In this paper the surface finish produced by turning of perlitic-ferritic nodular cast iron (NCI) with multilayer (TiC/Ti(C,N)/Al$_2$O$_3$/TiN) coated P20 carbide and nitride ceramic cutting tools is characterized using both 2D and 3D roughness parameters. The surface finish was characterized using a set of surface roughness parameters including vertical ($R_a$, $R_z$), horizontal ($R_{Sm}$), hybrid ($R_{dq}$), and additionally statistical ($R_{Sk}$, $R_{Ku}$) and functional parameters based on the bearing curve ($R_{mr(c)}$, $R_{pk}$, $R_{vk}$, $R_{hk}$). Some 3D roughness parameters were also considered and compared with 2D parameters. The data obtained can support the optimization of finishing operations of NCI parts.

Key words: nodular cast iron, finish turning, coated carbide tools, silicon nitride ceramic tools

1. INTRODUCTION

In recent years the development of new cast iron materials for components not traditionally manufactured from these materials has been observed [10]. In particular, the two materials with significantly higher strengths in comparison to classical grey cast irons are Compacted Graphite Iron (CGI) and Austempered Ductile Iron (ADI). Their excellent mechanical and fatigue strengths result from lamellar (vermicular) graphite and globular graphite structures respectively [1, 10].

Exemplarily, the increasing use of CGI (German acronym GGV) vermicular/compact graphite iron as a suitable material for engine blocks in high performance diesel engines to meet rigorous eco-standards is reported [1, 8]. Basically, they originated from the necessity of designing lighter and dimensionally smaller car engines with higher power trains, in comparison to traditional materials such as Al-Si alloys or grey cast irons [10].

In general, machining the range of grey and ductile irons is complicated by the fact that these materials can vary in machinability so greatly, often within the
same batch [3]. In addition, the data which quantify the machining process of nodular cast iron, especially including tool wear and surface finish, rarely appear in the metal cutting literature [4, 5]. The suitability of uncoated WC/Co and TiCN/TiC/TiCN/Al2O3/TiN coated carbide tools for machining of nodular cast iron with pearlitic-ferritic structure was investigated by Yigit et al. [11]. Such cutting characteristics as cutting, feed and radial forces, flank wear and surface roughness were measured at cutting speeds ranging from 125 to 200 m/min. It is concluded that the multilayer TiCN/TiC/TiCN/Al2O3/TiN of 10.5 μm thickness guarantees the highest flank wear resistance and provides the best surface finish (Ra = 1.5 – 3 μm for 500 mm cutting length, when keeping vc = 200 mm/min and f = 0.25 mm/rev). On the other hand, Ghani et al. [2] have revealed that mixed ceramics (Al2O3+TiC) tools are unsatisfactory in terms of flank wear, cutting vibrations and surface roughness when turning nodular cast iron (UTS = 263 MPa, 222 HB) at high cutting speeds of 364 – 500 m/min. It should be pointed out that the maximum tool life achieved in this range of cutting speeds was only about 1.5 min.

The present study concerns the surface finish produced in machining a PF nodular EN-GJS 500 iron with TiC/Ti(C,N)/Al2O3/TiN coated carbide and silicon nitride ceramic tools under variable cutting parameters. In particular, changes of many 2D and 3D surface roughness parameters due to application of these cutting tool materials, and variable cutting speeds and feed rates, are presented and discussed.

2. EXPERIMENTAL PROCEDURE

2.1. Machining conditions

Cutting tool configuration of ISO-TGNR 2020-16 type and two inserts were used in machining tests. The ISO-TNMA 160408 of NTH1 multilayer grade CVD-TiC/Ti(C,N)/Al2O3/TiN by Sandvik-Baildonit, Poland as well as TNGA 160408T02520 silicon nitride Si3N4 based ceramic insert of a CC 6090 grade by Sandvik Coromant with chamfer width and the chamfer angle equal to 0.2 mm and 20° were employed.

Cutting parameters and cutting tool angles selected are listed in Table 1. Two series of longitudinal turning trials, first with variable cutting speed and second with variable feed rate were carried out during the experimental program. All trials were repeated, each for three-times.
Finish turning of nodular cast iron using different cutting tool inserts

Table 1

<table>
<thead>
<tr>
<th>Cutting speed $v_c$ [m/min]</th>
<th>Feed rate $f$ [mm/rev]</th>
<th>Depth of cut $a_p$ [mm]</th>
<th>Cutting tool geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>160, 193, 230, 280, 320</td>
<td>0.16</td>
<td>2</td>
<td>$\kappa_c = 90^\circ, \alpha_c = 5^\circ, \gamma_c = -5^\circ, \lambda_c = -4^\circ$</td>
</tr>
<tr>
<td>270</td>
<td>0.04, 0.08, 0.10, 0.16, 0.20, 0.28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In general, ductile cast-irons have ferritic, pearlitic and pearlitic-ferritic matrixes with graphite nodules varying between 20 and 60 $\mu$m. In this study the workpiece material was the pearlitic-ferritic (PF) nodular iron of EN-GJS-500-7 grade containing approximately 50% pearlite, 40% ferrite and 10% graphite.

Table 2

<table>
<thead>
<tr>
<th>UTS ($R_m$) [MPa]</th>
<th>$Y (R_{0.2})$ [MPa]</th>
<th>Elongation $A$ [%]</th>
<th>Hardness $HB$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>320</td>
<td>7</td>
<td>175</td>
</tr>
</tbody>
</table>

The mechanical properties of nodular iron machined are listed in Table 2. The ultimate tensile strength UTS = 500 MPa and the measured average hardness was about 175 HB. Bars of 100 mm in diameter, which were primarily machined under roughing and finishing conditions, were used.

2.2. Measurements of 2D and 3D surface roughness

In the first step of measurements, a set of 2D surface roughness parameters was recorded on a 2D Hommel Tester 1000 profilometer. 2D roughness parameters were determined by simple roughness measurements using a shop floor Hommel Tester 1000 profilometer with a diamond stylus radius of 5 $\mu$m.

In the second step of investigation, 3D parameters (additionally 2D roughness parameters to compare the values obtained with standard 2D profilometry) were measured using scanning technique. In these series of measurements both 2D and 3D roughness parameters were estimated from a 2.5 mm×2 mm surface area on a 3D TOPO 01P profilometer, keeping the scanning distance of 10 $\mu$m in the $y$ direction and the distance of 0.5 $\mu$m between subsequent probes in the $x$ direction (along the selected profile). The Gaussian filter with cut-off length of 0.8 mm was selected and the evaluation length was equal to $l_n = 4.8$ mm.
3. EXPERIMENTAL DETAILS AND DISCUSSION

3.1. 2D characterization of surface finish

Basically, a set of 2D surface roughness parameters was recorded on a 2D Hommel Tester 1000 profilometer. Some 2D roughness parameters listed in Tables 3 and 4 were measured along with relevant 3D parameters. Fig. 1 illustrates how the cutting speed and feed rate influence the average surface roughness \( Ra \) and reduced peak height \( Rpk \) for both cutting tool materials tested. It is evident from Fig. 1a that for cutting conditions used, the minimum value of \( Ra \) parameter of about 1 \( \mu m \) was recorded when machining with nitride ceramic tools. Moreover, the \( Ra \) value changes only between 1 and 1.2 \( \mu m \) (course #2) when the cutting speed is varied from 160 to 320 m/min. For the cutting speed of 160 m/min, for which the \( Ra = 1.21 \mu m \), other 2D roughness parameters were as follows: \( Rz = 9.93 \mu m \), \( RSm = 149.97 \mu m \), \( Rq = 12.58 \mu m \), \( Rsk = 0.24 \), \( Rku = 2.75 \).

![Fig. 1. Ra roughness mean parameter (a) and reduced peak height Rpk (b) vs. cutting speed for \( f = 0.16 \) mm/rev and feed rate for constant \( v_c = 270 \) m/min](image)

The possibility of obtaining lower \( Ra \) value for nitride ceramic tools is also confirmed when varying feed rate from 0.04 to 0.28 mm/rev, as in Fig. 1a. For this variable machining parameter, surface roughness \( Ra \) does not differ substantially for coated and ceramic tools, despite one characteristic peak recorded for \( f = 0.08 \) mm/rev. In particular, the shape of the \( Ra-f \) curve for nitride ceramic
tools (course #2') is similar to an ideal curve without side flow effect for the feeds less than 0.1 mm/rev [6]. In contrast, the effect of increasing surface roughness due to BUE phenomenon occurs for coated carbide tools, which is evidently documented by visible increase of Ra parameter for small feeds of 0.08 mm/rev.

Second important finding documented in Fig. 1b is that the reduced peak height Rpk is distinctly higher for surfaces machined with coated carbide tools (excluding specific case with vc = 230 m/min) as presented in Fig. 1b. Lower values of Rpk parameter for silicon nitride tools correspond well with blunter irregularities indicated by lower value of the mean slope Rǻq presented in Fig. 2a (for instance 8.57° vs. 12.58° for vc = 160 m/min). It should be remembered that higher Rpk values mean that more material from peaks will be removed during running-in period of the part service. On the other hand, higher values of Ra, ranging between 1.4 and 2.0 µm, were recorded for TiC/Ti(C,N)/Al2O3/TiN coated tools, whereas the skew was positive (Rsk = 0.24). It is also interesting to note that for vc = 270 m/min low Ra values were obtained for coated carbide (2.03 µm) and Si3N4 (1.13 µm) tools.

For both multilayer and nitride ceramic tools the mean slope RΔq changes slightly, between 12.35° and 13.55° for coated carbide tools and between 8.57° and 6° for nitride ceramic tools. More visible variations of RΔq parameter can be
obtained when varying feed rate, and sharper feed marks are produced for higher feeds (courses # 1' and 2' in Fig. 2a).

It is evident in Fig. 2b that the regular (close to deterministic type) surface profiles can be produced because feed rate is equal to the mean line peak spacing $R_{Sp}$ (for example for Si$_3$N$_4$ tools 160 µm feed vs. 175.5 µm $R_{Sp}$ for $v_c = 270$ m/min). On the other hand, the spacing between feed marks recorded for coated tools is below the feed value, for example for the same case as previously 160 µm feed vs. 153.3 µm. It should be noted that for low feeds $f \leq 0.1$ mm/rev, the average value of $R_{Sp}$ is about two times higher than the feed rate.

In such a case, the surface profile contains components with periods exceeding the feed used or the tool generates non-periodic surface profile. Other roughness parameters measured for silicon ceramic tools at $v_c = 160$ m/min are: $R_z = 7.92$ µm, $R_{Sp} = 168.68$ µm, $R.Aq = 8.57°$, $Rsk = -1.76$, $Rku = 5.41$. Negative and very low values of $Rsk$ parameter obtained for surface profiles produced by coated and ceramic tools suggest their good bearing properties. It can be observed in Fig. 3a and 3b that values of $Rku$ varied between 1.99 and 5.26 under machining conditions applied and $Rsk$ values were positive or negative depending on the machining conditions used. One characteristic case (#2 in Fig. 3b for nitride ceramic tools) concerns negative $Rsk$ values for all cutting speed used. Figures 4 and 5 show several bearing curves, also called Abbot-Firestone’s curves, obtained for varying cutting speed and feed rate respectively.
Finish turning of nodular cast iron using different cutting tool inserts

Fig. 4. Bearing curves obtained for varying cutting speeds: (a) 160 m/min, (b) 230 m/min, (c) 320 m/min and constant feed rate $f = 0.16$ mm/rev

Rys. 4. Krzywe udziału materiałowego po toczeniu ze zmienią prędkością skrawania: (a) 160 m/min, (b) 230 m/min, (c) 320 m/min; $f = 0.16$ mm/obr

Fig. 5. Bearing curves obtained for varying feeds: (a) 0.04 mm/rev, (b) 0.16 mm/rev, (c) 0.28 mm/rev and constant cutting speed $v_c = 270$ m/min

Rys. 5. Krzywe udziału materiałowego po toczeniu ze zmiennym posuwem: (a) 0.04 mm/obr, (b) 0.16 mm/obr, (c) 0.28 mm/obr; $v_c = 270$ m/min
3.2. 3D characterization of surface finish

Apart from standard 2D roughness parameters also 3D parameters were measured using scanning technique. In these series of measurements both 2D and 3D roughness parameters were estimated from a 2.5 mm×2 mm surface area on a 3D TOPO 01P profilometer, keeping the scanning distance of 10 μm in the y direction and the distance of 0.5 μm between subsequent probes in the x direction (along the selected profile). The Gaussian filter with cut-off of 0.8 mm was selected.

All measured values of 2D and 3D roughness parameters obtained for two cuttings speeds of 160 m/min and 320 m/min are collected in Tables 3 and 4. Some scanned fragments of the machined surfaces are illustrated in Fig. 6 and 7.

![Fig. 6. Surface topographies obtained by coated carbide tools (a) and silicon nitride tools (v_c = 160 m/min, f = 0.16 mm/rev, a_p = 2 mm)](image)

![Rys. 6. Topografia powierzchni otrzymana po toczeniu ostrzem pokrytym wielowarstwowo (a) i z ceramiki azotkowej (v_c = 160 m/min, f = 0.16 mm/obr, a_p = 2 mm)](image)

![Fig. 7. Surface topographies obtained by coated carbide tools (a) and silicon nitride tools (v_c = 320 m/min, f = 0.16 mm/rev, a_p = 2 mm)](image)

![Rys. 7. Topografia powierzchni otrzymana po toczeniu ostrzem pokrytym wielowarstwowo (a) i z ceramiki azotkowej (v_c = 320 m/min, f = 0.16 mm/obr, a_p = 2 mm)](image)
First important observation from the surface topographies shown in Fig. 6 and 7 is that sharper ridges are characteristic geometrical components of the machined surface produced by coated carbide tools. Second observation is that rarely distributed high peaks appear on the NDI surfaces. They consist of the crown of metallic flakes (probably soft ferrite) on the basis of 70 μm in diameter and sharp cone of graphite. Moreover, multiple small, egg-shaped bubbles of about 20 μm produced by plastic deformation of the metallic PF matrix are well visible on the ridges.

Fig. 8. Comparison of 2D (Hommel Tester 1000 profilometer) and 3D (TOPO 01P profilometer) parameters. (a) coated carbide and (b) silicon nitride ceramic tools

Rys. 8. Porównanie parametrów 2D (profilometr Hommel Tester 1000) i 3D (profilometr TOPO 01P): (a) ostrze pokrywane wielowarstwowo, (b) ostrze z ceramiki azotkowej
These two specific surface features are more intensive for surfaces produced by four-layer coated carbide tools ($S_z = 22.57 \mu m$ versus $13.86 \mu m$ for silicon nitride tools when $v_c = 160 \text{ m/min}$). In consequence, values of some 3D roughness parameters such as $S_z$ and $S_{sk}$ differ substantially (two times or more) from 2D equivalents. In particular, for both tested cutting tools and the two cutting speeds applied the average skew $Rsk$ is negative whereas the value of $Ssk$ is positive (for example $-0.45$ versus $1.53$ for coated carbide tools and $v_c = 160 \text{ m/min}$).

It is reasonable that the comparison between 2D and 3D roughness parameters is of practical importance. Previously, some important differences between $S_z$ and $R_z$ roughness parameters observed for hard machining with mixed ceramic tools ($S_z = 2.4 \mu m$ versus $R_z = 1.7 \mu m$ for $v_c = 100 \text{ m/min}$ and $f = 0.04 \text{ mm/rev}$ when hard turning AISI 5140 steel) were also reported by Grzesik and Wanat [7]. For this study, comparison of 2D and 3D roughness parameters is presented in Fig. 8 and their values are collected in Table 4.

### Table 3

3D roughness parameters measured for surfaces machined at $v_c = 160 \text{ m/min}$ and $v_c = 320 \text{ m/min}$

<table>
<thead>
<tr>
<th>3D parameters</th>
<th>4L-CCT</th>
<th>SNCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_p$, $\mu m$</td>
<td>13.51/11.97</td>
<td>4.77/9.60</td>
</tr>
<tr>
<td>$S_v$, $\mu m$</td>
<td>9.06/8.44</td>
<td>9.09/8.01</td>
</tr>
<tr>
<td>$S_z$, $\mu m$</td>
<td>22.57/20.41</td>
<td>13.86/17.61</td>
</tr>
<tr>
<td>$S_r$, $\mu m$</td>
<td>1.56/1.57</td>
<td>1.07/1.03</td>
</tr>
<tr>
<td>$S_q$, $\mu m$</td>
<td>1.90/1.85</td>
<td>1.29/1.29</td>
</tr>
<tr>
<td>$S_{sk}$</td>
<td>1.53/1.45</td>
<td>1.52/1.63</td>
</tr>
<tr>
<td>$S_{ku}$</td>
<td>2.78/2.57</td>
<td>2.92/3.41</td>
</tr>
</tbody>
</table>

Note: 4L-CCT – four-layer coated carbide tools, SNCT – silicon nitride ceramic tools, 160 m/min/320 m/min.

### Table 4

Roughness parameters for TiC/Ti(C,N)/Al$_2$O$_3$/TiN coated carbide and silicon nitride ceramic tools

<table>
<thead>
<tr>
<th>Roughness parameters</th>
<th>Cutting speed $v_c = 160 \text{ m/min}$</th>
<th>Cutting speed $v_c = 320 \text{ m/min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4L-CCT</td>
<td>SNCT</td>
</tr>
<tr>
<td>$R_a$</td>
<td>1.58</td>
<td>1.21</td>
</tr>
<tr>
<td>$S_a$</td>
<td>1.56</td>
<td>1.07</td>
</tr>
<tr>
<td>$R_z$</td>
<td>9.93</td>
<td>7.92</td>
</tr>
<tr>
<td>$S_z$</td>
<td>22.57</td>
<td>13.86</td>
</tr>
<tr>
<td>$R_q$</td>
<td>1.95</td>
<td>1.52</td>
</tr>
<tr>
<td>$S_q$</td>
<td>1.90</td>
<td>1.29</td>
</tr>
<tr>
<td>$R_{sk}$</td>
<td>0.24</td>
<td>-1.76</td>
</tr>
<tr>
<td>$S_{sk}$</td>
<td>1.53</td>
<td>1.52</td>
</tr>
<tr>
<td>$R_{ku}$</td>
<td>2.75</td>
<td>5.41</td>
</tr>
<tr>
<td>$S_{ku}$</td>
<td>2.78</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Note: 4L-CCT – four-layer coated carbide tools, SNCT – silicon nitride ceramic tools.
4. CONCLUSIONS

1. Silicon nitride cutting tools produce better and stable surface finish under finish cutting conditions. For example, at the cutting speed of 270 m/min, the $Ra$ roughness parameter varies from 0.44 μm to 1.0 μm when feed rate increases from 0.04 mm/rev to 0.16 mm/rev respectively.

2. The reduced peak height $Rpk$ is distinctly higher for surfaces machined with coated carbide tools. Lower values of $Rpk$ parameter for silicon nitride tools correspond well with blunter irregularities indicated by lower value of the mean slope $RΔq$.

3. The surface profiles can produced as regular and close to deterministic type because feed rate is close to the mean line peak spacing $RSm$. The spacing between feed marks recorded for coated tools is 5% lower than the feed value, and about 10% higher for silicon nitride tools.

4. The surface profiles with good bearing properties (confirmed by negative skew) can be generated during machining. Moreover, surface profiles generated by $Si₃N₄$ tools contain blunter peaks resulting in lower values of the $Rpk$ parameter. This parameter represents the top portion of the surface being worn away quickly when sliding wear starts.

5. Some descriptions between 2D and 3D surface roughness parameters, especially between $Rz$ and $Sz$ and $Rsk$ and $Ssk$, were observed.

REFERENCES

W artykule scharakteryzowano chropowatość powierzchni z żeliwa sferoidalnego po toczeniu płytkami ostrzowymi z węglików spiekanych P20 z powłoką (TiC/Ti(C,N)/Al2O3/TiN) i z ceramiki azotkowej Si3N4 za pomocą parametrów 2D i 3D. Chropowatość powierzchni oceniano na podstawie zestawu parametrów pionowych (Ra, Rz), poziomych (RSm), mieszanych (hybrydowych) (Rq), rozkładu statystycznego (Rsk, Rku) i funkcjonalnych (Rmr, Rpk, Rvk, Rk) na podstawie krzywej nośności. Rozpatrzonono niektóre parametry 3D i porównano z odpowiednikami 2D. Uzyskane dane mogą wspomóc optymalizację toczenia wykańczającego części z żeliwa sferoidalnego (NCI).

Słowa kluczowe: żeliwo sferoidalne, toczenie, obróbka wykańczająca, węgliki spiekane, ceramika azotkowa, chropowatość powierzchni