, grinding time, and peripheral speeds. In addition, the plan for future research includes measuring the components of the grinding force and the geometric structure of the surface.

Practical implications: Grinding process is a crucial stage of steel treatment in almost every industrial branch. 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.

Originality/value: The proposed test stand, together with the authors' device, makes it possible to conduct machining of the external surfaces of cylindrical workpieces on a flat surface grinder. In this case, the innovation of the grinding process consists of the non-parallel alignment of the cylindrical rotational axis of the specimen and the rotational axis of the grinding wheel with respect to the plane of the magnetic grinding table.

Keywords: Cylindrical grinding, Grinding kinematics, Thermo-chemical treatment, Microhardness, Residual stresses

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PROPERTIES

1. Introduction

Grinding is a complex machining process of great importance in the modern manufacturing industry. As is well known, the way this process is carried out affects the functional properties of the workpiece by forming a technological surface layer (TSL) with appropriate parameters. The parameters that determine the state of the TSL are primarily microhardness and residual stress. Their final form depends on the applied machining conditions, of which the type of heat treatment preceding grinding and the type of workpiece material, the variety of the grinding process (process kinematics), the values of grinding [1], and dressing [2] parameters, the strategy of feeding the coolant and the characteristics of the grinding wheel are of significant importance.

In the context of the type of thermal surface treatment preceding grinding, it should be noted that one of the most commonly used is carburizing, followed by hardening and tempering. Due to its numerous advantages, the carburizing process is often carried out in a low-pressure variety, superior to conventional carburizing, among others, in terms of efficiency and quality of the carburized layer [3-6]. It is generally believed that the residual stress state induced in the surface layer after heat treatment should include compressive stresses in the surface layer compensated by tensile stresses occurring in the core. Such a stress state increases the fatigue strength of components subjected to service stresses from external forcing.

Considering the applied kinematics of the grinding process, it should be mentioned that brittle materials are characterized by the phenomenon of anisotropy of strength in relation to the grinding direction [7,8]. Accordingly, microcracks occurring in the technological surface layer differ from each other. In the case of longitudinal microcracks, consistent with the grinding direction, they are generally deeper and longer than transverse (radial) cracks [8,9]. The larger size and elongation of longitudinal cracks means that the corresponding fracture strength in the transverse direction tends to be lower than that measured parallel to the grinding direction. This is due to tensile stress in the transverse direction, which activates longitudinal rather than radial cracks.

Accordingly, the paper [9] proposes new innovative kinematics for the grinding process of external cylindrical surfaces. In contrast to conventional kinematics, the grinding wheel was located along the axis of rotation of the workpiece. In addition, the axis of rotation of the grinding wheel was twisted with respect to the workpiece axis in order to wear its active surface uniformly. The conducted tests showed that such grinding kinematics is characterized by a significantly smaller contact area between the grinding wheel and the workpiece, which leads, among others, to a reduction in the value of grinding force. In addition, the proposed kinematics made it possible to increase the bending strength by about 30% with respect to longitudinal conventional grinding.

With regard to the next component of the grinding process - the grinding wheel, it should be mentioned that the process can be carried out using different grades of abrasive grains and their compositions. In the case of grinding using grinding wheels with Al_2O_3 abrasive grains, the grinding power is increased as a result of increased efficiency. The consequence of this is an increase in ground temperature in the workpiece [10], which is the main cause of changes in microhardness and residual stress with respect to the material after heat treatment [11,12]. Increased thermal loading of the surface layer results in unfavorable tensile stresses that reduce the fatigue strength of dynamically loaded machine parts, as well as a decrease in microhardness deep into the technological surface layer.

A way to reduce the risk of adverse thermal effects on the surface layer is to improve the efficiency of the coolants reaching the contact zone of the active abrasive grains with the ground surface [13,14]. One possible solution is to introduce an oil mist into the grinding zone using the MQL (Minimum Quantity Lubrication) method [15-17]. The MQL method is constantly being examined in various research centers. The results achieved allow its development through, for example, the optimization of oil mist parameters [18-20], the introduction of new and improved coolants [21-23], and techniques for their feeding to the grinding zone [24-26].

A literature review has shown that the application of the MQL method during grinding is evaluated differently in terms of the technological condition of the surface layer [27-29]. This is because the varieties of the grinding process and the conditions under which they are carried out differ significantly from each other, and for this reason, it is not possible to directly transfer the results of research relating to the application of the MQL method for a specific variety of the grinding process to other varieties of the process and generalize them.

Considering the above, this article describes an experimental study on the application of various coolants delivery methods, including the MQL method, when grinding the outer cylindrical surfaces of specimens made of 13CrMo4-5 steel (56±1 HRC). The ring-shaped specimens were longitudinally ground after the thermo-chemical treatment using the innovative kinematics described in the next section. For this purpose, the original device mounted on the table of the flat-surface grinder was used. For comparison purposes, the specimens were also plunged ground using the same test stand. No description of research conducted in this area was found in the available literature. The experimental research aimed to determine the effect of selected machining conditions on the value and distribution of microhardness and residual stress developed in the technological surface layer. The results of the research, together with their analysis, are discussed in the next chapter, while the final chapter contains a summary and conclusions.

2. Materials and methodology

2.1. Thermo-chemical treatment

In the first stage of the study, a thermo-chemical treatment process was carried out on specimens made of 13CrMo4-5 alloy steel. Table 1 shows the chemical composition of the steel used.

The specimens were ring-shaped with an outer diameter of ø50 mm, an inner diameter of ø40 mm, and a thickness of 8 mm (Fig. 1a). For the purposes of microhardness and residual stress measurements, described later in the article, the specimens after the thermo-chemical treatment (TCT) process and subsequent grinding treatment were cut using a wire EDM cutter. In this way, a gap of 5 mm in width was created, as shown in Figure 1b.

In the thermo-chemical treatment process, eight specimens were vacuum carburized, obtaining an effective depth of carburized layer ECD = 0.5 mm. Further, the specimens were quenched in nitrogen at a pressure of 8 bar then tempered at 180ºC for 2 hours. The thermo-chemical treatment parameters are presented in Table 2.

Table 1.
Chemical composition of the 13CrMo4-5 steel

Content of elements, wt. %									
C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Al
0.11-0.18	0.40-0.70	0.15-0.35	Max. 0.04	Max. 0.04	Max. 0.25	0.70-1.00	Max. 0.35	0.40-0.55	Max. 0.02

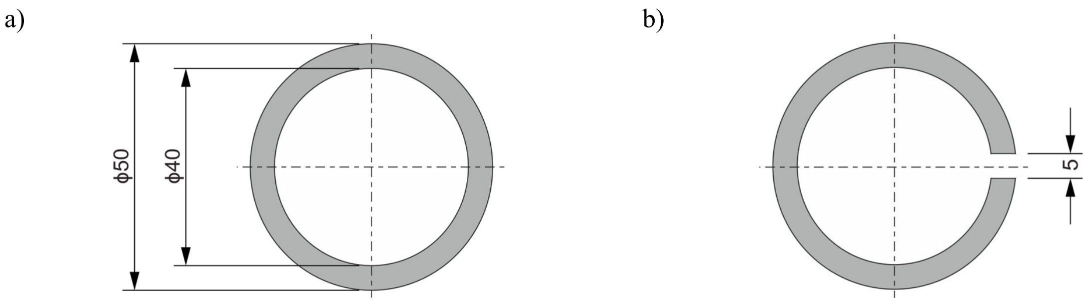

Fig. 1. Shape of the specimen for (a) thermo-chemical treatment and grinding, (b) residual stress measurements

Table 2.
Thermo-chemical and thermal treatment process parameters of 13CrMo4-5 steel specimens

Vacuum carburizing	Quenching in nitrogen	Tempering	Effective case depth ECD
950°C / 90 min	870°C / 8 bar	180°C / 120 min	0.5 mm

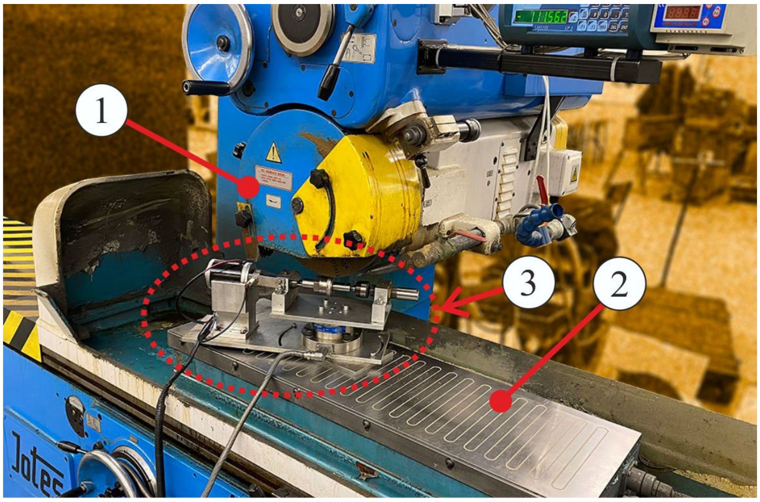

Fig. 2. General view of the stand for grinding external cylindrical surfaces: 1) SPD-30b grinding machine from Jotes SA (Poland), 2) magnetic table, 3) special device

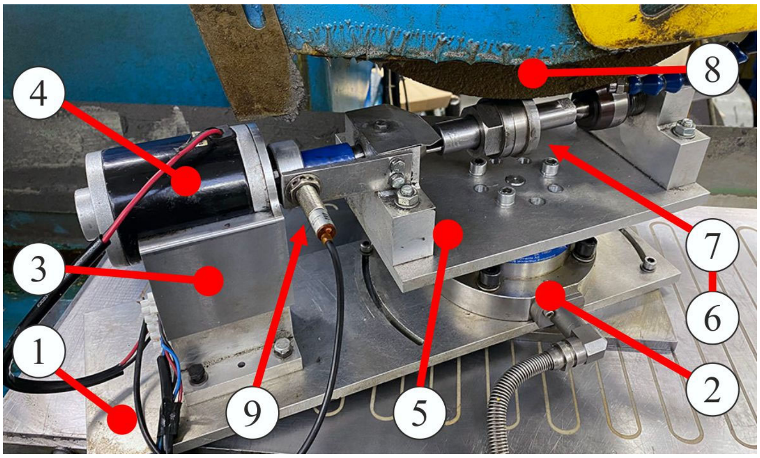

Fig. 3. General view of the special device for grinding external cylindrical surfaces: 1) rotating plate assembly, 2) piezoelectric actuator 9272 from Kistler (Switzerland), 3) bracket, 4) electric motor, 5) claw device, 6) cylindrical specimen, 7) grinding wheel, 8) Hall effect sensor

2.2. Grinding

Figure 2 shows a general view of the stand designed for grinding external cylindrical surfaces used in the second stage of the research. The stand was created based on the SPD-30b flat surface grinding machine (1) from Jotes SA (Poland), together with a special device (3) mounted on its magnetic table (2). The special device is an original design, the view of which is shown in Figure 3.

As shown in Figure 3, the special device consists of a set of rotating plates (1), the lower plate (fixed) of which is fixed to the magnetic table of the machine tool. In contrast, the upper plate (rotating) is used to mount a piezoelectric dynamometer 9272 (2) made by Kistler (Switzerland) and a bracket (3) supporting an electric motor (4). A claw device (5) of the authors' design is attached to the dynamometer (2), in which a mandrel (6) with a cylindrical specimen (7) seated on it is placed. A set of rotating plates makes it possible to change the angular position of the axis of rotation of the claw device and the specimen with respect to the axis of rotation of the grinding wheel (8) in the working plane of the magnetic grinding table.

An electric motor is connected to the claw device and causes the sample to rotate. The device in question uses a 100 W DC motor. A Pulse-Width Modulation (PWM) control method was used to control the motor. Using a PWM controller allows real-time reading of such parameters as voltage and current, power and energy. The motor rotational speed is read using a tachometer with a non-contact Hall effect sensor (item 9 in Fig. 3) triggered by a magnet. A PWM controller with the symbol CCM6DS-K SG was used to control the electric motor, while a power meter PZEM-031/051 was used to read voltage and current, power, and energy.

Before the grinding tests, the specimens were pre-ground to improve their shape on the inner cylindrical surface and by whitening their cylindrical outer surface. Then, as already mentioned, the cylindrical outer surface of the surface-hardened specimens to 830 HV was ground. The machining was carried out using two variations of the grinding process – plunge grinding with conventional process kinematics (denoted as CK) and longitudinal grinding with innovative kinematics (denoted as IK). In this case, the innovation consists of the non-parallel alignment of the cylindrical rotational axis of the specimen and the rotational axis of the grinding wheel with respect to the plane of the magnetic grinding table, as explained in Figure 4.

As shown in Figure 4, a different angle ψ of the position of the two axes was set for each grinding variation:

- for plunge grinding (for CK) the angle $\psi = 0°$, the axes are parallel (Fig. 4a),
- for longitudinal grinding (for IK), the angle $\psi = 75°$, the axis of rotation of the cylindrical specimen is deviated from the original position by 75° and at this angle is set with respect to the axis of rotation of the grinding wheel (Fig. 4b).

A ceramic-bonded electro-corundum grinding wheel, designation 38A60K8V, was used as the tool. The grinding wheel was conditioned before each grinding test using a single-point diamond dresser type M1020. During grinding, the machining allowance was removed in a single pass using a grinding depth of a_{e1} = 0.01 mm. A constant value of the peripheral speed of the grinding wheel v_s = 27.52 m/s and the peripheral speed of the workpiece v_w =5.2 m/s was assumed for the tests.

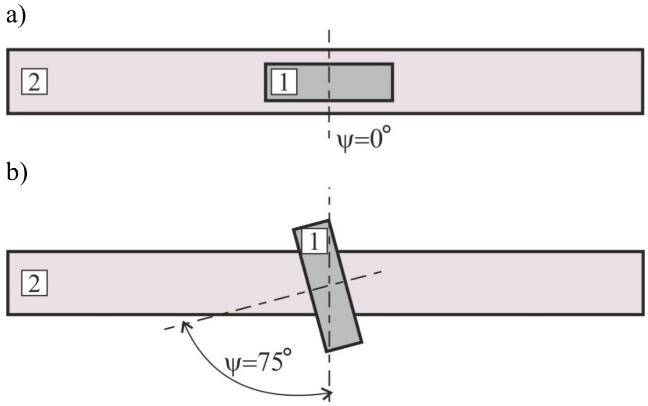

Fig. 4. Diagram of the angular alignment of the grinding wheel rotation axis with respect to the shaft rotation axis: a) angle ψ = 0°, b) angle ψ = 75°; 1 – ground sample, 2 – grinding wheel

The specimens were ground using three coolant feeding strategies:

- without PCS participation – "dry" (DRY),
- flooding method in abundance mode (WET),
- with minimum expenditure by MQL method.

An aqueous oil emulsion using Emulgol ES-12 oil (5%) was used as the conventional coolant fed by the flood method, and it was fed into the grinding zone through a single nozzle with a flow rate of Q_{WET} = 4 L/min. An external Ecolubric MQL Booster from Accu-Svenska AB (Sweden) generated oil mist in the MQL method. Ecolubric E200L rapeseed oil, supplied by the device manufacturer, was used as the coolant in the MQL method. The coolant was sprayed through a single nozzle positioned tangentially to the active surface of the grinding wheel at a flow rate of Q_{MQL} = 100 mL/h.

Table 3 summarizes the grinding conditions used during the tests.

2.3. Microhardness measurements

The microhardness of the surface of the specimens after grinding was measured using a KB10BVZ-FA micro-hardness meter from KB Prüftechnik GmbH (Germany). The microhardness was determined on the Vicers scale with a load of 0.9807 N, according to PN-EN ISO 6507. The measurements were carried out on grindings perpendicular to the ground surface to a depth of 0.95 mm. Three microhardness measurements were made for each specimen tested. The average measurement results obtained were interpolated using cubic B-spline functions.

Table 3.
Processing conditions during grinding of the tested specimens

Grinding mode	1) Plunge cylindrical grinding with conventional kinematics (CK), 2) Traverse cylindrical grinding with innovative kinematics (IK)
Grinding machine	Flat-surface grinder SPD-30b by Jotes S.A. (Poland)
Workpiece	Cylindrical sample: • dimensions (O. DIA.×I. DIA.×LGTH.): 50 × 40 × 8 mm, • material: 13CrMo4-5 (15HM) alloy steel, • hardness on the surface: 830 HV0.1.
Grinding wheel	• symbol: 38A60K8V, • dimensions: ø350 × 12 × ø127 mm.
Grinding wheel rotational speed	n_s = 1500 rpm
Grinding wheel peripheral speed	v_s = 27.5 m/s
Workpiece rotational speed	n_w = 500 rpm
Workpiece peripheral speed	v_w = 5.2 m/s
Workpiece feed speed (for IK)	v_{fa} = 0.2 mm/s
Working engagement (machining allowance)	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
Cooling conditions	1) Flood method (WET) using water-oil emulsion as coolant: • Emulgol ES-12 oil in a 5% concentration, • Flow rate Q_{WET} = 8 L/min. 2) Minimal Quantity Lubrication (MQL) method: • Ecolubric MQL Booster – oil-mist generator with two external nozzles, • Ecolubric E200L – cold-pressed rapeseed oil with additives, • Air supply pressure p = 0.6 MPa, • Flow rate Q_{MQL} = 100 mL/h.

2.4. Residual stresses measurements

A test stand, a schematic diagram shown in Figure 5, was used to determine the residual stress distribution in the samples.

The stand was made at the Institute of Machine Tools and Production Engineering of the Lodz University of Technology. Appropriate modification of the standby replacing the elements holding the specimen and the electrode makes it possible to realize measurements for flat and cylindrical samples. The stand consists of an electronic sensor with a reading resolution of 0.001 mm, which, via an Opto RS232 cable, is connected to the BOX-27 interface, from where, via the M-Box/PC connector, the signal is directed to a computer with copyright software RW_TRAW. For electrochemical etching, a Unitra Unima type 5352 DC power supply with a voltage of 0-20 V and adjustable current from 0 to 5 A was used by connecting it to the electrode. The current density averaged 0.4 A/cm^2. The tank was filled with an aqueous solution of HNO3 (5-10%) with a forced flow of electrolytes through a stirrer.

Figure 6 shows the developed algorithm of the RW_TRAW program. It allows data acquisition and subsequent calculation of the residual stress distribution and performs calculations after each measurement.

The distribution of residual stresses was determined as a function of depth from the cylindrical surfaces of the specimens using the Dawidenkov-Sachs method, recording the displacement of one end of a split ring specimen during the dilation of the machined surface in the electro-etching process. Determining the values of residual stresses in the surface layer involves converting deformations into residual

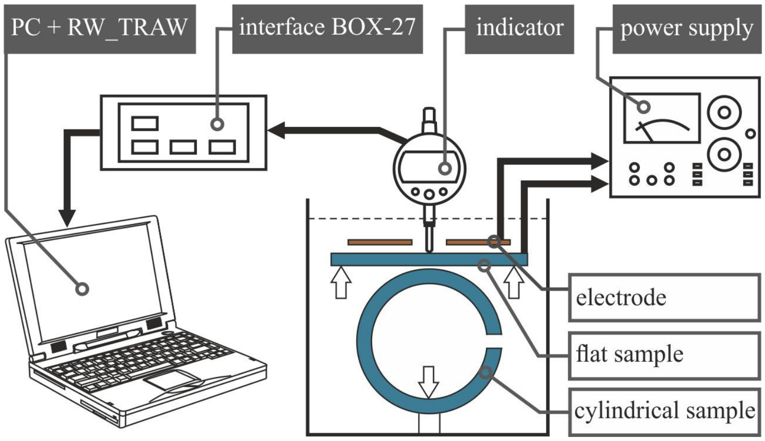

Fig. 5. Scheme of connections of the stand for residual stresses determination

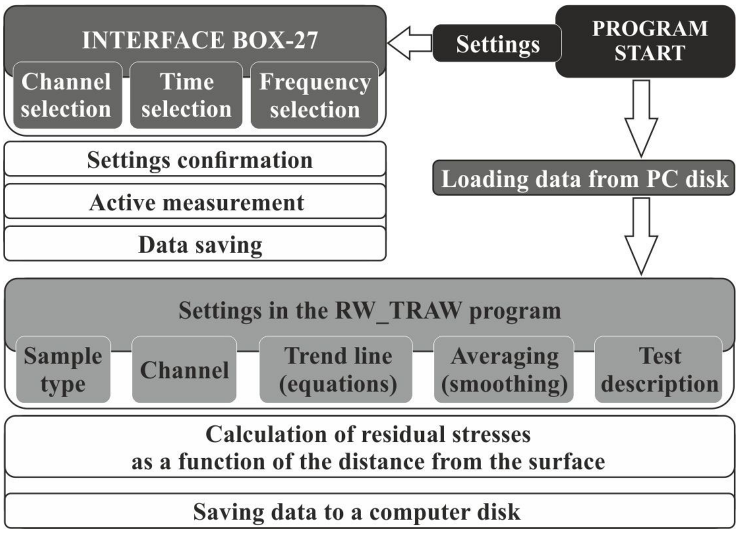

Fig. 6. Block diagram of the “RW_TRAW” program

stresses involving individual layers distant from the ground surface by a distance h_i, using the relationship for the resulting tangential stresses:

$$\sigma_{hi} = \sigma_{hi}' \pm \sigma_{hi}'' \qquad (1)$$

where:

- σ_{hi}' – linear component of residual stress defined by the formula:

  $$\sigma_{hi}' = 2Ef / D^2 \, k_g \, (H/2 - h_i) - E\varepsilon, \qquad (2)$$

- σ_{hi}'' – the nonlinear component of residual stress, which can be determined by assuming that $H/h_i \leq 0.1$, using the simplified formula:

  $$\sigma_{hi}' = E\,(H - h_i)\, 3D^2 \, k_g \, [(H - h_i)\, df_{hi} / dh_i - 4f_{hi}], \qquad (3)$$

where:

- E – Young’s modulus [GPa],
- f – deformation of the ring after cutting, $f = D_p - D_r$ [mm],
- D_r, D_p – diameter of the cylindrical surface before and after cutting [mm],
- f_{hi} – deformation of the ring after removal of a layer of thickness h_i [mm],
- h_i – distance of the considered layer from the cylindrical surface [mm],
- D – average diameter of the cylindrical surface [mm],
- B – width of the cylindrical surface [mm],
- H – thickness of the cylindrical surface [mm],
- df_{hi} / dh_{hi} – derivative determined from the graph,
- ε – relative elongation,
- k_g – deformation amplification factor.

Simplified formulas (1), (2), and (3), written in the following form, were adopted for the study:

$$\sigma_{hi}' = 203{,}5 \cdot f(1{,}5 - h_i) \text{ [MPa]}, \quad (4)$$

$$\sigma_{hi}'' = 33{,}8(3 - h_i) [(3 - h_i)\, df_{hi} / dh_i - 4f_{hi}] \text{ [MPa]}. \quad (5)$$

A constant etching speed (df_{hi}/d_{hi}) was additionally assumed, which was calculated as a function of angle. The value of etching speed v = 0.0022 mm·min^{-1} was assumed assuming a scale of $k_f = f_h/f_{hi}$= 0.01/6.

During the research, the relationships (4-6) were determined using the computer application RW_TRAW.

3. Results and discussion

3.1. Microhardness

Figure 7 shows microhardness changes in plunge-ground samples using conventional process kinematics (CK). The three waveforms represent results obtained for samples ground with different coolant supply strategies – without coolants (DRY), in abundant mode using the flooded (WET) method, and with minimum coolant supply using the MQL method. In addition, the figure shows the fourth course of microhardness changes characterizing the surface layer of the specimen after thermo-chemical treatment (TCT) before grinding.

Figure 8 shows a graph analogous to Figure 7, with the microhardness waveforms corresponding to samples ground longitudinally using innovative process kinematics (IK).

As shown in Figure 7, grinding resulted in a decrease in the microhardness of the material compared to the initial microhardness (after TCT) before grinding. The greatest decrease in microhardness at the surface was recorded after grinding without coolants (DRY), followed by grinding in WET mode. The reduction in hardness at the surface was 166 HV for DRY and 70 HV for WET. In the case of dry grinding, a decrease in hardness was seen throughout the carburized layer, which is due to the generation of high temperatures during the grinding process, causing structural changes in the process volume of the surface layer. The smallest changes at the surface (20 HV) occurred in the case of specimens ground with the use of coolant fed at a minimum rate by the MQL method. These changes were observed from the surface to a depth of 0.3 mm, then the microhardness for the WET and MQL methods reached similar values.

The micro-hardness distribution (Fig. 8) obtained using the innovative process kinematics (IK), showed no significant differences with respect to the thermal-treated material (after TCT), which may indicate that both the flooded method (WET) and the MQL method are comparably capable of providing suitable grinding conditions, including temperature. In the case of the non-coolant method (DRY), a significant decrease in hardness at the surface (133 HV) occurring to a depth of about 0.15 mm was observed relative to the thermal-treated material.

3.2. Residual stresses

Figure 9 shows the residual stress distribution in the surface layer of plunge-ground (CK) specimens using three strategies for supplying coolant to the machining zone – without coolants (DRY), using aqueous oil emulsion supplied by the flooded method (WET) and with a minimum expenditure by the MQL method.

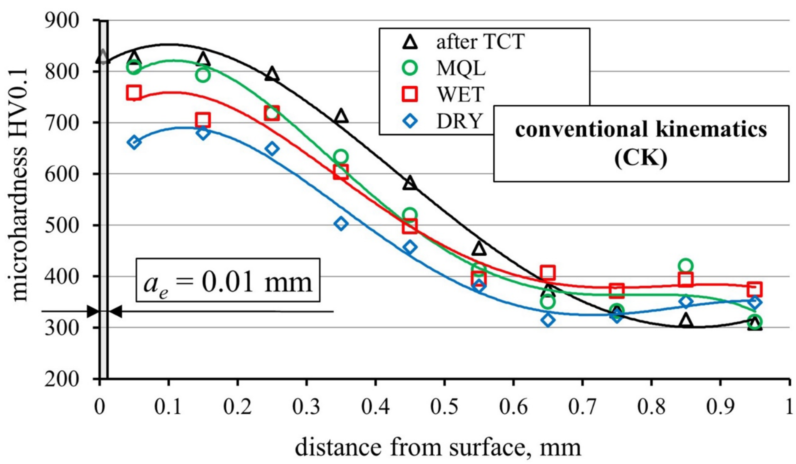

Fig. 7. Microhardness distribution in the surface layer of the specimen after vacuum carburizing and plunge grinding (CK) using different coolants feeding strategies

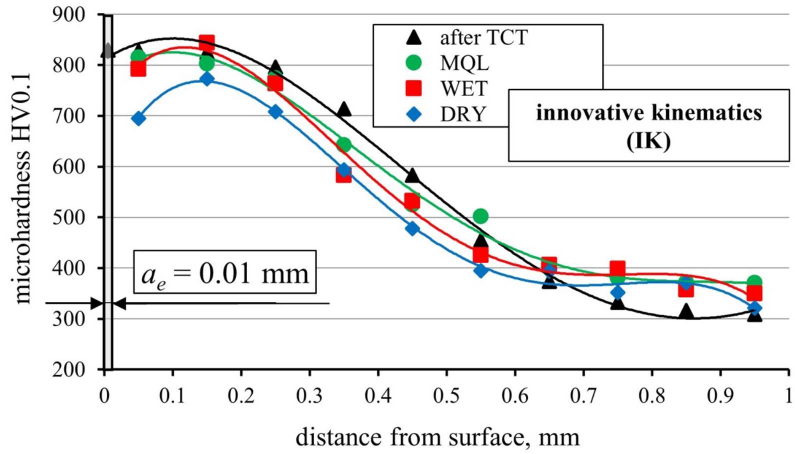

Fig. 8. Microhardness distribution in the surface layer of the samples after vacuum carburizing and longitudinal grinding (KI) using different coolants feeding strategies

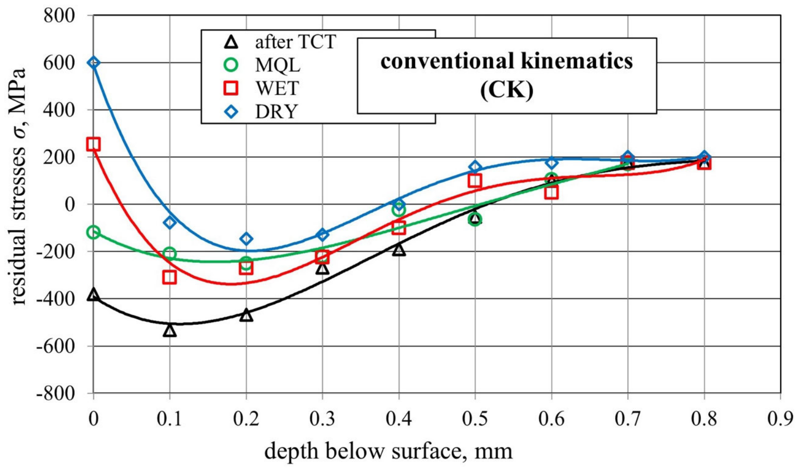

Fig. 9. Distribution of residual stresses in the surface layer of plunge-ground (CK) specimens

The value of the residual stress on the surface of the vacuum-carburized samples was -380 MPa. Then, as can be seen from the figure, these stresses increased monotonically with the distance from the surface, reaching a value of -50 MPa at a depth of 0.5 mm and then aiming for a value of 175 MPa at a depth of 0.8 mm.

As seen from the graphs in Figure 9, the highest values of tensile residual stresses were obtained for the case of grinding without coolant. Using the flood method reduced the values of the obtained residual stresses. The use of the MQL method, which improves lubrication in the contact zone between the abrasive grains and the workpiece material, resulted in the appearance of compressive residual stresses.

In the investigated range of machining conditions, grinding (CK) induces a deterioration in the state of residual stress with respect to the material before grinding. This observation applies both to samples ground using the DRY method (600 MPa) and the WET method (253 MPa). In both cases, unfavorable tensile residual stresses were obtained just below the surface of the samples. It is due to the large amount of heat flowing into the workpiece and the relatively high grinding temperatures causing unfavorable structural changes (including a tempering process in the steel). More favorable values of residual stresses were obtained for specimens' ground with the use of coolants feed with minimum output by the MQL method (-120 MPa). For this method, despite the change in the value of residual stresses, compared to the sample after TCT, the stresses in the technological surface layer were compressive.

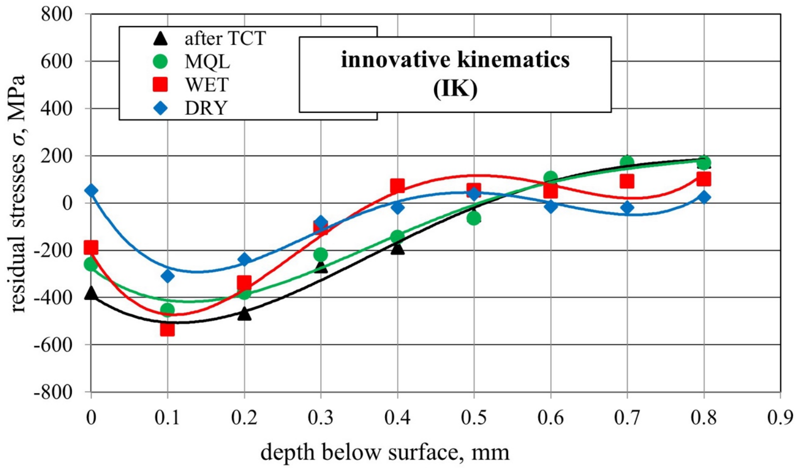

Fig. 10. Distribution of residual stresses in the surface layer of longitudinally ground samples (IK)

Figure 10 shows residual stress distribution in the surface layer of specimens ground longitudinally with innovative kinematics (IK) using three strategies for feeding coolant into the machining zone – without coolants (DRY), using aqueous oil emulsion fed by the flood method (WET) and the MQL method.

Using innovative kinematics of the grinding process (IK) makes it possible to obtain a more favorable distribution of residual stresses compared to those obtained during plunge grinding (CK). More favorable values of residual stresses were obtained for specimens ground using coolants feed by the MQL method (-260 MPa) and WET (-189 MPa). For the DRY method, in spite of obtaining tensile stresses on the surface itself (53 MPa), already at a depth of 0.1 mm, their value changes the sign to compressive (-310 MPa), and their nature, in spite of the lower compressive values of the residual stresses, is similar to the other two coolants feeding strategies analyzed. It indicates that the cooling and lubricating abilities of the grinding process varieties are better than those of the CK method.

4. Conclusions

This paper presents a study aimed at determining the effect of the grinding process on the microhardness and residual stress occurring in ring-shaped specimens made from 13CrMo4-5 steel. Carburizing and two varieties of grinding were used – plunge grinding with conventional kinematics (CK) and innovative kinematics (IK), for which a test stand based on a conventional flat-surface grinding machine and an original special device was used. The specimens were ground with a grinding wheel of fine electro-corundum (38A60K8V). As part of the study, microhardness and residual stress were measured, before and after grinding.

Based on the results obtained in the applied range of grinding conditions, it can be noted that:

- the greatest reduction in microhardness for both process variations was recorded during dry grinding (DRY), indicating the need to use coolants to improve cooling and lubrication conditions and to clean the machining zone,
- grinding using innovative kinematics (IK) did not result in significant changes in microhardness distribution with respect to the material immediately after thermo-chemical treatment. The smallest changes in microhardness near the surface were achieved using the MQL method. In general, microhardness decreases greater with plunge grinding.
- the use of innovative kinematics of the grinding process (IK) makes it possible to obtain a more favorable distribution of residual stresses compared to those obtained during plunge grinding (CK). The most favorable state of residual stresses was obtained in the sample ground using the MQL method. According to the authors, this is due to the fact that a greater amount of lubricant is supplied to the contact zone of the active abrasive grains with the workpiece material, which reduces friction and leads to a lower grinding temperature. The lower grinding temperature has a more favorable effect on the stress state induced in the surface layer of the ground steel.

It is worth noting that the proposed test stand, together with the authors' device, makes it possible to conduct machining of the external surfaces of cylindrical workpieces on a flat surface grinder.

Further research work will focus on, among others, selecting the angular settings of the workpiece axes relative to the grinding wheel axes depending on their dimensions. Grinding guidelines should include coverage ratio, infeed value, grinding time and peripheral speeds. In addition, the plan for future research includes measuring the components of grinding force and the geometric structure of the surface.

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