Comparison of the roughness of concave cylindrical surfaces machined with spherical milling cutters and toroidal milling cutters

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Abstract. The paper aims to process the concave cylindrical surfaces. This proposes a comparison between the processing of concave cylindrical surfaces with toroidal milling and the processing of concave cylindrical surfaces with spherical milling. The variable process parameters are the cutting speed, the feed per tooth and the inclination angle between the tool axis and the normal to surface. After processing, the surface with the best roughness is tracked according to the regimes and the tool used. A number of 27 concave cylindrical surfaces machined with toroidal milling cutter and 27 concave cylindrical surfaces machined with spherical head milling are machined. The aim is to measure the arithmetic roughness Rₐ and the total roughness Rₜ, these being measured parallel and perpendicular to the direction of advance. In order to confirm the correctness of the measured values, microscopic images with the best surfaces will be captured.

1. Introduction
An important factor that influences the quality of the surface and the evolution of the roughness of the machined surface is the direction of inclination of the tool axis. In this case, it is the value of the angle at which the cutting edge is inclined compared to the normal surface. This factor requires the establishment of the optimal values of the angle of inclination of the tool axis, a value after which the roughness is the lowest. The values of the angle of inclination of the tool axis where high surface roughness’s are determined are also avoided.

Han [1] investigated the influence of the tool tilt angle on the surface integrity, in particular the surface roughness and the residual effort in fast steel milling by milling experiments, including 8 cases of free-form surface milling. Finally, the optimum tilt angles of the tools, including the feed angle, the tilt angle and the milling method, were obtained for 5-axis milling with the ball mill.

The researcher Tonshoff, in the paper [2], indicates that the best results are obtained by inclining the semi-finished product by 15°. In this case the best results being from the point of view of the surface roughness, of the tool wear and of the productivity. Other works such as [3] indicate that the optimum value of the tilt angle is in the range 15°-20°, while in the work [4] the optimal value indicated is 20°.

As a result of these analyses, it is necessary to investigate this process in order to identify both the optimum value of the inclination angle and the optimum inclination direction. Researches such as those of [5 - 9] analyse particular cases in order to identify the optimum value of the inclination angle.
2. The experimental part
This paper highlights the practical experiments performed on the concave cylindrical surface, 27 made with the toroidal milling presented by table 1 and 27 concave cylindrical surfaces made with the spherical milling as presented in table 2.

The organization has a decisive role in carrying out the experiments, so we noted with CCV-TR the concave cylindrical surfaces processed with toroidal milling cutter and with CCV-SF the concave cylindrical surfaces processed with spherical milling cutter.

The concave cylindrical surface has a cylindrical height along the plate with a diameter of Ø85mm and a maximum height of 5mm.

Referring to the cutting regimes, the three variables are presented in the tables, and constant throughout the experimentation is the cutting depth, which is 0.5mm ($a_p=0.5\text{mm}$) and the radial depth, having the value of 0.3mm ($a_e=0.3\text{mm}$). The experiments were performed in the presence of the coolant, the way of holding the specimens being in jaw vice.

It is necessary to emphasize the fact that during the whole processing of surfaces with both toroidal and spherical milling, the tool axis constantly maintains its inclination angle throughout the surface.

**Table 1.** Carrying out experiments on the processing of concave cylindrical surfaces with toroidal milling.

| No. | Cutting speed [m/min] | Tilt angle [°] | Advance on tooth [mm/tooth] | Surface CCV-TR |
|-----|-----------------------|----------------|-------------------------------|----------------|
| 1   | 80                    | 15°            | 0.11                          | CCV-TR-1       |
| 2   | 80                    | 15°            | 0.15                          | CCV-TR-2       |
| 3   | 80                    | 15°            | 0.19                          | CCV-TR-3       |
| 4   | 80                    | 35°            | 0.11                          | CCV-TR-4       |
| 5   | 80                    | 35°            | 0.15                          | CCV-TR-5       |
| 6   | 80                    | 35°            | 0.19                          | CCV-TR-6       |
| 7   | 80                    | 55°            | 0.11                          | CCV-TR-7       |
| 8   | 80                    | 55°            | 0.15                          | CCV-TR-8       |
| 9   | 80                    | 55°            | 0.19                          | CCV-TR-9       |
| 10  | 170                   | 15°            | 0.11                          | CCV-TR-10      |
| 11  | 170                   | 15°            | 0.15                          | CCV-TR-11      |
| 12  | 170                   | 15°            | 0.19                          | CCV-TR-12      |
| 13  | 170                   | 35°            | 0.11                          | CCV-TR-13      |
| 14  | 170                   | 35°            | 0.15                          | CCV-TR-14      |
| 15  | 170                   | 35°            | 0.19                          | CCV-TR-15      |
| 16  | 170                   | 55°            | 0.11                          | CCV-TR-16      |
| 17  | 170                   | 55°            | 0.15                          | CCV-TR-17      |
| 18  | 170                   | 55°            | 0.19                          | CCV-TR-18      |
| 19  | 210                   | 15°            | 0.11                          | CCV-TR-19      |
| 20  | 210                   | 15°            | 0.15                          | CCV-TR-20      |
| 21  | 210                   | 15°            | 0.19                          | CCV-TR-21      |
| 22  | 210                   | 35°            | 0.11                          | CCV-TR-22      |
| 23  | 210                   | 35°            | 0.15                          | CCV-TR-23      |
| 24  | 210                   | 35°            | 0.19                          | CCV-TR-24      |
| 25  | 210                   | 55°            | 0.11                          | CCV-TR-25      |
| 26  | 210                   | 55°            | 0.15                          | CCV-TR-26      |
| 27  | 210                   | 55°            | 0.19                          | CCV-TR-27      |
Table 2. Carrying out experiments on the processing of concave cylindrical surfaces with spherical milling.

| No. | Cutting speed [m/min] | Tilt angle [°] | Advance on tooth [mm/tooth] | Surface CCV-SF |
|-----|----------------------|----------------|-----------------------------|----------------|
| 1   | 280                  | 15°            | 0.05                        | CCV-SF-1       |
| 2   | 280                  | 15°            | 0.09                        | CCV-SF-2       |
| 3   | 280                  | 15°            | 0.13                        | CCV-SF-3       |
| 4   | 280                  | 35°            | 0.05                        | CCV-SF-4       |
| 5   | 280                  | 35°            | 0.09                        | CCV-SF-5       |
| 6   | 280                  | 35°            | 0.13                        | CCV-SF-6       |
| 7   | 280                  | 55°            | 0.05                        | CCV-SF-7       |
| 8   | 280                  | 55°            | 0.09                        | CCV-SF-8       |
| 9   | 280                  | 55°            | 0.13                        | CCV-SF-9       |
| 10  | 370                  | 15°            | 0.05                        | CCV-SF-10      |
| 11  | 370                  | 15°            | 0.09                        | CCV-SF-11      |
| 12  | 370                  | 15°            | 0.13                        | CCV-SF-12      |
| 13  | 370                  | 35°            | 0.05                        | CCV-SF-13      |
| 14  | 370                  | 35°            | 0.09                        | CCV-SF-14      |
| 15  | 370                  | 35°            | 0.13                        | CCV-SF-15      |
| 16  | 370                  | 55°            | 0.05                        | CCV-SF-16      |
| 17  | 370                  | 55°            | 0.09                        | CCV-SF-17      |
| 18  | 370                  | 55°            | 0.13                        | CCV-SF-18      |
| 19  | 430                  | 15°            | 0.05                        | CCV-SF-19      |
| 20  | 430                  | 15°            | 0.09                        | CCV-SF-20      |
| 21  | 430                  | 15°            | 0.13                        | CCV-SF-21      |
| 22  | 430                  | 35°            | 0.05                        | CCV-SF-22      |
| 23  | 430                  | 35°            | 0.09                        | CCV-SF-23      |
| 24  | 430                  | 35°            | 0.13                        | CCV-SF-24      |
| 25  | 430                  | 55°            | 0.05                        | CCV-SF-25      |
| 26  | 430                  | 55°            | 0.09                        | CCV-SF-26      |
| 27  | 430                  | 55°            | 0.13                        | CCV-SF-27      |

For each test, the CAM programs will be made using the PowerMILL software, it gives the possibility to create the tool, to find the best strategy so that, for each experiment the processing will be done in one direction, the tool paths are parallel to the corresponding inputs and outputs.

Referring to the achievements of the program CAM machining the cylindrical surface of the concave shaping toroidal, if the angle of 15° was required for 147 lines in the case of inclination of 35° was required for 140 lines, and for 55°, 138 lines. In the case of the spherical milling machine, it worked the surface at 15° with 159 lines, at 35° with 162 lines, and for the 55° inclination, 142 lines were needed.

Figure 1 shows three images during the simulation of the toroidal tool path on the concave cylindrical surface, in the three cases of inclinations, and figure 2 consists of three images with the simulation of the route followed by the spherical milling on the concave cylindrical surface, in the three cases of inclination.

The image with the practical experiment itself carried out on the OKUMA MU-400VA numerical control centre is illustrated in figure 3; the figure contains three images with the toroidal mill that processes the concave cylindrical surface at the three types of inclinations.

In figure 4 there are three images with spherical milling during the processing of the concave cylindrical surface in the case of the three types of inclinations.
Figure 1. Images taken following the simulation of the toroidal mill trajectory in PowerMILL on CCV-TR.

Figure 2. Images taken from the simulation of the toroidal milling trajectory in PowerMILL on CCV-SF.

Figure 3. The processing of the concave cylindrical surface with the toroidal mill in the case of the 3 types of inclinations.

Figure 4. Processing of the concave cylindrical surface with the spherical mill in the case of the 3 types of inclinations.

Thus, at the end of the experiments twenty-seven toroidal milling surfaces of concave cylindrical surfaces and twenty-seven other concave cylindrical surfaces are processed, and the roughness measurement will be carried out in the next chapters.
Figure 5. The concave cylindrical surfaces processed with the two types of milling cutters ready for measurement.

3. Certification of experimental results
In order to determine the quality of the surface, the principle of replication will be applied, thus three measurements will be made in the direction parallel to the advance direction, and the average of the three measurements will be made. Another three measurements will be made in the direction perpendicular to the advance, followed by calculating the average. Table 3 presents the results of machining the concave cylindrical surface with the spherical mill and table 4 presents the results of the processing of the concave cylindrical surface with the toroidal mill.

Table 3. The results related to the processing of the concave cylindrical surface with the ball mill.

| Surface type | Parallel roughness $R_a$ [µm] | Perpendicular roughness $R_a$ [µm] | Parallel roughness $R_t$ [µm] | Perpendicular roughness $R_t$ [µm] |
|--------------|-------------------------------|------------------------------------|-------------------------------|------------------------------------|
| CCV-SF-1     | 0.176                         | 0.345                              | 1.513                         | 2.773                              |
| CCV-SF-2     | 0.334                         | 0.527                              | 2.673                         | 4.186                              |
| CCV-SF-3     | 0.318                         | 0.477                              | 2.466                         | 3.533                              |
| CCV-SF-4     | 0.220                         | 0.425                              | 1.679                         | 2.826                              |
| CCV-SF-5     | 0.393                         | 0.394                              | 2.427                         | 2.713                              |
| CCV-SF-6     | 0.417                         | 0.415                              | 3.413                         | 3.127                              |
| CCV-SF-7     | 0.249                         | 0.367                              | 2.173                         | 3.186                              |
| CCV-SF-8     | 0.266                         | 0.395                              | 2.199                         | 4.730                              |
| CCV-SF-9     | 0.438                         | 0.403                              | 3.640                         | 4.999                              |
| CCV-SF-10    | 0.202                         | 0.552                              | 1.586                         | 3.540                              |
| CCV-SF-11    | 0.328                         | 0.467                              | 2.486                         | 3.493                              |
| CCV-SF-12    | 0.268                         | 0.405                              | 1.919                         | 3.526                              |
| CCV-SF-13    | 0.333                         | 0.497                              | 2.313                         | 4.143                              |
| CCV-SF-14    | 0.364                         | 0.453                              | 2.553                         | 3.020                              |
| CCV-SF-15    | 0.414                         | 0.420                              | 2.859                         | 3.426                              |
| CCV-SF-16    | 0.357                         | 0.480                              | 2.666                         | 3.806                              |
| CCV-SF-17    | 0.276                         | 0.489                              | 2.385                         | 3.753                              |
| CCV-SF-18    | 0.375                         | 0.456                              | 3.200                         | 3.280                              |
| CCV-SF-19    | 0.233                         | 0.525                              | 1.580                         | 3.260                              |
| CCV-SF-20    | 0.270                         | 0.557                              | 1.993                         | 3.373                              |
By analysing the roughness values of the concave cylindrical surfaces processed with the spherical mill, the following deductions were reached.

According to figure 6, the lowest value obtained of the roughness $R_a=0.176\mu m$, is the case of the concave cylindrical surface with the number 1 (CCV-SF-1) with the cutting regimes $v_c=280m/min$, $f_z=0.05mm/tooth$ and inclination of the tool axis of $15^\circ$, according to table 4.8.

![Figure 6](image)

Figure 6. Arithmetic mean $R_a$ of the concave cylindrical surface processed with the spherical milling.

The highest roughness value $R_a=0.552\mu m$, was achieved on the concave cylindrical surface with the number 10 (CCV-SF-10) with the cutting speeds $v_c=370m/min$, $f_z=0.05mm/tooth$ and the axis of the tool axis of $15^\circ$, according to table 3.

According to figure 7, the total minimum $R_t$ roughness is equal to $1.513\mu m$ on the concave cylindrical surface with the number 1 (CCV-SF-1), and the maximum $R_t$ is $4.739\mu m$, generated on the concave cylindrical surface with the number 21 (CCV-SF-21) with the cutting speeds $v_c=430m/min$, $f_z=0.13mm/tooth$ and the inclination of the tool axis by $15^\circ$ according to table 3.

![Figure 7](image)

Figure 7. Arithmetic mean $R_t$ of the concave cylindrical surface processed with the spherical milling.
Table 4. Results related to the processing of the concave cylindrical surface with the toroidal mill.

| Surface type | Parallel roughness \( R_a [\mu m] \) | Perpendicular roughness \( R_z [\mu m] \) | Parallel roughness \( R_t [\mu m] \) | Perpendicular roughness \( R_z [\mu m] \) |
|--------------|--------------------------------------|---------------------------------------------|--------------------------------------|---------------------------------------------|
| CCV-TR-1     | 0.607                                | 0.579                                       | 4.232                                | 5.580                                       |
| CCV-TR-2     | 0.404                                | 0.527                                       | 3.959                                | 5.307                                       |
| CCV-TR-3     | 0.532                                | 0.455                                       | 4.193                                | 3.926                                       |
| CCV-TR-4     | 0.435                                | 0.424                                       | 3.379                                | 3.586                                       |
| CCV-TR-5     | 0.432                                | 0.393                                       | 3.106                                | 3.687                                       |
| CCV-TR-6     | 0.398                                | 0.362                                       | 2.387                                | 3.839                                       |
| CCV-TR-7     | 0.410                                | 0.573                                       | 4.020                                | 4.946                                       |
| CCV-TR-8     | 0.346                                | 0.498                                       | 2.273                                | 4.386                                       |
| CCV-TR-9     | 0.414                                | 0.406                                       | 3.346                                | 4.273                                       |
| CCV-TR-10    | 0.359                                | 0.562                                       | 2.173                                | 3.493                                       |
| CCV-TR-11    | 0.453                                | 0.485                                       | 2.453                                | 2.913                                       |
| CCV-TR-12    | 0.374                                | 0.447                                       | 2.760                                | 3.286                                       |
| CCV-TR-13    | 0.437                                | 0.384                                       | 3.659                                | 3.273                                       |
| CCV-TR-14    | 0.360                                | 0.452                                       | 2.259                                | 3.700                                       |
| CCV-TR-15    | 0.361                                | 0.388                                       | 2.693                                | 4.526                                       |
| CCV-TR-16    | 0.485                                | 0.648                                       | 3.927                                | 6.273                                       |
| CCV-TR-17    | 0.375                                | 0.603                                       | 3.047                                | 5.380                                       |
| CCV-TR-18    | 0.397                                | 0.600                                       | 2.799                                | 5.353                                       |
| CCV-TR-19    | 0.416                                | 0.599                                       | 2.639                                | 5.533                                       |
| CCV-TR-20    | 0.326                                | 0.384                                       | 3.300                                | 2.413                                       |
| CCV-TR-21    | 0.268                                | 0.356                                       | 2.346                                | 2.860                                       |
| CCV-TR-22    | 0.330                                | 0.469                                       | 2.059                                | 3.913                                       |
| CCV-TR-23    | 0.286                                | 0.538                                       | 3.379                                | 5.039                                       |
| CCV-TR-24    | 0.378                                | 0.460                                       | 3.513                                | 3.233                                       |
| CCV-TR-25    | 0.453                                | 0.773                                       | 2.746                                | 7.699                                       |
| CCV-TR-26    | 0.398                                | 0.590                                       | 4.713                                | 5.099                                       |
| CCV-TR-27    | 0.339                                | 0.503                                       | 2.593                                | 3.533                                       |

According to figure 8, the concave cylindrical surface processed with the toroidal milling saw the smallest value of \( R_a = 0.268 \mu m \) on the concave cylindrical surface with the number 21 (CCV-TR-21) with the cutting regimes \( v_c = 210 \text{m/min}, f_t = 0.19 \text{mm/tooth} \) and the inclination of the tool axis by 15°, according to table 4.

![Figure 8](image_url)  
Figure 8. Arithmetic mean \( R_a \) of the concave cylindrical surface processed with the toroidal milling.
The highest $R_a$ value is 0.773µm, on the concave cylindrical surface with the number 25 (CCV-TR-25) with the cutting regimes $v_c=210$ m/min, $f_z=0.11$ mm/tooth and the inclination of the tool axis of 55°, according to table 4.

According to figure 9, the minimum $R_t$ obtained is 2.059µm, on the concave cylindrical surface with the number 22 (CCV-TR-22) with the cutting speeds $v_c=210$ m/min, $f_z=0.11$ mm/tooth and the inclination of the tool axis 35° according to table 4.7, and the maximum value $R_t$ is 7.699µm, on the concave cylindrical surface with the number 25 (CCV-TR-25).

![Figure 9. Arithmetic mean $R_t$ of the concave cylindrical surface processed with the toroidal milling.](image)

Figure 9 shows microscopic images obtained with the IOR stereoscopic microscope and with the MM1-200 microscope of the best qualities of the concave cylindrical surfaces processed with spherical milling (CCV-SF) and toroidal (CCV-TR).

![Figure 10. Microscope images with the best roughness of the concave cylindrical surfaces processed with the spherical mill and the toroidal mill.](image)
4. Conclusions
The purpose of this work is to determine the surface quality which has a main role in the precision and lubrication of surfaces. It was chosen to compare the processed surfaces with the toroidal milling, respectively the spherical milling. The surface on which the roughness was investigated is the concave cylindrical surface.

As variable parameters, it was chosen to combine the cutting speed, the feed on the tooth and the inclination angle of the tool. During the practical experiments, twenty-seven surfaces were processed with toroidal milling and twenty-seven surfaces were processed with spherical milling.

Comparing the concave cylindrical surfaces processed with the spherical and the toroidal milling, the spherical milling has an advantage of 0.092µm compared to the toroidal milling, but also from the point of view of Rₜ all the spherical milling is in advantage.

The concave cylindrical surface has the best roughness after processing with the spherical milling machine. In this case the spherical mill works the surface at an angle of inclination of 15°. In this case, the wear value of the spherical mill is slightly higher than in the case of the toroidal mill.

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