Effects of sulfurization of grinding wheels on internal cylindrical grinding of Titanium Grade 2®

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This paper presents an assessment of the influence exerted upon the internal cylindrical grinding of Titanium Grade 2® by the sulfurization of grinding wheels with ceramic bond. The sulfurization method of ceramic grinding wheels is presented against the background of a chemical basis for abrasive machining. The experimental investigation methodology is described. It includes a presentation of the proposed method for comparison of the sulfurization influence on the grinding results, which consists in performing a short grinding test in the plunge grinding kinematics. The paper emphasizes the multicriterial analysis of the experimental test results. It also describes the condition of the grinding wheel active surface (GWAS) that has not been sulfurized and one that has been impregnated with sulfur after grinding of the Titanium Grade 2®. The assessment has been carried out on the basis of the acquired SEM micrographs, as well as measurements of the surface microtopography with an optical profilometer and laser scatterometry method. The paper also analyzes the workpiece surface roughness measured with the stylus profilometry method, as well as the elemental composition of the surface inclusions, using Energy Dispersive X-ray Spectroscopy (EDS). The experimental results show that impregnation with sulfur makes it possible to significantly limit the phenomenon of smearing the GWAS with the machined material.

Keywords: Grinding process, Sulfurization, Grinding wheels, Internal cylindrical grinding, Surface roughness

Modern automated production processes aim at limiting costly finish processing. However, there still remains a wide group of products for which grinding must be used. This usually results from high quality demands concerning the workpiece surfaces. Modern grinding processes guarantee a high quality surface finish, with greater and greater material removal rates1-5. This is usually obtained through application of new grinding materials1,6, developing new kinematic variants of the grinding process2-5, or modernization of the grinding wheel structures6,7.

Development of new construction materials such as alloys of titanium, aluminum, magnesium, nickel, cobalt, as well as high-alloy steels, which can be found under the names INCONEL®, INCOLOY®, NIMONIC®, HASTELLOY® and others, create new requirements for the grinding processes8-14. These materials are included in the hard-to-cut materials group due to their:

− high ductility which is the reason for intensive smearing of the grinding wheel active surface (GWAS),
− high strength and hardness, which causes the rapid wear of the abrasive grains as a result of resistance wear,
− low thermal conductivity, causing high temperature increases in the machining zone, which results in intensive thermal wear of the abrasive grains and bond bridges.

Such materials are applied mainly for production in the automotive, aircraft, chemical and petrochemical industries but also in medical science. They are often used for production of parts operating in environments characterized by high temperatures and aggressive conditions, e.g., elements of gas turbines, aircraft engines (blades and toothed ring)15. These are usually precise casting alloys.

The fact that the titanium alloys are hard-to-cut results from their high mechanical resistance, high relative elongation and low heat conductivity. High resistance and plasticity leads to the creation of heat in the grinding process, which, paired with low heat conductivity, is poorly transferred from the machining zone and is transmitted to the abrasive tool almost completely13,14.

One of the most important problems with grinding titanium alloys is the intensive smearing of the GWAS with malleable chips8-14. They are created as a
result of the temperature-induced workpiece chips adhering to the abrasive grains.

Figure 1 presents a macrograph of the ceramic GWAS constructed from microcrystalline sintered corundum grains, after reciprocating internal cylindrical grinding in Titanium Grade 2. Both minor smearing of single abrasive grain vertexes and major smearing of grain groups with intergranular spaces were clearly visible. Smears lead to a decrease in the cutting ability of the grinding wheel, an increase of the grinding force and to higher participation of friction in the entire process. A significant increase of temperature, caused by friction, in the area of contact between the grinding wheel and the machined material may show itself in grinding defects of the surface layer of the workpiece, such as, grinding burns, microcracks and compressive stresses.

That’s why a very important matter is monitoring and diagnosis of the GWAS’s condition, whose task is to detect smears as soon as possible and to prevent their negative effects, e.g., by altering the grinding parameters or stopping the process and dressing the grinding wheel.

Chemical principles of abrasive machining

In the grinding zone, in which the abrasive tool comes into contact with the workpiece, four basic elements come into contact with each other: the abrasive grains, the bond, the workpiece and the environment. Contact between these elements at high temperatures, caused by friction and the rapid dynamics of the process can lead to chemical reactions (Fig. 2).

The most important chemical phenomena in abrasive machining include the influences of the grains and the machined material, as well as the interaction between the machined material and the filler, or impregnated substances, in the abrasive tools in the abrasive tools. The interactions between the abrasive grains and the machining environment are also important. The machining environment refers to the machining liquids introduced into the grinding zone, deliberately, as well as the atmospheric conditions. The oxygen contained in air plays the key role as it oxidizes the machined material and the abrasive grains. The interaction between the active components with the machined material is very important in the machining liquids.

In order to protect the abrasive grains from their chemical wear, intentionally introduced chemical influences are aimed at decreasing the resistance of the machined surface, which increases the machining effectiveness. Grinding effectiveness is also dependent upon actions aimed at decreasing the temperature in the abrasive cutting zone and to prevent chip adhesion upon the machined surface and the machined material. Such actions aim at:

- decreasing the temperature by heat removal, using the machining liquids;
- reducing the friction between the abrasive and the machined material through the creation of lubricating films and controlling the course of endothermic reactions;
- chemical separation of chips from the freshly exposed machined surface, and the tool surface, by oxidizing and introducing protective layers;
- chemical etching of the machined surface, leading to a decrease in the cutting resistance.

Realization of the above described aims takes places through:

- introduction of various fillers, which become an integral component of the bond, into the abrasive tool;
-...
impregnation of the ready abrasive tool with various types of chemical substances;
application of machining fluids with various degrees of chemical activity.

One of the easiest methods of insertion into the abrasive tool structure is through the impregnation of a melted substance directly into the grinding wheel pores. After the self-cooling of the impregnant, the grinding wheel can be used as an abrasive tool. Such an operation can be carried out by both tool producers and users by adapting the impregnated substance composition to the current technological needs.

This work examined the possibility of reducing adhesion of the grinding products, including chips of the machined material, to the GWAS, as a result of the introduction of impregnated sulfur.

Method of sulfurization of ceramic bonded grinding wheels

Due to its anti-adhesive properties, sulfur is used as a means of actively influencing the contact conditions in the grinding zone. Currently, sulfur compounds are mostly used as additives for cutting fluids and introduced into the grinding wheel in the form of impregnate.

Sulfur-impregnated grinding wheel is mainly used to reduce the intensity of smearing of the GWAS by workpiece material, thus prolonging its life, and also positively affects the quality of the surface finish. Sulfured grinding wheels are widely used in bearing and automotive industry. It is estimated, that about 70% to 80% honing tools are impregnated with sulfur. The amount of sulfur, which is introduced into the volume of the grinding wheel in the impregnation process is so small, that it doesn't adversely affect the machining environment.

The applications of the well-known methods of sulfur-treating of the grinding wheels (in the conditions of gravity or high pressure), often causes uneven distribution of sulfur in the total volume of the grinding wheel and filling intergranular free spaces. In the case of grinding hard-to-cut materials it is important to use a high-porosity grinding wheels in order to ensure efficient transport of long and tough chips outside of the working area. Impregnating this type of grinding wheels with sulfur in a conventional manner would result in a large loss of the grinding wheel structure openness. Therefore in described experiments, a new sulfur impregnation method was used in which the excess of sulfur was centrifuged.

Before the sulfurization process was undertaken, the grinding wheel underwent draining to eliminate water. The grinding wheel was drained using a laboratory drier with a temperature of 80°C (353 K) over a period of 30 min. The dried grinding wheel was placed in the desiccators and left to cool. Next, the grinding wheel was weighed on an analytical balance with internal calibration, WPA 180/S type, produced by Radwag (Poland) with readability of 0.0001 g and capacity of 180 g. The non-sulfurized grinding wheel mass was \( m_1 = 24.28 \) g.

When the grinding wheel was prepared, the sulfurization process was begun. In room temperature sulfur is a solid body. Its melting temperature is approximately 115°C. In order to introduce sulfur into the whole grinding wheel volume, the sulfurization process was performed in the temperature range of 120°C to 160°C, in which sulfur became liquid.

Figure 3 presents a schematic of the experimental setup used for sulfurizing the grinding wheels with ceramic bond. The main element of the setup was the heating mantle, type CMUT1000/CE, produced by Thermo Fisher Scientific Inc. (USA). It was used to create and maintain the desired temperature in the round-bottom laboratory flask, in which the sulfurization process was realized. The solid sulfur was placed in a
flask made from thermoresistant glass and heated using the heating mantle to the temperature of 150°C (Fig. 3a).

The grinding wheel was mounted on the arbor connected with the engine providing rotational movement $n_r$ of the grinding wheel with speed from 0 to 2900 min$^{-1}$. Moreover, the engine along with the arbor was mounted to the slide rail allowing for vertical movement in the range of 200 mm. When the correct temperature was obtained, the grinding wheel was immersed in liquid sulfur for 10 min (Fig. 3b). This time allows for heating the grinding wheel and leveling the sulfur temperature throughout the whole volume, which guaranteed its uniform penetration of the grinding wheel pores. After 10 min the grinding wheel was raised to the height of 30 mm over the liquid sulfur and set into rotary motion with the speed of $n_r = 1200$ min$^{-1}$ to centrifuge the excess sulfur (Fig. 3c).

Next, the heating mantle was turned off so that the temperature inside the flask lowered to the sulfur solidification temperature. The centrifuging process was finished after $t_r = 3$ min, when the sulfur did not remove itself from the grinding wheel under the influence of the centrifugal force. The centrifuging degree can be regulated by selecting the proper values of its parameters (the centrifuging speed $n_r$ and the centrifuging time $t_r$).

The final centrifuging of the liquid sulfur is crucial due to the technology of the grinding process. As a result of centrifuging, the sulfur is distributed evenly throughout the entire mass of the grinding wheel. Not all of the intergranular spaces are filled with sulfur, which makes both the advancement of the liquid coolant into the grinding zone and the removal from the grinding zone of the processed products possible. After cooling, the grinding wheel was weighed again and its mass was $m_2 = 26.90$ g. This means that 2.62 g of sulfur was introduced into the grinding wheel and the mass increase expressed in percentage terms was 10.79%.

Figure 4 presents a comparison of the microscopic images of the GWAS before (Fig. 4a) and after the sulfurizing process (Fig. 4b). To illustrate the sulfurization effect better, grinding wheel areas with visible sulfur were marked in Fig. 4c.

The most important difference, visible after comparison of the micrographs of the GWAS before (Fig. 4a) and after sulfurizing (Fig. 4b), is the significant participation of sulfur on the grinding wheel surface (marked in Fig. 4c) and a decrease in the volume of free intergranular spaces. The open structure of the grinding wheel, visible in Fig. 4a, guaranteed even sulfur impregnation throughout the whole tool volume. The obtained sulfurization effect allows for the sulfur to directly reach the contact area of the grinding wheel with the machined material. The fact that the sulfur filled the grinding wheel pores to a considerable degree guarantees that the processes of
dressing, conditioning and sharpening of the grinding wheel will not influence the participation of sulfur in the grinding process significantly. However, it should be noted that filling the grinding wheel pores up limits the positive results of application of grinding wheels with open structure, or high-porous grinding wheels.

Methodology of experimental investigations

This chapter discusses the methodology of assessing the influence of impregnating the grinding wheel with sulfur on the course, and results, of the hard-to-cut material grinding process, with the plunge grinding method, using a grinding wheel with zones of various diameters. The experimental investigations were carried out on Titanium Grade 2®, whose description is presented later in this work. Before the grinding process was carried out, the workpiece was initially ground by a grinding wheel with silicon carbide grains SiC.

Internal cylindrical plunge grinding

The applied grinding method consists generally in running a short grinding test, which lasts, for example, 6 s, with a specially shaped grinding wheel from the kinematics of the plunge grinding method. The stage of finish grinding and sparking out is omitted in such a test. The grinding wheel carried out the working movement with the applied table feed speed \( v_{fr} \), after which it is immediately removed from the machined material. This allows for drawing conclusions about the course of the rough grinding process on the basis of the analysis of the GWAS condition and that of the workpiece surface.

Modification of the grinding wheel macrogeometry in the described investigations consisted in forming three zones of different diameter on its active surface (Fig. 5a) in the dressing cut. Thus, the plunge grinding process results are realized of the grinding wheel shape on the workpiece surface (Fig. 5b).

Special shaping of the grinding wheel macrogeometry makes particular zones of its active surface operate at different times and remove different material volume. As a consequence, in particular GWAS zones, the process of wearing of the abrasive grains and the phenomenon of chip forming, or smearing of the intergranular spaces, occur with differing intensities and can take various forms.

The plunge grinding process was carried out with the following constant values of the main machining parameters: \( v_s = 60 \text{ m/s} \), \( v_w = 0.75 \text{ m/s} \), \( v_{fr} = 0.02 \text{ mm/s} \). The investigations were carried out for two grinding depth values: \( a_e = 0.06 \) and 0.12 mm. A 5% water solution of Castrol Syntilo RHS oil, which was brought into the grinding zone using the flooding method with the rate \( Q_c = 3.0 \text{ L/min} \), and was used as the coolant. Table 1 presents the general characteristics of grinding conditions.

![Fig. 5 — (a) Schematic diagram of the grinding process and (b) the setting-up of measured axial profiles of the grinding wheel and workpiece after plunge grinding, using a grinding wheel with zones of various diameter](image-url)
Experimental Procedure

In testing universal grinding machine RUP 28P (Fig. 6) equipped with electro-spindle type EV-70/70-2WB produced by Fisher AG, Switzerland (maximum rpm 60 000 min⁻¹, power 5.2 kW) was used.

Grinding wheel and workpiece

Grinding wheels with the following technical designations were used in the experimental investigations: 1-35×20×10-SG/F46G10VTO. They were made from microcrystalline sintered alumina grains SG and from ceramic glass-crystalline bond. The grinding wheels were divided into two groups, one of which remained unmodified, and the other of which underwent the process of sulfur impregnation in the Applied Chemistry Group, Faculty of Mechanical Engineering, Koszalin University of Technology, Poland. As a result of the applied process, the grinding wheel mass increased by 10%, which corresponded to the sulfur mass that had been distributed evenly throughout the whole volume of the grinding wheel.

The workpieces were in the form of rings with diameter \(d_w = 56\) mm and width \(b_w = 20\) mm. The rings were made from Titanium Grade 2®, whose general description is given in Table 2.

Methodology of assessment of the grinding results

When the grinding process was completed, a result assessment was performed by making measurements of the GWAS and of the workpiece surface (WS). Before the measurements were carried out, the available methods were analyzed in respect to their possible application in the assessment of two types of surfaces. As a result of the analysis three methods, which should provide the greatest extent of information about both GWAS and WS according to the authors, were selected. Two optical measurement methods were used to assess the GWAS condition: laser scatterometry supported by image processing and analysis techniques and optical profilometry. The WS assessment was carried out using the stylus profilometry, additionally scanning electron microscopy (SEM), with energy dispersive X-ray spectroscopy (EDS), was used to assess the

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**Table 1** — General characteristics of grinding conditions

<table>
<thead>
<tr>
<th>Process</th>
<th>Peripheral internal cylindrical plunge grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding machine</td>
<td>Universal grinding machine RUP 28P equipped with spindle type EV-70/70-2WB produced by Fisher AG, Switzerland (max. rpm 60 000 l/min, power of machine cutting 5.2 kW)</td>
</tr>
<tr>
<td>Grinding wheel</td>
<td>1-35×20×10-SG/F46G10VTO with three zones of different diameter</td>
</tr>
<tr>
<td>Dressing parameters</td>
<td>(d_r = 1.25) kt, (n_{sd} = 12 000) rpm, (v_{sd} = 10) m/s, (a_d = 0.0125) mm</td>
</tr>
<tr>
<td>Grinding parameters</td>
<td>(v_s = 60) m/s, (v_w = 0.75) m/s, (v_{fr} = 0.04) mm/s, (a_e = 0.12) mm, (Q_c = 3.0 ) l/min</td>
</tr>
<tr>
<td>Coolant</td>
<td>5% water solution of Castrol Syntilo RHS oil</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Internal cylindrical surface of rings, made of Titanium Grade 2®, internal diameter: (d_w = 56) mm, width: (b_w = 20) mm</td>
</tr>
</tbody>
</table>

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**Table 2** — The general characteristics of Titanium Grade 2®

<table>
<thead>
<tr>
<th>Material</th>
<th>Titanium Grade 2®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material No.</td>
<td>3.7035</td>
</tr>
<tr>
<td>Standard</td>
<td>UNS R50400 ASTM B861</td>
</tr>
<tr>
<td>Chemical composition and percentage of elements (%)</td>
<td>C(0.08)+Fe(0.25)+O(0.25max)+Ni(0.03)+H(0.015 max)+Ti(Balance)</td>
</tr>
<tr>
<td>Physical properties</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>4.51</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength, Ultimate (MPa)</td>
<td>344</td>
</tr>
<tr>
<td>Tensile Strength, Yield (MPa)</td>
<td>275-410</td>
</tr>
<tr>
<td>Hardness</td>
<td>170/80/145</td>
</tr>
<tr>
<td>(Knoop/Rocwell B/Vickers)</td>
<td></td>
</tr>
<tr>
<td>Modulus of Elasticity (GPa)</td>
<td>105</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.37</td>
</tr>
<tr>
<td>Thermal properties</td>
<td></td>
</tr>
<tr>
<td>Heat of Fusion (J/kg)</td>
<td>325</td>
</tr>
<tr>
<td>Specific Heat Capacity (J/kg °C)</td>
<td>523</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m°C)</td>
<td>20.8</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>approx. 1660</td>
</tr>
</tbody>
</table>

Material is produced by Special Metals Corporation (USA) and distributed in Europe by Bibus Metals (Switzerland)
GWAS and WS. Table 3 presents a general comparison of the measurement methods and tools used during the GWAS and WS assessment.

Results and Discussion

A series of experiments with the total value of the machining allowance \( a_e = 0.06 \) mm were carried out at the first step of the investigations. In such conditions (with grinding time \( t \approx 3 \) s) the material removal rate was \( Q_w \approx 21 \text{ mm}^3/\text{s} \). In the second step of the investigations, the machining allowance was doubled and it was 0.04 mm in Zone I, 0.08 mm in Zone II and 0.12 mm in Zone III. The machining time resulted from the adopted radial table feed speed \( v_{fr} = 0.04 \) mm/s and had the following values for respective zones: \( t_I \approx 1 \) s, \( t_{II} \approx 2 \) s, \( t_{III} \approx 3 \) s. With such machining parameters, three zones with variable material removal values \( V_w \) were obtained and their value changed from 42.22 mm\(^3\) for Zone I to 126.67 mm\(^3\) in Zone III. The internal cylindrical plunge grinding, with intentionally applied high material removal rate \( (Q_w \approx 42 \text{ mm}^3/\text{s}) \), intensified the creation of smearing on the GWAS considerably.

Table 3—Measurement methods and instruments used in assessment of the GWAS and WS

<table>
<thead>
<tr>
<th>Method</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser scatterometry and image analysis</td>
<td>Talysurf CLI 2000 Talley Hobson Ltd. (UK)</td>
</tr>
<tr>
<td>Optical profilometry</td>
<td>Taylor Hobson Ltd. (UK)</td>
</tr>
<tr>
<td>Stylus profilometry</td>
<td>Hommel-Tester T8000 Hommelwerke GmbH (Germany)</td>
</tr>
<tr>
<td>Scanning Electron Microscopy</td>
<td>JSM-5500LV JEOL Ltd. (Japan)</td>
</tr>
<tr>
<td>Energy dispersive X-ray spectroscopy</td>
<td>INCAPentaFET-x3 Oxford Instruments (UK)</td>
</tr>
</tbody>
</table>

Figure 7 presents a comparison of the results of analysis of the geometric structure of the non-impregnated GWAS, with the one that had been impregnated with sulfur, after grinding of Titanium Grade 2\(^\circ\) with machining allowance \( a_e = 0.06 \) mm.

![Fig. 7 — Comparison of microtopography and values of selected surface texture parameters of the three zones of the GWAS after grinding of Titanium Grade 2\(^\circ\) with machining allowance \( a_e = 0.06 \) mm obtained by optical profilometer Talysurf CLI 2000 produced by Taylor Hobson Ltd.: (a) grinding wheel without sulfur, (b) grinding wheel after sulfurization and (c) setting-up of selected surface texture parameters](image-url)
The comparison of the selected parameter values describing the geometrical structure of the non-impregnated GWAS with the values estimated for the grinding wheel impregnated with sulfur (Fig. 7c), shows that the impregnated grinding wheels are characterized by considerably less surface roughness. This is caused by the sulfur filling the free intergranular spaces (pores) of the GWAS. The differences in the values of the analyzed surface texture parameters are significant and can reach levels up to 500%. This results from the very open structure of the grinding wheels, that feature an applied glass-crystalline bond, used in the investigations.

In the case of the sulfur-impregnated grinding wheel, the grinding wheel pores are filled with sulfur, which radically changes the height of the GWAS unevenness. Alteration of the surface character is also visible in the comparison of the GWAS microtopography images presented in Figs 7a and 7b. The microtopographies also reveal considerable areas of smearing in Zone III of the non-impregnated grinding wheel, which contributed to the significant (approximately 40%) decrease of the $S_{dr}$ parameter value in this zone (Fig. 7c).

The subsequent figures present the micrographs registered on the non-impregnated GWAS (Fig. 8), and on the one impregnated with sulfur (Fig. 9), after grinding of Titanium Grade 2®.

The results drawn from analysis of the registered microtopographies of the particular grinding wheel functional zones are confirmed by the registered micrographs. When images presented in Fig. 8 are compared with those in Fig. 9, it can be observed that the number of pores in the sulfur-impregnated grinding wheel is considerably lower. This is especially visible with small magnifications (Figs 8a and 9a).

In Fig. 8a Zone III shows extensive intergranular smearing created during the grinding of Titanium Grade 2®. The introduction of sulfur into the grinding wheel mass allowed for a considerable reduction in the smearing of the GWAS with grinding products, which can be observed in Fig. 9a. This corresponds to Zone III, which ground the longest, and from which the greatest machining allowance was removed ($a_c = 0.06$ mm).

The highly magnified images also show that, in the case of the sulfur-impregnated grinding wheel, small areas on the abrasive grains vertexes are smeared.

![Fig. 8 — SEM microphotographs of active surface of the grinding wheel without sulfur after grinding of Titanium Grade 2® with machining allowance $a_c = 0.06$ mm obtained by scanning electron microscope JEOL JSM-5500LV produced by JEOL Ltd.: (a) general view, (b) magnification 50x (c) magnification 200x and (d) magnification 500x](image-url)
(Figs 9c and 9d). This proves that the sulfur provision to those places, in which the cutting vertexes and the machined material were in direct contact, was hindered, as a result of which the considerable influence of sulfur impregnation, upon the grain vertexes smearing phenomenon, was missed. However, it can be demonstrated that sulfurizing the grinding wheel definitely limits the phenomenon extensive GWAS intergranular smearing.

Figure 10 depicts views of the workpiece vertex microtopography in three subsequent zones after grinding with the non-impregnated grinding wheel (Fig. 10a) and with the sulfur-impregnated wheel (Fig. 10b). Diagrams of the determined surface texture parameters of Titanium Grade 2® after grinding (Fig. 10c) are also included.

The obtained surface roughness parameter values prove a considerable roughness increase in Zone III. This means that the obtained machined surface quality is highly dependent upon the grinding depth. However, no significant or unequivocal, influence of sulfur impregnation of the active surface, within the parameters describing the geometric structure of the surfaces obtained after grinding, was observed. What is worth noting is the high value of surface texture parameter values. The \( S_a \) parameter value for the surface after grinding should not exceed \( S_a = 0.63 \mu m \). The machined surfaces roughness obtained in the described tests can, however, diverge from the norm due to the specific character of the applied research method in which the finish grinding and sparking out stages are omitted.

**Experiment results for machining allowance \( a_e = 0.12 \text{ mm} \)**

The second step of the experimental investigations was realized with a grinding depth \( a_e = 0.12 \text{ mm} \) with the same machining time \( t \approx 3 \text{ s} \). Such a change of parameters corresponded to increasing the
material removal rate from $Q_w \approx 21 \text{ mm}^3/\text{s}$ to $Q_w \approx 42 \text{ mm}^3/\text{s}$. This enabled the determination of the influence of the grinding material removal rate on the results of machining with the sulfur-impregnated grinding wheel.

Figure 11 shows a comparison of the results of analysis of the non-impregnated and the sulfur-impregnated grinding wheel surface geometric structures, after grinding of Titanium Grade 2 with machining allowance $a_e = 0.12 \text{ mm}$

When the values of selected surface texture parameters of the GWAS, determined after grinding with depth $a_e = 0.06 \text{ mm}$ (Fig. 7c), are compared with values after grinding with depth $a_e = 0.12 \text{ mm}$ (Fig. 11c), an approximately double increase of the Sa (arithmetic mean height) and Sk (kernel roughness depth) parameter values can be observed for the sulfurized grinding wheel. Values of the discussed surface texture parameters concerning the non-sulfurized grinding wheel were on a similar level in both cases. In case of the Sk and Sdr parameters, a considerable decrease can be observed in the case of Zone III, as a result of the smearing of the GWAS with machined material. The greatest changes are related to Sdr parameter value, describing the level of surface development. In case of the non-sulfurized

![Fig. 10 — Comparison of microtopography and selected surface texture parameters of the three zones of the Titanium Grade 2 surface after grinding with machining allowance $a_e = 0.06 \text{ mm}$ obtained by stylus profilometer Hommel-Tester T8000 produced by Hommelwerke GmbH: (a) using grinding wheel without sulfur, (b) using sulfurized grinding wheel and (c) setting-up of selected surface texture parameters](image)
grinding wheel, values of this parameter were twice as high in the three zones, which can be explained by the random character of GWAS construction. In case of the sulfurized grinding wheel, the difference was over 500% for Zone I (an increase from $Sdr = 21.1\%$ for $a_e = 0.06$ mm to $Sdr = 112\%$ for $a_e = 0.12$ mm) and II (an increase from $Sdr = 19.9\%$ for $a_e = 0.06$ mm to $Sdr = 106\%$ for $a_e = 0.12$ mm). In Zone III the $Sdr$ value increased over four times from $Sdr = 34.9\%$ for $a_e = 0.06$ mm to $Sdr = 145\%$ for $a_e = 0.12$ mm. The surface texture parameter value changes denote an increase of the grinding wheel surface roughness, which should be interpreted as an increase in porosity caused by extension of the intergranular spaces volume. This means that part of the sulfur placed in the GWAS during the sulfurization process is removed during grinding. Such a phenomenon could have occurred only in cases of excessive temperature increase in the machining zone. In the experiment this led to the sulfur becoming liquid and expelled from the GWAS. This hypothesis is confirmed by the measurements (Fig. 12) and observation of the workpiece surface using SEM (Fig. 13).

Figure 12 shows the microtopography of the workpiece surface after grinding with the non-impregnated (Fig. 13a) and the sulfur-impregnated grinding wheel (Fig. 12b), along with a comparison of the selected surface texture parameter values (Fig. 12c). The surface texture parameter charts prove there is an increase of the surface roughness of subsequent zones, which correspond to increases in the grinding depth. When the results registered after grinding with maximal machining allowance of $a_e = 0.06$ mm (Fig. 10c) and $a_e = 0.12$ mm (Fig. 12c) are compared, it can be stated that doubling the material removal rate caused the values of all parameters considered in Zones I and II to, approximately, double. Only the roughness of the

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**Fig. 11** — Comparison of microtopography and values of selected surface texture parameters of the three zones of the GWAS after grinding of Titanium Grade 2® with machining allowance $a_e = 0.12$ mm obtained by optical profilometer Talysurf CLI 2000 produced by Taylor Hobson Ltd.: (a) grinding wheel without sulfur, (b) grinding wheel after sulfurization and (c) setting-up of selected surface texture parameters.
surface machined by Zone III of the grinding wheel remained on a comparative level.

What needs particular attention are the specific upheavals observed in microtopographies in Zones II and III of the surface machined with the sulfurized grinding wheel (Fig. 12b). In order to identify the surface inclusions measured with the stylus method unequivocally, a scanning microscope equipped with an EDS analyzer was used. The analysis results are depicted in Fig. 13. It presents the microtopography of the machined surface (Fig. 13a) with magnifications of the contact-measured upheavals (Figs 13b and 13c), as well as the SEM micrographs and EDS analysis results for the surface machined with Zone I (Figs 13d-g) and Zone III of the sulfurized grinding wheel (Figs 13h-k).

The observations carried out (Figs 13d-f) show that no inclusions appeared on the surface machined with Zone I, which was confirmed by the EDS analysis results, in which the only component of the analyzed surface was identified as titanium (Fig. 13g). In the case of the surface machined in Zone III, numerous inclusions, similar to a drop, were observed (Fig. 13h-j). The observed forms corresponded, in size and distribution, to the upheavals measured earlier by the stylus method in size and (Figs 12b, 13b and 13c).

Fig. 12 — Comparison of microtopography and selected surface texture parameters of the three zones of the Titanium Grade 2® surface after grinding with machining allowance \( a_e = 0.12 \) mm obtained by stylus profilometer Hommel-Tester T8000 produced by Hommelwerke GmbH: (a) using grinding wheel without sulfur, (b) using sulfurized grinding wheel and (c) setting-up of selected surface texture parameters.
EDS analysis showed that they are made from sulfur (Fig. 13k). The residual titanium content, showed in the analysis, results from the nearness of the substrate on which the assessed objects were formed.

The presented results of the GWAS measurements (Fig. 11) and the measurements of EDS analyses of the machined surface (Fig. 13) prove that when the ground material removal rate was higher \( Q_w \approx 42 \text{ mm}^3/\text{s} \), a phenomenon opposing sulfurization occurred. As a result of a considerable temperature increase in the grinding zone, relatively large GWAS areas were heated to a temperature exceeding the sulfur melting point. As a result, the liquid sulfur was centrifuged from the grinding wheel surface at the speed of 33000 rpm. This led to the dispersal of sulfur over the workpiece surface, upon which it solidified immediately in drop-like form, resultant from the surface tension of liquid sulfur. This means that when grinding wheels, sulfurized with the described method, are used, it is crucial to prevent excessive temperature increase in the machining zone.

Results of measurements of the scattered light for the sulfurized and non-sulfurized grinding wheel after grinding with \( a_e = 0.12 \text{ mm} \)

At this step of the investigations the GWAS images of scattered light were acquired and analyzed. The

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**Fig. 13** — EDS analysis of the workpiece surface after grinding with machining allowance \( a_e = 0.12 \text{ mm} \) using sulfurized grinding wheel with: (a-c) microtopography of the workpiece surface, (d-f) SEM microphotographs of the workpiece surface in Zone I, (g) EDS analysis of workpiece surface in Zone I, (h-j) SEM microphotographs of the workpiece surface in Zone III and (k) EDS analysis of workpiece surface in Zone III
acquired images carried out processing and analysis in the Image-Pro® Plus 5.1 environment produced by Media Cybernetics (USA). The main aim of the analysis was to determine the values of the so-called key parameters, best describing the geometric and photometric features of the assessed images. The authors assumed the key parameters to be: (i) $A_n$ – area (of the bright regions of an image of scattered light)\textsuperscript{47-48} and (ii) $I_{Σ}$ – integrated optical density (of the bright regions of an image of scattered light)\textsuperscript{47-48}.

When the parameters, which required expressing in numerical values, were determined, the image processing began. In the first step segmentation of particular images was carried out to obtain the contours necessary to determine the geometric parameters. In the second step tonal correction was carried out (including improvements of the brightness and the contrast) to obtain correct photometric parameter values. In both cases the Count/Size function was applied. This function automatically counts all the objects in the assessed image. The software determined values of particular parameters on the basis of the counted objects. The statistical description of the measured data was obtained using the Statistics tool. It also allowed for exporting the data to any worksheet for the purpose of further processing and visualization.

Figure 14 includes a comparison of images of the scattered light acquisition and analysis run during the experimental investigations. The top part of Fig. 14 depicts exemplary images of the scattered light acquired for the GWAS impregnated with sulfur (Fig. 14a), and the non-impregnated one (Fig.14b), after grinding the Titanium Grade 2\textsuperscript{®} alloy. The images were classified in the following order: zone number, area number and number of the GWAS points for which the acquisition was made. Visual assessment of the images clearly demonstrated that wide light scattering, without any regularly shaped optical pattern, occurred in Zone 1 (smearing-free), regardless of whether the grinding wheel was, or was not, impregnated. What was observed in Zone II

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**Fig. 14** — Results of acquisition of images of the scattered light and its image analysis carried out in Image-Pro Plus 5.1 software: (a) images of the scattered light acquired for three zones of a sulfur -impregnated grinding wheel, (b) images of the scattered light acquired for three zones of a non-impregnated grinding wheel, (c) comparison of average values of the area (of the bright regions of an image of scattered light) for three zones of the GWAS, (d) setting-up of average values of integrated optical density (of the bright regions of an image of scattered light) for three zones of the GWAS.
(with minor smearings) was a zone of highly concentrated light wave reflecting from the surface of metallic smearing occurring in the central part of the images. This wave created a clearly visible optical pattern, which was a conic section fragment (of a circle) with an increased light intensity compared to the previous images. Wide light intensity occurred in the image of the scattered light of the sulfur-impregnated surface. It can be therefore concluded that the non-impregnated surface suppressed the radiation more effectively – therefore the light intensity value was lower in this case. In Zone III (with large smearings) amplification of the effects visible in the previous images was observed. In the central part of both assessed images there was a zone of highly concentrated light wave reflected from the smeared metallic surface. This zone was particularly visible for the non-impregnated GWAS. Moreover, numerous collateral light scatterings, related to unevenness present on the edges of the two smeared areas, were observed in both images.

The bottom part of Fig. 14 presents a comparison of the average values of the area (of the bright regions of an image of scattered light) and integrated optical density (of the bright regions of an image of scattered light) for the subsequent analyzed GWAS zones. The values of standard deviation $\sigma$ are also marked in the column charts. What has been marked below (in diagram form) are the average values of the area (of the bright regions of an image of scattered light) and integrated optical density (of the bright regions of an image of scattered light) for the subsequent analyzed GWAS zone. On the basis of the analysis of the above diagrams it can be concluded that the average values of both parameters for the assessed GWAS zones did not differ considerably and corresponded to the selected images of scattered light presented in the top part of Fig. 14. Higher values were registered for the GWAS after impregnation with sulfur and lower ones for the non-impregnated GWAS. The values of the area (of the bright regions of an image of scattered light) for the non-impregnated grinding wheel were respectively: 13.5% (Zone I) 9.8% (Zone II) and 5.9% (Zone III) lower than in case of the impregnated grinding wheel. The values of the integrated optical density (of the bright regions of an image of scattered light) for the non-impregnated grinding wheel were respectively: 19.0% (Zone I) 11.7% (Zone II) and 1.0% (Zone III) lower than for the impregnated grinding wheel.

**Conclusions**

The main aim of this study was to assess the influence of GWAS sulfurization on the course, and grinding results, and grinding results of Titanium Grade 2®. From this investigation, the following conclusions can be drawn:

(i) The introduction of sulfur into the grinding wheel as an impregnated substance result the adhesion of chips and other grinding products to the GWAS, and is an effective way of influencing the machining of Titanium Grade 2®.

(ii) The applied GWAS sulfurization method allowed for the effective introduction of sulfur into the machining zone.

(iii) The developed methodology of the experimental investigations allowed a research goal to be achieved through running a series of short grinding tests and later thorough comparative analysis of their results, with application of numerous measurement methods.

(iv) The applied research methodology allowed for simultaneous analysis of the influence of numerous factors (such as, GWAS smearing and the variable grinding time and depth) on the processing results.

(v) When sulfurized grinding wheels are used, the machined surface may be contaminated with sulfur which can become liquid as a result of excessive temperature increases in the grinding zone; because of this the selection of grinding parameters and the optimization of the method of introduction and removal of the coolant are of crucial importance.

(vi) It was proven that laser scatterometry can be successfully used for quick, non-contact detection of GWAS smearing and is an effective alternative to other measurement methods applied for this purpose.

(vii) What was observed in the case of the sulfur-impregnated grinding wheel was an increase in the values of parameters used for the assessment of images of the scattered light (area and integrated optical density).

(viii) An increase of the above-mentioned parameter values denotes an improvement of the reflective properties of laser radiation from such a surface, which is beneficial for reasons of measurement.
(ix) Impregnation of the grinding wheel with sulfur considerably decreases the intensity of GWAS smearing with the machined material;

(x) Impregnation of the GWAS with sulfur restricts the creation of extensive intergranular smearings, which are technologically least advantageous.

(xi) No significant influence of sulfur GWAS impregnation on the intensity of smear creation in the microareas of the grinding wheel active grains vertexes was observed.

(xii) Impregnating the GWAS with sulfur does not influence the machined surface roughness significantly.

(xiii) The machined surface roughness is most dependant on the grinding depth, due to which low values of machining allowance should be used.

(xiv) Doubling of the grinding material removal rate caused a proportional increase of the surface texture parameter values of the surfaces machined, both with the non-impregnated and the sulfurized grinding wheels.

(xv) The process of Titanium Grade 2® plunge grinding with grinding wheels from sintered microcrystalline alumina should be optimized with respect to the characteristics of the grinding wheel used and the parameters selected by way of separate tests.

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Nomenclature

EDS = energy dispersive X-ray spectroscopy
GWAS = grinding wheel active surface
SEM = scanning electron microscopy
WS = workpiece surface
\( a_w \) = working engagement, mm
\( A_s \) = area (of the bright regions of an image of scattered light), pixel
\( b_w \) = workpiece breadth, mm
\( d_s \) = grinding wheel diameter, mm
\( d_w \) = workpiece diameter, mm
\( D \) = grinding wheel outside diameter, mm
\( H \) = grinding wheel inside diameter, mm
\( I_w \) = integrated optical density (of the bright regions of an image of scattered light), u.a.
\( n_t \) = grinding wheel rotational frequency during sulfurization process, rpm
\( n_n \) = grinding wheel rotational frequency, rpm
\( n_w \) = workpiece rotational frequency, rpm
\( Q_r \) = coolant flow rate, l/min
\( Q_d \) = mass of diamond dresser, kt
\( Q_m \) = material removal rate, mm³/s
\( S_a \) = arithmetic mean height, µm
\( Sdr \) = developed interfacial area ratio, %
\( S_k \) = kernel roughness depth, µm
\( S_t \) = total height of the surface, µm
\( t \) = grinding time, s
\( T \) = grinding wheel total height in axial direction, mm
\( U_a \) = accelerating voltage, kV
\( v_r \) = radial table feed speed, mm/s
\( v_s \) = grinding wheel peripheral speed, m/s
\( v_w \) = workpiece peripheral speed, m/s
\( V_m \) = material removal, mm³/s
\( \sigma \) = standard deviation

References
