Experimental Research on the Processing of Concave Spherical Surfaces with Toroidal Mills Versus Spherical Mills

PhD. Student Eng. **Andrei OȘAN**[1]

[1] Technical University of Cluj-Napoca - North University Center of Baia Mare, Romania, osan.andrei@yahoo.com

Abstract: *The quality of the surface plays a very important role on the wear layer of the piece. There must be a balance so that the roughness is not too high but not too low. To determine the optimum roughness, several process factors must be correlated so that the results are the desired ones. This work aims to determine the roughness on the concave spherical surfaces. In order to determine it, the process factors but also the geometrical shape of the tool vary. As an additional argument in determining the optimal values, the execution time of each experiment is also pursued.*

Keywords: *Concave spherical surface, toroidal milling, spherical milling, optimum regimes, surface quality*

1. Introduction

Surface roughness is one of the most important parameters for determining product quality [5].
The presence of irregularities on the surface of a part transposes, under harsher operating conditions, a series of disadvantages: the effective contact surfaces are reduced, the conditions of friction and working conditions of the part are reduced, the resistance to alternating stresses of the material is reduced by the concentration of stresses. , reducing sealing, changing the actual dimensions of the part.
On the other hand, their absence makes it impossible to maintain the oil film on the contact surface at normal lubrication.
The roughness is determined according to the conditions of use, depending on: the processing speed, the size of the contact surface, the size and character of the requests, the precision of the dimensions and the geometric shape.
The roughness of the surfaces resulting from the milling operations are influenced by both the milling kinematics and the cutting conditions [3], [8], [1], [2].
The research carried out internationally, analyses the variation of the surface roughness processed with spherical milling cutters according to the following parameters: the angle of inclination of the cutting tool axis in relation to the normal one on the processed surface, the speed applied to the cutting tool, the advance on the tooth, the depth on the tooth, the depth of the tooth step by step etc.
The optimization of the processing strategies on machine tools with 5-axis numerical control is the theme of the work [4], where it is proposed to practice a variable angle of inclination of the tool axis in the direction of the processing advance, depending on the geometry of the processed surface. The results regarding the surface roughness, obtained on the basis of the experimental results are significantly higher.
The quality of the machined surface varies even if the machining strategy and the value of the inclination angle remain unchanged, but the orientation of the machining strategy changes with respect to the contour borders of the machined surface, by rotating the entire strategy with a certain angle, a fact highlighted in the paper [7].
The direction of inclination of the axis of the tool and the value of the angle at which the cutting tool is inclined in relation to the normal on the surface to be machined, is an important factor that determines the evolution of the roughness of the machined surfaces. As we established experimentally in the paper [6] the tool orientations have a great influence on the surface roughness, surface morphology as well as residual loading. For this reason, it is necessary to establish the optimum values of the inclination of the axis of the tool, for which the roughness has the lowest value, respectively avoiding the inclination directions and the angular values that determine high values of the roughness and implicitly low surface quality.

2. Presentation of the experimental stand

The experimental part will be realized on a centre with numerical control in 5 axes OKUMA MU-400VA. This is a fast and precise vertical CNC that offers superior simultaneous workability in 5 axes simultaneously. The Okuma MU-400VA has a rotary table that offers a plus in 5-axis processing as well as a fast and precise positioning and at the same time a rigidity in offering outstanding performance.
The spherical-concave surface is represented by a dome at the top of the plate, it is positioned in the centre of the plate representing the distance of 5mm from the maximum spherical height to the flat surface. The concave spherical shape has a diameter of Ø85 mm as provided in the following figure.

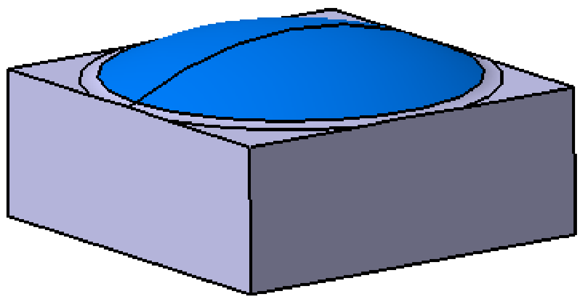

Fig. 1. The concave spherical surface

The two cutting tools used are: toroidal drill JHP780160E2R400.0Z4-M64 and spherical head drill JS534160D1B.0Z4-NXT.
TR200TIME is used to measure the roughness, this tester is applied on the production site and can be used to measure the roughness of the surfaces of the different processed parts, to calculate the parameters according to the selected measuring conditions and to clearly display all the measuring parameters and graphs. profile on the screen.

3. The experimental part

Within this subchapter we will experimentally research the development of 27 concave spherical surfaces with toroidal milling as shown in table 1 and 27 concave spherical surfaces processed with spherical milling as presented in table 2. At the same time, these tables contain a column where the basic times of each test are passed. These times represent strictly the moment spent during the processing, the auxiliary times being considered constant and equal avoiding their debate.
Regarding the cutting regimes only the 3 presented in the tables vary, the rest remain constant. Here the cutting depth equal to 0.5 mm (ap = 0.5 mm) and the radial depth equal to 0.3 mm (ae = 0.3mm) are entered. The emulsion is present as a cooling liquid throughout the process. Regarding the clamping mode, the plates will be attached to a clamp with a fingerprint being a rigid and secure system. For a better organization I decided to note with SFCV-TR the concave spherical surfaces processed with the toroidal milling machine and with SFCV-SF the concave spherical surfaces processed with the spherical milling machine.

Table 1: Carrying out experiments on the processing of concave spherical surfaces with toroidal milling

Nr.	Cutting speed [m/min]	Tilt angle [°]	Feed/tooth [mm/tooth]	Program name SFCV-TR	Time [min]
1	80	15°	0.11	SFCV-TR-1	04:09
2	80	15°	0.15	SFCV-TR-2	03:03
3	80	15°	0.19	SFCV-TR-3	02:24
4	80	35°	0.11	SFCV-TR-4	03:42

5	80	35°	0.15	SFCV-TR-5	02:43
6	80	35°	0.19	SFCV-TR-6	02:08
7	80	55°	0.11	SFCV-TR-7	03:41
8	80	55°	0.15	SFCV-TR-8	02:42
9	80	55°	0.19	SFCV-TR-9	02:08
10	170	15°	0.11	SFCV-TR-10	01:57
11	170	15°	0.15	SFCV-TR-11	01:26
12	170	15°	0.19	SFCV-TR-12	01:08
13	170	35°	0.11	SFCV-TR-13	01:44
14	170	35°	0.15	SFCV-TR-14	01:17
15	170	35°	0.19	SFCV-TR-15	01:01
16	170	55°	0.11	SFCV-TR-16	01:44
17	170	55°	0.15	SFCV-TR-17	01:16
18	170	55°	0.19	SFCV-TR-18	01:00
19	210	15°	0.11	SFCV-TR-19	01:35
20	210	15°	0.15	SFCV-TR-20	01:10
21	210	15°	0.19	SFCV-TR-21	00:55
22	210	35°	0.11	SFCV-TR-22	01:25
23	210	35°	0.15	SFCV-TR-23	01:02
24	210	35°	0.19	SFCV-TR-24	00:49
25	210	55°	0.11	SFCV-TR-25	01:24
26	210	55°	0.15	SFCV-TR-26	01:02
27	210	55°	0.19	SFCV-TR-27	00:49

Table 2: Carrying out experiments on the processing of concave spherical surfaces with spherical milling

Nr.	**Cutting speed [m/min]**	**Tilt angle [°]**	**Feed/tooth [mm/tooth]**	**Program name SFCV-SF**	**Time [min]**
1	80	15°	0.11	SFCV-SF-1	03:27
2	80	15°	0.15	SFCV-SF-2	01:55
3	80	15°	0.19	SFCV-SF-3	01:20
4	80	35°	0.11	SFCV-SF-4	03:48
5	80	35°	0.15	SFCV-SF-5	02:07
6	80	35°	0.19	SFCV-SF-6	01:28
7	80	55°	0.11	SFCV-SF-7	04:43
8	80	55°	0.15	SFCV-SF-8	02:37
9	80	55°	0.19	SFCV-SF-9	01:49
10	170	15°	0.11	SFCV-SF-10	02:37
11	170	15°	0.15	SFCV-SF-11	01:27
12	170	15°	0.19	SFCV-SF-12	01:01
13	170	35°	0.11	SFCV-SF-13	02:52
14	170	35°	0.15	SFCV-SF-14	01:36
15	170	35°	0.19	SFCV-SF-15	01:06

16	170	55°	0.11	SFCV-SF-16	03:34
17	170	55°	0.15	SFCV-SF-17	01:59
18	170	55°	0.19	SFCV-SF-18	01:22
19	210	15°	0.11	SFCV-SF-19	02:15
20	210	15°	0.15	SFCV-SF-20	01:15
21	210	15°	0.19	SFCV-SF-21	00:52
22	210	35°	0.11	SFCV-SF-22	02:28
23	210	35°	0.15	SFCV-SF-23	01:22
24	210	35°	0.19	SFCV-SF-24	00:57
25	210	55°	0.11	SFCV-SF-25	03:04
26	210	55°	0.15	SFCV-SF-26	01:42
27	210	55°	0.19	SFCV-SF-27	01:11

3.1 Surface processing

The CAM programs are made using the Powermill software capable of generating the desired trajectory depending on the required inclination, so we decided that the processing should be carried out in one direction, with the contour tracking movement with the interpolation function with the corresponding inputs and outputs having the possibility to create each tool separately. For a better expression in figure 2 are presented 3 images during the simulation of the milling process with the toroidal milling on the concave spherical surface with the 3 types of inclinations and in figure 3 are presented 3 images during the simulation of the concave spherical surface processing using the spherical milling in the 3 types of inclinations.

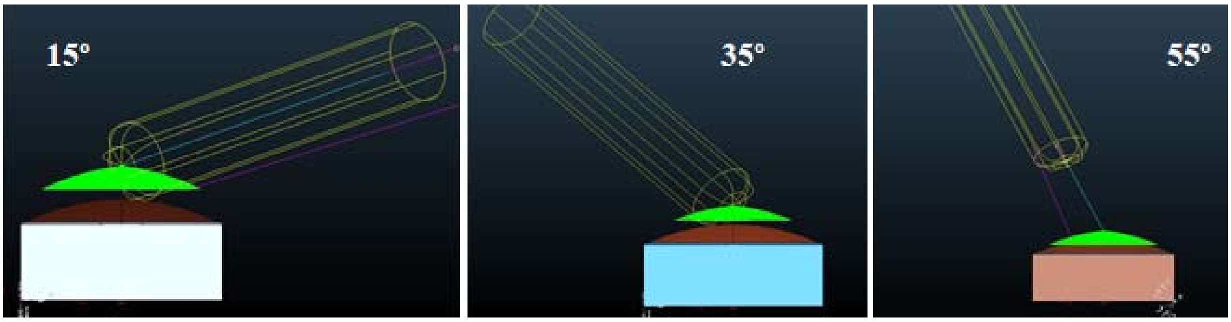

Fig. 2. Images taken following the simulation of the trajectory of the toroidal mill in Powermill on SFCV-TR

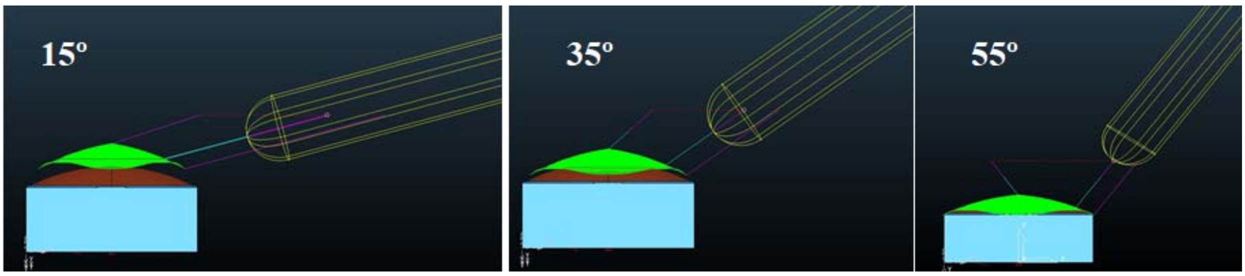

Fig. 3. Images taken following the simulation of the trajectory of the toroidal mill in Powermill on SFCV-SF

The practical experiment will be performed on the center with numerical control in 5 axes OKUMA MU-400VA as shown in figure 4 where 3 images are present during the processing of the concave spherical surface with the toroidal milling machine in the case of the 3 types of inclinations and in figure 5 it is presented processing of concave spherical surfaces with spherical milling for the 3 types of inclinations.

Fig. 4. Processing of the concave spherical surface with the toroidal milling machine in the case of the 3 types of inclinations

Fig. 5. Processing of the concave spherical surface with the spherical mill in the case of the 3 types of inclinations

It is noteworthy that, during the entire processing period, both in the case of toroidal milling and in the case of spherical milling, the axis of the tool keeps its angle of inclination constantly throughout the surface.
At the end of the experimental work performed on 27 concave spherical surfaces processed with toroidal milling and 27 concave spherical surfaces processed with spherical milling in the following figure are presented the plates prepared to be measured in terms of surface quality.

Fig. 6. The concave spherical surfaces processed with the two types of mills prepared for measurement

3.2 Analysis of the execution time

Analyzing the duration of the basic times of the processing of the concave spherical surface in the case of the two types of mills and of the 3 variables, the following was observed:
The maximum time obtained by the toroidal milling machine is 4 minutes and 9 seconds in the case of the minimum processing speeds but at an angle of inclination of 15º. As for the record, the shortest processing time of the concave spherical surface belongs to the toroidal milling of 49 seconds obtained at the maximum speed and at an angle of inclination of 55º.
The longest execution time is the one with spherical milling when the cutting regimes are at a minimum and the inclination angle is 55º with a time of 4 minutes and 43 seconds.
The spherical milling cut obtained the shortest for 57 seconds at maximum speeds and at an inclination angle of 35º.
At the conclusion of the graphical analysis of the basic times, they are close, there is a slight detachment of the toroidal drill for the inclination of 55º but the most important test is the quality of the surface.

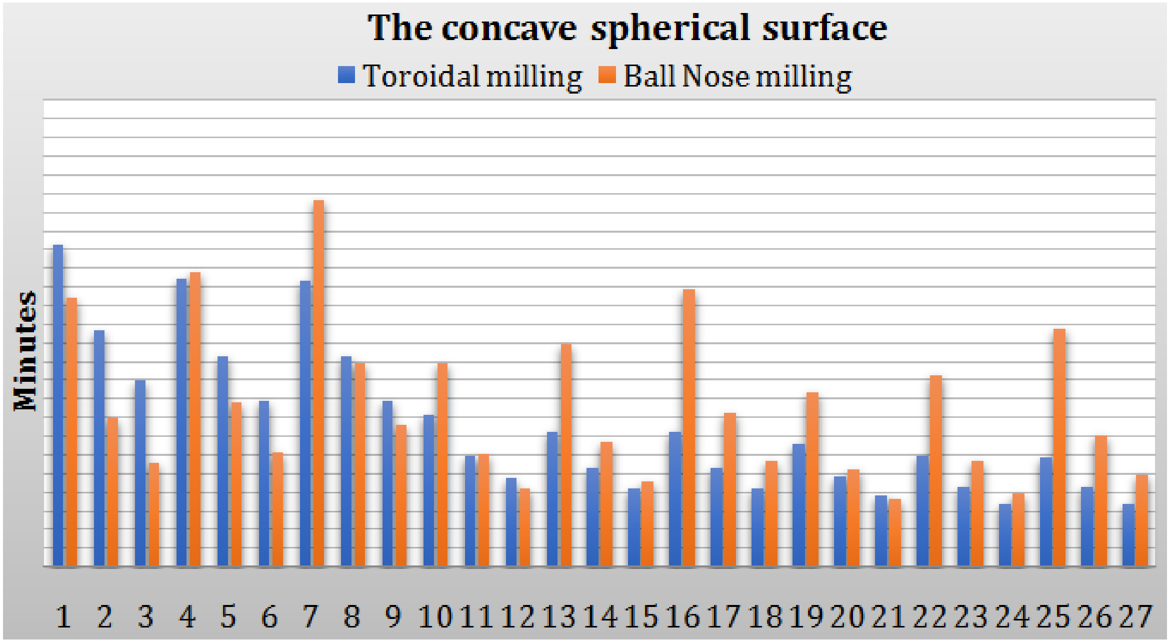

Fig. 7. Graphical analysis of the execution times for the processing of the concave spherical surface

3.3 Surface quality analysis

Regarding the concave spherical surface processed with the spherical milling, the smallest value of the arithmetic roughness Ra, is 0.296 [µm] for the SFCV-SF-10 surface processed with vc = 370 [m / min] fz = 0.05 [mm / tooth] and the inclination of the tool axis of 15º.
The highest roughness value Ra is 0.861 [µm] on the SFCV-SF-25 surface with vc = 430 [m / min] fz = 0.05 [mm / tooth] and the tool axis inclination of 55º.
The minimum value of the total roughness, Rt = 2,140 [µm] also in the case of the SFCV-SF-10 surface and the maximum value Rt = 8.860 [µm] on the SFCV-SF-25 surface.
The concave spherical surface processed with the toroidal milling saw the lowest arithmetic roughness, Ra = 0.220 [µm] measured in the direction parallel to the advance, the surface SFCV-TR-17 processed with vc = 170 [m / min] fz = 0.15 [mm / tooth] and 55º tool axis inclination.
The highest value of arithmetic roughness, Ra = 0.8 [µm] was recorded during SFCV-TR-4 surface processing with vc = 80 [m / min] fz = 0.11 [mm / tooth] and at the slope of 15º.
From the point of view of the total roughness Rt, the minimum value is 1,526 [µm] measured parallel to the advance direction on SFCV-TR-4. It is curious that this surface has the lowest roughness value Rt but it also holds the highest value of roughness Ra measured perpendicular to the feed direction.
The maximum value for the total roughness Rt is 6.433 [µm] measured perpendicular to the SFCV-TR-13 surface with vc = 170 [m / min] fz = 0.11 [mm / tooth] and the tool axis inclination of 35º.

Table 3: The results related to the processing of the concave spherical surface with the spherical mill

Surface type	Roughness Ra[μm]		Roughness Rt[μm]	
	Direction of measurement in relation to the direction of advance			
	Parallel	Perpendicular	Parallel	Perpendicular
SFCV-SF-1	0.429	0.556	3.626	3.496
SFCV-SF-2	0.429	0.493	2.279	3.860
SFCV-SF-3	0.338	0.543	2.786	3.880
SFCV-SF-4	0.392	0.484	3.300	3.803
SFCV-SF-5	0.443	0.606	3.639	3.880
SFCV-SF-6	0.385	0.536	2.927	3.783
SFCV-SF-7	0.448	0.513	3.059	5.093
SFCV-SF-8	0.476	0.495	2.453	3.846
SFCV-SF-9	0.400	0.541	3.166	5.093
SFCV-SF-10	0.296	0.485	2.140	3.867
SFCV-SF-11	0.329	0.543	2.473	4.093
SFCV-SF-12	0.379	0.543	3.053	4.039
SFCV-SF-13	0.383	0.573	2.620	4.466
SFCV-SF-14	0.390	0.555	3.346	4.113
SFCV-SF-15	0.504	0.403	4.206	3.293
SFCV-SF-16	0.413	0.666	3.326	6.399
SFCV-SF-17	0.456	0.771	3.679	7.080
SFCV-SF-18	0.409	0.670	4.220	5.406
SFCV-SF-19	0.370	0.785	3.153	5.313
SFCV-SF-20	0.396	0.683	3.220	5.566
SFCV-SF-21	0.436	0.580	3.146	4.200
SFCV-SF-22	0.479	0.674	3.679	5.246
SFCV-SF-23	0.546	0.660	4.566	5.533
SFCV-SF-24	0.486	0.505	4.700	3.686
SFCV-SF-25	0.522	0.861	3.873	8.860
SFCV-SF-26	0.548	0.614	4.660	4.980
SFCV-SF-27	0.467	0.607	4.312	4.886

Table 4: Results related to the processing of the concave spherical surface with the toroidal milling machine

Surface type	Roughness Ra[μm]		Roughness Rt[μm]	
	Direction of measurement in relation to the direction of advance			
	Parallel	Perpendicular	Parallel	Perpendicular
SFCV-TR-1	0.644	0.655	3.266	5.124
SFCV-TR-2	0.415	0.641	2.399	5.700
SFCV-TR-3	0.440	0.544	2.593	3.683
SFCV-TR-4	0.230	0.800	1.545	7.680
SFCV-TR-5	0.346	0.622	2.013	4.606

SFCV-TR-6	0.339	0.612	2.366	4.866
SFCV-TR-7	0.282	0.731	1.666	4.886
SFCV-TR-8	0.300	0.712	1.907	5.611
SFCV-TR-9	0.265	0.603	2.187	5.692
SFCV-TR-10	0.380	0.558	2.360	3.606
SFCV-TR-11	0.259	0.511	1.526	3.612
SFCV-TR-12	0.291	0.582	2.239	4.306
SFCV-TR-13	0.363	0.797	3.633	6.433
SFCV-TR-14	0.476	0.763	4.120	5.293
SFCV-TR-15	0.250	0.627	3.813	3.553
SFCV-TR-16	0.285	0.613	2.359	4.506
SFCV-TR-17	0.220	0.537	1.960	3.046
SFCV-TR-18	0.333	0.770	2.733	5.407
SFCV-TR-19	0.402	0.537	2.860	4.553
SFCV-TR-20	0.436	0.709	2.686	4.066
SFCV-TR-21	0.280	0.627	1.647	4.586
SFCV-TR-22	0.364	0.618	2.073	4.433
SFCV-TR-23	0.466	0.643	3.486	5.326
SFCV-TR-24	0.367	0.506	2.539	4.399
SFCV-TR-25	0.370	0.673	2.479	5.206
SFCV-TR-26	0.248	0.675	2.659	4.332
SFCV-TR-27	0.342	0.626	1.973	5.519

Comparing the quality of the concave spherical surfaces processed with the spherical mill and the toroidal mill, we can observe a slight advantage of 0.076 [µm] on the arithmetic mean depth for the toroidal mill in the case of surface processing with vc = 170 [m / min] fz = 0.15 [mm / tooth] and 55° tool axis inclination. And from the point of view of the total roughness Rt the toroidal mill has an advantage of 0.614 [µm].
The concave spherical surface represented by a dome proved that the best surface quality was obtained by toroidal milling at the inclination angle of 55º. In the case of surface processing at this angle the toroidal mill has developed less wear than the spherical mill.

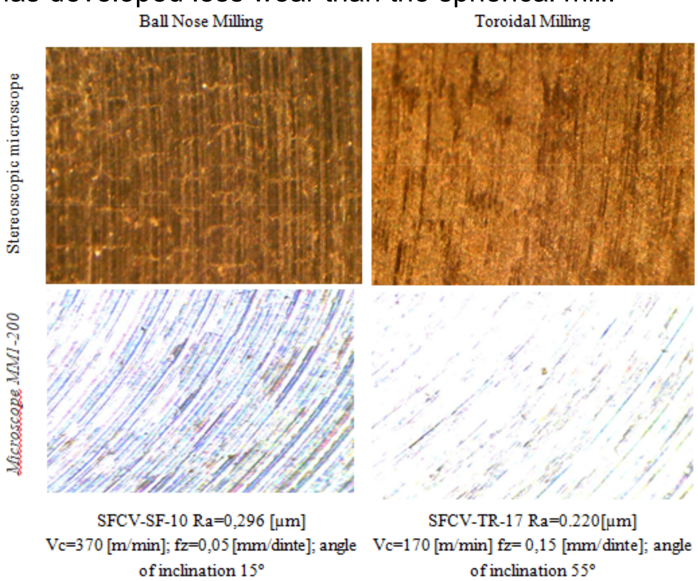

Fig. 8. Microscopic images of the quality of the surfaces processed with the two mills

Figure 8 shows microscopic images obtained with the IOR stereoscopic microscope and with the MM1-200 microscope of the best concave spherical surfaces processed with the toroidal or respective spherical mill.

4. Conclusions

The purpose of this work is to determine the quality of the surface. Surface quality plays a very important 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 decided to juggle with the cutting speed, the feed rate and the inclination angle of the tool. It was decided to process 27 surfaces with toroidal milling and 27 surfaces machined with spherical milling.

From the point of view of the execution time, the fastest processing was performed with the toroidal milling machine within a period of 49 seconds in the case of the maximum speeds at the 55º angle compared to the fastest processing obtained with the spherical milling in 57 seconds. at maximum speeds but at 35º inclination angle.

Regarding the surface quality, the best surface quality was obtained with the toroidal milling machine, having the value Ra = 0.220 [µm] with Vc = 170 [m / min], Fz = 0.15 [mm / tooth] and the inclination angle of 55º. In the case of spherical milling, the best surface quality was recorded using the regimes Vc = 370 [m / min], fz = 0.05 [mm / tooth] and the inclination angle of 15º recording the value Ra = 0.296 [µm].

According to the aspects investigated in this paper, it is proved that depending on the surface geometry and the tool geometry, as regards the processing of concave spherical surfaces, one can exit the pattern to use the toroidal milling instead of the spherical milling. This statement is confirmed both by the evolution of the execution time and by determining the quality of the surface.

Acknowledgments

The experimental research carried out with the support of the processing department of S.C. Ramira S.A., Baia Mare.

References

[1] Bieker, R. *CAM-compatible technology for CNC milling of hollow steel molds* / *CAM-gerechte technologie fuer die NCFraesbearbeitung von stahlhohlformen*. Diss. Thesis. Aachen, 1991.
[2] Bouzakis, K., D. Efstathiou, K. Antoniadis, A. Charachaliou, and P. Aichouh. "Analytical experimental determination of surface roughness in milling." Paper presented at 2nd International Conference on Tribology Balkantrib'96, Thessaloniki, June 5-7, 1996.
[3] Eversheim, W., W. Koenig, R. Bieker, and M.T. Cobanoglou. "NC Fraesbeareitung von vergueteten Schmiedegesenken." *VDI-Z integrierte Produktion* 131, no. 4 (1989): 99-103.
[4] Hikichi, T., K. Nakamoto, T. Ishida, and Y. Takeuchi. "Tool Path Generation for 5-Axis Control Machining Considering the Quality of Machined Surface." Proceedings of 5th International Conference on Leading Edge Manufacturing in 21st Century (LEM 21), Osaka, Japan, December 2-4, 2009, pp.107-112.
[5] Oșan, A. "Experimental Research on the Processing of Convex Spherical Surfaces with Toroidal Mills Versus Spherical Mills." *Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics "Hidraulica"*, no. 4 (December 2019): 63-72.
[6] Oșan, A., M. Bănică, and V. Năsui. "The influence of inclination of the axis of the toroidal on a flat surface roughness." Paper presented at the 23rd edition of Innovative Manufacturing Engineering&Energy International Conference – ImanE&E 2019, Pitești, Romania, May 22 – 24, 2019; *IOP Conf. Series: Materials Science and Engineering* 564 (2019): 012003, doi:10.1088/1757-899X/564/1/012003.
[7] Vijayaraghavan, A., A.M. Hoover, J. Hartnett, and. D.A. Dornfeld. "Improving endmilling surface finish by workpiece rotation and adaptive toolpath spacing." *International Journal of Macine Tools&Manufacture* 49 (2009): 89-98.
[8] Werner, A. *Process design and process reliability when using slim end mills* / *Prozessauslegung und Prozesssicherheit beim einstazt von schlanken schaftfraesern*. Thesis. Aachen, 1993.