EFFECT OF CUTTING SPEED ON SURFACE ROUGHNESS: FACE MILLING OF STEEL WITH A PARALLELOGRAM INSERT

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In the study, the roughness characteristics of the surfaces produced with symmetrical milling experiments of steel were analyzed. The cutting speed was changed while the chip cross-section remained constant. The tool was equipped with a single insert with κₗ=90°. In this article the 2D and 3D roughness characteristics are investigated; the average roughness (Rₐ, Sₐ) and the profile height parameters (Rₜ, Sₜ) were taken into account. The roughness measurements were made in five parallel planes, the change in roughness parameters was analyzed in different planes and the inhomogeneity of topography was shown in planes parallel to the direction of feed.

Keywords: surface roughness, face milling, cutting speed

INTRODUCTION

Surfaces have differing textures, which have characteristics that depend on the method of production. By this we mean the pattern on the surface which deviates from the nominal surface. The differences may be repeating or random and may result from roughness, waviness and/or flaws. Thus, the actual surface profile is the superposition of errors of form, waviness and roughness [1].

Due to its motion conditions, face milling is a machining process in which the edge of the tool creates different impressions on different parts of the surface, resulting in a surface with inhomogeneous topography.

This means that regardless of any pairing of tool and workpiece materials, if the machined surface is measured in different directions [2] and places – even in parallel planes [3,4] – variable roughness is generated. Zhenyu et al. stated that the highest values of roughness were found in the middle plane, and when we examine a parallel plane to it at a longer distance, the value of its roughness will be lower [5].

Face milling can be defined precisely from the point of view of the created surface that is described by the rotation of the tool and the feed motion of the workpiece perpendicular to the axis line simultaneously. Together, these generate the looped cycloid tool path that creates grooves on the surface and these traces can be seen on the finished surface.

There is extensive research around the world about the surface roughness of face milled surfaces, with the aim to create an appropriate topography of the surface for operating requirements, for fitting of parts and for manufacturing with cutting.
data for high productivity as well. This effort can be helped if the expected roughness can be planned, estimated, and the correct cutting data can be pre-selected to achieve optimum value [6].

Some of the research deals with simulations and attempts to confirm the results with experiments, where differences are observed and explained. Felho and Kundrak [4] show an example of this with an investigation of face milling where various feed rates were applied, and thus the cross-section of the chip. Based on their simulations, CAD models were generated which were used to determine the theoretical values of surface roughness. Then values of roughness parameters were estimated by the comparison of the theoretical and experimental results. They observed that with the increase in feed rate, the theoretical and real profiles were increasingly the same. Their simulation proved to be very useful, with only minimal differences from experimental data.

Various machining aspects are taken into consideration in cutting experiments, which are related to the change in surface roughness. One example is the examination of cutting speed, feed rate and depth of cut, which Zang et al. [7] dealt with. Zhenyu et al. [5] also took into account other important factors affecting roughness beyond cutting data, like the shape and geometry of the cutting inserts, radial and axial run-outs of cutting edges and vibrations of the tool (which is related to the stiffness of the WFMT system). The run-outs were also examined by Krüger et al. [8]. Cui et al. [9] examined the change in roughness based on the shape and discoloration of the chips. Razfar et al. [1] and Cui et al. [9] represent another direction of research, searching for optimal cutting data to minimize surface roughness. In their analyses, the cutting data considered were cutting speed $v_c$, feed rate $f_z$, axial depth of cut $a_p$ and cutting width $a_e$. Razfar et al. [1] used Analysis of Variances (ANOVA), Artificial Neural Network (ANN) and Harmony Search Algorithm (HS) methods. With these, the expected result with a 96% accuracy for $R_a$ was received. It was found that the HS method can be used reliably and provides a result close to the real value, as verified by comparison with experiments. Cui et al. [9] used the Taguchi method in their publication. It has been stated that, at a fixed feed rate and depth of cut, the static and dynamic cutting force, the tool wear and thus the vibrations have the local or absolute minimum of roughness values at the same cutting speed, and most of them also affect the average surface roughness $R_a$.

Some researchers use mathematical and statistical methods to estimate the expected roughness, and they examine how accurate their formula is with experiments. Zhenyu et al. [5] set a mathematical model in the direction of the feed rate where the highest roughness is expected, and the axial and radial run-outs of each edge were taken into account besides the cutting data ($f_z$, $v_c$, $a_p$). Based on these parameters, the static load of the machining system was written, and a dynamic model considering vibrations and damping was also created. Finally, the experimental and theoretical roughness was compared, and a 6% difference were found. Therefore, the model used for the estimation of roughness is well suited, especially in case of multi-edge face milling. They also found that the run-outs of the edges have a greater impact on expected roughness than feed rate $f_z$, depth of cut $a_p$, or corner radius $r_c$. 
There are examples of exploring different relationships between cutting data and surface roughness that are performed with factorial experimental design [10,11]. Others estimate the expected roughness from the cutting force $F_c$ [8]. Liu et al. [12], however, describes the correlation between tool wear and surface roughness.

We also deal with this topic continuously in our institute. A method has been developed that can consider the different geometry of the tool and the radial and axial run-outs in addition to the cutting data. Using this method, a CAD model from the surface can be created and the expected surface roughness can be estimated. Felho and Kundrak [4], based on their experiments, were convinced that the model predicted the real profile well. The same authors in their other articles deal with the prediction of roughness, for example in the case of different geometry inserts fixed simultaneously in a special milling head [13], or in the case of considering the run-outs of several inserts in the tool [14]. Varga et al. [3] examined aluminum specimens at different feed rates and cutting speeds and investigated the flatness and roughness of the surfaces. It was stated that increasing the feed rate increases all the amplitude parameters of roughness and that the roughness values are not equal on the entry and exit sides of the tool edge at the same distance from the symmetry plane, but always have smaller values on the exit side.

In this article, we want to carry out experiments to examine how the change in cutting speed in the planes parallel to the feed direction affects the roughness of the machined surface. During the experiments a symmetrical setting was used, and the roughness parameters were analyzed and compared in the measurement planes at the same distances.

**EXPERIMENTAL CONDITIONS**

The experiments were carried out on a Perfect Jet MCV-M8 vertical milling machine. During the works only one Sandvik R215.44-15T308M-WL parallelogram shape coated carbide insert was used in a Sandvik R252.44-080027-15M milling head with $D_t=80$mm nominal diameter. The shape of the insert and the manufacturing geometry are presented in Table 1.

<table>
<thead>
<tr>
<th>No</th>
<th>$v_c$ [m/min]</th>
<th>$a_p$ [mm]</th>
<th>$f_z$ [mm/r]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0.8 (const.)</td>
<td>0.4 (const.)</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0.8 (const.)</td>
<td>0.4 (const.)</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>0.8 (const.)</td>
<td>0.4 (const.)</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>0.8 (const.)</td>
<td>0.4 (const.)</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>0.8 (const.)</td>
<td>0.4 (const.)</td>
</tr>
</tbody>
</table>

The shape of the insert and the manufacturing geometry are presented in Table 1.
The workpieces used for the experiments were made of C45 grade steel in normalized condition with tensile strength 580 MPa and Brinell hardness 207 HBW [15]. The surfaces on the specimens prepared for milling were 58 mm and 50 mm in length and in width, respectively.

The cutting data used for the experiments are given in Table 1. The axial depth of cut $a_p$ and the feed rate per tooth $f_z$ were set to a constant 0.8 mm and 0.4 mm/rotation/tooth, respectively. The cutting speed $v_c$ was set to different values from 100 to 500 m/min. The specimens were produced of one material, plane surfaces were milled in symmetrical setting.

The roughness measurements were performed using an AltiSurf 520 three-dimensional surface roughness measuring device. A CL2 confocal chromatic sensor equipped with a MG140 magnifier was used for the recordings. The probe has the axial resolution of 0.012 μm. Evaluation was performed with AltiMap software.

RESULTS

Measurements were made in five planes (from A to E) following the tool edge. One of these is the plane of symmetry, which is located in the path of the tool axis, the rest are four parallel planes of equal distances. The places of the measurements on every surface were set according to the lines and areas illustrated in Figure 1. 2D measurements were carried out at two locations in each plane (as seen in Fig.1).

<table>
<thead>
<tr>
<th>$R_a$ [µm]</th>
<th>$v_c$ [m/min]</th>
<th>$R_z$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>4.86</td>
<td>4.88</td>
<td>4.58</td>
</tr>
<tr>
<td>2.24</td>
<td>2.76</td>
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</tr>
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<td>2.32</td>
<td>2.69</td>
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<tr>
<td>2.34</td>
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<td>2.81</td>
</tr>
<tr>
<td>1.79</td>
<td>2.67</td>
<td>2.82</td>
</tr>
</tbody>
</table>
Cutting experiments were performed at various cutting speeds. In the selected planes, the roughness profiles were recorded in addition to the roughness measurement.

Table 2 shows the values of the arithmetic mean roughness $R_a$ and average height of roughness profile $R_z$ of the 2D measurement results. The data presented here is the average of three measurements taken at two measuring points within each plane.

During the measurements, the roughness profile diagram (Fig. 2) as well as the 3D surface topography (Fig. 3) were recorded. Both figures refer to cutting speeds $v_c=100$ m/min and $v_c=500$ m/min.

In the profile curves (Fig. 2), the maximum height of the curves is in the symmetrical plane, and at higher cutting speeds the further away from the symmetrical plane, the lower the values become. In addition, the height of the curves decreases with increasing cutting speed in the beginning, but then later ($v_c=300$ to $500$ m/min) the phenomenon is not significant. Moreover, the diagrams show that higher cutting speed results in a much smoother surface, and the textures in the symmetry plane are quite regular. In the side planes fractures can be seen for
each period, resulting from the surface texture observed in the given plane, which is caused by the traces of the main and the minor cutting edge motion. These traces can also be seen on the corresponding surface topographies in Figure 3.

The values of $S_a$ and $S_z$ of the 3D measurement results are shown in Table 3. (3D roughness measurements were not performed for cutting speeds $v_c=200$ m/min and $v_c=400$ m/min in planes B and D, so the corresponding parts of the table were left blank.)

Table 3

<table>
<thead>
<tr>
<th>$S_a$ [µm]</th>
<th>$v_c$ [m/min]</th>
<th>$S_z$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
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<td>5.17</td>
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<td>3.46</td>
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<tr>
<td>2.55</td>
<td>3.38</td>
<td>2.29</td>
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<tr>
<td>2.61</td>
<td>2.82</td>
<td>2.86</td>
</tr>
<tr>
<td>2.57</td>
<td>2.98</td>
<td>1.74</td>
</tr>
<tr>
<td>2.08</td>
<td>2.56</td>
<td>3.02</td>
</tr>
</tbody>
</table>

Figure 3

3D topographies
It can be stated that at higher cutting speeds, the surface pattern is quite regular, and the imprint of the tool edge is clearly visible. On the other hand, profiles are distorted at lower speeds. In the symmetry plane the grooves that are perpendicular to the feed direction are visible. However, records made at different locations show the traces of movements of the cutting edge and the minor cutting edge, which are usually at different heights. This is probably due to the vibration of the tool and/or the workpiece or to failure to set the tool axis perfectly perpendicular to the workpiece.

EVALUATION AND DISCUSSION

For better overview and easier comparability, 2D and 3D roughness data are represented in diagrams.

The development of the values of all the 2D roughness parameters between planes is very similar (Figure 4). At low cutting speed ($v_c=100$ m/min) the roughness values are the highest, and when increasing the speed, the values of the parameters decrease. The decrease is significant in the range of $v_c=100$ to 300 m/min, and above that the difference is minor.

The assumption [3] that the roughness in the symmetry plane is the highest, is confirmed only from $v_c\geq200$ m/min. There is an exception at $v_c=400$ m/min, because here the change of the values of the planes C and D is reversed. However, if we ignore these small differences (0.04 µm in $R_a$ and 0.22 µm in $R_z$), then it can be said that the statement is confirmed within the range of $v_c=200$ to 500 m/min.

![Figure 4](image-url)

2D measured values for average roughness (a) and profile height (b) as a function of cutting speed
It was previously stated [3,4] that the roughness values decrease as the distance from the symmetry plane increase in both directions. Measurements confirm this at $v_c=200$ m/min and above.

At each cutting speed, the values are always greater on the entry side (plane A) than on the exit side (plane E). This can be explained by the fact that there is up-milling on the entry side until the symmetry line and then down-milling occurs until the cutting edge exits. However, the relationship between the results obtained in the intermediate planes (B, D) cannot be as clearly defined.

![Figure 5](image)

**Figure 5**

3D measured values for average roughness (a) and profile height (b) as a function of cutting speed

Figure 5 shows the development of the values of the 3D roughness parameters, $S_a$ and $S_z$. Basically, the same observations can as for 2D roughness apply, so only the differences are described below.

For each cutting speed, the relation between the measured values on the entry and exit sides (plane A and E) cannot be clearly defined. In contrast, the intermediate planes B and D show clearly that on the exit side, where there is down-milling, lower roughness values occur on the entry side, which is characterized by up-milling. This is proved at each cutting speed.

**SUMMARY**

In this article, the roughness of surfaces produced by symmetrical face milling was examined. During machining, only the cutting speed was changed. 2D and 3D measurement results measured in parallel planes were compared based on
roughness values, roughness profile curves and topographies. Our main findings are as follows.

The highest roughness can be measured in the symmetry plane only above \( v_c = 200 \) m/min.

By increasing the cutting speed, the roughness first decreased, but did not change significantly above \( v_c \geq 300 \) m/min. Figures 2 and 3 showed much smoother surfaces at higher speeds. However, the surface is distorted at low speeds since the effect of chip deformation is more significant in this case than is the effect of the edge geometry. An additional benefit is that the WFMT system has higher stiffness at higher rotational speeds. Therefore, cutting speeds above 300 m/min should be used to achieve good surface roughness.

The development of parameters of arithmetical mean roughness and roughness profile heights were similar in the 2D and the 3D cases.

In the examined range, it was always true that the roughness values on the entry side were higher than those on the exit side.

ACKNOWLEDGEMENTS

The authors greatly appreciate the support of the National Research, Development and Innovation Office – NKFIH (No. of Agreement: K 116876).

The described study was carried out as part of the EFOP-3.6.1-16-00011 “Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc aiming at intelligent specialization” project implemented in the framework of the program Széchenyi 2020.

Both grants are gratefully acknowledged.

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