Experimental Research on the Processing of Convex Spherical Surfaces with Toroidal Mills versus Spherical Mills

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Abstract: *The surface roughness plays a very important role on the wear layer, on the precision as well as on the lubrication environment. In terms of determining the quality of the surface, this is a complex process and highly influenced by the process factors. The present paper aims to determine the roughness of the convex spherical surface by using two types of mills with different geometries. The toroidal and spherical mills are subject to comparison. The processing with the two types of milling machines presents the processing with three variable regimes the rest keeping cash. In addition to determining the best quality obtained and the shortest execution time.*

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

1. Introduction

Surface roughness is one of the most important parameters to determine the quality of the product. The process of forming the roughness is very dynamic, complex and process dependent. There are two types of factors that influence the surface finish and implicitly the surface quality of a workpiece. The first factors are the kinematic geometry of the tool which theoretically affects the surface and can be calculated from so-called processing parameters and controllable factors such as rotational speed, feedrate and cutting depth. The second category of factors is represented by the nongeometric components including tool wear, work material deformation, vibration, tool deformation as well as errors of movement of the machine axes.
The roughness, as an important parameter of the surface layer, has a special influence on the wear resistance, the fatigue resistance, the corrosion resistance and the precision of the adjustments. In the case of the free adjustments, the irregularities (asperities) determine the decrease of the actual bearing surface compared to the theoretical one, considered in calculations, which produces local increases of the contact pressure, sometimes, far above those considered in the dimensioning calculations. These have the effect of accelerated wear of the surfaces in contact and the increase of the games, especially during the first period of operation (the period of running), the more accentuated the higher the initial roughness (technological). These effects justify the application of correct rolling programs of the adjustments after assembly.
Mike S. Lou et al. [6] states that surface roughness is an important measure of the technological quality of a product and a factor that greatly influences the cost of production. Surface quality plays a very important role in the performance of the processing through a good quality processed surface that significantly improves wear resistance or corrosion resistance. In addition, surface roughness also affects the friction surface, light reflection, the ability to retain a lubricant as well as electrical or thermal resistance.
Nowadays, the researchers carry out active studies on the quality of the surface introduced by the milling process of the different orientations of the tools. Toh studied in high speed milling of hardened steel and obtained a high cutting force when using a negative feed angle and minimal surface roughness when positive [9]. Gani established a geometrical model of the machining process and discussed the influence of the tool orientation on the five-axis milling process, and the results were verified experimentally [3]. According to a previous paper the results indicate that the tool orientations have a great influence on the surface roughness, surface morphology and residual loading, but little on the microhydration [8].
Daymin achieved the best surface finish when the inclination angle of the workpiece is 25 ° and the average compression stress slightly decreased at a larger angle of the workpiece [2]. Ko considered the cutting force, surface roughness and tool wear, the results indicating 15 ° of the tilt

angle of the workpiece were optimal [5]. Aspinwall studied the influence of tool orientation and tilt angle on surface integrity, results showed a downward horizontal orientation, providing better surface roughness, cutting force and tool wear obtained the highest residual compression pressure when the workpiece was machined without inclination angle [1]. Kalvoda indicated that positive or negative feed angle and tilt angle had a reduced effect on residual loading and provided the best surface roughness when both angles were negative, but the worst is when there is no inclination [4]. Min Fu studied the adjustment of the inclination angle which can optimize the cutting conditions, reduce the surface roughness and ensure the best surface quality when the angle between the tool axis and the vertical surface of the workpiece is 15 ° [7].

2. Presentation of the experimental stand

The experiments will be carried out on a 5-axis numerical control center 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-convex surface is represented by a recess at the top of the plate; it is positioned in the center of the plate representing the distance of 5mm from the maximum spherical recesses to the flat surface. The convex spherical shape has a diameter of Ø85 mm as shown in the following figure.

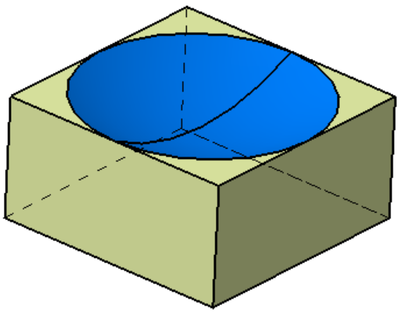

Fig. 1. The convex spherical surface

The TR200TIME roughness meter 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 on-screen profile graphics.

The two cutting tools used are: toroidal milling machine JHP780160E2R400.0Z4-M64 and spherical head milling machine JS534160D1B.0Z4-NXT.

3. The experimental part

During this research we will experimentally study the realization of 27 convex spherical surfaces with toroidal milling as shown in table 1 and 27 convex spherical surfaces processed with spherical milling as presented in table 2. In addition, these tables contain a column where the runtime of each test is passed. These times refer strictly to the moment of processing, the rest of the time being considered constant so that they were no longer considered for the study. Regarding the cutting regimes only the 3 presented in the tables vary the rest remain cash. Here we can talk about the cutting depth equal to 0.5 mm (ap = 0.5 mm) and the radial depth equal to 0.3 mm (ae = 0.3mm). During processing it is present as a cooling liquid, the emulsion. Discussing the clamping mode, the plates will be clamped in a fingerprint clamp being a rigid and secure system. In order for each experiment to be able to differentiate, I decided to write down with SFCX-TR the convex spherical surfaces processed with the toroidal milling and with SFCX-SF the convex spherical surfaces processed with the spherical milling.

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

No.	Cutting speed [m/min]	Tilt angle [°]	Feed/tooth [mm/dinte]	Program name SFCX-TR	Time [min]
1	80	15°	0.11	SFCX-TR-1	06:05
2	80	15°	0.15	SFCX-TR-2	04:37
3	80	15°	0.19	SFCX-TR-3	03:46
4	80	35°	0.11	SFCX-TR-4	06:06
5	80	35°	0.15	SFCX-TR-5	04:38
6	80	35°	0.19	SFCX-TR-6	03:48
7	80	55°	0.11	SFCX-TR-7	06:43
8	80	55°	0.15	SFCX-TR-8	05:08
9	80	55°	0.19	SFCX-TR-9	04:13
10	170	15°	0.11	SFCX-TR-10	03:10
11	170	15°	0.15	SFCX-TR-11	02:29
12	170	15°	0.19	SFCX-TR-12	02:05
13	170	35°	0.11	SFCX-TR-13	03:13
14	170	35°	0.15	SFCX-TR-14	02:32
15	170	35°	0.19	SFCX-TR-15	02:08
16	170	55°	0.11	SFCX-TR-16	03:35
17	170	55°	0.15	SFCX-TR-17	02:50
18	170	55°	0.19	SFCX-TR-18	02:24
19	210	15°	0.11	SFCX-TR-19	02:41
20	210	15°	0.15	SFCX-TR-20	02:07
21	210	15°	0.19	SFCX-TR-21	01:48
22	210	35°	0.11	SFCX-TR-22	02:43
23	210	35°	0.15	SFCX-TR-23	02:10
24	210	35°	0.19	SFCX-TR-24	01:51
25	210	55°	0.11	SFCX-TR-25	03:03
26	210	55°	0.15	SFCX-TR-26	02:26
27	210	55°	0.19	SFCX-TR-27	02:06

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

No.	Cutting speed [m/min]	Tilt angle [°]	Feed/tooth [mm/dinte]	Program name SFCX-SF	Time [min]
1	280	15°	0.05	SFCX-SF-1	06:53
2	280	15°	0.09	SFCX-SF-2	04:13
3	280	15°	0.13	SFCX-SF-3	03:12
4	280	35°	0.05	SFCX-SF-4	07:18
5	280	35°	0.09	SFCX-SF-5	04:47
6	280	35°	0.13	SFCX-SF-6	03:49
7	280	55°	0.05	SFCX-SF-7	06:04

8	280	55°	0.09	SFCX-SF-8	03:58
9	280	55°	0.13	SFCX-SF-9	03:00
10	370	15°	0.05	SFCX-SF-10	05:25
11	370	15°	0.09	SFCX-SF-11	03:24
12	370	15°	0.13	SFCX-SF-12	02:38
13	370	35°	0.05	SFCX-SF-13	05:55
14	370	35°	0.09	SFCX-SF-14	04:01
15	370	35°	0.13	SFCX-SF-15	03:17
16	370	55°	0.05	SFCX-SF-16	04:52
17	370	55°	0.09	SFCX-SF-17	03:11
18	370	55°	0.13	SFCX-SF-18	02:32
19	430	15°	0.05	SFCX-SF-19	04:47
20	430	15°	0.09	SFCX-SF-20	03:03
21	430	15°	0.13	SFCX-SF-21	02:23
22	430	35°	0.05	SFCX-SF-22	05:19
23	430	35°	0.09	SFCX-SF-23	03:41
24	430	35°	0.13	SFCX-SF-24	03:03
25	430	55°	0.05	SFCX-SF-25	04:20
26	430	55°	0.09	SFCX-SF-26	02:53
27	430	55°	0.13	SFCX-SF-27	02:20

3.1 Surface processing

CAM programs were created with the help of Powermill software, a software capable of creating the tool with which to process, but more importantly, a software capable of generating the tool trajectories on the surface to be processed. As an optimum variant, we chose to work in one direction, the tool paths being parallel, with the corresponding inputs and outputs. For the processing of the surface with toroidal milling, the program contains in the case of the 15º inclination a number of 139 lines, for the inclination of 35º, 146 lines and for the 55º inclination, 150 lines. In the case of spherical milling, the trajectory for all three inclines consists of 149 lines. In figure 2 are presented 3 images with the simulation of the convex spherical surface processing in the 3 types of inclinations using the toroidal milling beam and in figure 3 the images during the simulation of the convex spherical surface processing with the spherical milling in the 3 cases of inclinations are presented.

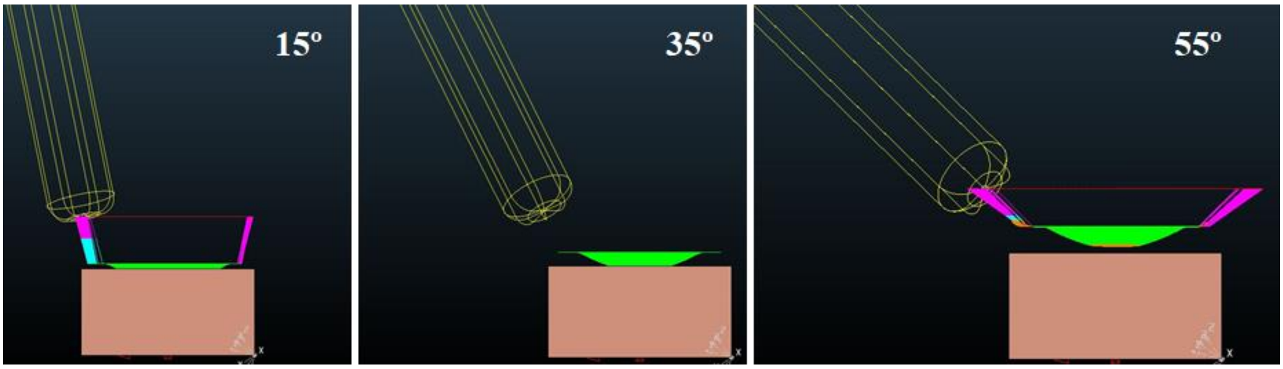

Fig. 2. Images taken following the simulation of the trajectory of the toroidal mill in Powermill on SFCX-TR

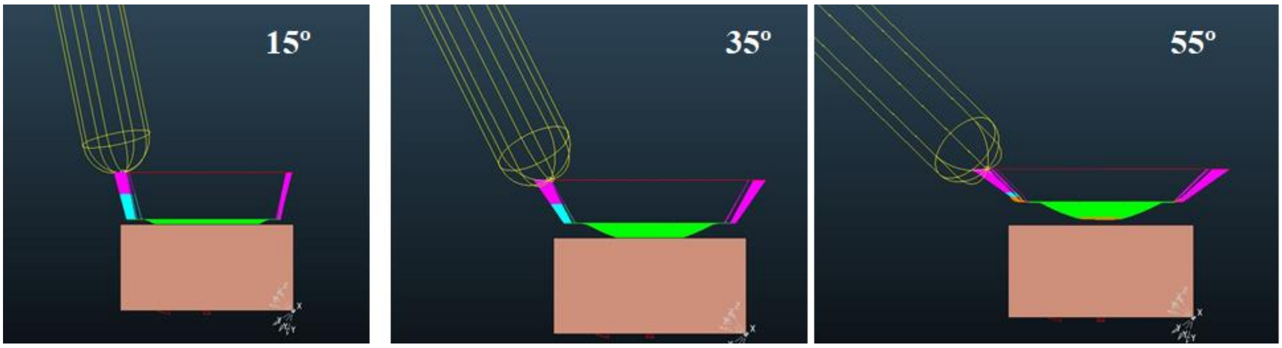

Fig. 3. Images taken following the simulation of the trajectory of the toroidal mill in Powermill on SFCX-SF

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 convex spherical surface with the toroidal milling in the case of the 3 types of inclinations and in figure 5 it is presented processing of the convex spherical surface with the spherical mill in the case of the 3 types of inclinations.

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

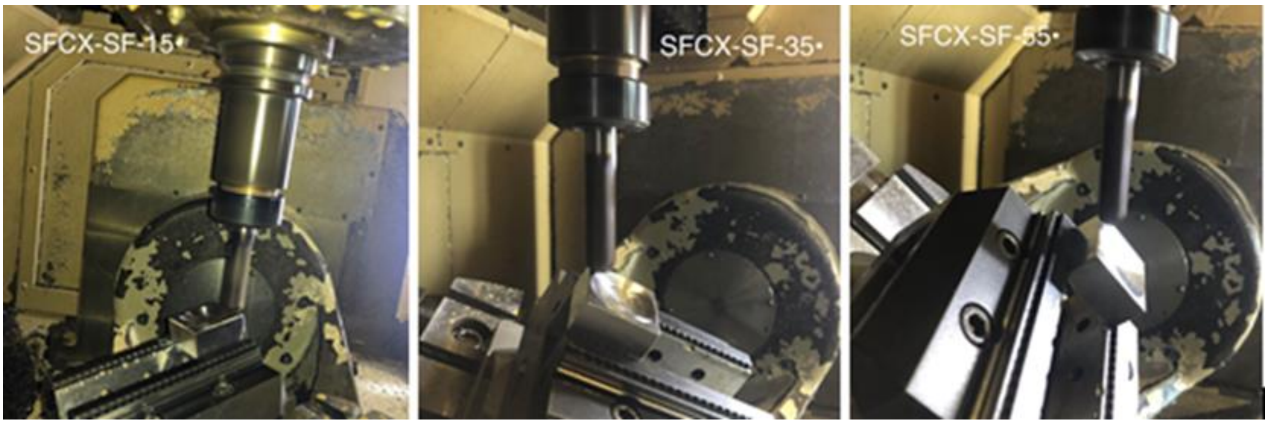

Fig. 5. Processing of the convex spherical surface with the spherical mill in the case of the 3 types of inclinations

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

At the end of the experimental work performed on 27 convex spherical surfaces processed with toroidal milling and 27 convex 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 convex spherical surfaces processed with the two types of mills prepared for measurement

3.2 Runtime analysis

Regarding the execution time, the processing of the convex surface lasts the most in the case of the spherical milling machine with a time of 7 minutes and 18 seconds with the minimum speeds set but at an angle of inclination of 35º compared to the maximum time obtained by the toroidal milling machine of 6 minutes and 43 seconds in the case of minimum speeds and the inclination angle of 55º.
The fastest surface processing was done with the toroidal milling machine in one minute and 48 seconds in the case of maximum speeds at the angle of 15º compared to the minimum time obtained with the spherical milling machine of 2 minutes and 20 seconds also at maximum speeds but at 55º inclination.
From the point of view of the execution time of the most cost-effective surface is the toroidal milling machining at the inclination of the tool axis of 15º following the establishment of the best quality of the surface.

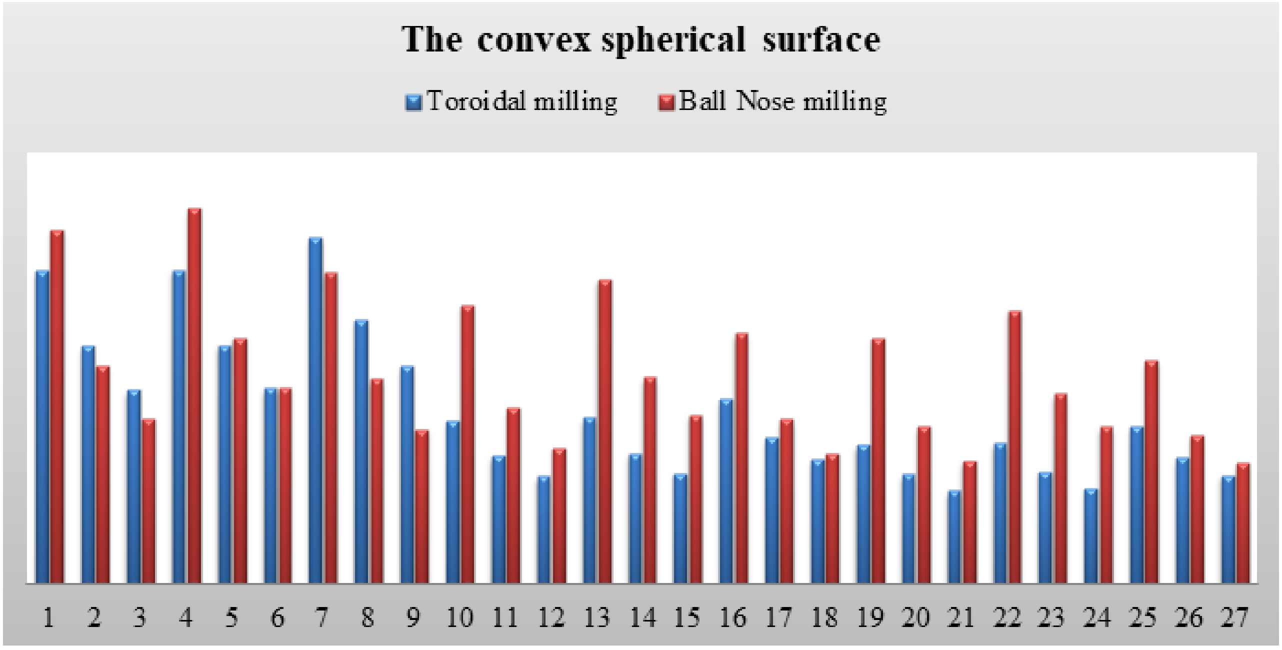

Fig. 7. Graphical analysis of the execution times for the processing of the convex spherical surface

3.3 Surface quality analysis

The analysis of table 3 reveals the measured values of the roughness on the convex spherical surface processed with the spherical mill. The smallest value of the arithmetic mean Ra was recorded in the parallel direction on the SFCX-SF-15 surface with the value Ra = 0.439 [µm] having variable processing parameters vc = 370 [m / min] fz = 0.13 [mm / tooth] and the inclination of the 35º tool axis. The highest value recorded for Ra is 1,194 [µm] for the SFCX-SF-11 surface processed with vc = 370 [m / min] fz = 0.09 [mm / tooth] and the tool axis inclination of 15º.
According to ISO, the minimum value of the theoretical roughness Rt is recorded with the value of, Rt = 2,567 [µm] on the surface SFCX-SF-15, where the smallest arithmetic mean of the roughness Ra is recorded and the highest value of the theoretical roughness Rt is recorded is 8.133 [µm] measured perpendicular to the feed direction on the SFCX-SF-11 surface where the highest roughness value Ra was recorded.
In the case of the convex spherical surface processed with the toroidal milling cutter the smallest value for Ra is 0.372 [µm] in the case of the SFCX-TR-8 surface processed with vc = 80 [m / min] fz = 0.15 [mm / tooth] and 55º tool axis inclination. The maximum value Ra is 1.199 [µm] measured perpendicular to the feed direction for the SFCX-TR-1 surface processed with vc = 80 [m / min] fz = 0.11 [mm / tooth] and the tool axis inclination of 15º. The minimum Rt value is 2.786 [µm] for the SFCX-TR-8 surface and the maximum value for Rt is 7.606 [µm] for the SFCX-TR-1 surface.

Table 3: The results related to the processing of the convex 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
SFCX-SF-1	0.595	0.492	4.101	3.246
SFCX-SF-2	0.717	0.440	4.466	3.609
SFCX-SF-3	0.630	0.722	4.012	4.926
SFCX-SF-4	0.563	0.582	4.613	3.746
SFCX-SF-5	0.511	0.592	3.602	4.180
SFCX-SF-6	1.218	0.958	7.286	6.920

SFCX-SF-7	0.701	0.748	4.213	5.046
SFCX-SF-8	0.915	0.634	5.646	4.693
SFCX-SF-9	0.832	0.847	5.667	5.379
SFCX-SF-10	0.588	0.935	4.219	7.046
SFCX-SF-11	1.194	0.992	3.680	8.133
SFCX-SF-12	0.747	0.649	4.866	5.166
SFCX-SF-13	0.656	0.955	4.153	6.739
SFCX-SF-14	0.651	0.465	4.866	3.280
SFCX-SF-15	0.439	0.696	2.567	7.752
SFCX-SF-16	0.708	0.466	4.303	3.346
SFCX-SF-17	0.667	0.645	4.846	4.560
SFCX-SF-18	0.695	0.911	4.380	7.330
SFCX-SF-19	0.485	0.749	4.076	4.993
SFCX-SF-20	0.503	0.620	3.599	4.373
SFCX-SF-21	0.742	0.831	4.893	5.260
SFCX-SF-22	0.547	0.473	3.746	3.079
SFCX-SF-23	0.532	0.511	3.136	3.993
SFCX-SF-24	0.773	0.545	6.226	3.733
SFCX-SF-25	0.731	0.624	4.890	3.966
SFCX-SF-26	0.896	0.746	6.033	4.793
SFCX-SF-27	0.611	0.561	4.792	3.373

Table 4: The results of the processing of the convex spherical surface with toroidal milling

Surface type	**Roughness Ra[μm]**		**Roughness Rt[μm]**	
	Direction of measurement in relation to the direction of advance			
	Parallel	**Perpendicular**	**Parallel**	**Perpendicular**
SFCX-TR-1	0.672	1.199	3.599	7.606
SFCX-TR-2	0.711	0.903	4.253	6.153
SFCX-TR-3	0.653	0.702	4.339	3.900
SFCX-TR-4	0.632	0.737	4.066	4.652
SFCX-TR-5	0.909	0.862	5.140	6.927
SFCX-TR-6	0.705	0.979	4.567	6.033
SFCX-TR-7	0.622	0.522	3.306	3.673
SFCX-TR-8	0.372	0.497	2.786	2.813
SFCX-TR-9	0.641	0.881	3.873	4.619
SFCX-TR-10	0.591	0.636	3.626	5.547
SFCX-TR-11	0.556	0.673	3.693	3.899
SFCX-TR-12	0.629	0.887	3.693	6.920
SFCX-TR-13	0.622	0.544	4.113	5.173
SFCX-TR-14	0.697	0.634	3.953	5.686
SFCX-TR-15	0.721	0.717	3.953	5.386
SFCX-TR-16	0.604	0.506	3.360	2.780

SFCX-TR-17	0.530	0.551	2.927	3.580
SFCX-TR-18	0.588	0.798	3.486	4.506
SFCX-TR-19	0.520	0.453	3.827	4.287
SFCX-TR-20	0.624	0.486	4.020	4.073
SFCX-TR-21	0.540	0.999	4.400	6.566
SFCX-TR-22	0.673	0.488	6.587	3.286
SFCX-TR-23	0.691	0.760	5.146	4.792
SFCX-TR-24	0.763	1.003	3.899	7.100
SFCX-TR-25	0.550	0.480	3.039	2.793
SFCX-TR-26	0.625	0.599	3.767	3.226
SFCX-TR-27	0.599	0.572	3.273	2.086

Comparing the quality of the convex spherical surfaces, the smallest value of the roughness Ra is integrated by the toroidal milling process with a difference of 0.067 [µm]. Regarding Rt, the smallest value is recorded by the spherical milling process, with a difference of 0.219 [µm] compared to the toroidal milling.

The convex spherical surface was a challenge in the tool path, representative for me was the realization of a spherical convex surface with both spherical and toroidal milling. From the point of view of the surface quality, the toroidal mill has a slight advantage over the spherical mill, the inclination angle being 55º, where at this angle and the toroidal milling wear is smaller than the spherical milling wear.

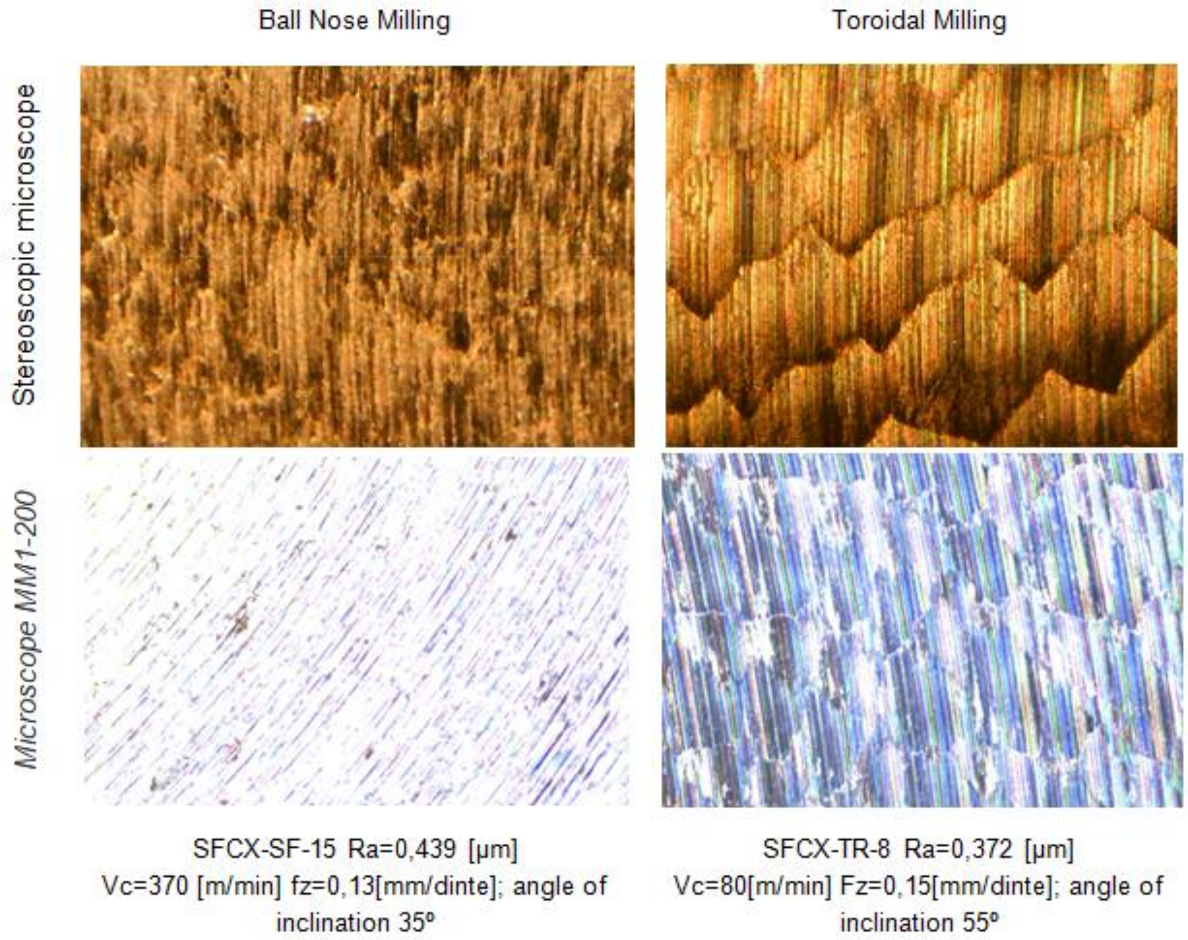

Fig. 8. Microscopic images of the quality of the surfaces processed with the two mills

Figure 8 illustrates the microscopic topography obtained with the IOR stereoscopic microscope and the MM1-200 microscope on the surfaces with the best roughness processed with the spherical and toroidal milling.

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 the surfaces. It was chosen to compare the processed surfaces with the toriodal milling, respectively the spherical milling. The surface on which the roughness was investigated is the convex cylindrical surface.

As variable parameters it was decided to juggle with the cutting speed, the tooth advance and the inclination angle of the tool. It was decided to process 27 surfaces with toroidal milling and 27 surfaces processed with spherical milling.

From the point of view of the execution time, the fastest processing was done with the toroidal milling machine in one minute and 48 seconds in the case of the maximum speeds at the angle of 15º compared to the fastest processing obtained with the spherical milling machine in 2 minutes and 20 of seconds also at maximum speeds but at 55º angle of inclination.

Regarding the surface quality, the best surface quality was obtained with the toroidal milling machine, having the value Ra = 0.372 [µm] with Vc = 80 [m / min], Fz = 0.15 [mm / tooth] and the angle inclination of 55º. In the case of spherical milling, the best surface quality was recorded using the regimes Vc = 370 [m / min], fz = 0.13 [mm / tooth] and the inclination angle of 35º recording the value Ra = 0.439 [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 convex 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

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