ACCURACY ANALYSIS OF MILLING MACHINE BASED ON TEST PIECE MACHINING AND MEASUREMENT

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Abstract: *This study proposed to perform machining of a test piece with a characteristic preset shape in order to evaluate the accuracy of a three-axis CNC milling machine. The finishing of the test surfaces was carried out with a carbide end mill for a fixed position of the test piece on the machine table. The dimensional and shape accuracy of the test piece was evaluated by measurements on a coordinate measuring machine. The flatness of the machined surfaces and their mutual parallelism and squareness were measured. Furthermore, the roundness and cylindricity of the machined hole were tested. The obtained results indicate on the possibility of indirectly assessment of milling machine accuracy.*

Key words: *3-axis milling machine, test piece, coordinate measuring machine, accuracy test*

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1. Introduction

In recent years, the machine tool industry has seen an increase in demand for the use of multi-axis machining centers in manufacturing processes. Diagnostic tests of currently utilized CNC milling machines have recently gained importance. Determination of a current technical status of a machine and predictability of its changes over time leads to improvement of its properties. Ultimately it results in maintaining the primary properties of a milling machine, which translate into the precision of milled items (Polzer et al., 2014).

A detailed description on identification of errors of utilized CNC milling machines and prediction of their occurrence based on the history of changes of a milling machine technical condition was published (Jozwik, 2018). Another study included an exemplary analysis of a CNC milling machine accuracy, determined with a ballbar method (Jozwik et al., 2010). Selected errors with their respective causes were identified and described, together with proposed methods of their minimization.

The essential diagnostic tools used to determine the geometric accuracy of a milling machine are: laser interferometer (Okafor & Ertekin, 2000), HMS - Head Measuring System (Honczarenko & Kwasniewicz, 2008), R - test (Weikert & Knapp, 2004) oraz QC - 20 ballbar (Wolny, 2018).

The most important tasks of a machine tool include the cutting process. Cutting of a test piece is a basic test that indirectly evaluates the geometric accuracy and positioning precision of a machine. Furthermore, many factors must be taken into account when conducting tests that may alter the accuracy of the test piece.

The aim of the current study was to assess the dimensional and shape accuracy of a three axis CNC milling machine through machining and measuring of a test piece. The present paper proposes a cube-shaped test piece that was finish-milled on the pocket and hole surfaces, for a fixed position in the machine tool workspace. Its accuracy was checked by measurements on a coordinate measuring machine. The flatness of the machined surfaces and their parallelism and squareness were measured. Roundness and cylindricity were determined for the machined hole. The results obtained provide opportunities for an indirect evaluation of the accuracy of the milling machine.

2. Basic standards for machining test pieces

One of the first tests to evaluate the accuracy of multi-axis machine tools was NAS 979, developed by the Aerospace Industries Association of America, Inc. Chapter 4.3 characterizes the truncated cone test piece and test conditions (NAS 979, 1969).
Figure 1 shows a simplified cone machining diagram according to NAS. In practice, both machine tool manufacturers and users perform finish machining of the truncated cone and set their own test conditions. Since this method is simple and most commonly used, it is likely to be modified and introduced as a new standard.

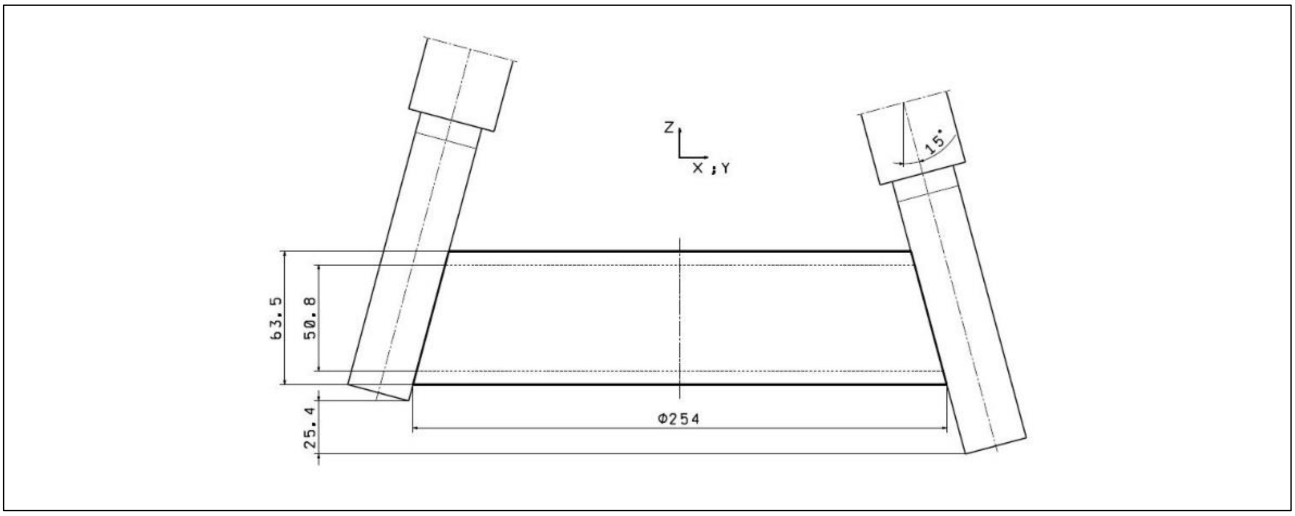

Fig. 1. Machining of a truncated cone according to NAS 979.

ISO 10791-7 standard, which was established in 1998, consists of two machining tests. The first is a test of making a complex test piece using an end mill tool. The second is a test of machining a flat surface by face milling (PN-ISO 10791-7, 2014). Figure 2 shows a test piece made in accordance with the requirements of the standard. In 2009, work began on revising the standard by designing a new test piece for testing 5-axis machine tools.

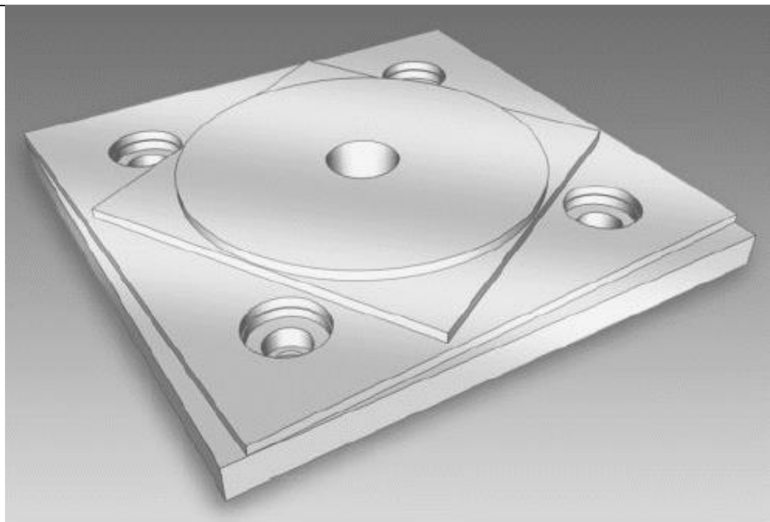

Fig. 2. Test piece according to ISO 10791-7.

In a study by Bossoni (Bossoni, 2010), a test piece (Fig. 3) was proposed as a basis for modifying the ISO standard without considering its position and orientation (ISO/DIS 10791-7, 2012).
Other suggestions for the use of test piece machining to evaluate the accuracy of machine tools are presented in papers (Takeshima & Ihara, 2009; Ibaraki et al., 2010; Wolny, 2016). A new, very interesting approach to the accuracy analysis of CNC milling machines was presented in the work (Piorkowski & Skoczynski, 2021) and Figure 4 shows test piece. In all the cited studies, the test piece was characterized by a complex shape and was used to evaluate the accuracy of 5-axis machining centers.

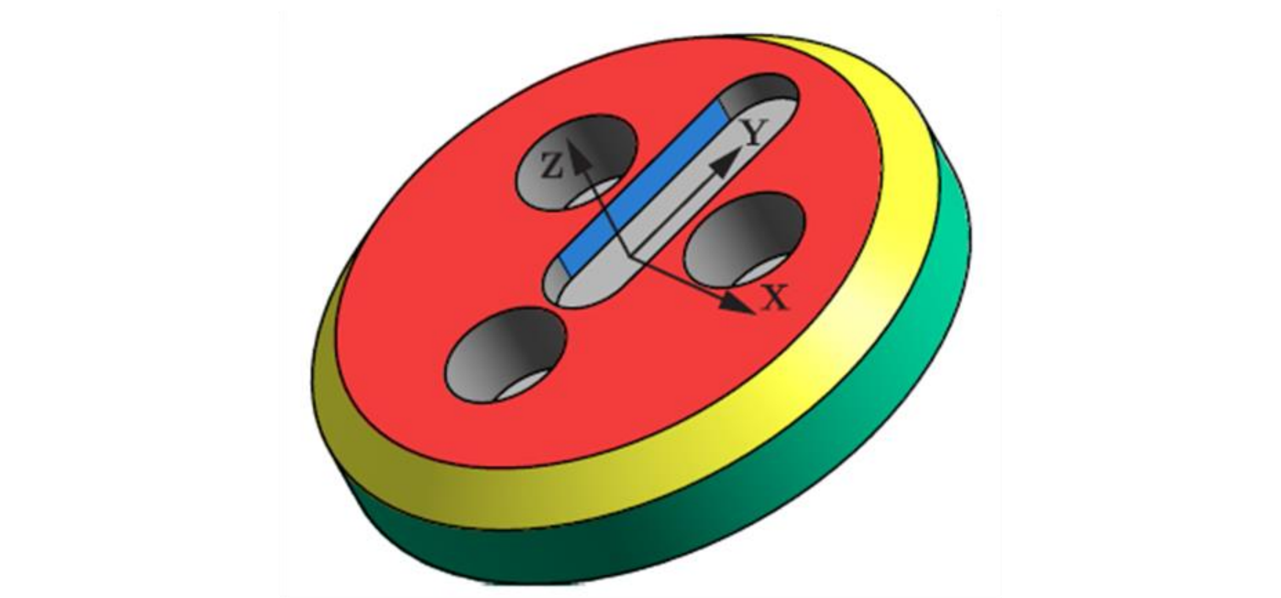

Fig. 3. Test piece proposed in a study (Bossoni, 2010).

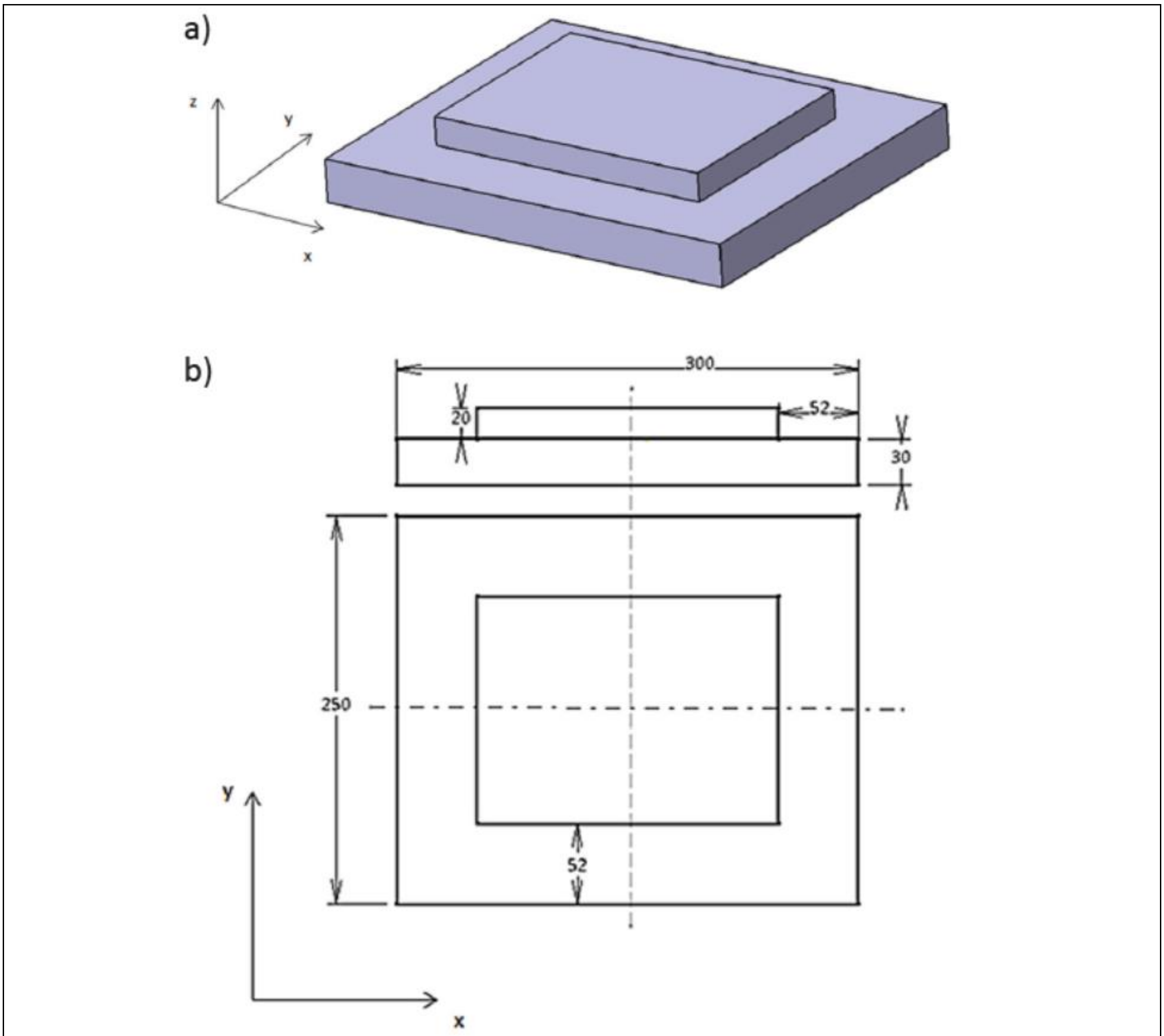

Fig. 4. Test piece of a numerically controlled milling machine (a) model, (b) dimensions (Piorkowski & Skoczynski, 2021).

3. CNC machine tool studied

The accuracy test was performed for a vertical milling center R550 (Andrychowska Fabryka Maszyn DEFUM, Poland). The machine tool was manufactured in 2016 and has been used in the students didactic process.
The CNC milling machine had three numerically controlled axes (Fig. 5) and SINUMERIK 828D software (DEFUM, 2022).

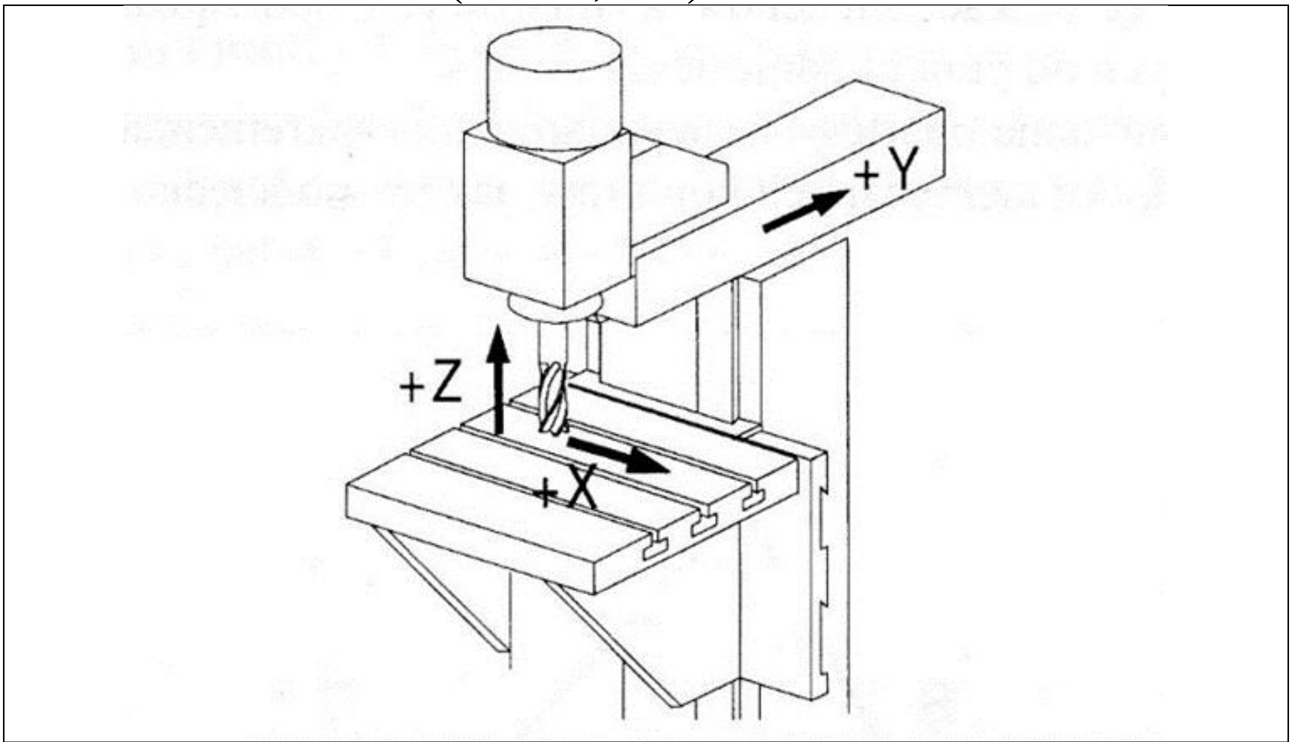

Fig. 5. Arrangement of axes of a vertical milling center R550.

4. Machine tool accuracy test

A cube-shaped test piece, with its 3D model and dimensions as shown in Figure 6, was proposed to perform the accuracy test.
In the process of designing the shape and size of the test piece it was assumed that the milling machine will be performing working movements along all numerically-controlled axes during the process of test machining.
The adopted solution enables the multiple use of the same piece for the diagnostics of a machine tool. Further tests of a milling machine should be performed according to a predefined schedule.
The test piece, made of aluminum alloy, was rough machined with an allowance of 0.7mm for finishing the pocket and cube hole surfaces.

The accuracy test consisted in finish machining of the pocket and the hole using a brand new carbide cutter with a diameter of d_1=8mm. A three-edged tool with an overall length of l_1=100mm and a shank diameter of d_2=10mm was characterized by a helix angle of 45° and a hardness of 55HRC (Fig. 7). The finishing program was generated using the Sinutrain Shop Mill system. The cutting parameters of the pocket surface and hole of the test piece and the machining process are shown in Table 1.

Parameters	**Dimension**
Spindle speed, n	3800 r.p.m.
Cutting tool diameter, DC	8 mm
Cutting speed, v_c	100 m/min
Feed rate, v_f	400 mm/min
Feed per tooth, f_z	0,04 mm/tooth
Depth of cut, a_p	0,2 mm

Tab. 1. Finishing parameters for milling operation.

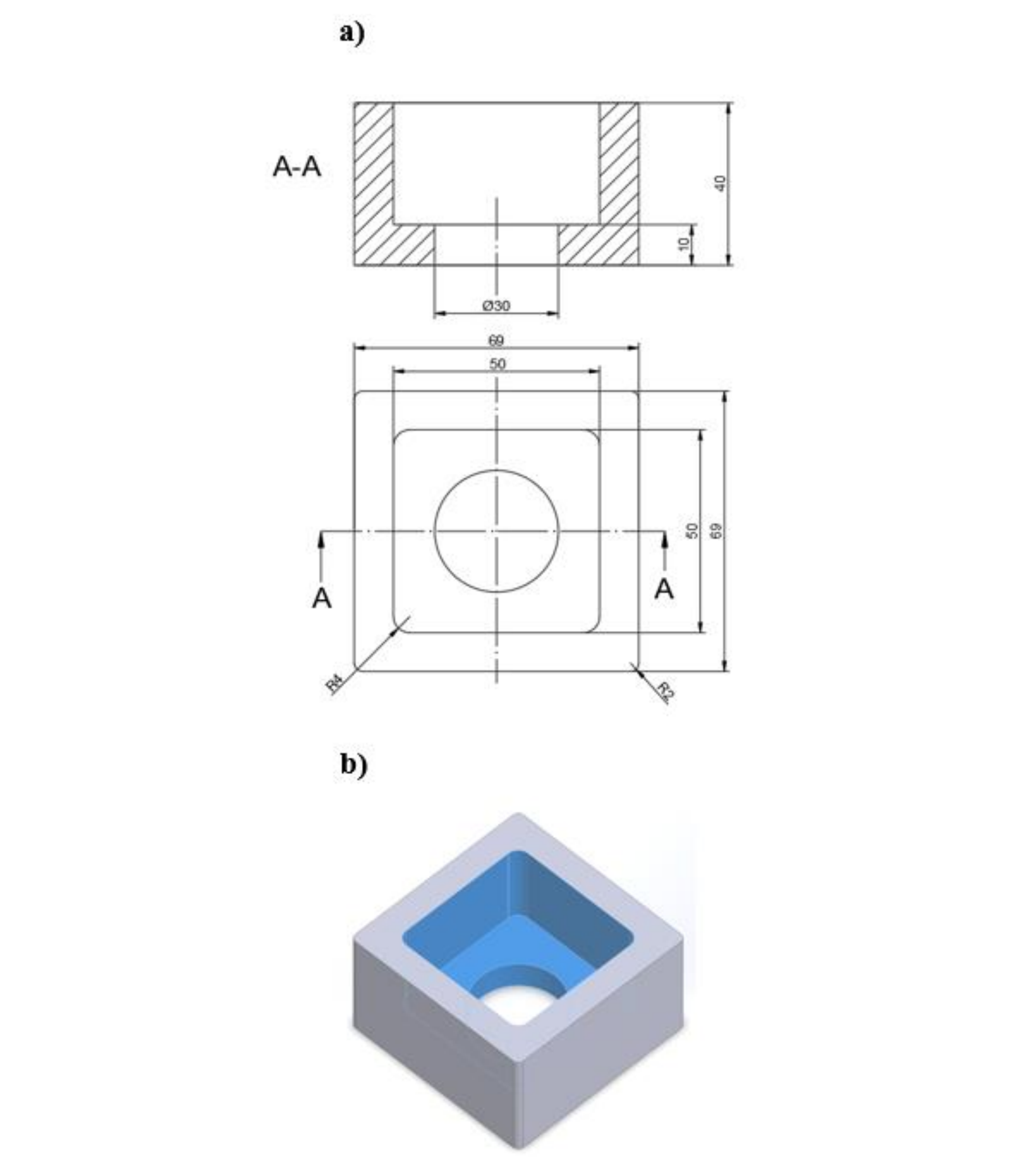

Fig. 6. Test piece designed: a) dimensions, b) model.

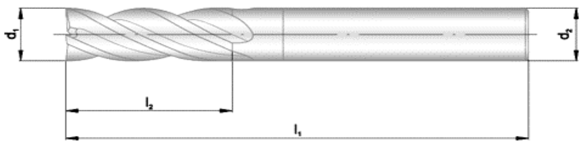

Fig. 7. Test milling cutter for finishing.

5. Measurement analysis of the test piece

The machined test piece was measured on a Carl Zeiss Eclipse 700 coordinate measuring machine using Zeiss Calypso 4.2.08 software (Fig. 8).

Fig. 8. View of the measuring station.

The accuracy analysis of coordinate measuring machines (CMM), the issue of measurement uncertainty and methods of assessing their precision were presented in the following paper (Adamczak et al., 2017). Tests of measurement uncertainty performed for two CNC machine tools with the use of inspection probes as well as the analysis of random and systematic errors were included in the study (Semotiuk, et al., 2013). Figure 9 presents the test piece on the CMM table, which was subjected to a precise measurement analysis.

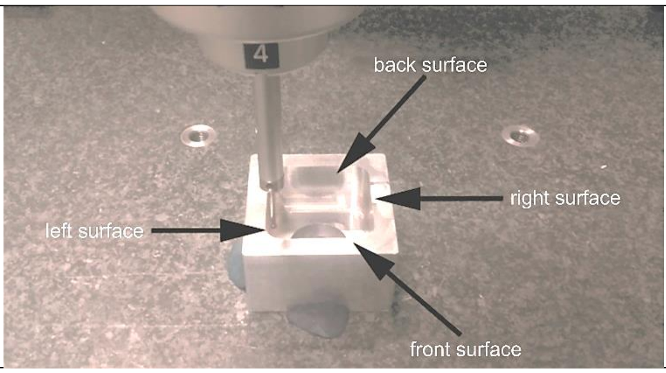

Fig. 9. Test piece on a coordinate measuring machine.

The flatness of the machined surfaces, the parallelism of the opposite pocket walls, and their mutual squareness were measured. Furthermore, measurements of roundness and cylindricity of the hole were made.

The flatness, parallelism, and squareness values were determined using 400 measurement points for each of the four pocket surfaces of the test piece. The roundness of the hole was measured at three different heights, each with 200 points of contact of the measuring head. The cylindricity of the hole was determined at four heights, yielding a total of 800 measured values. Measurement results of flatness, parallelism and squareness of test piece machining surface are shown in Table 2.

Kind of measurement	**Result of measurement [mm]**	**Dimension deviation [mm]**	
		max	**min**
Flatness left surface	0,0148	0,0074	-0,0074
Flatness right surface	0,0143	0,0071	-0,0071
Flatness back surface	0.0148	0,0074	-0,0074
Flatness front surface	0,0164	0,0082	-0,0082
Parallelism left-to-right surface	0,0260	0,0133	-0,0127
Parallelism front-to-back surface	0,0443	0,0226	-0,0216
Squareness back-to-right surface	0,0165	0,0113	-0,0052
Squareness back-to-left surface	0,0168	0,0113	-0,0055
Squareness front-to-right surface	0,0191	0,0117	-0,0074
Squareness front-to-left surface	0,0193	0,0120	-0,0073

Tab. 2. Measurement results of flatness, parallelism and squareness of test piece machining surface.

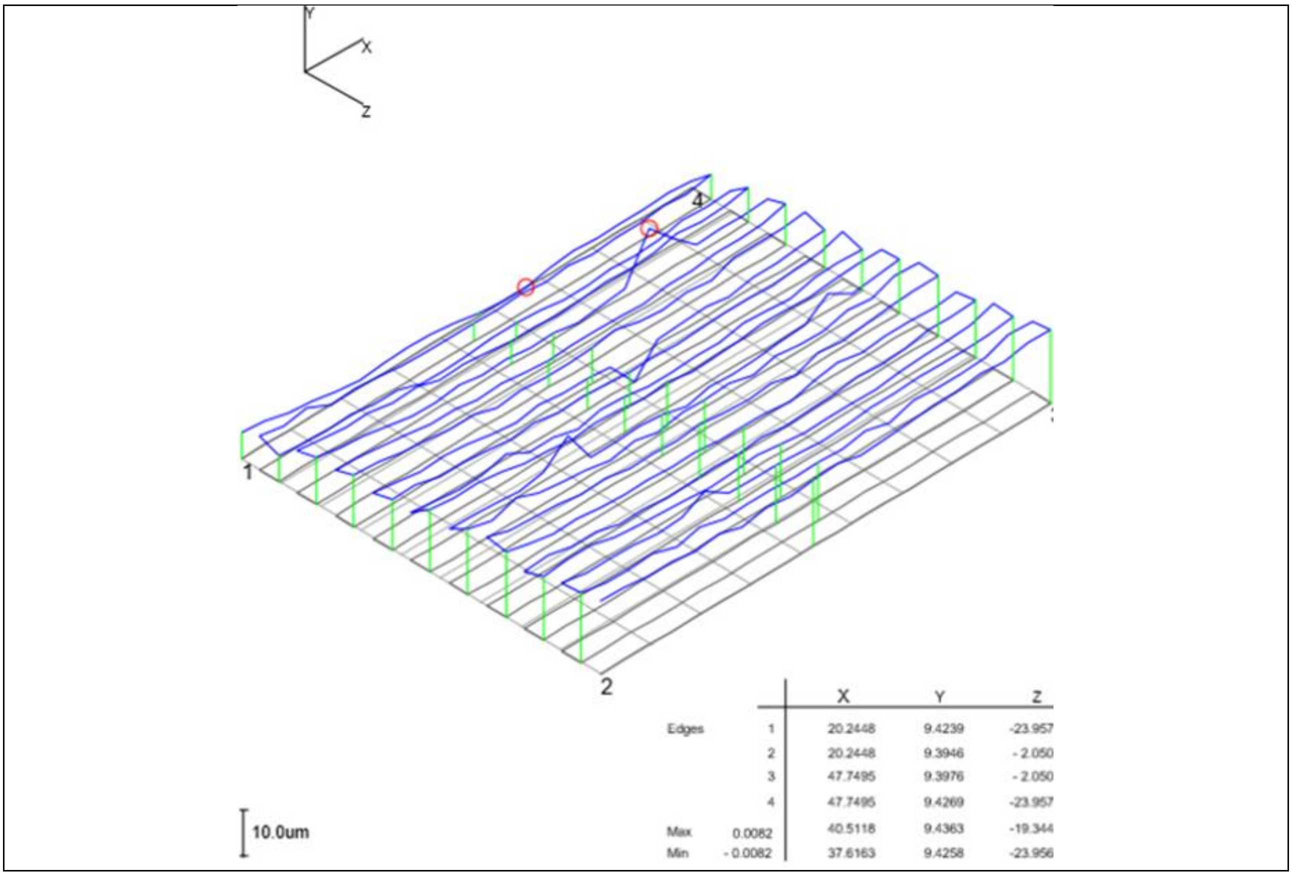

Fig. 10. Flatness of the front surface.

The flatness of all surfaces was within the set tolerance of T=0.02mm and was 0.015mm for the left surface, 0.014mm for the right surface, 0.015mm for the back surface, and 0.016mm for the front surface. The measurement deviation was ±0.008mm. A graphical illustration of the flatness of the front surface is shown in Figure 10.

The measurement of surface flatness is closely related to the straightness deviation of the machine axis. This deviation occurs in the case of local deformation of the guides and is likely to be caused by wear or damage of the guides. The magnitude of the straightness error does not depend on the feed rate.

The measurements of the left-to-right surface parallelism were 0.026mm and within the set tolerance of T=0.05mm. The parallelism of the front and back surfaces was determined to be 0.044mm and was also within the set tolerance.

Squareness means the deviation of a machine tools axis direction from a right angle, which can be local or caused by the incorrect shape of the slides along their length. Machine tool axes may exhibit deformation in the vertical plane and excessive wear resulting in increased backlash during motion. The squareness error in the machine tool translates into a deviation in the squareness of the milled surfaces and problems with shaping cylindrical surfaces.

All squareness measurements of the machined surfaces of the test piece pockets were within tolerance T=0.05mm. This means that all the measurement points of a given surface were located between two planes 0.05mm apart and perpendicular to the adjacent plane. The largest squareness error was obtained for the front and left surfaces at 0.019mm. An image of squareness measurement back to left surface is shown in Figure 11.

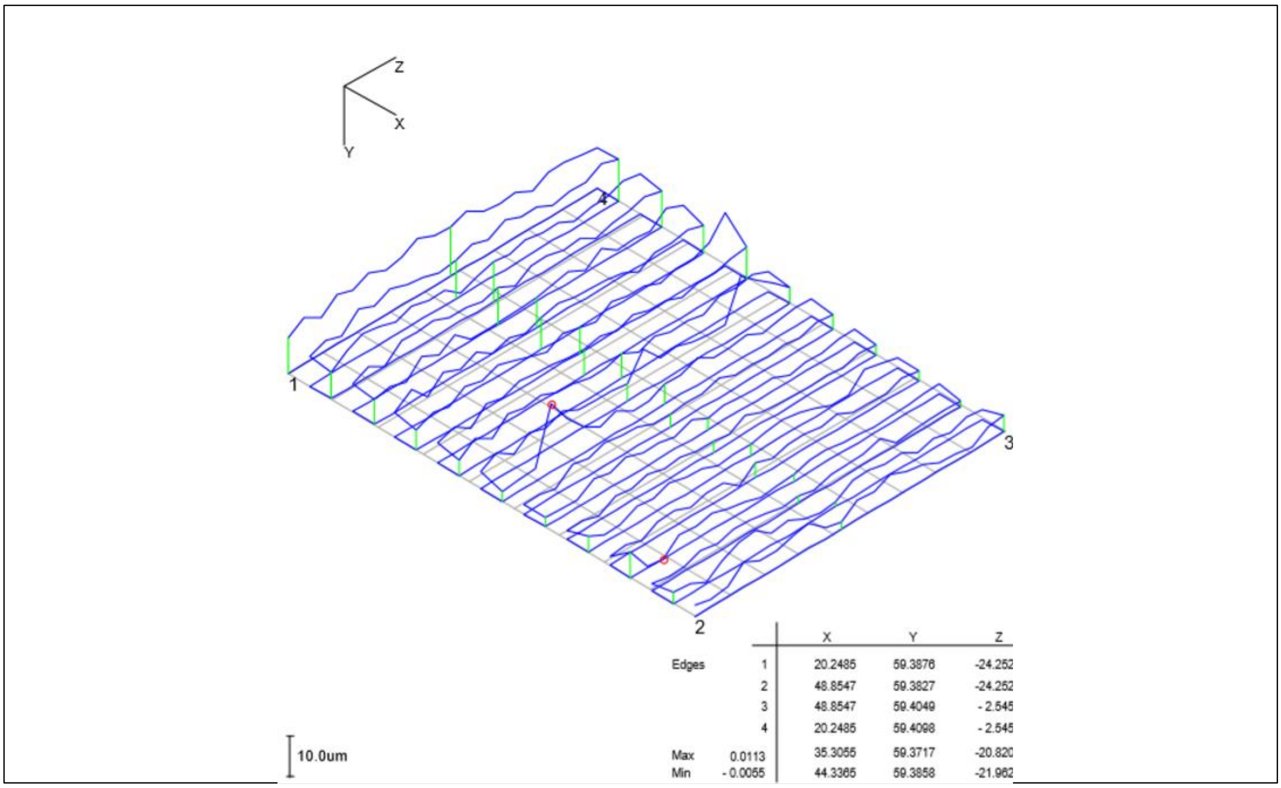

Fig. 11. Squareness of the back to left surfaces.

In Table 3 were presented measurement results of roundness and cylindricity of test piece machining hole.

Kind of measurement	Result of measurement [mm]	Dimension deviation [mm]	
		max	min
Top roundness	0,0180	0,0027	-0,0027
Center roundness	0,0191	0,0027	-0,0027
Bottom roundness	0.0219	0,0027	-0,0027
Hole cylindricity	0,0887	0,0163	-0,0163

Tab. 3. Measurement results of roundness and cylindricity of test piece machining hole.

The roundness of the machined hole in the test piece was measured at three different heights. The results obtained were 0.018mm for the top position, 0.019mm for the middle position, and 0.022mm for the bottom position. An unequal backlash can be identified through analysis of the measurements results. The causes of this error include torsional stress on the ball screw and wear of the ball screw or the guides. Possible countermeasures are compensation of backlash in individual axes of the machine tool and checking the condition of the ball screw and the nut, and the accuracy of the milling machine guides.

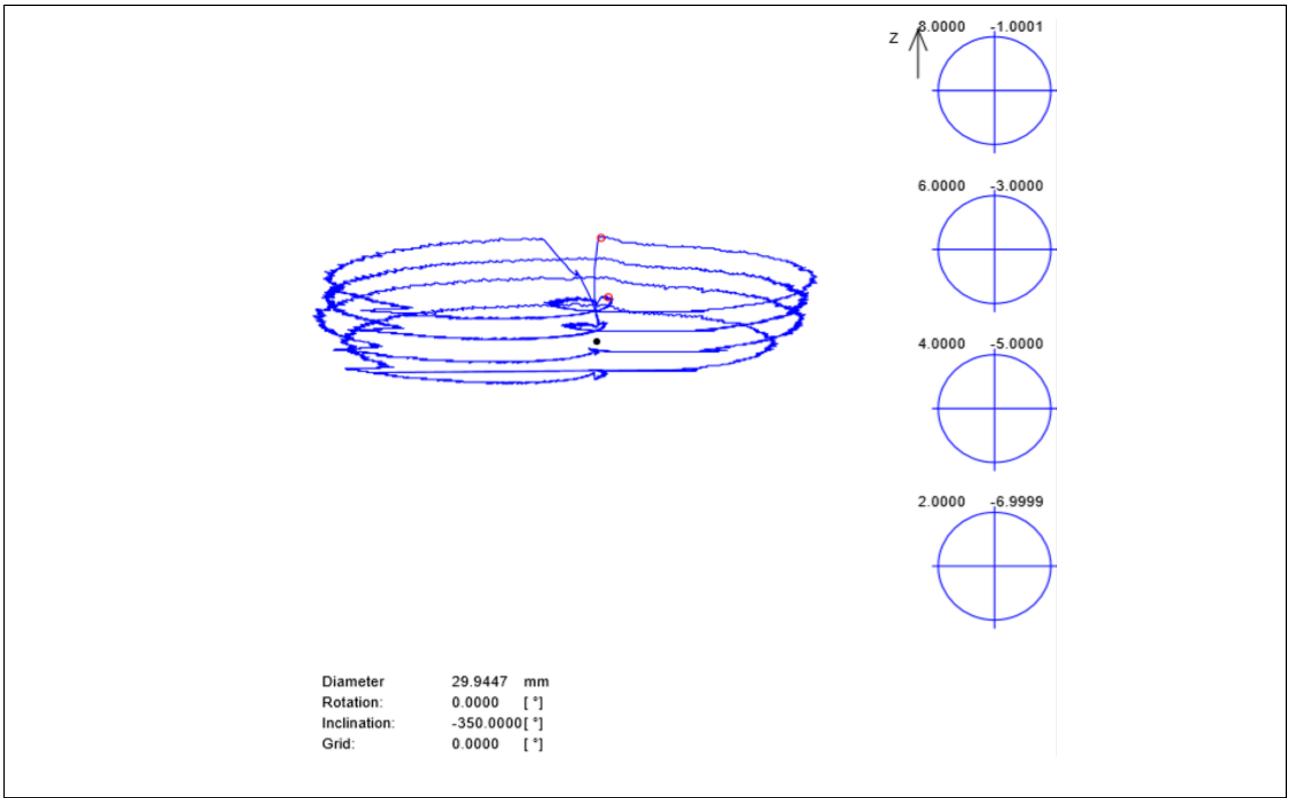

Fig. 12. Measurement of the cylindricity of the hole at four different heights.

The last step was the measurement of the cylindricity of the hole in the test piece. The measured value was not within the set tolerance of T=0.05mm and was 0.089mm (Fig. 12). Based on a careful analysis of the obtained results it is possible to identify reversal spikes, which occur where the feed direction is changed for individual axes. The value of this error usually depends on the set value of the machine feed rate.

6. Conclusion

According to the aim of the paper, a specifically shaped test piece was designed, which subsequently underwent finish machining and measurements with the use of coordinate measuring machine in order to perform an indirect accuracy assessment of a 3-axis CNC milling machine.

The results are as follows:

1. The shape and size of the test piece requires simultaneous operation of servo mechanisms of each axis of the milling machine during finish machining.
2. The proposed solution allows for repeated use of the same test piece in the diagnostic process of a milling machine, according to a predefined schedule.
3. Machining accuracy of the test piece can be easily determined by measuring the following parameters with CMM: flatness, parallelism, squareness, roundness and cylindricity.
4. The finish machining of the test piece indirectly determines the accuracy of the 3-axis CNC milling machine.

Based on the obtained results it cannot be unequivocally confirmed that the tested of a milling machine meets the requirements. It should be noted that the results of the test of a 3-axis machining center depend on the knowledge and skills of the programmer technologist, the experience of the machine tool operator, and the qualifications of the controller. Therefore, it should be considered whether the proposed accuracy test can be regarded as the norm.

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