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Marcin MATUSZAK
Maritime University of Szczecin, Poland
Mechanical Department
m.matuszak@am.szczecin.pl

Alessandro GARBELLINI
University Of Brescia, Italy
Department Of Mechanical And Industrial Engineering

Bartosz POWAŁKA
West Pomeranian University of Technology, Szczecin, Poland
Department of Mechanical Engineering and Mechatronics

Aldo ATTANASIO
University Of Brescia, Italy
Department Of Mechanical and Industrial Engineering

Emilia BECHTIAK-RADKA
West Pomeranian University of Technology, Szczecin, Poland
Department of Mechanical Engineering and Mechatronics

ACCURACY ANALYSIS OF THE MICRO-MILLING PROCESS

Key words: micro milling, machining accuracy, cutting forces, prototype machine tool.

Abstract: Machining errors can be caused by various factors, such as thermal deformations of milling machine, drives and milling machine accuracy, tool run out, tool deflections during the machining process, and workpiece setup errors. The main purpose of this paper is to determine and compare machining errors of a Kern Pyramid Nano milling machine and a prototype micro milling machine built at West Pomeranian University of Technology in Szczecin. Since not all of the errors can be measured with specialized measurement equipment, a milling experiment of a complex part with various geometrical features was performed. Machining errors can change in time due to thermal deformations; therefore, the milling experiment was performed on a cold machine and for machine after a warm up procedure. In order to avoid workpiece set up errors, the workpiece surface was first milled before machining. The influence of tool run out and tool deflections were neglected. Major factors that affect the milling process are both the machine and drive accuracy. During the milling experiment, cutting forces were recorded. The machined sample was measured in order to compare machining errors with the reference geometry.

Analiza dokładności procesu mikrofrezowania

Słowa kluczowe: mikrofrezowanie, dokładność obróbki, siły skrawania, prototypowa obrabiarka.

Streszczenie: Błędy obróbki skrawaniem mogą być spowodowane różnymi czynnikami takimi jak: odkształcenia termiczne obrabiarki, dokładność napędów oraz obrabiarki, bicie osiowe narzędzia, odkształcenia narzędzia podczas obróbki oraz błędy ustawienia przedmiotu obrabianego. Głównym celem prezentowanego artykułu jest określenie i porównanie błędów obróbki precyzyjnej frezarki Kern Pyramid Nano oraz prototypowej mikrofrezarki zbudowanej w Zachodniopomorskim Uniwersytecie Technologicznym w Szczecinie. Nie wszystkie błędy frezarki mogą być zmierzone za pomocą wyspecjalizowanej aparatury pomiarowej. Z tego względu zdecydowano się wykonać frezowanie części o złożonej geometrii. Błędy obróbki mogą zmieniać się w czasie z powodu odkształceń termicznych obrabiarki. Z tego względu eksperyment mikrofrezowania wykonano zarówno dla maszyny zimnej, jak i dla maszyny po procedurze rozgrzewania jej. Aby uniknąć błędów ustawienia przedmiotu obrabianego, powierzchnia przedmiotu obrabianego została najpierw przefrezowana. Wpływ bicia osiowego oraz odkształceń narzędzia podczas obróbki został pominięty. Głównym czynnikiem, który wpływa na dokładność obróbki, to dokładność obrabiarki oraz dokładność napędów. Podczas eksperymentu rejestrowano siły skrawania. Obrobiona próbka została zmierzona, aby porównać błędy obróbki z geometrią odniesienia.

Introduction

Accuracy of the micro-milling process can be affected by various factors, such as machine tool accuracy (perpendicularity and parallelism of machine axes), drive accuracy and repeatability, tool run out, thermal deformations [4, 8], tool deformations [7, 9], tool wear [9], and errors in setting the workpiece. Commercially available precision milling machines can be equipped with systems, such as a cooling system with temperature stabilization that can ensure high accuracy and low thermal deformations. These machines usually have a precision of machining better than 1 μm and a workspace that gives the possibility of more than micro-component machining.

Other kinds of machine tools that can be considered are experimental and prototype micro-milling machine tools. These machine tools are built in research centres and at universities [2, 5, 6] to investigate the micro-milling process and ensure high machining accuracy. These machine tools usually have a smaller workspace and can ensure better accuracy than commercially available machines. The main disadvantage of these machines is that they usually cannot be used in a production line.

Another aspect that must be considered is the method of machine error measurement. This can be achieved by using special equipment used for machine error measurement or by machining parts that have complex shapes. The investigated milling machines are located at different universities with a large distance between them; therefore, the usage of the same error measurement equipment at both machine tools was not possible. Machining of a complex part was chosen for machine tool accuracy comparisons.

1. Milling machine tools

The milling experiment was performed on two different machine tools. The first machine tool is a commercially available KERN Pyramid Nano. The second machine tool is a SNTM-CM-ZUT-1 prototype micro-milling machine built at the West Pomeranian University of Technology in Szczecin.

The KERN Pyramid Nano (Fig. 1a) is a CNC machining centre that has a clamping area of 600x600 mm and axes travel in X, Y, and Z directions of 500, 500, and 400 mm. It is equipped with hydrostatic drives that can ensure 1 μm precision of the workpiece machining and 0.3 μm positioning scatter. To avoid thermal deformations, it has a water cooling system for the milling spindle, a dividing head, a hydraulic unit, an electrical cabinet, and the coolant device. Moreover, the machine room has to be air conditioned to ensure stable temperature.

The prototype SNTM-CM-ZUT-1 micro-milling machine (Fig. 1b) was specially designed for the machining of micro-components as a part of micro-milling investigation system [3]. The machine tool has workspace dimensions of 50x50x50 mm. It is equipped with Aerotech drives that have 2.5 μm accuracy in the X direction, 4 μm accuracy in the Y direction, and 3 μm accuracy in the Z direction. All axes have 0.1 μm repeatability. The machine body is made from granite to eliminate vibrations and avoid thermal deformations; however, some thermal deformations due to drive temperature changes can occur [8]. The machine spindle is SycoTec 4015 DC which has a run out less than 1 μm.

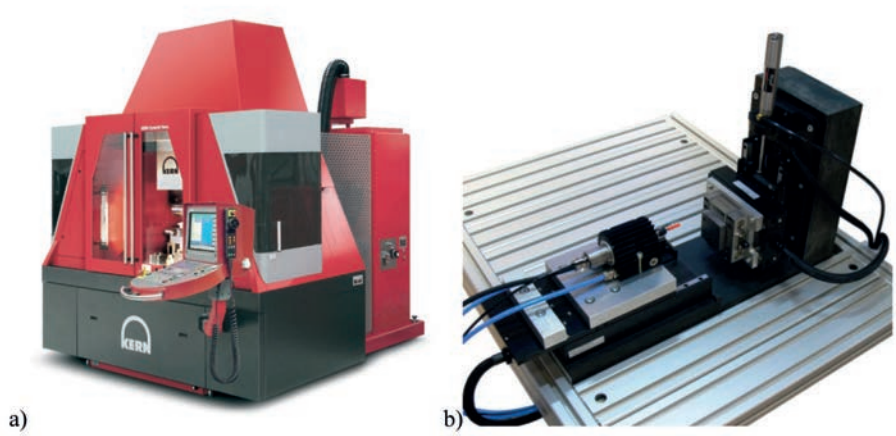

Fig. 1. View of a) KERN Pyramid Nano, b) prototype SNTM-CM-ZUT-1 micro-milling machine
Source: Photographs by the authors.

2. Workpiece geometry

The experiment was planned in a way that will provide the possibility to compare the accuracy of the two milling machines by comparing errors of a machined workpiece with complex geometrical features. The workpiece geometry is shown in Fig. 2. The geometry was designed to use the tool that has a 0.8 mm diameter and a 4 mm length. The geometry contains a 150 μm thin wall with a 4 mm deep pocket. It also has grooves of various depths (from 20 μm to 100 μm) at various angles. The tool used during experiment was Rime HM79/08. The workpiece was made of brass.

The machined part was mounted in a specially designed clamping system that was attached to the Kistler 9256C1 dynamometer (SNTM-CM-ZUT-1 prototype micro-milling machine) or the Kistler 9317C force sensor (KERN Pyramid Nano). During the experiment, cutting forces in the X, Y, and Z directions were recorded. The clamping system, the workpiece, and the force sensor at KERN Pyramid Nano are shown in Fig. 3a. Figure 3b shows the workpiece mounted on the prototype micro-milling machine tool. To avoid set up errors, the workpiece surface was machined after mounting it in the clamping system. For both KERN and prototype machine, tool experiments were performed for a cold machine and after a warm up procedure.

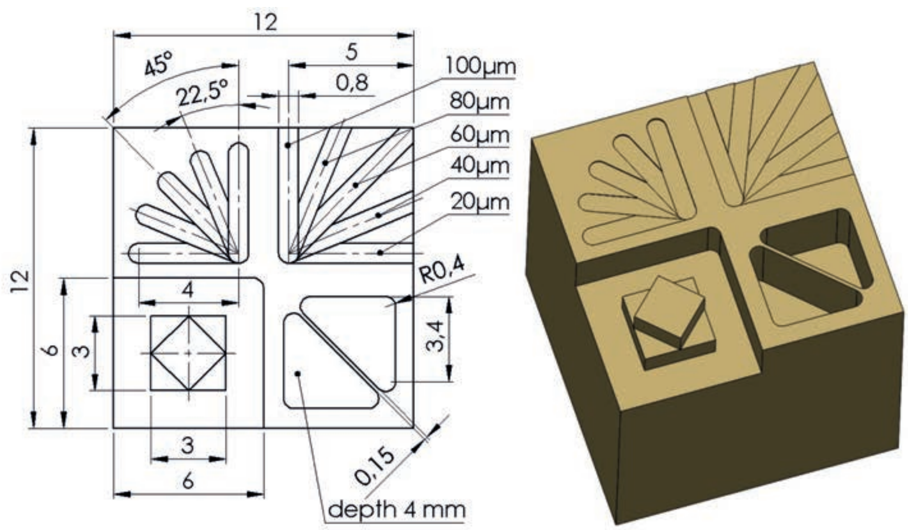

Fig. 2. The workpiece geometry
Source: Authors.

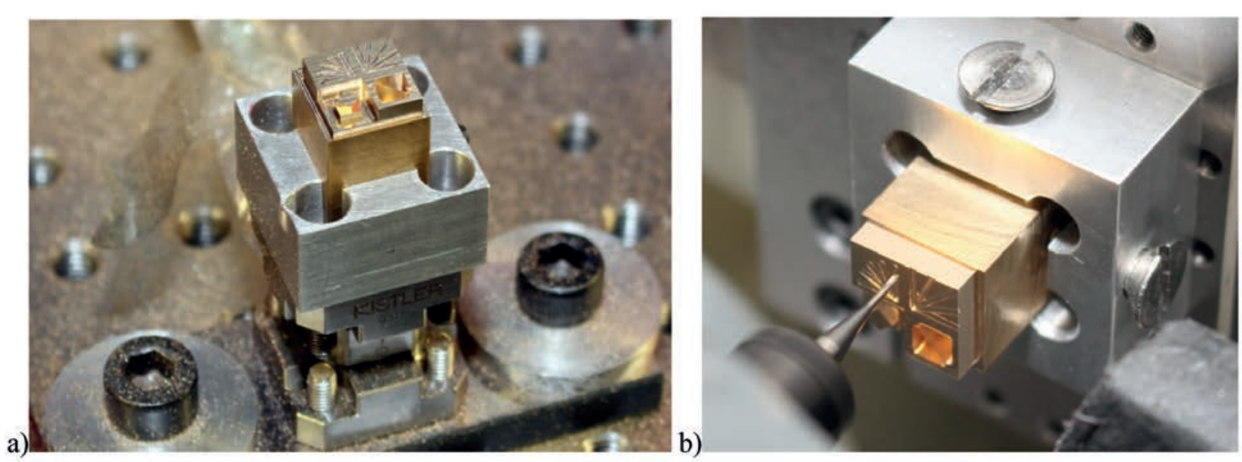

Fig. 3. The workpiece, the clamping, and the force sensor: a) KERN Pyramid Nano, b) prototype SNTM-CM-ZUT-1 micro-milling machine
Source: Photographs by the authors.

3. Part program and machining parameters

The KERN Pyramid Nano machine tool uses a Heidenhain numeric control. The prototype micro-milling machine tool is controlled by an Aerotech Ensemble Motion Composer. Part programs for these two control systems have to be written in different CNC machine programming languages; however, both control systems support a linear interpolation and give the possibility to move to a specified position at a certain speed. Therefore, part programs for both control systems were developed in Matlab to obtain the same tool paths and feed rates. For the thin wall machining approach showed in Figure 4, [1] was used in order to minimize its deformations due to the machining process.

The tool path for the machined workpiece is shown in Fig. 5.

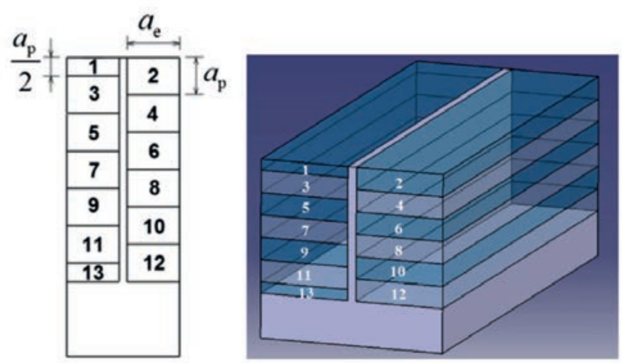

Fig. 4. Method of the thin wall machining [1]
Source: [1].

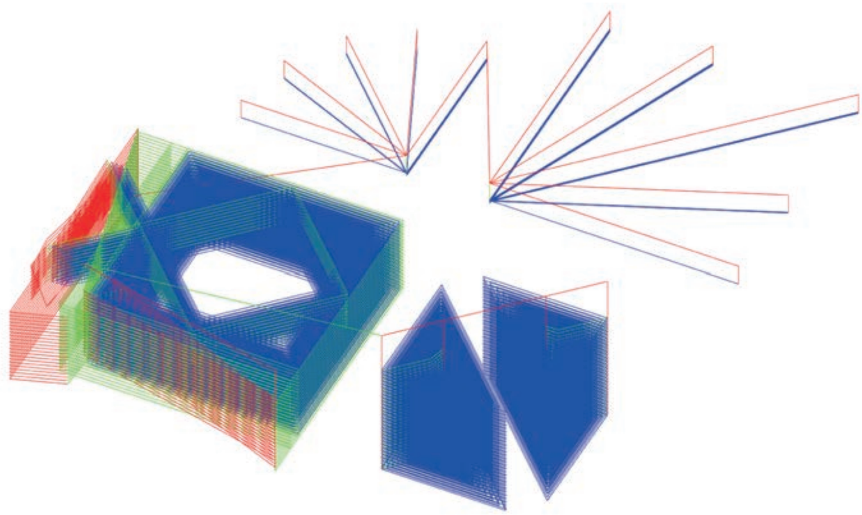

Fig. 5. The tool path simulation
Source: Authors.

Cutting parameters for the deep pocket machining and square geometry machining are shown in Table 1 (bottom geometrical features – Fig. 2). Cutting parameters were the same for the KERN Pyramid Nano and the SNTM-CM-ZUT-1 prototype micro-milling machine.

Table 1. Cutting parameters for deep pocket machining and square geometry

Rotational speed n [RPM]	Feed f_z [mm/tooth]	Feed v_f [mm/min]	Axial depth of cut a_p [µm]	Radial depth of cut a_e [µm]
45 000	0.020	1800	100	80

Grooves were milled with a full tool diameter; therefore, the feed rate was lower than for machining without full radial immersion. Cutting parameters for groove machining are shown in Table 2.

Table 2. Cutting parameters for grooves machining

Rotational speed n [RPM]	Feed f_z [mm/tooth]	Feed v_f [mm/min]	Axial depth of cut a_p [µm]	Radial depth of cut a_e [µm]
45 000	0.016	1440	20	800

4. Experimental results

The workpiece geometry was measured on the Alicona InfiniteFocusSL, which is typically used for a roughness measurement. The accuracy of the measurement is 0.5 μm in the X and Y directions and 0.05 μm in the Z direction. According to the manufacturer's data, the maximum measurable slope angle is 87°, which does not allow vertical wall geometry. Without vertical wall geometry, there is no possibility to measure most of geometrical features of a machined part. This disadvantage of the measurement method cannot be solved without using a different measurement method (e.g., computer tomography), which was not available during the experiment.

Due to difficulties with the full workpiece geometry registration, dimensions of the workpiece after machining were not measured. However, the obtained geometry gives the possibility to show and compare some geometrical features of machined parts. Machining thin walls is one of the most challenging task for machine tooling. The thin wall has a thickness of 150 μm, and it is machined with a 100 μm axial depth of cut. The depth of pocket is 4 mm. A view of the thin wall from Alicona InfiniteFocusSL after machining is shown in Fig. 6. Figure 6a presents a thin wall machined on the prototype SNTM-CM-ZUT-1 micro-milling machine. The only valid information from the used measurement method is that the thin wall is straight. Other machining errors cannot be evaluated without the wall surface registration, which is not possible with the used measurement method. Figure 6b shows the thin wall machined on the KERN Pyramid Nano machine tool. There can be noticed a large error of straightness of the machined thin wall. Moreover, the thickness of the wall is smaller than required. Dimensions of the thin wall showed in Fig. 6 were evaluated based on the end of surface. It cannot be measured accurately, because points on the thin wall surface were not registered by the method used for workpiece geometry registration.

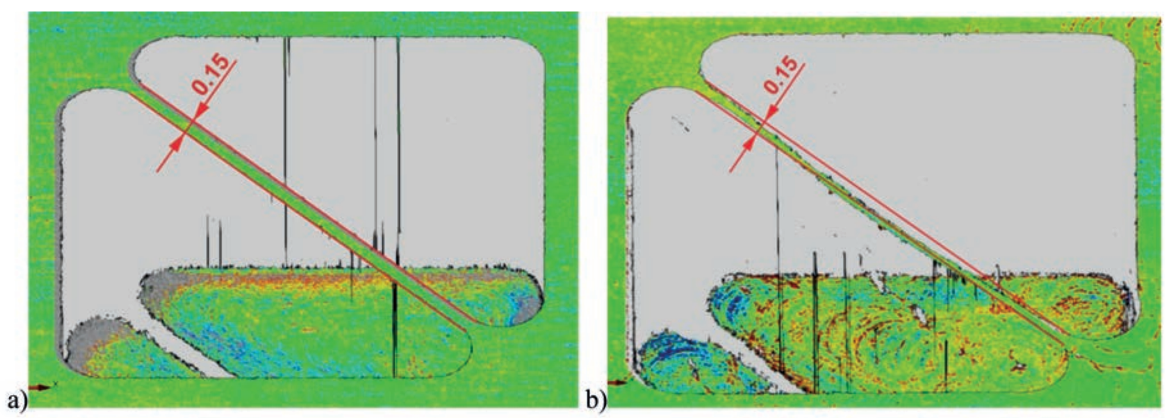

Fig. 6. Thin wall errors: a) prototype SNTM-CM-ZUT-1 micro-milling machine tool, b) KERN Pyramid Nano
Source: Authors.

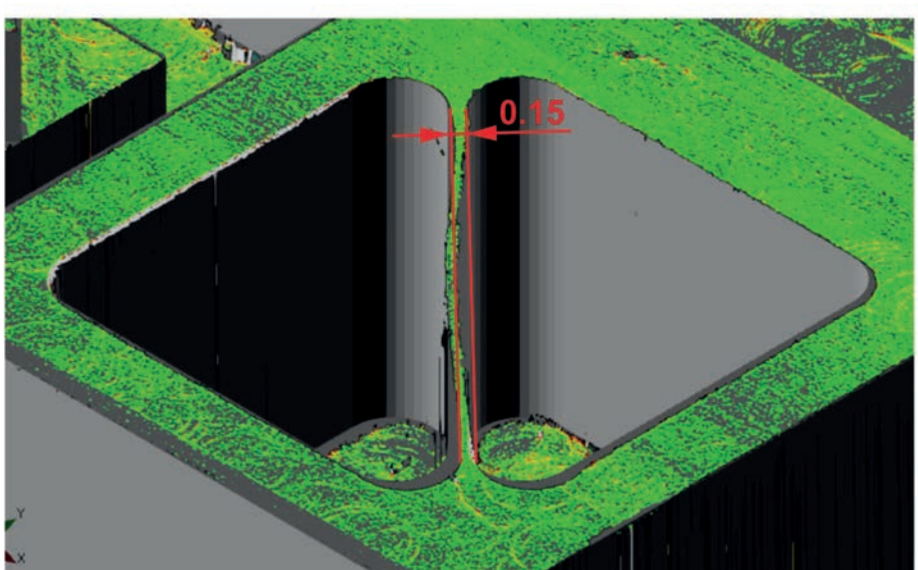

Fig. 7. Detailed view of the thin wall errors at KERN Pyramid Nano
Source: Authors.

A detailed view of the thin wall machined on the KERN Pyramid Nano is shown in Fig. 7. It can be seen that the wall is not straight, which was confirmed by the optical observation of the workpiece. The same results were obtained for a cold machine and after a warm up procedure.

During the experiment, cutting forces were recorded in order to compare them. With the KERN Pyramid Nano, a Kistler 9317C force sensor with three Kistler 5015 charge amplifiers were used. Charge amplifiers were connected to a National Instruments cDAQ-9174 with a NI 9234 module, which was used as analogue to the digital converter. With the SNTM-CM-ZUT-1 prototype micro-milling machine, a Kistler 9256C1 dynamometer with a 5070 charge amplifier was used, which was connected to a National Instruments PXI with a NI-PXIe-4499 module. Different force sensors were used because of the large distance between Szczecin and Brescia where the machine-tools are located.

Geometry errors observed during the thin wall and the deep pocket machining on the KERN Pyramid Nano suggested that there could be a difference in cutting forces between machining on the KERN machine tool and the prototype SNTM-CM-ZUT-1 machine. Comparison of an upper envelope of cutting forces in the X direction during first 70 seconds of the thin wall machining is shown in Fig. 8. Major differences in cutting times can be seen. Due to large masses and a short machining length, the KERN machine tool may not fully achieve the required feed rate.

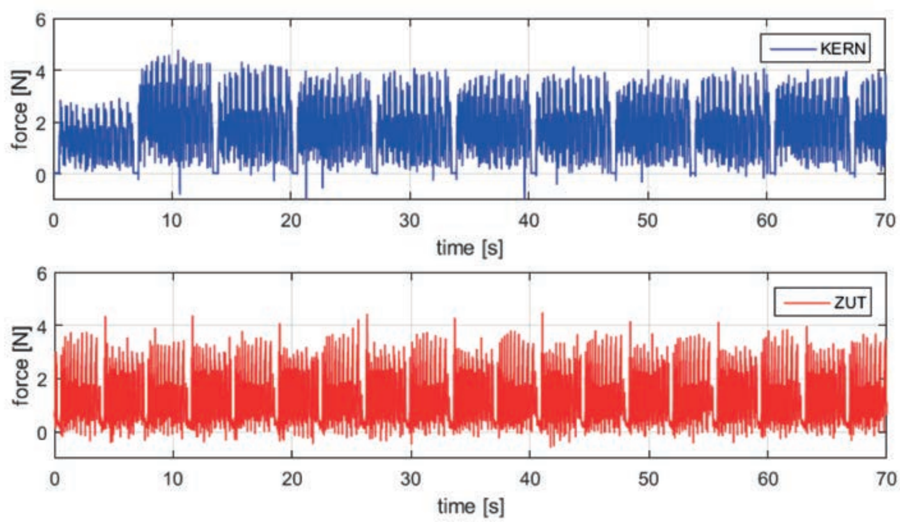

Fig. 8. Envelope of cutting forces in X direction during first 70 seconds of deep pocket machining
Source: Authors.

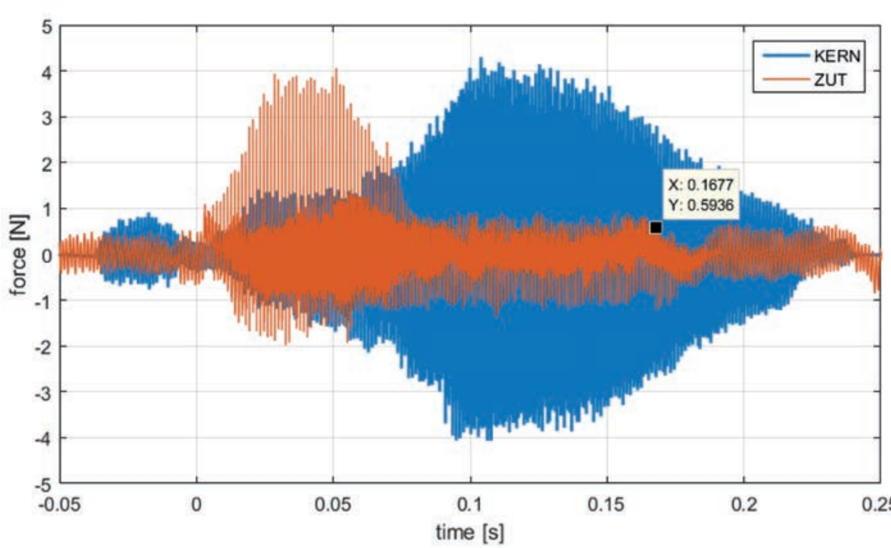

Fig. 9. Cutting forces during first 0.25 s of groove machining
Source: Authors.

Differences in the time of the thin wall machining shown in Fig. 8 can be confirmed by analysis of cutting forces during groove machining. Cutting force signals in the X direction for groove machining are shown in Fig. 9. Based on feed rate (1440 mm/min.) and the groove length (4 mm), the time of cut for one grove should be 0.167 s. The prototype SNTM-CM-ZUT-1 machine tool can obtain the required machining time and a feed rate. The machining time of the KERN Pyramid Nano machine tool is longer than it should be for the required feed rate. The KERN machine tool cannot achieve a desired feed rate as fast as the prototype machine tool. Moreover, because of the larger masses of the machine tool elements, it has to start to slow down faster than the prototype micro-milling machine tool before the end of groove. Another disadvantage of a lower feed rate is a longer machining time.

Conclusions

The performed experiment shows that machining errors, especially for the thin wall machining, are larger for the KERN Pyramid Nano machine tool. The main influence on these errors was machine drive dynamics. The KERN machine tool cannot achieve the desired feed rate at a short distance of machining. This was confirmed by analysis of cutting force signals, both for the thin wall machining and grooves machining. The workpiece machined on the prototype SNTM-CM-ZUT-1 machine tool does not have significant machining errors for the thin wall. Cutting force signals show that the SNTM-CM-ZUT-1 machine tool also has better dynamics, since it can achieve the desired feed rate. That can be caused by the smaller masses of the prototype micro-milling machine tool compared to the KERN machine tool.

The design of the test part was complex, and it was intended to facilitate the collection of data on machine accuracy; however, the only available measurement methods could not register all workpiece geometry. Therefore, the measurement of geometrical features was not possible. The only valid and significant geometrical feature that can be evaluated is the straightness of the thin wall.

The largest weakness of the conducted experiment is the optical method of the workpiece geometry measurement, which does not give the possibility to register wall surfaces. To perform detailed geometry analysis and machined workpieces dimension analysis, there is a need to use a method that can ensure wall surface registrations, e.g., computer tomography, which is currently not available for the authors and would be possibly available in further research work.

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References

1. Annoni M., Rebaioli L., Semeraro Q. 2015. Thin wall geometrical quality improvement in micromilling. The International Journal of Advanced Manufacturing Technology: 1–15.
2. Young-bong Bang, Kyung-min Lee, and Seungryul Oh. 2005. 5-axis micro milling machine for machining micro parts. The International Journal of Advanced Manufacturing Technology 25, 9–10: 888–894.
3. Broel-Plater B., Waszczuk P., Kobyłkiewicz A. 2011. System diagnostyki procesu mikroskrawania. Napędy i sterowanie 6, 2011: 32–35.
4. Creighton E., Honegger A., Tulsian A., Mukhopadhyay D. 2010. Analysis of thermal errors in a high-speed micro-milling spindle. International Journal of Machine Tools and Manufacture 50, 4: 386–393.
5. Huo D., Cheng K., Wardle F. 2010. Design of a five-axis ultra-precision micro-milling machine – UltraMill. Part 1: holistic design approach, design considerations and specifications. The International Journal of Advanced Manufacturing Technology 47, 9–12: 867–877.
6. Huo D., Cheng K., Wardle F. 2010. Design of a five-axis ultra-precision micro-milling machine – UltraMill. Part 2: integrated dynamic modelling, design optimisation and analysis. The International Journal of Advanced Manufacturing Technology 47, 9–12: 879–890.
7. Mamedov A., Ehsan Layegh K.S., Lazoglu I. 2013. Machining Forces and Tool Deflections in Micro Milling. Procedia CIRP 8: 147–151.
8. Pajor M., Maćkowiak H., Zapłata J. 2013. Examination of thermal deformation of micro milling machine tool SNTM-CM-ZUT-1. Diagnostyka 14.
9. Uriarte L., Herrero A., Zatarain M., et al. 2007. Error budget and stiffness chain assessment in a micromilling machine equipped with tools less than 0.3 mm in diameter. Precision Engineering 31, 1: 1–12.