EXAMINATION OF THERMAL DEFORMATION OF MICRO MILLING MACHINE TOOL SNTM-CM-ZUT-1

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Summary

This paper presents thermal analysis of micro milling machine tool SNTM-CM-ZUT-1. Infrared camera images are utilised to identify major heat sources in the machine tool. The influence of the heat generated in linear motors and frictional heat generated in spindle on the machine tool body temperature is examined. Basing on the CAD geometry and IR measurement, the thermal expansion of the machine is evaluated by means of the FEM analysis. The study indicates places where constructional improvements can be made in order to decrease thermal error influence. Moreover, the time period ensuring the thermal stability is identified.

Keywords: thermal error, micromachining, FEM, IR measurement.

OCENA ODKSZTAŁCEŃ CIEPLNYCH
OBRABIARKI DO MIKROFREZOWANIA SNTM-CM-ZUT-1

Streszczenie

W pracy przedstawiono analizę odkształceń cieplnych obrabiarki do mikrofrezowania SNTM-CM-ZUT-1. Celem zidentyfikowania głównych źródeł ciepła maszyny wykorzystano pomiar kamerą termowizyjną. Zbadano wpływ ciepła wydzielanego podczas pracy napędów liniowych oraz wrzeciona na temperaturę korpusów mikrofrezarki. Na podstawie zmierzonych temperatur oraz znajomości geometrii obrabiarki opracowano model MES. Pozwolił on oszacować odkształcenia cieplne jakim poddawana jest obrabiarka podczas pracy. Wskazano potencjalne elementy konstrukcji, których modyfikacja może zredukować wielkość odkształceń cieplnych. Dodatkowo, wyznaczono cieplne stałe czasowe maszyny.

Słowa kluczowe: odkształcenia cieplne, mikroobróbka, MES, termografia.

1. INTRODUCTION

The influence of the thermal error in traditional machining is usually noticeable at the stage of the finishing treatment. In the case of micromachining, where feed rates and machine depth have micrometer orders of magnitude, the influence of thermal error might be crucial [1].

Conventional mechanical FEM analysis, used to project and examine features of machine tools design, augmented with multiphysics analysis, allows to predict the thermal expansion of machine tool body causing the thermal errors [2, 3]. Thus, it allows to implement the necessary structural changes in future machines or algorithms compensating thermal errors in the existing ones [4, 5].

In the described method, the FEM model consists of two parts: the thermal one and the mechanical one. The temperature distribution obtained on the basis of the thermal analysis constitutes a part of the boundary conditions for further mechanical analysis.

In this paper, an IR measurement of an existing facility was used in order to simplify the modelling process by taking the thermal boundary conditions a priori. IR measurements, owing to the use of high-resolution radiometric matrixes, are characterised by good imaging properties in order to examine the whole of thermal phenomena [6]. The combination of multiphysical FEM modelling with thermography provides a convenient way to estimate the machine thermal deformation.

2. IR MEASUREMENT OF A MACHINE

The negative features of IR measurements include the measurement uncertainty based upon the measurement scheme itself. It has to be emphasised that in not the temperature of the examined surfaces that is recorded, but the amount of radiation reaching the radiometric converter. The amount of the radiated energy from the surface which is examined depends on the temperature of the measured body, as well as the condition of this surface – emissivity coefficient. In addition, the impact on recorded value have the ambient radiation and the radiation of external sources reflected from the examined surface. Therefore, IR measurements always require due diligence, attention and in-depth knowledge from the operator performing the measurement.

To make the value of the registered temperatures independent from the surface condition, the observed machine was covered with tape, which had a known emissivity coefficient. To verify the conducted IR measurements, additionall PT100 temperature sensors were mounted on the observed machine. Those are indicated in Fig. 1 with the following symbols: S1, S2 and S3.

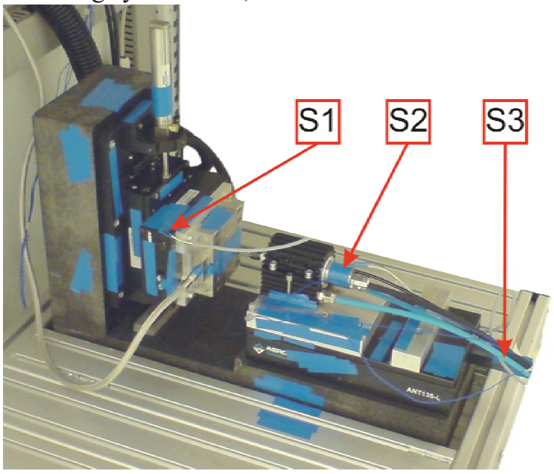

Fig. 1. Micro-milling machine tool covered with a tape with a reference emissivity coefficient, the temperature sensors marked: S1, S2, S3

2.1. Infrared observation of the spindle

The measurement of the current supplying the spindle of the SNTM-CM-ZUT-1 micro milling machine tool showed that the thermal power emitted in the spindle is somewhat between 8÷50W, depending on the rotational speed. The device is provided with two parallel spindle cooling methods: with a radiator (by convection and radiation) and flowing water.

The amount of heat convected and emitted from the radiator to ambient air dependents form temperature of both. The ambient temperature is to be maintained at a constant level, by means of air-conditioned chamber, in which the device is located. The amount of the heat convected and emitted only radiator is insufficient for the micro milling machine to reach stable thermal conditions quickly. At rotational speed rate 35,000 rpm, heat generation rate equal to P = 8W, the stable conditions were not achieved at this conditions even after 45min, if additional cooling is not used. (see Fig. 2).

In order to quickly stabilise the temperature of the milling machine and prevent seizure of the bearings with higher rotational speeds, it is necessary to activate the water cooling system.

The effectiveness of water cooling is dependent on the temperature of coolant and its flow rate. The installed cooling system enables achieving stable conditions already after 20 minutes.

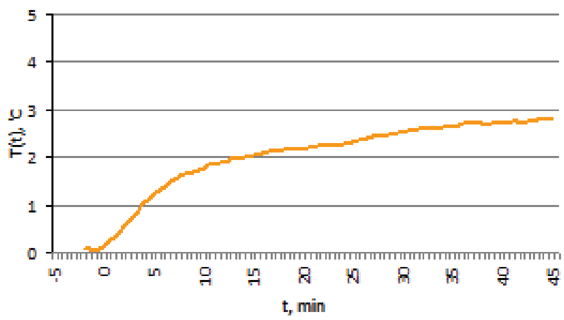

Fig. 2. Temperature surplus of the spindle, relative to ambient, registered by sensor S2 during the work of the micro milling machine tool. Water cooling system off, spindle velocity - 35,000 rpm

Changing the spindle rotational speed affects the temperature of the system. During the experiment for the rotational speed of 75,000 rpm, heat generation rate equal to P = 40W, the spindle temperature stabilises after about 20 minutes at the level of 5 ºC below the ambient temperature. For the rotational speed of 35,000 rpm, heat generation rate equal to P = 8W, the temperature of the previously heated spindle stabilises after about 20 minutes at the level of 6.5 ºC below the ambient temperature (Fig. 3).

The conducted measurements suggest that in order to eliminate the influence of thermal deformation resulting from thermal elongation of the spindle, basing the tool relative to the workpiece should be performed after about three time constants. Knowing the $\tau \approx 5$ min, this results in about 15 minutes time for thermal stabilization from the moment of switching on the spindle.

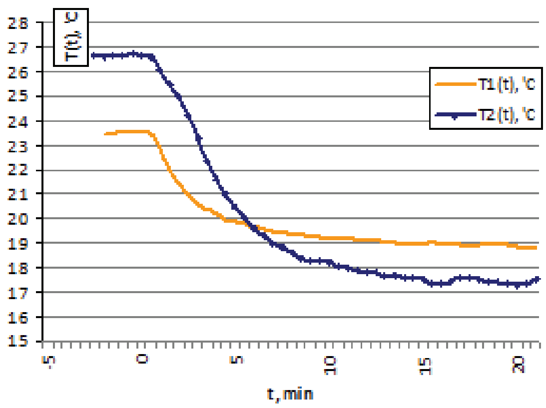

Fig. 3. The temperature recorded by sensor S2 during the work of the micro milling machine with active water cooling system, constant ambient temperature, different initial temperatures of the system, the rotational speeds of:
T1: v_r = 75,000 rpm, T2: v_r = 35,000 rpm

In addition, Fig. 3. shows the fact that with a significant change of the spindle rotational speed it may be necessary to rebase the tool.

Fig. 4. presents the impact of water cooling system work on the temperature of headstock and the body elements of the micro milling machine.

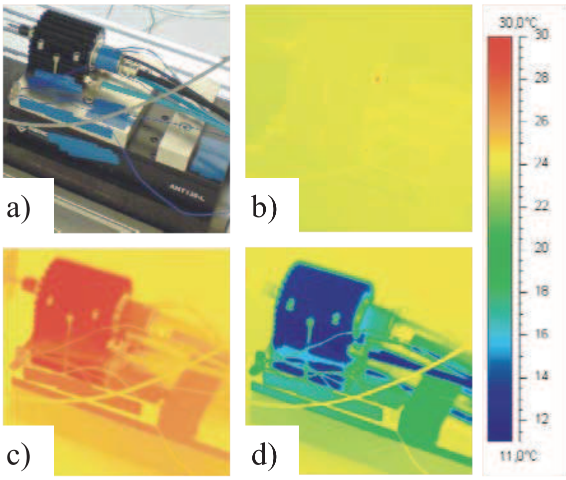

Fig. 4. Results of the IR spindle temperature measurements: a) photo of the spindle taken in the visible range; b) spindle under conditions of the thermal equilibrium with the surroundings; c) spindle heated by turning on the rotation d) spindle heated by turning on the rotation with an activated water cooling system

2.2. Infrared observation of the Z axis

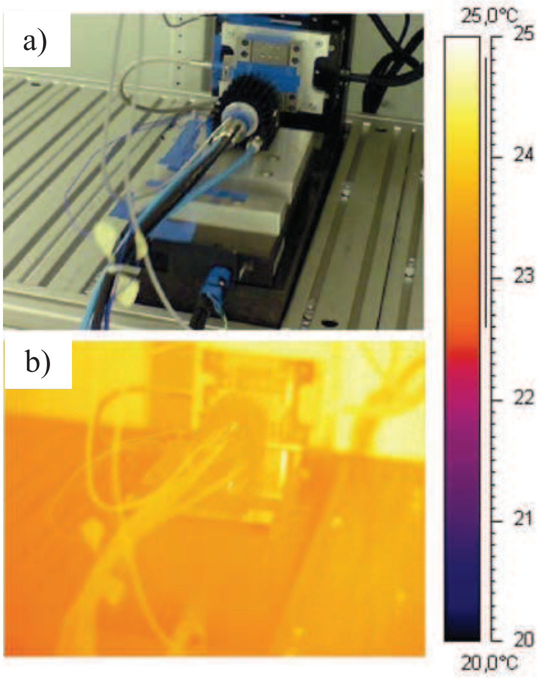

Fig. 5. Results of IR measurement of axis Z temperature: a) photo of the micro milling machine taken in the visible range; b) negligible impact of the Z axis movement on the temperature of the micro milling machine

The relative motion of the the tool in relation to the workpiece is driven by linear motors, different power each. The thermal image (Fig. 5.) indicates that the amount of heat generated in the linear motor of the Z axis when it moves, is insignificant for the machine tool temperature, even when its velocity reaches 50mm/s.

2.3. Infrared observation of the X and Y axis

The work of the motors in the X and Y axis has a significant impact on the temperature of the micro milling machine body.

In order to balance the gravitational vertical load of the micro milling machine axis Y, this axis is equipped with a pneumatic actuator powered by constant pressure at an adjustable level. However, despite the apparent relief of the linear motor of the feed axis Y by means of a pneumatic actuator, the linear motor of the Y axis is constantly loaded. This causes the heating of the Y axis motor from the moment of turning on, even if it is seemingly idle. The heating rate of the micro milling machine is presented in the reading from the sensor S1 located on the movable table of the feed axis X (Fig. 6.).

The movements of the feed axis X and Y were activated in the 40th minute, which may be observed as an increase in the rate of temperature measured by the S1 sensor.

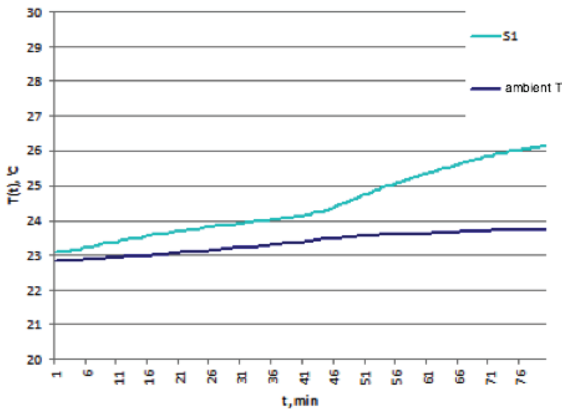

Fig. 6. The temperature recorded by sensor S1 and ambient temperature during the idle operation of the micro milling machine linear motors, movement of the feed axis X and Y activated approximately at 40-th minute

The heat flux generated in the linear motor of the Y and X axis causes heating of the vertical granite column of the device base. Pictures taken with the infrared camera provide information on the temperature distribution field of the machine tool (Fig. 7).

Due to low conductivity and high heat capacity of the granite, both in transient and fixed states, a clear temperature gradient can be observed in the abovementioned column. The occurrence of the temperature gradient in this element results in the thermal deflection of the granite column.

Approximating the measured change of the temperature in the column in time with the exponential function, we receive a time constant of the temperature change in the column, amounting to approx. 1h. To eliminate the effect of thermal deformation of the column on the relative position of the tool and the workpiece, it is necessary to wait until the system reaches stable thermal conditions or introduce structural changes, reducing the impact of the described effect.

The remaining elements, mostly made of aluminium, are characterised by high thermal conductivity and low heat capacity. These elements, with a good approximation, may be treated as lumped capacity elements.

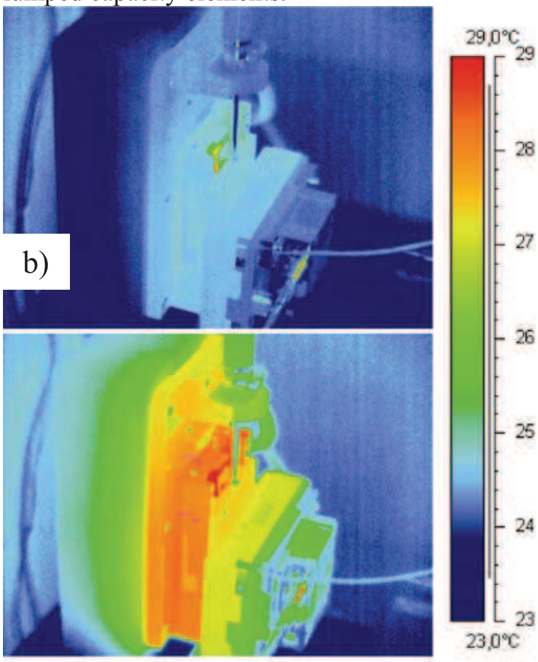

Fig. 7. Photo of the feed X and Y axis of the micro milling machine taken with an IR camera: a) immediately after switching on the motors; b) after 35 min from the moment of switching on the motors

3. FEM MODEL

On the basis of the possessed CAD data, a simplified model of the machine tool geometry for the FEM calculation purposes was constructed. The assumed physical properties of materials are presented in Table 1.

Tab. 1. Assumed physical properties of materials

	Granite	Aluminium	Steel
Thermal expansion coefficient α, μm/m/°C	10	24	12
Density ρ, kg/m³	2700	2700	7850
Specific heat cp, J/kg/°C	700	300	500
Thermal conductivity coefficient λ, W/m/°C	3,5	230	50
Young modulus, GPa	14	37	210

It was assumed that the elements of the driving components are made of aluminium [12], the column of granite, and the spindle elements of steel. The view of the geometric model divided into elements is presented in Fig. 8. The grid consists of default elements: "chexa" and "ctetra." To simplify the calculation process, only the symmetric part of the machine was modelled.

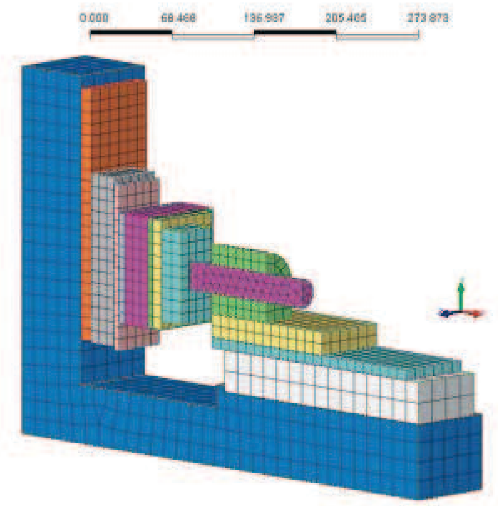

Fig. 8. FEM model of a micro milling machine tool

3.1. Thermal model

On the basis of the analytical dependencies and the IR measurements, some assumptions allowing to calculate the temperature distribution field of the machine tool were made. Furthermore, it was assumed the heat transfer coefficient on free surfaces is equal to 5 $W/m^2/°C$. In order to map the conduction of heat to the table on which the machine tool is located, it was assumed that the heat transfer coefficient at the base surface amounts to 100 $W/m^2/°C$.

It was assumed that the density of the heat flux penetrating the column of the headstock amounts to 100W/m^2, which corresponds to the heat rate 1.6W transferring to the granite column. The ambient temperature was set at the level of 26°C. In addition, it was assumed that the elements made of aluminium with a good approximation, have a uniform temperature amounting respectively to: 29.5°C - dynamometer, 30.0°C - plate under the dynamometer; 31.0°C - X axis, the upper part; 31,5°C - X axis, the lower part, plate under the X axis, Y axis, the upper part; 33.0°C - Y axis, the lower part; 32.5°C - plate under the Y axis; 26.0°C - spindle, radiator, Z axis, the upper part, Z axis, the lower part, plate under the Z axis.

It should be emphasised that calculating the temperature distribution field of the whole micro milling machine is necessary, since the IR measurements provide data only concerning the surface temperature distribution of the machine tool, whereas in order to estimate heat deformations, it is necessary to provide the data concerning the temperature of the machine tool throughout its whole volume. Due to the fact that there is no heat flow between the elements of the same temperature, it was assumed that the plane of symmetry is an excellent insulator.

Comparing Fig. 9. and Fig 10., which present the temperature distribution field calculated using the numerical method and recorded with an infrared camera, it can be assumed that the results were satisfactorily consistent.

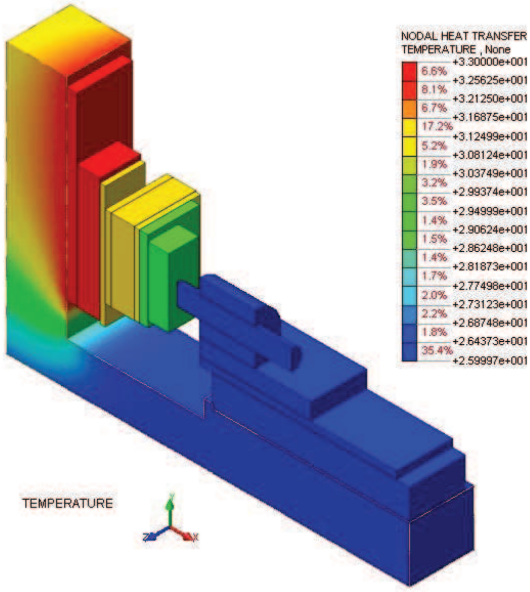

Fig. 9. Temperature field distribution of the micro milling machine calculated by means of FEM

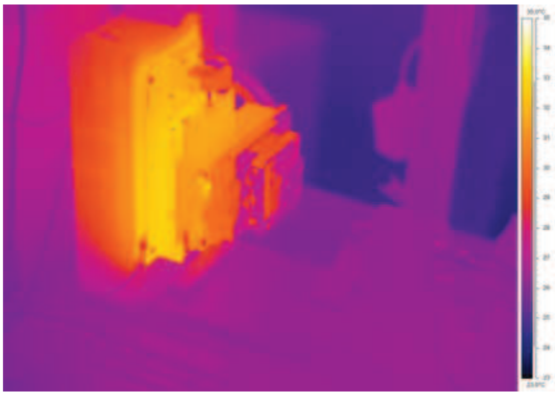

Fig. 10. Temperature distribution field of the micro milling machine recorded with an infrared camera

3.2. Mechanical Model

In the mechanical model it was assumed that the plane of symmetry has removed degrees of freedom connected with translation in the Z axis. In addition, it was assumed that the tool tip point has removed degrees of freedom corresponding to X and Y axis translation.

In the presented Fig. 11, apart from the errors resulting from the translation of the tool relative to the workpiece as a result of linear thermal expansion of structural elements, it is visible that the occurrence of the temperature gradient in the granite column leads to its deflection. This phenomenon will cause the distancing of the tool from the workpiece.

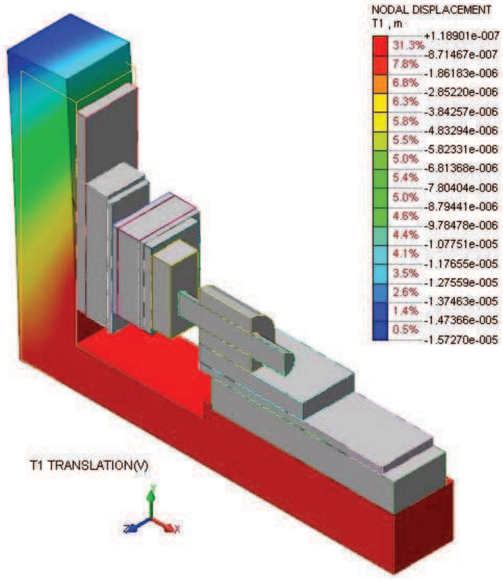

Fig. 11. Deformation of the granite base in the X axis calculated with the use of the finite element method

4. Experimental verification

The verification studies focused on the thermal deformation of the column. In order to verify the calculations, it was necessary to measure the translation of the point located on the granite column.

Fig. 12. Photo of the measurement system used to measure thermal deformations of the micro milling machine

The measurement was conducted with a Renishaw XL80 laser interferometer. The first mirror was mounted on the granite column, whereas the second one on the stationary Z axis (Fig. 12). Thermographic pictures show that the increase in the temperature of the interferometer mirrors was so slight that it was possible to neglect thermal expansion of these optical elements.

The study showed that the heat deformations of the column, expected according to an estimate of deformations by means of the FEM method, occurred. The order of magnitude of deformations is consistent with the conducted estimate, which is confirmed by Fig. 13.

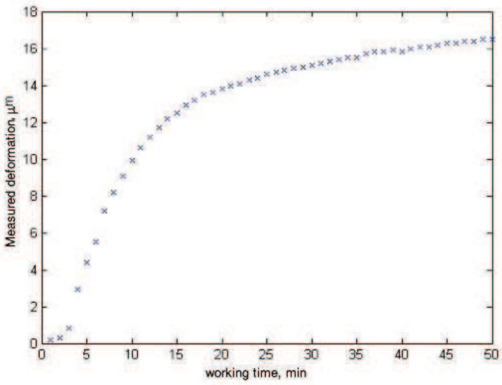

Fig. 13. The measurements of thermal deformations of the granite base collected in the experiment, along X axis

5. CONCLUSIONS

The conducted investigation showed that thermal deformations can have a significant impact on the geometric errors of the micro milling machine. This as a result, leads to the disruption of micromachining parameters, which orders reach micrometers.

IR measurement on the basis of the engineering knowledge allows for diagnosing the modes of thermal deformations essential for the work of the machines.

The application of the finite element method in terms of heat flow analysis in connection with the traditional mechanical modelling allows to estimate the nature and range of thermal deformations.

Precise estimation of thermal deformations is problematic due to the non-stationary nature of heat phenomena and multiplicity of parameters within the models.

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