Correlation Studies of Dimensional Accuracy with Temperature Changes of Selected Elements of a Machine Tool in the Machining Process

Damian Basara[1*], Leszek Skoczylas[1]

[1] Faculty of Mechanical Engineering and Aviation, Rzeszów University of Technology, al. Powstańców Warszawy 8, 35-959 Rzeszów, Poland

* Corresponding author's e-mail: d453@stud.prz.edu.pl

ABSTRACT

The article presents the characteristics of temperature changes of selected components of the machine tool and the temperature of the machining coolant in relation to the selected dimensions of finished parts, such as the AGB gear cover. The tests were carried out on the basis of serial production on the FMS line in a plant producing components for the aviation industry. As part of the research, the machine tool was modernized to the extent that it was possible to register temperatures in real-time. Temperature changes were compared with the dimensions of the machined part in search of dependencies. Correlation calculations between temperature and dimensional data were made with the use of a statistical process control program. Dimensional data were obtained from CMM machines used daily to measure parts from series production.

Keywords: temperature changes of machine components, FMS, serial production, correlation.

INTRODUCTION

The realization of machining processes is associated with the performance of specific work, which is accompanied by heat release. Various factors can be the source of heat and hence temperature changes. First of all, the friction that occurs between the tool and the workpiece during cutting the material can be mentioned here. Temperature changes also come from friction in driving elements (guides, ball screws), machine drive units (motors), and finally the machine tool environment in the form of other heat-emitting units or the environment itself (season). Temperature change causes thermal expansion of materials, which in turn affects the accuracy of the treatment. The authors of [1–2] indicate that the thermal error accounts for about 40–70% of the total machining error on machine tools. For this reason, this issue is commonly taken up in the literature relating to the expansion of the machined part, tooling, and the machine tool itself.

To analyze the influence of temperature, FEM analysis is commonly used both for the machine tool and the workpiece [3–5]. Many works concern tests of machine tool components (lead screw, electrospindle, encoder) [6–7]. There are many systems on the market, such as a kinematic rod, laser interferometer, or object probes, used to measure the mutual displacements of machine tool elements, geometric accuracy, or positioning accuracy [8]. These solutions are successfully used to determine the dependence of mutual displacements on temperature [9–11]. Environmental influences such as the ambient (workshop) temperature lead to slow changes and affect the overall volumetric accuracy of the machine tool. Less predictable impacts caused by the internal sources of the machine tool (bearings, guides, drives, propellers) lead to local deformations and cause partial changes in the volumetric error, e.g. change of the TCP (tool center point) position in the direction of the spindle axis [12–14]. Measurements of thermal errors are difficult to

implement because they must take into account as much as possible of all relevant geometric parameters in a given working volume in a relatively short time. So that the influence of temperature changes on the geometric error parameter can be properly monitored. The authors [3, 15–17] show that an effective and economical method of minimizing the adverse effect of temperature on the accuracy of machining is real-time compensation with the use of mathematical models taking into account the changing temperatures of specific components.

Due to the importance of the influence of temperature changes on the machining accuracy, some issues in this area were subject to normalization. In the last twenty years, the International Organization for Standardization (ISO), in response to market needs, has published standards containing recommendations for the assessment / determination of thermal error of machine tools. ISO 230-3 [18] concerning thermal deformation of machine tools, ISO 10791-10 [19], covering thermal deformation on NC machining centers and ISO 13041-8 [20] covering temperature deformation of NC turning centers.

Knowledge of the influence of temperature changes on the stability of the machine tool – workpiece system, and thus the accuracy of machining, is particularly important in the case of aviation production. An example of such a part is the gear cover made of aluminum, which is the subject of the research. As part of the research work, tests were carried out to determine the impact of temperature changes of the components of the CNC machine and the part itself during the machining

process on the geometric linear characteristics of the finished product, such as the positions of the bearing holes in relation to the based hole.

TEST STAND

The test stand was based on three basic modules; CNC machining center, CMM (coordinate measuring machine), statistical process control software. The block diagram of the test stand allocated in the FMS line is shown in Figure 1.

The five-axis horizontal CNC milling machining center, which is part of the FMS line [22], was equipped with temperature sensors allocated following Figure 2 and a recorder (industrial computer) to register the temperatures during the machining process. In addition to the temperature of the CNC machine components, the temperatures of the machining emulsion, glycol circulating in the cooling system of the drives, and the environment (8 sensors in total) were recorded. To register the temperature of the machined parts in key moments of the process, the Hexagon stick probe TP44.10 was used [23]. The selection and distribution of temperature sensors on the CNC machine were limited due to health and safety reasons and the guidelines of the machine manufacturer (production machine, warranty).

The machine tool is equipped with a temperature stabilization system for the: machining coolant, Y-axis block, servo drives, and electro-spindles. The task of the system is to stabilize the temperature of individual areas by receiving thermal energy in the event of their excessive heating above
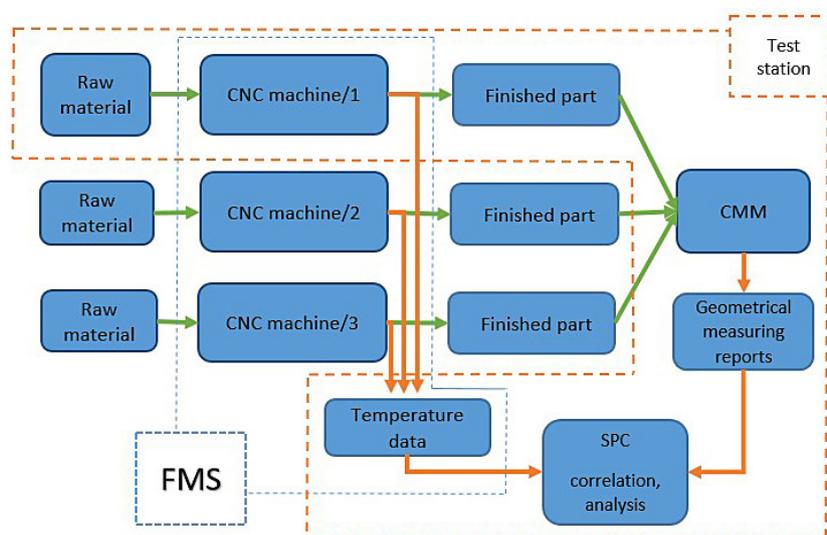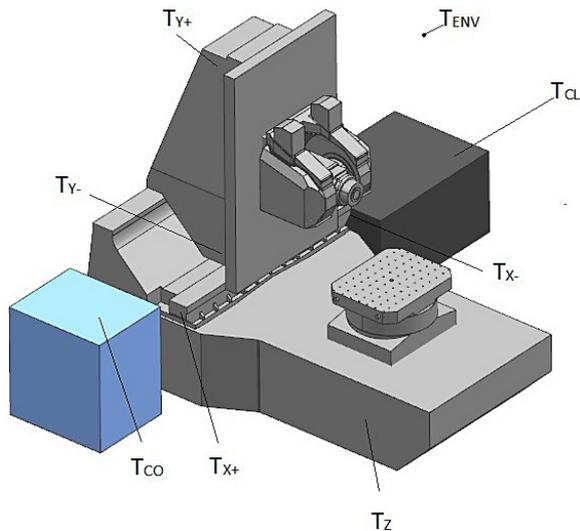

Fig. 1. Block diagram of the test stand separated from the FMS production line

Fig. 2. Diagram of the arrangement of temperature sensors on the machining center. T_{CO} – glycol temperature sensor for servo cooling system and Y-axis pole, T_{CL}– cutting coolant temperature sensor (measurement in the main tank), T_{ENV} – environment temperature sensor, T_{X+}, T_{X-}, T_{Y+}, T_{Y-}, T_{Z}, – sensors located on the body of the machine.

the ambient temperature with a specified deviation. The machine tool should be classified as large-size machines, the ranges in the linear axes are; X-axis 1600 mm, Y-axis 1600 mm, Z-axis 1020 mm.

To collect dimensional data from the finished product, a CMM machine by LK Metrology, model Altera M, was used. The CMM machine is placed in a special room with temperature stabilization and is used every day to measure production parts. In addition to geometric data, the temperature of parts and components of the CMM machine was recorded during the measurement.

The results of temperature measurements on the CNC machine and geometric measurements from CMM machines were sent to the program for statistical process control (SPC Vision).

RESULTS

The tests of temperature changes were carried out based on data obtained in the serial-production cycle. The workpiece during testing is the cover shown in Figure 3.

The characteristic values, which are compared with the course of temperature changes, are linear components of the positions of the holes for bearings made by using boring technology. The measurements were made in the drawing layout of the parts in the main directions Y, Z (Fig. 3). 47 parts manufactured over a period of approximately 2 months were analyzed. In all cases, the machining process was performed with the use of a machining coolant supplied to the walls of the housing of the machine tool working space. Coolant was also applied to the machining tooling and directly into the area of the material cutting to enable effective chip removal and minimize the machining error resulting from excessive heating of the part resulting from the work performed during cutting aluminum. All steps from roughing to finishing were performed in one operation without repositioning part in the tooling.

Figure 4 shows the temperature curves for one selected part from the study group of 47 parts. The markings of the temperature characteristics correspond to the markings of the sensors shown in Figure 2.
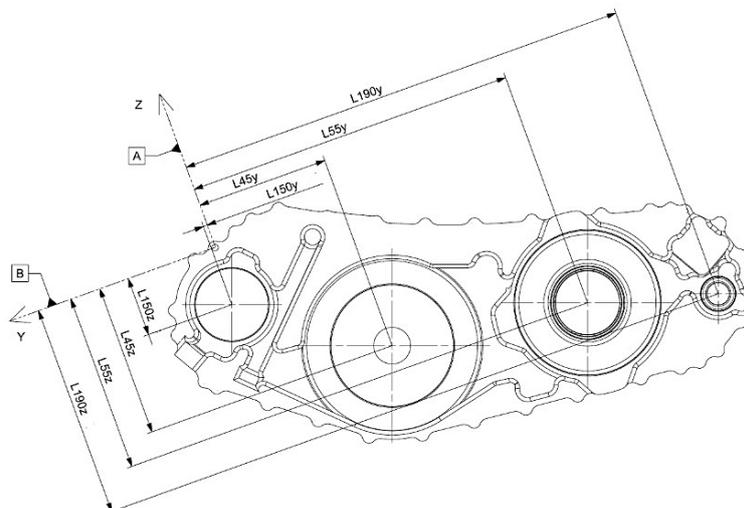
Fig. 3. The illustrative drawing of the AGB cover with the analyzed dimensions marked
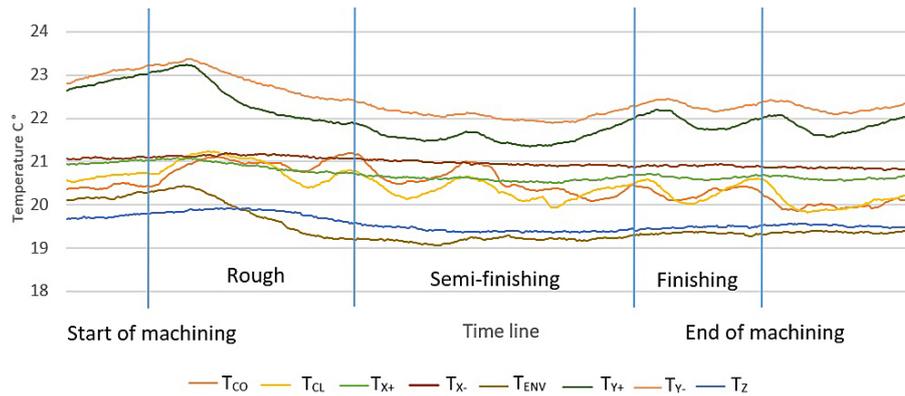
Fig. 4. The course of temperature changes of the machine tool components and fluids in the machine tool during the machining process of a selected part from the tested sample

The temperature of individual components and fluids was recorded at intervals of 1 minute. The temperature of the machined part, due to technological and economic limitations, was recorded in three key stages of machining, i.e. at the beginning of the process t_1 moment (blank temperature), before the start of the finishing machining in t_3 moment, and after the end the finishing machining in t_4 moment (Fig. 4). The part temperature at t_2 moment, was not recorded as it was not relevant for the analyzes.

Figure 4 shows that the temperature variation in the case of T_{X+}, T_{X-}, T_Z, are less dynamic in relation to other temperatures. Temperature variation for T_{Y+}, T_{Y-}, T_{CL}, T_{CO}, sensors are similar to sinusoidal and they were caused by the operation of the temperature stabilization system in the machine (refrigerator). In all considered cases (47 parts), the behavior of the machine in terms of temperature variation was at a similar level, the character of changes was similar.

To systematize the naming of temperature characteristics in this article, let assume that the coolant temperature measured at the moment t_3 i.e. before the commencement of the finishing operations (Fig. 4 and Fig. 5), is $T_{CL}(t_3)$, analogically, the glycol temperature at the same time $T_{CO}(t_3)$, etc.

To quantify the similarity of changes between the dimensional position characteristics of the bored holes and temperatures, a correlation analysis was performed in the SPC Vision software. The analysis included the finishing stage from t_3 to t_4 (Fig. 5). Three variants were analyzed. In the first variant, the correlation was made between the temperatures of $T_{CL}(t_{3.1})$, $T_{CO}(t_{3.1})$..., recorded at the time of boring the base hole ($t_{3.1}$), against which the key characteristics are measured. Correlation analysis of this variant did not show a significant level of correlation.

In the second variant, the temperatures of the components of the machine $T_{CL}(t_{3.2})$, $T_{CL}(t_{3.3})$, $T_{CL}(t_{3.4})$..., were taken into account when the characteristics of interest were made. This variant of the analysis also did not show a significant level of correlation between linear dimensions
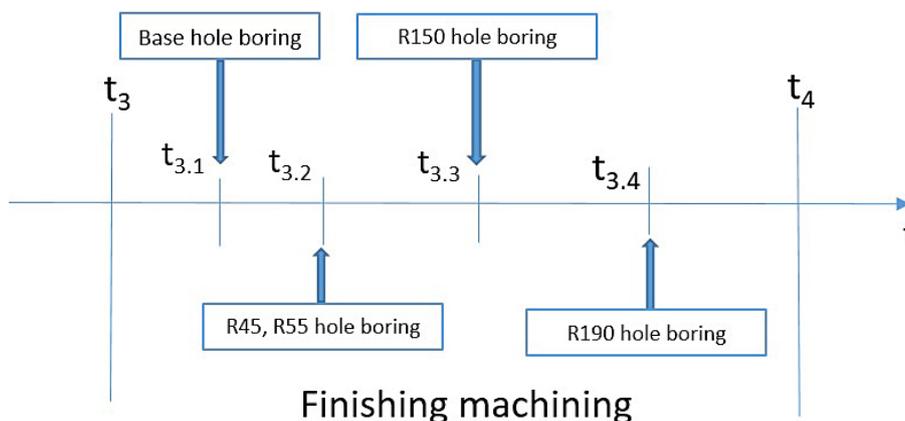

Fig. 5. Sequence of performance of the analyzed characteristics over time

and temperatures levels. The third variant takes into account the temperature difference between the temperature in moment base hole boring and the temperature in the moment of analyzed characteristics boring, eg. $T_{Diff\ CL}(R45,\ R55) = T(t_{3.2})$ – $T(t_{3.1})$. The obtained results of temperature measurements were compared with the results of measurements of linear characteristics obtained from CMM machine. For example $L190_Y$, $L190_z$, are linear distances between the base hole and R190 hole, in Y and Z drawing coordinate system (Fig. 3). Due to the large amount of data, it is not possible to present all the measurements in this

article in the form of a table. Therefore, it was decided to present the part of the results with the highest level of correlation between the temperature change and the linear dimension, using correlation graphs (Fig. 6).

Some trends can be noticed indicating that the increase in the temperature of glycol ($T_{Diff\ CO}$) has an influence on the change of dimensions in the Z direction of the analyzed part, causes its decrease (Fig 6a, b, e, f). On the other hand, an increase in the temperature of the coolant ($T_{Diff\ CL}$) w causes an increase in the dimension $L45_y$ (Fig. 6c), and a decrease in the dimension $L150_Y$ (Fig. 6f, d).
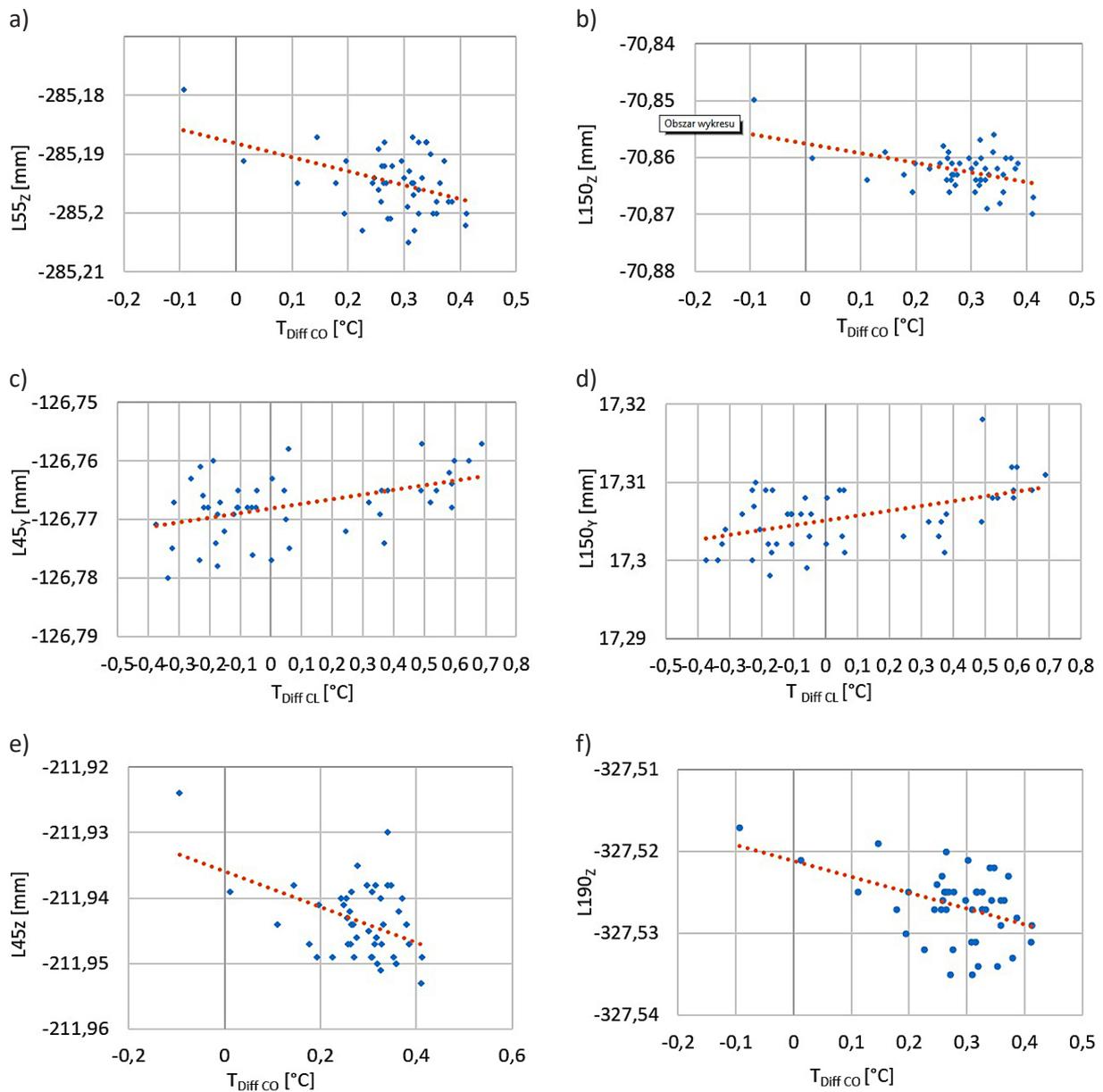
Fig. 6. Measurement results presented in the form of a correlation diagram between: a) linear dimension $L45_z$ and $T_{Diff\ CO}$ temperature difference, b) linear dimension $L55_Z$ and $T_{Diff\ CO}$ temperature difference, c) linear dimension $L150_Z$ and $T_{Diff\ CO}$ temperature difference, d) linear dimension $L150_Y$ and $T_{Diff\ CL}$ temperature difference, e) linear dimension $L45_Z$ and $T_{Diff\ CO}$ temperature difference, f) linear dimension $L190_Z$ and $T_{Diff\ CO}$ temperature difference

Table 1. Pearson linear correlation coefficients in the T_{Diff} temperature difference in relation to the dimensional characteristics obtained on the CMM machine for 47 analyzed parts (variant 3 of the analysis)

Distance	$T_{Diff\ CO}$	$T_{Diff\ CL}$	$T_{Diff\ X+}$	$T_{Diff\ X-}$	$T_{Diff\ ENV}$	$T_{Diff\ Y+}$	$T_{Diff\ Y-}$	$T_{Diff\ Z}$
$L190_Y$	-0.11	0.32	0.17	-0.26	-0.2	0.16	0.08	-0.13
$L190_Z$	*-0.44*	-0.14	-0.1	0.07	-0.16	-0.07	0	0.08
$L55_Y$	-0.17	0.28	0.12	-0.24	-0.23	0.13	0.06	-0.19
$L55_Z$	*-0.43*	-0.16	-0.08	-0.12	-0.14	-0.04	0.01	0.08
$L45_Y$	-0.03	*0.46*	0.26	-0.3	-0.29	0.23	0.1	-0.31
$L45_Z$	*-0.45*	-0.25	-0.14	-0.01	-0.17	-0.1	-0.03	0.12
$L150_Y$	0.13	*0.49*	0.23	-0.29	-0.31	0.17	0	-0.38
$L150_Z$	*-0.45*	0.15	0	0.11	-0.17	0.11	0.19	0.12

Table 1 presents the Pearson correlation coefficients for variant 3. It can be noticed that some of the analyzed characteristics showed a moderate linear correlation in relation to the temperature differences ($T_{Diff\ CO}$, $T_{Diff\ CL}$). The analyzed variants: 1, 2; did not show a significant level of correlation, for this reason, no results have been presented for them.
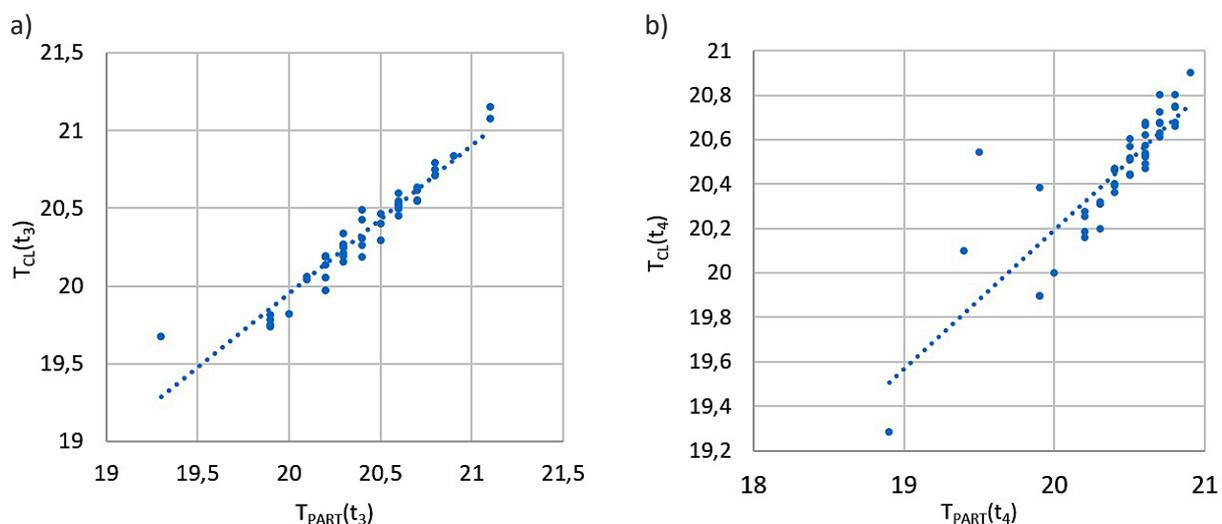
The correlation coefficient at the level of 0.43 to 0.49 (Table 1), does not indicate a clear direction of corrective actions aimed at improving the accuracy of the part. For this reason, it was decided to look for other relationships between the obtained results. As a result of many analyzes, a significant relationship between the temperature of the part and the temperature of the coolant was noticed.

Figure 7 shows the correlation of the measurements for 47 parts relating to the temperature of the part T_{PART}, and the temperature of the coolant T_{CL}, measured at t_3 and t_4 moment.

In the case of $T_{CL}(t_3)$ and $T_{PART}(t_3)$ (measurement at time t_3) the correlation is positive and the Pearson correlation coefficient is 0.96, for $T_{CL}(t_4)$ and $T_{PART}(t_4)$ (measurement at time t_4) the correlation is positive and Pearson linear correlation coefficient is 0.89. In both of the above cases, the level of correlation is high and it can be assumed that the temperature of the part is comparable to the temperature of the cutting fluid.

CONCLUSIONS

The results obtained do not show a close correlation between the temperature changes of the selected machine tool elements and the dimensions of the machined part. The analysis of the dependence of the temperature changes of the machine tool elements and cooling factors in relation to the dimensions of the machined part shows

Fig. 7. Correlation diagram for 47 production parts: a) temperature of the coolant $T_{2\ coolant}$ recorded at the time of recording the temperature of part T_2, b) temperature of the coolant $T_{3\ coolant}$ recorded at the time of recording the temperature of part T_3

divergent results. The correlation coefficient at the level of 0.43 to 0.49 does not indicate a direction of corrective actions aimed at improving the accuracy of the part. We found a trend of decreasing or increasing the dimension depending on the temperature difference. The temperature of the coolant in relation to the temperature of the analyzed group of parts at the time of the finishing operations takes a high correlation coefficient of 0.89 to 0.96, which is an important indication in the implementation of further research related to the dimensional repeatability and of the performed characteristics.

Acknowledgements

REFERENCES

1. Bryan J. International status of thermal error research. CIRP Annals. 1990. 39(2): 645-656.

2. Weck M., et al. Reduction and compensation of thermal errors in machine tools. CIRP Annals, 1995. 44(2): 589-598.

3. Zapłata J. Modelowanie odkształceń cieplnych obrabiarki precyzyjnej metodą mes. Modelowanie inżynierskie. 2017; 63:114-122. [In Polish]

4. Wąsik M., Kolka A., Śliwka J. Symulacja odkształceń termicznych przedmiotu obrabianego na maszynie cnc przy wysokodokładnej obróbce szybkościowej. Modelowanie Inżynierskie. 2018; 66:87-94. [In Polish]

5. Li Y., Zhao W., Lan S., Ni J., Wu W., Lu B. A review on spindle thermal error compensation in machine tools. International Journal of Machine Tools and Manufacture 2015; 95:20-38.

6. Gurauskisa D., Kilikeviciusb A., Borodinasb S., Kasparaitis A. Analysis of geometric and thermal errors of linear encoder for real-time compensation. Sensors and Actuators A. 2019;296:145–154.

7. Pajor M., Zapłata J. Zastosowanie metod sztucznej inteligencji do kompensacji odkształceń cieplnych śrub pociągowych obrabiarek CNC. Modelowanie Inżynierskie. 51:70-76. [In Polish]

8. Józwik J. Experimental methods of error identification in CNC machine tool operation. Wydawnictwo Politechniki Lubelskiej; 2018.

9. Delbressine F., Florussen G.H.J., Schijvenaars L.A., Schellekens P.H.J.. Modelling thermomechanical behaviour of multi-axis machine tools. Precision Engineering. 2005;30:47-53.

10. Groos L., Held C., Keller F., Wendt K. Mapping and compensation of geometric errors of a machine tool at different constant ambient temperatures. Precision Engineering. 2020;63:10-17.

11. Ibaraki S., Hong C.-F. Thermal test for error maps of rotary axes by R-test. Key Engineering Materials. 2012;523-524: 809–814.

12. Zverev I.A., Eun I.-U., Chung W.J., Lee C.M. Thermal modelling of high-speed spindle units. KSMEInt.J. 2003;17(5):668–678.

13. Li H., Shin Y. Analysis of bearing configuration effects on high speed spindles using an integrated dynamic thermo-mechanical spindle model. International Journal of Machine Tools and Manufacture. 2004;44:347–364.

14. Li H., Shin Y. Integrated dynamic thermo-mechanical modelling of high speed spindles Part 2: Solution Procedure and Validation. Journal of Manufacturing Science and Engineering 2004;126:159–168.

15. Mares M., Horejš O., Havlík L. Thermal error compensation of a 5-axis machine tool using indigenous temperature sensors and CNC integrated Python code validated with a machined test piece. Precision Engineering. 2020;66:21-30.

16. Feng W., Li Z., Gu Q., Yang J. Thermally induced positioning error modelling and compensation based on thermal characteristic analysis. International Journal of Machine Tools and Manufacture. 2015 ;93:26-36.

17. Yung-Cheng W., Ming-che K., Chung-Ping C. Investigation on the spindle thermal displacement and its compensation of precision cutter grinders. Measurement 2011;44 :1183-1187

18. ISO 230-3, 2007, Test Code for Machine Tools – Part 3: Determination of Thermal Effects, Genf, Schwitzerland

19. ISO 10791-10, 2007, Test Conditions for Machining Centres – Part 10: Evaluation of Thermal Distortion, Genf, Schwitzerland.

20. ISO 13041-8, 2004, Test Conditions for Numerically Controlled Turning. Machines and Turning Centres – Part 8: Evaluation of Thermal Distortions, Genf, Schwitzerland.

21. Brechec C., Hirsch P., Weck M.. Compensation of thermo-elastic machine tool deformation based on control internal data. CIRP Annals - Manufacturing Technology. 2004;53(1):299-304.

22. Kostal P, Velisek K. Flexible manufacturing system. Engineering and Technology. 2011;53 :723-727

23. Hexagon Manufacturing Inteligence. Part of Hexagon - m&h Radio-Wave Touch Probe V01.00-REV01.00. Releasedate: 2016-01-15.