Effects of the tool edge design on the roughness of face milled surfaces

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Abstract. Increasing the cutting speed and/or the feed rate is often chosen to increase the efficiency of the material removal. Of course, there are limits to the selection of specific values in both cases, such as, the rigidity of the machining system, the loadability and lifetime of the cutting edges, the prescribed roughness values of the surfaces, etc. When increasing the feedrate in face milling, the conditions of the chip removal change considerably, because at low feed values, the material forming effect of the side edge (i.e. the edge on the lateral surface of the tool) is the most determinative and the chip deforms perpendicular to it, while increasing the feed gradually moves the determinative part of the chip removal to the edge which lies perpendicular to the tool axis. Therefore, both of the two edges have a distinct role in chip removal due to both their position and geometry. The two edges are located on one cutting insert; therefore, their geometry needs to be examined individually and collectively in the search for the most suitable for effective chip removal. The study investigates how the different tool geometrical characteristics affect the roughness parameters of surfaces in normal and in high-feed face milling.

1. Introduction

In face milling, the extent of roughness values on the different points and surface elements of the milled surface differs due to the movement (trajectory) of the cutting edge. This roughness inhomogeneity characteristic of the surface means that the roughness values in planes measured in different directions are different [1]. In the path of the rotation axis of the tool, in the direction of feed, in relation to the symmetry line, theoretically, only those planes have the same roughness values which are at the same distance, and the greatest roughness of the milled surface is in the symmetry plane. In addition, the magnitude of roughness is influenced by the settings and conditions of the surface generation. These topics are undergoing extensive research, which is also very diverse in methods and testing purposes.

In the modelling introduced in [2], which is based on the geometric analysis of the trails left behind on the milled surface, particular attention has been paid to the consideration of tool set-up errors (axial and radial). The procedure used not only determines the theoretical roughness characteristics, but also generates two-dimensional theoretical roughness profiles. The effect of different technological
parameters such as speed, feed rate and depth of cut on the roughness, flatness and shape errors of machined surfaces was investigated experimentally in [3] when face milling of wrought cast steel (WCB) workpieces, using ANOVA to analyse the results. Kroczek et al. [4] investigated the surface texture (two- and three-dimensional surface roughness) in the turning of austenitic stainless steel by coated carbide tools. The effects of the runout errors of milling cutter inserts on surface topography, surface location error and stability were investigated in [5]. The authors concluded that runouts in milling remain an important issue in milling, because they significantly affect the machining process and can lead to premature failure of the cutting edges. In the surface roughness estimation method described in [6], not only the cutting parameters and the axial and radial setting errors were taken into account, but also the dynamic phenomena resulting from the cutting tool errors in end milling. Miko et al. [7] investigated the effects of the feed per tooth \( f_z \), depth of cut \( a_p \), and width of cut \( a_t \) on different surface roughness parameters in ball-end milling. The measured surface roughness was compared with the analytically calculated theoretical roughness and an estimation method was presented. Ref. [8] also analyses the flatness deviations in addition to 2D and 3D roughness parameters in the milling of aluminium alloys. Miko and Farkas [9] also investigated the flatness as well as 2D and 3D surface roughness parameters in face milling and face turning with different parameters. The effect of the coolant and lubricant fluid, technological data (spindle speed, feed rate and depth of cut) and the milling method (down- and up-milling) on residual stresses, cutting forces and roughness of the machined surface was investigated in [10] by the RSM method. Theoretical description of the surface pattern in face milling was studied in [11], where both mathematical calculations (MATLAB) and CAD simulations were used to study the effects of different workpiece and tool designs and positions, the feed rate and the angle of the milling axis to the surface on the quality (roughness) of the machined surface. A so-called gray-fuzzy modelling procedure was used in [12] to determine the optimal process parameters for end milling of an aluminium alloy. The examined process parameters were the arithmetical average roughness (Ra) of the root mean square roughness (Rq) and the material removal rate (MRR). A hybrid approach for the modelling of surface roughness in slot milling is described in [13], where the analytical calculation of the specific energy consumption (SCEC) and the empirical relationship between SCEC and surface roughness were combined in a model. It was found that there is a direct relation between the specific energy consumption and the roughness parameter Ra, and a new model was suggested to estimate the expected roughness. Ref. [14] focuses on the determination of the optimal cutting parameters that result in minimal roughness characteristics in plain peripheral down milling, where theoretical parameters were estimated using a model using an artificial neural network (ANN). RSM and ANOVA methods were used to determine input and output parameters. Experiments were conducted for the training and verification of the model by machining Ti-6Al-4V ELI titanium alloys. A formula for estimating surface roughness was reported in z-level milling of steep surfaces in [15] when using a 2.5D milling strategy. The technological parameters considered in the estimation are the depth of cut \( (a_p) \), feed per tooth \( (f_z) \), and the milling strategy (climb or zig-zag milling). The analytical modelling of theoretical roughness was described for face milling in [16], where the effect of technological parameters (feed rate, cutting speed) was investigated on the roughness of the machined surface in case of two different cutting insert geometries. A new procedure was described in [17], where the determination of the theoretical 2D and 3D roughness characteristics is based on the CAD modelling of the machined surface. The article describes the application of the method in face milling. The great advantage of the process is that it can be used to determine the theoretical roughness of practically any surface machined by a tool having defined edge geometry. The efficiency of the milling can be increased by increasing the cutting speed and feedrate, but changing their value also modifies the surface finish. The effect of the technological parameters on the three-dimensional roughness parameters of the machined surface was investigated in [18] for high speed face milling. It was found that the feedrate has the greatest impact on the surface topography.

In this paper, the effect of the feed on the roughness of the milled surface was examined. More specifically, the study analyses how the values of roughness parameters vary in the rotation axis (symmetry plane) in symmetrical face milling depending on the edge angles and chip ratios \((a_p/f_z)\).
2. Characteristics of the tool edge geometry in face milling

The goal of the investigation was to determine the effect of different \( \frac{a_p}{f_z} \) (b/h) ratios on the surface roughness when face milling with different insert geometries and axial rake angles. It is important to examine the ratio of the depth of cut and feed because by increasing the feed value, the shape of the chip changes, and the role of the cutting edges in chip removal also changes. When the \( \frac{a_p}{f_z} \) ratio is much greater than one (\( \frac{a_p}{f_z} \gg 1 \)), the chip deformation is predominantly perpendicular to the edge on the outer surface, while in case of \( \frac{a_p}{f_z} \ll 1 \) is perpendicular to the face edge. This change takes place not only for a tool with \( \kappa_r = 90^\circ \) (Fig. 1), but also with \( \kappa_r = 45^\circ \) (Fig. 2).

![Figure 1](image1.png)  
**Figure 1** Chip formation for different \( \frac{a_p}{f_z} \) ratios when \( \kappa_r = 90^\circ \)

![Figure 2](image2.png)  
**Figure 2** Chip formation for different \( \frac{a_p}{f_z} \) ratios when \( \kappa_r = 45^\circ \)

In face milling, in addition to the placement angles, the chip removal ability of the insert is predominantly determined by the rake and clearance angle as well as the inclination angle, similar to other machining operations such as turning. The markings used in Figure 1 show the change in the role of working edges on the rake and peripheral surfaces of the insert. Depending on the ratio of the depth of cut (\( a_p \)) to the feed per tooth (\( f_z \)), the working edges and angles also change (Table 1). If this ratio is greater than one, the chip deformation occurs along the peripheral edge of the tool; when it is less than one, it takes place along its face edge.
It has been established by analyzing the work of the cutting-edge in face milling that due to the changing of cutting conditions (technological data) not only the distributed load of the cutting edge varies, but the ratio of the load interchanges as well between the edges that are parallel to and perpendicular to the lateral surface of the tool [19]. This is illustrated in Figure 3. This means that the major and minor cutting edges and thus the inclination and rake angles are also interchanged. Because of the changed conditions, the method of generating the machined surface also changes. This justifies the examination of the effects of altered (active) angles on both the chip removal and on the machined surface topography.

3. Experimental conditions

3.1. Cutting tool

The applied milling tool is a unique tool design was developed at Otto von Guericke University in Magdeburg [17]. The essence of the tool design is that the cutting inserts are fixed by means of fixing cylindrical shafts in the tool body, and the insert seats in these shafts are individually formed, adapted to the desired insert geometries. This construction allows the usage of a variety of edge geometries and different cutting edge orientation angles in one milling head. For example, for examining different radial and axial rake angles, it is enough to produce the fixing shafts for each setting rather than to modify the whole milling head.

Two different milling insert geometries were used during the experiments:

- Garant XOEW 120508 PDER-W insert (“Garant”). This insert has a major cutting edge angle of 90°. The other characteristics are summarized in Table 3.
- Sandvik Coromant R24512 T3 EW K15W (“Wiper”). This insert has a major cutting edge angle of 45°. The other characteristics are summarized in Table 4.
### Table 3. Characteristics of the “Wiper” insert

| a<sub>e</sub> [mm] | κ<sub>r</sub> [°] | r<sub>c</sub> [mm] | r<sub>p</sub> [mm] | D [mm] | v<sub>c</sub> [m/min] | γ<sub>p</sub> [°] | γ<sub>f</sub> [°] | α [°] |
|-----------------|-------------|-------------|-------------|--------|----------------|-------------|-------------|------|
| 70*             | 45          | 1.5         | 0.015       | 103    | 200            | 0           | 0           | 30   |

3.2. Machine tool
A Heller FT 2000 five-axis machining center was used in the milling tests.

3.3. Workpiece
The milling samples were designed as 70×70×170 mm<sup>3</sup> blocks. The workpiece material was C45 medium carbon steel (WNr 1.0503, Ck45), which is widely used for general mechanical engineering and for automotive components.

3.4. Measurement of surface roughness
2D and 3D surface roughness measurements were performed using an AltiSurf 520 surface roughness tester device using a CL2 confocal chromatic distance measuring sensor and an MG140 magnifier. The measurement head which has been assembled in this way has an approximate axial precision of 0.01 μm. The 2D measurements were measured and evaluated in accordance with ISO 4287: 1997 and ISO 4288-1996 standards, while for 3D surfaces the recommendations of ISO standard 25178 were followed.

3.5. Evaluation method
To evaluate the measured results of the 2D and 3D surface roughness parameters, we use the Full Factorial Experiment Design method. According to the literature, experimental designs can be labelled full factorial when all experiments are performed at each level combination of all factors to be tested. We perform the measurements on two levels, although only linear effects can be considered at this time. Within the examined range of factors, the results are shown visually and the empirical (experimental) formulas describing the correspondence between the examined parameter and the factors are determined. When applying the method, from among factors shown in “Experimental conditions” the radial inclination angle (γ<sub>f</sub>) was chosen to be γ<sub>f</sub> = 0 and is kept constant, while the values of the additional three factors (κ<sub>r</sub>, a<sub>p</sub>/f<sub>z</sub>, and γ<sub>p</sub>) are determined on two different levels (bottom and top). Table 4 contains the data for the experiments required for the factorial analysis.

### Table 4. Experiments necessary for the factorial analysis

| No. | κ<sub>r</sub> [°] | a<sub>p</sub>/f<sub>z</sub> | γ<sub>f</sub> [°] | γ<sub>p</sub> [°] |
|-----|--------|----------------|--------------|----------|
| 1   | 45     | 0.1            | 0            | 0        |
| 2   | 90     | 0.1            | 0            | 0        |
| 3   | 45     | 10             | 0            | 0        |
| 4   | 90     | 10             | 0            | 0        |
| 5   | 45     | 0.1            | 0            | 12       |
| 6   | 90     | 0.1            | 0            | 12       |
| 7   | 45     | 10             | 0            | 12       |
| 8   | 90     | 10             | 0            | 12       |

4. Experimental results
After completing the planned experiments, the results shown in Figure 4 were obtained. The figure shows the experimental settings and the 2D and 3D roughness profiles.
Run No. 1: $a_p/f_z = 0.1; \kappa_r = 45^\circ; \gamma_p = 0^\circ$

Run No. 2: $a_p/f_z = 0.1; \kappa_r = 90^\circ; \gamma_p = 0^\circ$

Run No. 3: $a_p/f_z = 10; \kappa_r = 45^\circ; \gamma_p = 0^\circ$

Run No. 4: $a_p/f_z = 10; \kappa_r = 90^\circ; \gamma_p = 0^\circ$

Run No. 5: $a_p/f_z = 0.1; \kappa_r = 45^\circ; \gamma_p = 12^\circ$

Run No. 6: $a_p/f_z = 0.1; \kappa_r = 90^\circ; \gamma_p = 12^\circ$

Figure 4. Measured 2D profiles and 3D surfaces
The roughness data measured on surfaces of the specimens are shown in Table 5.

| No. | κᵣ [°] | a₀/fₓ [°] | γᵢ [°] | Ra [µm] | Rz [µm] | Rq [µm] | Sa [µm] | Sz [µm] | Sq [µm] |
|-----|--------|-----------|--------|---------|---------|---------|---------|---------|---------|
| 1   | 45     | 0.1       | 0      | 1.520   | 14.2    | 1.93    | 4.144   | 14.7    | 1.89    |
| 2   | 90     | 0.1       | 0      | 4.010   | 19.2    | 4.69    | 4.150   | 20.3    | 4.85    |
| 3   | 45     | 10        | 0      | 1.380   | 11.2    | 1.71    | 1.350   | 12.4    | 1.71    |
| 4   | 90     | 10        | 0      | 0.798   | 7.18    | 1.04    | 0.813   | 8.97    | 1.07    |
| 5   | 45     | 0.1       | 12     | 1.170   | 9.79    | 1.46    | 0.848   | 6.99    | 1.04    |
| 6   | 90     | 0.1       | 12     | 3.540   | 19.0    | 4.07    | 3.580   | 18.2    | 4.15    |
| 7   | 45     | 10        | 12     | 1.310   | 9.73    | 1.63    | 1.260   | 10.9    | 1.62    |
| 8   | 90     | 10        | 12     | 1.310   | 11.0    | 1.68    | 1.250   | 10.5    | 1.58    |

5. Evaluation and discussion

Analyzing the profile graphs, the following statements can be made: In the first two figures (Runs 1 and 2) it can be seen that at κᵣ = 90° the roughness indexes are lower and a more uniform profile was obtained than for κᵣ = 45°. If the cutting ratio changes (Runs 3 and 4), the effect of κᵣ also changes.

The response function was approximated by a 3-parameter first-degree (linear) polynomial. The individual and joint effects of the change of the three parameters were investigated to determine the polynomials of the response function of 2D roughness parameters (Ra), (Rz) and (Rq) and 3D roughness parameters (Sa), (Sz) and (Sq). All the lower and upper levels of the 3 factors resulted in a total of n = 2³ = 8 total experiments. The coefficients of the first polynomial of the three variables were determined by the coefficients of the roughness measurements of the 8 different settings, so that the coefficients of 8-8 of the linear three-factor equation for the approximation of the three 2D and three 3D roughness parameters were determined. For the evaluation of the factorial experiment, the response function (y) was approximated with the linear polynomial for the surface roughness parameters of 2D as (Ra), (Rz) and (Rq) and of the 3D as (Sa), (S) and (Sq).

\[
y = k₀ + k₁ \cdot κᵣ + k₂ \cdot a₀ \cdot fₓ + k₃ \cdot γᵢ + k₁₂ \cdot κᵣ \cdot a₀ \cdot fₓ + k₁₃ \cdot κᵣ \cdot γᵢ + k₂₃ \cdot a₀ \cdot fₓ \cdot γᵢ + k₁₂₃ \cdot κᵣ \cdot a₀ \cdot fₓ \cdot γᵢ
\]

(1)
The results of the measured roughness values shown in Table 1 were processed by the factorial experimental design method to determine the response functions, the constants of which are given in Table 6.

### Table 6. The constants of the response function for every dependent variables

|    | Ra    | Rz    | Rq    | Sa    | Sz    | Sq    |
|----|-------|-------|-------|-------|-------|-------|
| k0 | -0.9996 | 9.1392 | -0.8624 | -1.3019 | 9.032 | -1.1045 |
| k1 | 0.056 | 0.113 | 0.062 | 0.061 | 0.126 | 0.067 |
| k2 | 0.296 | 0.296 | 0.324 | 0.319 | 0.68 | 0.345 |
| k3 | -0.019 | 0.608 | -0.026 | -0.051 | 1.117 | -0.084 |
| k12 | -6.896 \times 10^{-3} | -0.02 | -7.699 \times 10^{-3} | -7.288 \times 10^{-3} | -0.02 | -8.081 \times 10^{-3} |
| k13 | -2.354 \times 10^{-4} | 7.773 \times 10^{-3} | -2.941 \times 10^{-4} | 3.129 \times 10^{-5} | 0.01 | 2.694 \times 10^{-4} |
| k23 | -3.552 \times 10^{-3} | 0.016 | -4.04 \times 10^{-3} | -2.525 \times 10^{-5} | 0.074 | 2.609 \times 10^{-3} |
| k123 | 1.313 \times 10^{-4} | 2.02 \times 10^{-4} | 1.627 \times 10^{-4} | 9.446 \times 10^{-5} | 4.826 \times 10^{-4} | 8.418 \times 10^{-5} |

The roughness values calculated by the equations of the response function are shown in axonometric representation in Fig. 5. To evaluate the effect of the change of the edge geometry, to make the evaluation simpler and to make the representation more apparent, we showed the measured roughness values in the form of three-dimensional response surfaces as the function of \( \kappa_z \) and \( \alpha_p/\ell_z \) with constant values of \( \gamma_p \). To make the evaluation more representative, we have depicted the surfaces of \( \gamma_p = 0^\circ \) and \( \gamma_p = 12^\circ \) in one diagram (Fig. 5).

After studying Fig. 5, it can be stated that both the 2D and 3D drawings are similar for Ra and Sa; Rz and Sz; as well as for Rq and Sq. In the 2D case, the \( \kappa_z = 90^\circ \), \( \alpha_p/\ell_z = 10 \) and \( \gamma_p = 0^\circ \) factor levels provide the lowest roughness values for all three parameters (Ra, Rz and Rq). For 3D roughness parameters, the situation is not so homogeneous. For Sa, the set values (\( \kappa_z = 90^\circ \), \( \alpha_p/\ell_z = 10 \) and \( \gamma_p = 0^\circ \)) gave the lowest roughness value (Sa = 0.813 \( \mu m \)). However, for the roughness parameters Sz and Sq, the minimum roughness values were obtained when setting the values \( \kappa_z = 45^\circ \), \( \alpha_p/\ell_z = 0.1 \) and \( \gamma_p = 12^\circ \).

When analyzing the two-dimensional roughness, it can be stated that the \( \alpha_p/\ell_z \) parameter has the maximum effect on the roughness parameters. For Ra its value reduces from Ra = 4.01 \( \mu m \) to Ra = 0.798 \( \mu m \), if the \( \kappa_z = 90^\circ \) and \( \gamma_p = 0^\circ \) are left unchanged, the \( \alpha_p/\ell_z \) is increased to \( \alpha_p/\ell_z = 10 \). So, the improvement rate is 80%.

In this technology and geometric parameter setting, Rz is reduced from Rz = 19.2 \( \mu m \) to Rz = 7.18 \( \mu m \) (63% improvement), while for Rq these two characteristic values are Rq = 4.69 \( \mu m \) and Rq = 1.04 \( \mu m \) (78% improvement). In case of Sa the situation is similar: with the increase of \( \alpha_p/\ell_z = 0.1 \) to \( \alpha_p/\ell_z = 10 \) the Sa is reduced from Sa = 4.15 \( \mu m \) to Sa = 0.813 \( \mu m \), which is also a 80% reduction. In case of Sz, the change in the angle \( \kappa_z \) has the greatest effect on roughness. If the values \( \alpha_p/\ell_z = 0.1 \) and \( \gamma_p = 12^\circ \) are left unchanged and only the side cutting edge angle is reduced from \( \kappa_z = 90^\circ \) to \( \kappa_z = 45^\circ \), the roughness value of Sz will decrease from Sz = 18.2 \( \mu m \) to Sz = 6.99 \( \mu m \), i.e. the improvement rate is 62%. By a similar adjustment, Sq decreases from Sq = 4.15 \( \mu m \) to Sq = 1.04 \( \mu m \) with a 75% improvement.

### 6. Summary

In face milling, the edges of the inserts in the milling head - by altering the \( \alpha_p/\ell_z \) ratio - affect the chip removal differently, resulting in the roughness of the milled surface. If the deviation of the \( \alpha_p/\ell_z \) ratio is significantly different from the value of 1 in any direction, the characteristics of the chip deformation also change, i.e. the deformation is performed either by the peripheral or the face edge. As a result, the loads on the edges of the inserts, the force components, the magnitude and direction of the thermal effects are changed, thus the roughness of the milled surface also changes, and consequently the position of the edges of the insert are also of decisive importance.
Figure 5. Relationship between surface roughness parameters and factors. In case of a) 2D roughness parameters; b) 2D roughness parameters
Overall, it was found that the roughness can be minimized by selecting the κr value of 90°, the higher a/p/fz with γr = 0° and γp = 0°. At the same time, in the case of κr = 45°, the lowest roughness value can be observed for the lower a/p/fz ratio and for γp = 12°, but its value is slightly larger than the previous value. Favorable surface roughness can be achieved for both 45° and 90° κr when a/p/fz = 10 and γp = 12°.

In our further research, we would like to frame our research task in order to identify how the required roughness requirements for the production can be provided at higher feed rates and with which variations of the different cutting edge angles.

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