The results of studies of the grinding process of titanium alloys by the grinding wheels with chrome electrocorundum aluminum oxide, silicon carbide, CBN and GP were presented in the article. During the grinding of surfaces propylene glycol and commercial cutting fluids were applied, dedicated used to passing with minimum flow into the cutting zone. The results were compared with those of dry grinding.

Key words: grinding, titanium alloys, minimum quantity lubrication

1. INTRODUCTION

High impact on the machinability of titanium alloy has a chemical composition, in particular adversely affected the increased content of oxygen, hydrogen and carbon [3]. The tendency of this type of alloys to the reaction at elevated temperatures is generally known [2]. Difficulties in machining of titanium alloys result from wear of the grinding wheel which affects in a bad condition of the surface layer, an increase of structural changes such as temperature, a low smoothness of the grinded surface [14, 15, 18, 19]. During the research two titanium alloys were used, Ti-6Al-4V (by Timet) and alloy WT-22 with the composition presented in Table 2. These two-phase alloys are well known and well described in the literature [8]. The paper introduces designation of titanium alloy (U), which contains a considerable amount of elements stabilizing β-phase. Excessive influence of temperature and high cooling rate increase the embrittlement of the alloy. Titanium alloy marked (P) belongs to a group of transient two-phase (α + β) alloys having a phase β in the structure.

During the research the tangent and normal forces were measure. The indicator W was calculated which is the quotient of normal to the tangential force, and it depends on the actual depth of cut and Bp, which is the product of the energy flux density and the time of contact of the grinding wheel with the work piece, is described by equation (1) [20].

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\[ B_p = P' \cdot t_c \]  \hspace{1cm} (1)

energy flux density (2)

\[ P' = \frac{F_t v_s}{b_D \cdot l_e} \]  \hspace{1cm} (2)

the time of contact of the grinding wheel with the work piece (3)

\[ t_c = \frac{l_e}{v_w} \]  \hspace{1cm} (3)

Product of energy (2) and time (3) is described (4)

\[ B_p = \frac{F_t v_s \cdot l_e}{b_D \cdot v_w} \]  \hspace{1cm} (4)

Indicator \( B_p \) grinding of flat samples (5)

\[ B_p = \frac{F_t v_s}{b_D v_w} \]  \hspace{1cm} (5)

where: \( F_t \) – tangential force of grinding,
\( v_s \) – velocity of grinding wheel,
\( l_e \) – the actual length of contact of the grinding wheel with the sample,
\( b_D \) – width of grinding,
\( v_w \) – velocity of the work piece

There are research, during which is looking for the abrasive tools for greater wear resistance. Regeneration of the active surface of these grinding wheels should be the same as in case of the conventional materials, because they can be easily regenerated, especially in the production of individual or small series. CBN grinding wheels [4, 11] require special and specific methods of regeneration. Research is also conducted on grinding wheels with a group of TGP, XGP.

During the investigation the new cooling fluids and way of their application into the cutting zone are being looked for to maintain proper surface layer during grinding process, [7, 9, 15–17, 20, 22]. Application of the minimum quantity lubrication (MQL) to the grinding zone reduces the cost of manufacture and use of cutting fluids, which also should be environmentally friendly and safe for the health and life of the machine operators [10, 11, 19, 21], such criteria meets polyethylene glycol [12].

The machinability of the titanium alloys depends on their chemical composition. Especially the increased content of oxygen, hydrogen and carbon has unfavorable influence on their machinability.

The predisposition of this type of alloys to a reaction with surroundings in raised temperatures is a generally well-known fact [2, 3, 8]. The wear of the grinding wheel makes the grinding process of titanium alloys difficult, because it
influences: the increase of temperature, low smoothness of the surface and structural transformations in the material.

Abrasive tools with a larger resistance to wear are still sought after. The regeneration of active surfaces of such grinding wheels should be identical, as in conventional ones [7], because they can be regenerated easily, especially in individual production or small lot production. The grinding wheels of the super-hard group [4, 16, 20] require special and specific methods of regeneration. Studies of grinding wheels from TGP, XGP (the microcrystalline corundum) group are also being conducted.

Searches for new cutting fluids are being conducted, as well as new ways of introducing the cutting zone because the object should have the proper features [4, 9] after grinding. Applying minimum quantity of liquid (MQL) to the grinding zone, reduces the costs of production [9, 11, 22] and makes it possible to use cutting fluids, which are harmless both for the worker and the environment.

2. CONDITIONS OF THE STUDIES

The aim of the investigation was to analyze the influence of chosen grinding wheels and cutting cooling lubricants on the grinding forces, the grinding energy indicator and the roughness of the surface. The usefulness of the cutting fluids was tested with a view to selecting the appropriate cooling and lubricating conditions which will guarantee the desired roughness of the surface and will not allow excessive deformations of the thinner elements.

The experiments were conducted for three titanium alloys: Ti -6Al-4V, WT-22 and TIGER 5. The chemical composition of the alloys is presented in Table 1. The analysis of the alloys was conducted with the quantometer ARL 360.

<table>
<thead>
<tr>
<th>Sign</th>
<th>Alloy</th>
<th>Chemical analysis [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>U</td>
<td>Ti-6Al-4</td>
<td>6.12</td>
</tr>
<tr>
<td>P</td>
<td>WT-22</td>
<td>4.85</td>
</tr>
<tr>
<td>T</td>
<td>TIGER 5</td>
<td>6.51</td>
</tr>
</tbody>
</table>

The investigation was made on the grinding machine SPD – 30 with grinding parameters as shown on Table 2. In the elaboration the following designation of the grinding wheels was assumed: (A) electrocorundum, (C) silicon carbide, (B) borazon, as well as, mikrocorundum TGP (3T), (5T) and XGP (3X). Samples
were grinded without the fluid (S) or by means of cutting fluid (PCS): (E) emulsion (5% aqueous solution of emulsifying oil ES – 12, ISO – L-MAA), (O) oil (Poligrind 1A) recommended by the manufacturer for cutting processes.

The second part of the investigations concerns only TIGER 5 and Ti-6Al-4 alloys, which were ground with the usage of propylene glycol – symbol (GP). The results received from grinding with commercial grinding fluids applied in conventional grinding were compared with propylene glycol. The trade names of the liquids are: (MC) – Micro 3000, (EC) – EcoCut micro 82, (BO) 3000. The samples were ground by grinding wheels with microcorundum TGP and XGP.

The grinding fluid, in the form of oil fog under a pressure of 0.6 MPa, at a quantity of 50 ml/hour, was applied through a nozzle to the sample surface. The distance of the nozzle to the sample surface was 4 mm, at an inclination angle of 25°.

### Table 2

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Grinding wheel</th>
<th>Fluids</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>25A 80 G 12 VBEP (A)</td>
<td>Emulsion (E)</td>
<td>Dry grinding (S)</td>
</tr>
<tr>
<td>P</td>
<td>CBN80/63/B75U (B)</td>
<td>Emulsion (E)</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>39C 46 J8 VK (C)</td>
<td>Emulsion (E)</td>
<td></td>
</tr>
<tr>
<td>T, P</td>
<td>5TGP 54K VX (5T)</td>
<td>Glycol (GP)</td>
<td>Micro 3000 (MC)</td>
</tr>
<tr>
<td></td>
<td>3TGP 60K VX (3T)</td>
<td>EcoCut micro 82 (EC)</td>
<td>BioCut 3000 (BO)</td>
</tr>
<tr>
<td>T, P</td>
<td>3XGP 54K VX (3X)</td>
<td>Glycol (GP)</td>
<td>Micro 3000 (MC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EcoCut micro 82 (EC)</td>
<td>BioCut 3000 (BO)</td>
</tr>
</tbody>
</table>

The grinding process was carried out as a single passage: wheel speed \( v_w = 26.5 \text{ m/s} \) – to research assumed constant value, the width of the grinding samples was \( b_D = 10 \text{ mm} \), speed of work piece \( v_w = 0.1 \pm 0.5 \text{ m/s} \), grinding depth \( a_r = 0.01 \pm 0.05 \text{ mm} \).

To measure the grinding forces a dynamometer 9272 was used, on which a grip handle with a sample was mounted. The signal from the dynamometer was sent to an amplifier 5011A and card DAS 1602, which was placed in a computer. The station, together with the software was described in articles [9, 11, 12].
3. RESULTS OF THE INVESTIGATION

Particular attention was paid to the measurement of tangential and normal forces of grinding process. Tangential force is introduced into an equation (5), \( B_p \) index allows us to predict the state of residual stresses in the surface layers. To elaborate the results the indicator \( W \) was also used [16, 18, 19, 21].

In first the part of the investigations, the samples were grinded with the participation of grinding fluid: emulsion (E) or oil (A). The results were compared to dry grinding (S). The experiments were executed for titanium alloys with the markers: (P, U, T).

Figure 1 presents the diagram of the tangential force of the used grinding fluids and alloys, which were ground with the grinding wheel of the chromic electrocorundum (A) and of preset parameters: \( \nu_w = 0.3 \) m/s, \( a_e = 0.02 \) mm, \( \nu_s = 26.5 \) m/s. The tangential force for the dry grinding of the alloys: (P and U) achieve: (P) – 127 N, (U) – 121 N, (T) – 145 N respectively. The influence of oil on the tangent force is insignificant; whereas emulsion causes growth of this force, regardless of the alloy.

![Figure 1](image.png)

Figure 1. The tangent force for grinding surfaces of titanium alloys by a grinding wheel (A) with the use of: (E) – emulsified oil, (O) – grinding oil and (S) – dry grinding

Figure 2a shows the values of the indicator \( W \) for the grinding process by a grinding wheel (B) of two titanium alloys (A and P). The real the depth of grinding for the grinding wheel (B) was two times smaller in comparison with conventional grinding wheels. Furthermore, indicator \( W \) practically did not change in the whole range of changes of the real depth of grinding the alloy (U). Essential differences only concerned alloy (P).
During the grinding of alloy (P) by conventional grinding wheels it was observed that the values of indicator $W$ were comparable in the whole range of real depths of grinding (Figure 2b) with those of the grinding wheel with silicon carbide (C). Essential differences were noticed only with the grinding wheel with chromic electrocorundum (A).

Moreover, the real depths of grinding the titanium alloys with a borazon grinding wheel and conventional grinding wheels were defined by keeping the same depth $a_r$ and speed $v_w$. The real grinding depth $a_r = 0.024$ mm for the borazon grinding wheel as well as $a_r = 0.036$ mm for of the conventional grinding wheels (A) and (C) were measured.

Indicator $W$ was compared for borazon and conventional grinding wheels mentioned above.

![Figure 2](image.jpg)

**Figure 2.** The influence of the type of grinding wheel on the $W$ indicator during the grinding of titanium alloys with the use of emulsified oil: a) grinding wheel (B) – alloy WT-22 and Ti-6Al4-V, b) grinding wheel (A) and (C) – alloy WT-22

The influence of depth and feed on the value of the $B_p$ indicator for the grinding the titanium alloys with borazon grinding wheels, chromic electrocorundum and silicon carbide is illustrated by Figure 3. Figure 3a shows the results for alloy Ti-6Al-V4 and Figure 3a results for alloy WT-22. The experiments showed that the growth of indicator $B_p$ is influenced by: the growth of depth and reduction of feed. The increase of feed $v_w = 0.1$ m/s to $v_w = 0.5$ m/s at identical grinding depths reduces the $B_p$ value. The smallest values were obtained at the grinding of titanium alloy Ti-6Al-4V (P) and a grinding wheel with chromic electrocorundum for all depths and feeds. However, indicator $B_p$ increased by about 50% for the tested piece of alloy WT-22, in the whole range of changes of feeds and depths.
The grinding of titanium alloys

Figure 3. The influence of grinding parameters on the $B_p$ indicator with the use of grinding wheels with: chromium electrocorundum (A), silicon carbide (C) and CBN (B) for a titanium alloy: a) Ti-6Al-4V, b) WT-22

The results of deep-seated grinding of the surface samples of titanium alloys Ti-6Al-4V (P), by the grinding wheels 39C 46 J8 VK and CBN 80/63 are illustrated on a Figure 4. Figure 4a shows a visible zone of small heat changes, which were formed by dry grinding with the parameters: $v_w = 0.1$ m/s, $a_e = 0.05$ mm, $v_s = 22.5$ m/s. Finally, Figure 4 shows the outflow of material on the side of the test piece, as result of the deformation after the plunge grinding with parameters: $v_w = 0.5$ m/s, $a_e = 0.05$ mm, $v_s = 22.5$ m/s.

Figure 4. A test piece of the titanium alloy Ti-6Al-4V (P) after dry grinding with the grinding wheel a) 39C 46 J8 VK, b) CBN 80/63)
4. THE RESULTS OF GRINDING WITH MQL

Comparative investigations of the results of grinding titanium alloys (P and T) were executed, when the processing liquid was passed with minimum quantity lubrication – MQL. To simplify the description of the graphs the liquids used in the experiment were marked:

- GP – Propylene glycol,
- MC – Micro 3000,
- EC – EcoCut mikro 82,
- BO – Biocut 3000.

The smallest values of the tangent forces $F_t$ were obtained for the grinding wheels (3T and 5T) during the grinding of titanium alloy TIGER5 with the use of Propylene glycol (GP) with MQL. In case of the grinding wheel (3X); the tangent forces differed considerably from the remaining grinding wheels.

The difference in tangent force for propylene glycol and Biocut 3000 was 66 N. Similar results were achieved for the 3XG grinding wheel, namely 56 N.

The tangent force was considerably higher for titanium alloy (P), in comparison to alloy (T), for all of the liquids used in the experiments. The smallest the forces were noted when associating: the grinding wheel (3X) and grinding fluid (BO).

Use of propylene glycol eliminated the burning of the grinding surface, which was observed for other fluids. This shows that applying propylene glycol with MQL during the grinding of titanium alloys is beneficial.

![Figure 5. The forces used by grinding wheels (5T, 3T, 3X) with the use of cutting fluid with MQL for alloy: a) (T), b) (P)](image-url)
The measurements of roughness were executed for plunge grinding with a single passage.

Table 3 shows the minimum, maximum and average values for parameter $R_a$, measured five times.

The smallest average value, as well as, small changeability of the $R_a$ parameter was achieved during the grinding of the TIGER 5 alloy by grinding wheel 5T – 0.47 µm. The middle value $R_a$ for another grinding wheel is: 0.63 µm for 3T and 0.73 µm for 3X. Other grinding fluids show: BO – 0.55 µm, whereas for MC and EC the $R_a$ value is highest. In case of grinding the titanium alloy Ti-6Al-4V (P), the middle $R_a$ value was smallest for GP – 0.58 µm.

| Grinding fluid          | Titanium alloys – grinding wheel |           |           |           |           |
|-------------------------|----------------------------------|-----------|-----------|-----------|
|                         | TIGR5 – (5T)                     | Ti-6Al-4V – (5T) |           |           |           |
|                         | Surface roughness [µm]           | $R_a$ min | $R_a$ max | $R_a$ avg | $R_a$ min | $R_a$ max | $R_a$ avg |
| GP – Propylene glycol   | 0.44                             | 0.49      | 0.47      | 0.49      | 0.66      | 0.58      |
| MC – Micro 3000         | 0.86                             | 1.07      | 0.97      | 0.96      | 1.21      | 1.09      |
| BO – Biocut 3000       | 0.52                             | 0.58      | 0.55      | 0.61      | 0.86      | 0.74      |
| EC – EcoCut mikro 82   | 0.90                             | 1.01      | 0.96      | 0.66      | 0.86      | 0.76      |

| Grinding fluid          | Titanium alloys – grinding wheel |           |           |           |           |
|-------------------------|----------------------------------|-----------|-----------|-----------|
|                         | TIGR5 – (3T)                     | Ti-6Al-4V – (3T) |           |           |           |
|                         | Surface roughness [µm]           | $R_a$ min | $R_a$ max | $R_a$ avg | $R_a$ min | $R_a$ max | $R_a$ avg |
| GP – Propylene glycol   | 0.58                             | 0.68      | 0.63      | 0.64      | 0.72      | 0.68      |
| MC – Micro 3000         | 1.26                             | 1.34      | 1.30      | 1.26      | 1.75      | 1.51      |
| BO – Biocut 3000       | 0.84                             | 1.37      | 1.11      | 0.68      | 0.92      | 0.80      |
| EC – EcoCut mikro 82   | 0.97                             | 1.46      | 1.22      | 0.74      | 1.18      | 0.96      |

| Grinding fluid          | Titanium alloys – grinding wheel |           |           |           |           |
|-------------------------|----------------------------------|-----------|-----------|-----------|
|                         | TIGR5 – (3X)                     | Ti-6Al-4V – (3X) |           |           |           |
|                         | Surface roughness [µm]           | $R_a$ min | $R_a$ max | $R_a$ avg | $R_a$ min | $R_a$ max | $R_a$ avg |
| GP – Polypropylene glycol | 0.68                           | 0.78      | 0.73      | 0.78      | 0.92      | 0.85      |
| MC – Micro 3000         | 1.26                             | 1.68      | 1.47      | 0.70      | 1.30      | 1.00      |
| BO – Biocut 3000       | 0.84                             | 1.37      | 1.11      | 1.31      | 1.44      | 1.38      |
| EC – EcoCut mikro 82   | 0.97                             | 1.46      | 1.22      | 0.84      | 1.43      | 1.14      |

The test pieces underwent deformation – inflexion during the grinding. The state of the test piece after plunge grinding is shown on Figure 6. The opinion on deformations was based on the following methodology. The test pieces were
ground with a large stream of grinding fluid to the depth $a_e = 0.005$ mm only when they reached the temperature of the surroundings. The initial state recorded was the moment of contact of the test piece and the grinding wheel. The process was executed until the entire surface of the test piece was reground. The deviation of flatness between the initial and final state of the test piece was measured with an accuracy of 0.005 mm.

The deformation of the test piece depends on the grinding fluid and the material of the grinding wheel – Figure 7. The results are for grinding wheels TGP (3T and 5T), 3XGP (3X) as well as studied of the grinding fluid.

The smallest deformations were obtained for the grinding fluid with the GP symbol, whereas the biggest for MC, regardless of the grinding wheel used. Comparable deformations are for grinding wheels 3X and 3T, but the largest are for grinding wheel 5T, regardless of the grinding fluid. The condition of minimizing deformations during the grinding of titanium alloys was met when the 3X grinding wheel and GP grinding fluid were used simultaneously.
5. CONCLUSIONS

Results show, that not for all studied titanium alloys, grinding wheels and grinding fluids can the results show the desired state of the top layer and minimal deformations. The effect of grinding depends on the chemical constitution of the titanium alloy which influences the temperatures of the structural transformation $\alpha \rightarrow \beta$. The temperature of transformation $840+870^\circ C$ for (P) and $990^\circ C$ for (U) directly influences the physical and chemical properties of the alloy.

Propylene glycol can be applied to the grinding of titanium alloys as grinding fluid with a minimum expense of 50 ml/hour. This fluid is cheap, easily accessible and is not harmful for the operator, as well as, the environment.

The consumption of glycol by the grinding of titanium alloys with MQL is small. The lubricating properties contribute to the decrease of cutting forces, limit deformation and damage of the top layer of thin objects.

REFERENCES


SZLIFOWANIE STOPÓW TYTANU

Streszczenie

W artykule zaprezentowano badania procesu szlifowania stopów tytanu ściernicami z elektrokorundu chromowego, węglika krzemu, cBN oraz GP. Podczas szlifowania płaszczyzn zastosowano glikol propylenowy i handlowe płyty obróbkowe, podawane z minimalnym przepływem do strefy skrawania. Wyniki badań odniesiono do szlifowania na sucho.