Experimental research of tool axis inclination angle influence upon surface roughness in ball-nose end milling of polyetheretherketones (Tecapeek natural)-Part I

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Abstract. In order to find solutions for different medical applications like implants and reconstructions in clinical dentistry, orthopaedic or spinal implants, the polyetheretherketones have achieved a remarkable application because of their properties. The polyetherketone materials combine excellent wear resistance with very good mechanical properties, even under thermal load. Because of these qualities it is used also in different applications in automotive, aerospace and food industry. For each application, no matter if the process to obtain different shape is extrusion, injection moulding or machining by turning or milling, the surface roughness value is critical. For pieces with complex surfaces some finishing operations are necessary. The ball nose end milling process is recommended in this case because of its versatility. In ball nose end milling process the influence of tool axis inclination angle has a big influence upon surface roughness value. In this way theoretical studies are required in order to establish the influence of this parameter upon effective cutting speed. Also, experimental research method was needed in order to establish the quality of surface in terms of surface roughness. The experimental research results establish the most favourable values of inclination angle for Tecapeek-natural material in comparison with C45 material.

1. Introduction
Recently, the interest for polyetheretherketone (Peek) material has been growing in different areas like arthroplasty. It can be used for articulations in the spine [1,2] but also in total knee implants. With good results it can replace the Co-Cr-Mo material in knee arthroplasty [3]. Tecapeek natural, one of particularly form is a thermoplastic polymer recommended for its resistance to fatigue strain. Its characteristics include also high melting and glass transition temperature [3]. The mechanical characteristics can be compared to titanium [3,4]. Clinically, it’s used in cranial implants and orthopaedic applications because it is radiologically transparent (figure 1). Research studies demonstrate lower risk for toxicity, mutagenicity, teratogenicity and carcinogenicity [1]. Theoretically, the complications are always induced by the wear debris in area of contact between different surfaces where pronounced wear of surfaces is generated that can lead to osteolysis around the prosthesis and eventually the loss of the prosthesis.

The hardness and smoothness are properties of surfaces that can influence wear resistance. Another parameter that influences wear value is resistance to fatigue and fracture. A higher value of surface hardness leads to a better value for the wear [3,5,6].
The use of the milling process with ball end mill of polyetheretherketone in various industry branches (figure 1) generates the need for this process to be optimized. For this reason, it is necessary to identify the factors that can influence the outputs of process and establish the values which guarantees the favourable results in terms of quality and quantity. In the milling process the successful optimization is reflected, in most cases, by the value of surface roughness obtained after surface generation [7].

![Applications of polyetheretherketone material](image)

**Figure 1.** Applications of polyetheretherketone material [2].

In flat end milling of polyetheretherketone the results indicate that the mechanisms of the surface finish obtained from machining of polymeric based composites are different from those obtained from machining of the metals [8]. By reducing the feed rate it was observed that the surface roughness values will be reduced. From another point of view, if the depth of cut is increased the surface roughness values will be reduced. The optimal combination between parameters is necessary to ensure that the machining performance can be achieved [8].

In order to determine the optimal conditions in machining of industrial plastics by chip remove methods, some researchers conclude that when processing in cryogenic conditions the behaviour of industrial plastics is different from processing in the normal temperature [9].

In their research, Diciuc and Lobonțiu [10] presented a review of the main modelling types of the cutting process using ball nose end mills, underlining the specificity, the advantages and disadvantages for each type.

2. Analysis of tool axis inclination

The ball nose end milling process, which uses a ball nose cutter, is very complex and generates a pronounced area variation of the cross section in the uncut chip [11]. In practice of ball nose end milling, the tool axis inclination has a big influence upon surface roughness of the work-piece [12]. In finishing operations of a curved surface, the ball nose end milling process has great adaptability. A particular property of ball nose end milling is that the surface quality can be improved by the selection of a suitable value for tool axis orientation reported to the orientation of the machined surface [12].

For milling of C45 material, Pașca concluded that the minimum roughness values are reached when the specimens are machined with the tool axis inclination of 15° and in most cases for a 45° inclination of the tool axis a pronounced increase of roughness occurs [13].

After establishing the code A for tool axis inclination in direction of feed, and B for directions of steps, the researcher concludes that tilt on B direction is most favourable in comparison to axis A direction. For values of tilting angle greater than 60 degrees a higher spindle speed is recommended for better surface quality [13].

In ball nose end milling of Ti-6Al-4V, the best surface finish was obtained when the inclination angle was 25° that also lead to reducing of compressive stress [14].

The tool orientation has a great influence upon the surface roughness, surface morphology and the residual stress, but not so big on the micro-hardness [12]. The better results for surface integrity can be obtained when the tool axis rotation values are 0° and 90°, and the inclination angle is equal with 30° or 60° [12,14].
In order to obtain the best value for surface roughness, by optimisation of milling process it is necessary to choose the right value of inclination angle between tool axis and normal surface. The most recommended value for tool axis inclination is $15^\circ$ [15].

In order to achieve specific roughness, in ball nose end milling, the setting of individual optimal parameters does not suffice and there is a need for an analysis with several parameters, by taking into account the effective cutting speed.

The geometrical parameters that were used on the experiments are listed in table 1.

Taking into account the results of analysis from different studies, we used in our experiments the tilting angle (figure 2), around Y axis in counterclockwise with values indexed by $15^\circ$. The values of effective cutting speed for each angle are presented in table 2.

![Figure 2. Tool axis inclination.](image1)

![Figure 3. Five axis milling machine MU500-VA.](image2)

### Table 1. Geometrical and cutting parameters used.

| No. | Geometric elements          | Units of measurement | Value |
|-----|----------------------------|----------------------|-------|
| 1   | Diameter of ball end mill  | [mm]                 | 10    |
| 2   | Cutting depth              | [mm]                 | 0.15  |
| 3   | Axial depth                | [mm]                 | 0.15  |
| 4   | Feed per tooth             | [mm]                 | 0.15  |

### Table 2. Variation of effective cutting speed.

| No. | Spindle speed [rpm] | Tilting angle B positive [degrees] | Variation of effective cutting speed [m/min] |
|-----|---------------------|----------------------------------|---------------------------------------------|
|     |                     | 15  | 30  | 45  | 60  | 75  | 90  |                                |
| 1   | 7500                | 114.22 | 163.67 | 202.05 | 226.31 | 235.26 | 235.55 |

### Table 3. Work-piece material properties.

| No. | Properties                    | Value       | Unit |
|-----|--------------------------------|-------------|------|
| 1   | Polyetheretherketones          | Tecapeek-natural |     |
| 2   | Tensile strength at yield      | 116         | Mpa  |
| 3   | Ball indentation hardness      | 253         | Mpa  |
| 4   | Modulus of elasticity          | 4200        | Mpa  |
| 5   | Density                        | 1.31        | g/cm$^3$ |
| 6   | Glass transition temperature   | 150         | °C   |
| 7   | Compression modulus            | 3400        | Mpa  |
3. Experimental work and conditions
The best results for surface roughness, in ball end milling process, can be obtained only by practicing the optimal combinations of different values for tilt angle and of spindle speed.

This combination is needed in order to establish the conditions of process deployment which ensure the best stability in ball nose end milling. The value of effective cutting speed depends on inclination angle in different directions and also on spindle speed value.

In order to establish the optimal value for effective cutting speed, in terms of surface quality, it is necessary to identify that individual values of tilt angle and spindle speed.

Heating in ball nose end milling process must be reduced in order to maintain a good performance. It was used coolant to reduce the heating.

3.1. Experimental setup
The type of ball nose end mill chosen for these applications was executed by Iscar LTD. with code MM TS-A-L080-C10-T06 for tool holder, and MM EBA100B07-2T06 IC08 for inserts. In order to have an equipment that matched in terms of stability of process, respecting all conditions of precision, we used Okuma MU-500VA vertical center machine (figure 3) with the support of technicians from S.C. RAMIRA S.A.

3.2. Work-piece material
Motivated by the increased use of Tecapeek-natural material in different areas, we conclude that it is important to use this material for the work-piece. The Polyetheretherketones (Tecapeek-natural) thermoplastic polymer sheet (195 mm by 95 mm) with thickness of 25 mm, that we used was purchased from the manufacturer Ensinger Gmbh. Some of the mechanical and physical properties are described in table 3. The shape of work-piece used in experiments has 24 surfaces machined with ball nose end mill. Each of them was machined at different values of tilt angle and effective cutting speed (figure 2).

3.3. Surface roughness measurements
In order to have a better image of surface morphology we made the measurements in terms of arithmetic mean deviation of the assessed profile \( R_a \) but also in terms of average maximum height of the profile \( R_z \).

The device used for surface roughness measurements was TR200 equipment using a Gaussian filter. The measurements of surface roughness were made in feed direction and perpendicular to feed direction, in order to establish a complete topography and characteristics of the machined surface.

3.4. Experimental conditions.
In all experiments it was used the milling in feed direction. The values of different parameters practiced are indicated in table 1, table 2 and table 3.

3.5. Experimental results.
After surface roughness measurements it was obtained the values centralized in table 4 and table 5.

In according with experimental results, the best surface roughness \( R_a \) and \( R_z \), for measurements made in feed direction, was identified for a tilt angle of 15°. The results for measurements made perpendicular to feed direction reveals that the smallest values for surface roughness in terms of \( R_a \) are obtained by practicing tool tilt angle at 30°, and 60° in terms of \( R_z \) surface roughness.

| No | Spindle speed [rpm] | Tilt angle value [degrees] | Surface roughness [\( R_a \) \( R_z \)] |
|----|------------------|----------------|----------------|
|    | 15   | 30  | 45  | 60  | 75  | 90  |
|    | 7500 | 0.34| 1.88| 0.407| 2.483| 0.43| 1.952| 0.408| 2.236| 0.47| 2.276| 0.456| 2.819|

Table 4. Experimental data for measurements made in feed direction.
Table 5. Experimental data for measurements made perpendicular to feed direction.

| No | Spindle speed [rpm] | Tilt angle value [degrees] | Surface roughness [µm] |
|----|---------------------|---------------------------|-----------------------|
|    | 15                  | 30                        | 45                    | 60 | 75 | 90 |
|    | Ra      | Rz      | Ra      | Rz      | Ra      | Rz      | Ra      | Rz      | Ra      | Rz      |
| 1  | 7500    | 0.574   | 2.992   | 0.519   | 3.363   | 0.594   | 2.807   | 0.525   | 2.623   | 0.573   | 3.267   | 0.603   | 3.376   |

4. Analysis of surface roughness variation

Tilting of tool axis in B positive direction identified in paper [7], when machining material Tecapeek-natural, lead to experimental data presented in figure 4 and figure 5.

In analysis of surface roughness parameters by point of $R_a$ (figure 4), in feed direction, it can be noted that the most favourable values of tilt angle are 30° and 60°. Not the same variation was obtained for the measurements made perpendicular to feed direction where the smallest value of surface roughness was obtained in interval (15°, 30°).

Evaluation of surface roughness in terms of $R_z$ parameters, shows that in interval of (45°, 60°) good results can be obtained. Also, around 15° value of tilting angle the results are favourable in terms of surface roughness.

![Figure 4](image1)

![Figure 5](image2)

![Figure 6](image3)

![Figure 7](image4)

When machining Tecapeek-natural the surface roughness $R_a$ values varies between 0.34 µm to 0.47 µm (138%) for measurements made in feed direction, and between 0.519 µm to 0.603 µm (116%) for measurements made perpendicular to feed direction. In terms of roughness $R_z$ was obtained a variation between 1.88 µm to 2.819 µm (150%) for measurements made in feed direction, and 2.623 µm to 3.376 µm (128%) for measurements made perpendicular to feed direction.
The researcher Pasca investigated in his Ph.D. dissertation the most favorable intervals for tilting angle in ball nose end milling of C45 material (figure 6, 7) [13].

In ball nose end milling of C45 material the surface roughness values are situated between 0.384 μm and 0.686 μm (178%) for measurements made in feed direction, and between 0.784 μm and 1.837 μm (234%) for measurements made perpendicular to feed direction. In terms of roughness Rz the obtained variations were between 2.043 μm and 3.847 μm (188%) for measurements made in feed direction, and 5.960 μm to 10.210 μm (171%) for measurements made perpendicular to feed direction.

The comparison between variation of surface roughness, in ball nose end milling, of Tekapeek-natural, investigated in present experimental research and C45 material investigated by Pasca [13] show that the favourable values of inclination angle are situated almost in the same intervals (figure 8 and figure 9).

5. Conclusions
The surface roughness in ball nose end milling of polyetheretherketone (Tecapeek-natural), upon tool axis inclination angle influence, varies similar to surface roughness in ball nose end milling of C45 material. Choosing the right value of tool axis inclination angle in ball nose end milling of Tecapeek-natural the surface roughness Rz can be improved by 38% for measurements made in feed direction and by 16% for measurements made perpendicular to feed direction. In terms of Rz surface roughness can be improved by 50% for measurements made in feed direction and by 28% for measurements made perpendicular to feed direction. We conclude also that influence of tool axis inclination angle in milling of Tecapeek-natural is less than in milling of C45 material. The surface roughness in ball nose end milling can be significantly improved by choosing the right combinations of different parameters not only an optimal value for one of them.

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