Scientific Research Publishing

World Journal of Engineering and Technology, 2024, 12, 258-273
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Further Analysis of Machine Tool Dimensional Accuracy and Thermal Stability under Varying Floor Temperature

Joel Arumun, Shadrack Abiola

Department of Control Systems and Instrumentation, University of Huddersfield, Huddersfield, UK
Email: joeleve2@gmail.com

How to cite this paper: Arumun, J. and Abiola, S. (2024) Further Analysis of Machine Tool Dimensional Accuracy and Thermal Stability under Varying Floor Temperature. *World Journal of Engineering and Technology*, **12**, 258-273.
https://doi.org/10.4236/wjet.2024.122017

Received: February 27, 2024
Accepted: April 20, 2024
Published: April 23, 2024

Abstract

Machining is as old as humanity, and changes in temperature in both the machine's internal and external environments can be of great concern as they affect the machine's thermal stability and, thus, the machine's dimensional accuracy. This paper is a continuation of our earlier work, which aimed to analyze the effect of the internal temperature of a machine tool as the machine is put into operation and vary the external temperature, the machine floor temperature. Some experiments are carried out under controlled conditions to study how machine tool components get heated up and how this heating up affects the machine's accuracy due to thermally induced deviations. Additionally, another angle is added by varying the machine floor temperature. The parameters mentioned above are explored in line with the overall thermal stability of the machine tool and its dimensional accuracy. A Robodrill CNC machine tool is used. The CNC was first soaked with thermal energy by gradually raising the machine floor temperature to a certain level before putting the machine in operation. The machine was monitored, and analytical methods were deplored to evaluate thermal stability. Secondly, the machine was run idle for some time under raised floor temperature before it was put into operation. Data was also collected and analyzed. It is observed that machine thermal stability can be achieved in several ways depending on how the above parameters are joggled. This paper, in conclusion, reinforces the idea of machine tool warm-up process in conjunction with a carefully analyzed and established machine floor temperature variation for the approximation of the machine tool's thermally stability to map the long-time behavior of the machine tool.

Keywords

Dimensional Accuracy, Machine Tool, Machine Floor, Thermal Stability, Temperature, Thermal Deviation

1. Introduction

The history of machine tools can be traced as far back as the beginning of the 18th century, and the issue of machine accuracy is as old as the machine tool itself [1]. The dimensional accuracy of these machine tools is essential to measure, validate or produce parts of given tolerances.

The dimensional accuracy of a machine tool can be influenced right from the design of the machine tool to its production, installation and even the machine operating conditions as provided by the end-user [2]. The machine tool operating environment is of great importance to the thermal stability of the machine tool [3]. The dimensional accuracy of machine tools influences the outcome of any manufacturing process. Furthermore, it is said that the machining processes also influence the machine tool. While it is obvious how much the process depends on the machine tool, the opponent dependency is more complex [4]. Machining indirectly changes the configuration of a machine tool through the impact of heat occurring during operation. The machine tool and process combination can be called a "machining system" [5].

According to Nicolescu and Rashid [5], the machining system's accuracy is influenced by four main factors, as shown in **Figure 1**: The positioning accuracy of the machine tool, thermal deflections, dynamic flexibility and the static deformation of the system. All four parts are determined not only by the machine tool but also by the process itself. Significantly, thermal deflections can influence the other three areas as a change in the thermal conditions.

Induced displacements in machine tools due to thermal expansion or contraction caused by changes in the temperature of the machine's internal or external environment cannot be eliminated by the design concept only [6]. One of the most commonly used methods of software compensation to correct induced displacement is cheap but has limitations.

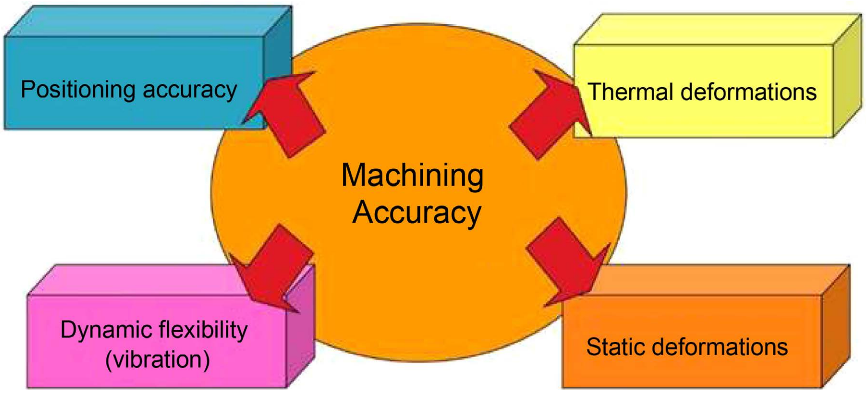


Figure 1. Four factors affecting machine tool accuracy [6].

1.1. Sources of Heat in Machine Tools

There are external and internal heat sources that influence the performance of a machine tool. The most crucial external heat source is the machine floor temperature. Apart from these external heat sources, several internal heat sources impact the temperature distribution within the machine tool. The primary heat source inside a machine tool is the spindle system, including the spindle motor and the bearings [7]. Also, heat is generated in the ball screws and other bearings of the axial drives. Apart from spindle motors, even the motors for axial drives are a heat source in the machine. Additionally, bearings and other parts may include couplings, brakes, and hydraulic and pneumatic systems [8].

Generally, all the parts mentioned above impact the machine tool's thermal deviation and, thus, its thermal stability. The internal heat sources are primarily responsible for local deformations in the machine tool, while external heat sources, such as machine floor temperature, influence the whole volumetric performance [9]. Therefore, the impact of internal heat sources may lead to immediate reactions.

1.2. Thermal Deviation

Thermal deviation is one of the most critical factors affecting the ability of a machine tool to perform accurately, and [10] is commonly regarded as the primary contributor to the errors associated with the machine tool [2] [9] [11]. Thermal drifts of the spindle system are significantly often relatively large and massively influence the quality of the process [11]. Thermal errors cause this displacement by deformation or expansion of single machine tool elements due to a temperature change [10]. Schwenke *et al.* [12], highlight that changed thermal conditions might be reasons for location or component errors of machine tools. There has been a continuous awareness that thermal deviations significantly impact the quality of the finished product, and research aiming to reduce this impact is of crucial importance [8].

Extensive warm-up processes are still used today to get the machine tool up to a thermally stable level before starting production [9]. As mentioned, these warm-up programs can be time and energy-consuming, though they have advantages. Another request to the machine tool user was to level the environmental conditions to erase influences from changes in the external environment, even though this may require much effort for the machine floor to be equipped with an extensive air-conditioning system.

The reason for deformations of a machine tool due to thermal deviations is its non-conformal response to changes in temperature. The ability to keep the demanded configurations under changing thermal conditions can be defined as thermal stability. The higher the thermal stability of a machine, the less vulnerable it is to thermal changes [8]. Many factors influence the evaluation of the thermal stability of a machine tool. It is not only the direct influence of the internal and external heat sources but also the structure of the machine tool itself.

Bryan [13] lists sources of thermal influences on a machine tool:

1) Heat generated by different heat sources inside the machine;
2) Thermal influences provided by heating or cooling systems;
3) Environmental conditions;
4) The effect of people.

All these sources affect the machine tool's accuracy. They can interact with each other, influence different parts of the machine tool with contradictory effects and create a non-uniform temperature field on the machine tool structure. Some consider a change in the ambient temperature as the primary contributor to thermal deviations in machine tools [9]. Others say an increase in machining speed has been observed in recent years, as in the application of high-speed machining processes. This increase in machining speed also increases the heat generated in the machining processes [14]. While this leads to an even more complicated situation in the machine tool, the requirements for machining accuracy are growing at the same time. That makes it necessary to control and reduce the thermally introduced errors.

One of the main problems in reducing the thermally introduced errors is the combination mentioned above of several heat sources that create a non-uniform temperature distribution. Even with a constant temperature gradient, it would be difficult to predict the resulting error due to the number of parts in a machine tool and their diverse reactions to thermal changes. However, the interaction of the different sources leads to a highly complex machine tool error that is hard to predict. [15] While it is known that the primary mode of heat transfer is conduction [6], it is still impossible to create suitable models for whole machine tools considering all kinds of heat transfer (conduction, conversion and radiation) and the non-ideal reality of machine tools.

Moreover, according to various authors [7] [16], the elastic displacement of a machine tool due to thermal deviations has a significant time constraint which also influences the standard technique of using warm-up processes to achieve a steady state. Especially the response to external heat sources, such as machine floor temperature, leads to slow changes in the whole structure of the machine tool. Thus, those external influences affect the whole volumetric performance. In contrast, internal heat sources like bearings or motors have a more local impact and lead to local deformations that may partially affect the machine's accuracy [9].

Measuring the thermal impact on the accuracy of a machine tool is a challenging task in today's production. In conclusion, thermal errors are most likely the main contributor to geometrical errors on the final workpiece. While the effort and, therefore, the cost involved in handling these problems is high, this can be equalized by the achievements that can be made by reducing this problem [10].

While the influence of thermal deviation on the accuracy of machine tools was and is an object of intensive research, the impact of changing temperatures on the stiffness of machine tools is widely ignored by researchers. The stiffness of a machine tool is determined by the stiffness of every part of the structural chain, but the contact stiffness in the many fixed or moving joints is equally essential. [17] Due to this complexity, the influence of thermal changes on the overall stiffness of a machine tool is hard to predict and needs to be evaluated experimentally.

In addition to establishing ways of reducing thermal deviations, we propose a proper understanding of each machine tool, given its advantages and drawbacks and the machine floor temperature, through a series of carefully planned experiments. Data is obtained and analyzed to determine the most suitable combination of these factors and what works best for achieving high dimensional accuracy. Measurement accuracy is crucial to instrument calibrators [18], and dimensional accuracy is vital to machine tools.

2. Experiments and Results

A stable granite block was probed to determine the effect of gradual machine heating and varying machine floor temperature with (measurement) accuracy in the three axes of the machine to identify the deviation resulting from the impact of the machine floor heating. This was achieved with experiment one and two below.

2.1. Experiment One: Machine Heating through Gradual Increase of Machine Floor Temperature

This work is coming on the heels of our previous work [3] in this regard, and this time, it is the machine heating through a gradual increase in machine floor temperature. Robodrill CNC machine tool is used here. The operation lasted a total of four hours of actual machining. The temperature of the machine floor was raised gradually for two hours to about 31˚C before taking the machine off the emergency stop to probe the granite block. At this point, the temperature of the Z-axis motor, the column bolt top, and the Z-ball nut were 29.75˚C, 23.25˚C, and 22.31˚C, respectively. These values are significant compared to around 22˚C derived from previous experiments for most components. The automatic temperature control of the machine floor meant that the high ambient temperature could not hold for long. Hence, there was a rapid drop in ambient temperature to 22.75˚C in two hours while probing was ongoing. This temperature drop caused the machine components to respond similarly, with the Z-axis motor temperature dropping rapidly to 26˚C for two hours. The column bolt top and the Z-ball nut also remained within this temperature boundary of 26˚C.

It can be seen from **Figure 2** that the deviation measurement for the X-axis got a maximum of about 25 microns at corners 1 and 2 after probing for an hour. Corner 4 also experienced a 10-micron deviation in just less than 3 hours.

Corner 4 had the highest deviation measurement on the Y-axis at 10 microns. The Z-axis, however, saw a tremendous deviation from the datum points in a

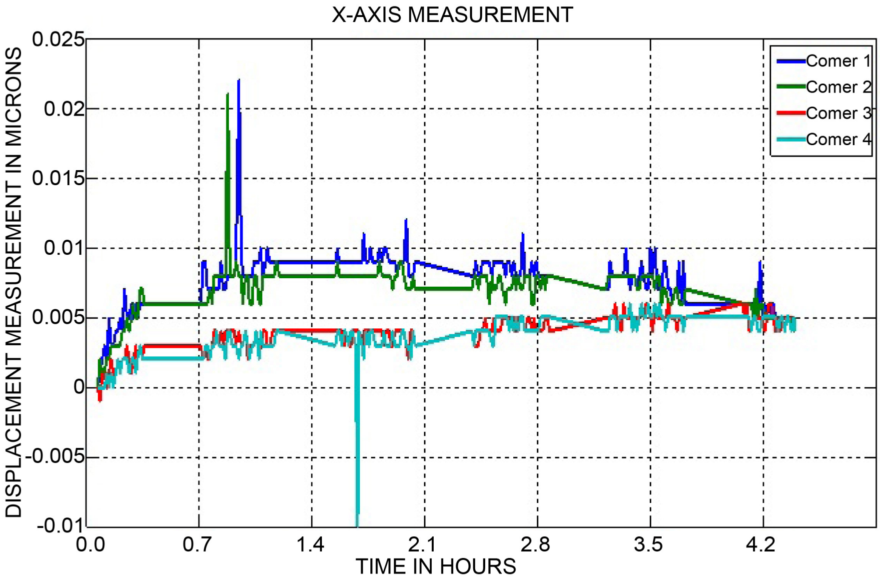


Figure 2. Deviation measurement for regular heating in the X-axis.

very short time compared to other axes, rising to an average of 40 microns in thirty minutes and climaxing at 55 microns after an hour on all corners, remaining at that measurement for three more hours. Figures 2-4 show the deviation measurement for all three axes in MATLAB plots.

The machine, however, came to an abrupt halt after four hours of probing due to unforced machine errors. At the continued ambient temperature of 22.75˚C, the temperature of the Z-axis motor stabilized at about 26˚C. After the machine's abrupt stoppage, the machine was taken off emergency stop, and the probing continued for four more hours, with the ambient temperature remaining unchanged. Within the next four hours, the temperature of the Z-axis motor rose to 26.375˚C, as well as the column bolt top and the Z-ball nut. The deviation measurements for the last four hours are shown in Figures 5-7.

The X-axis had a maximum deviation of 11 microns on the 4th corner after 3 hours of probing. The Y-axis largely stayed within an average of around 4 microns but had a maximum of 8 microns. As with the previous Z-axis measurement, the Z-axis had a quick rise and climaxed at 90 microns after three hours and 12 minutes.

2.2. Experiment Two: The Z-Axis Rapid Heating through Raised Machine Floor Temperature

Figures 9-14 show the deviation measurements for all three axes at the four corners of the granite block for the rapid Z-axis heating. This experiment continues the gradual machine heating and probe process outlined above in experiment one. While the machine ran idle for eight hours, the workshop's ambient temperature gradually rose to 31˚C.

Looking at the temperature graph of Figure 8, the temperature of the Z-axis motor rose to 27˚C within the 8-hour idle mode. The Robodrill was then removed

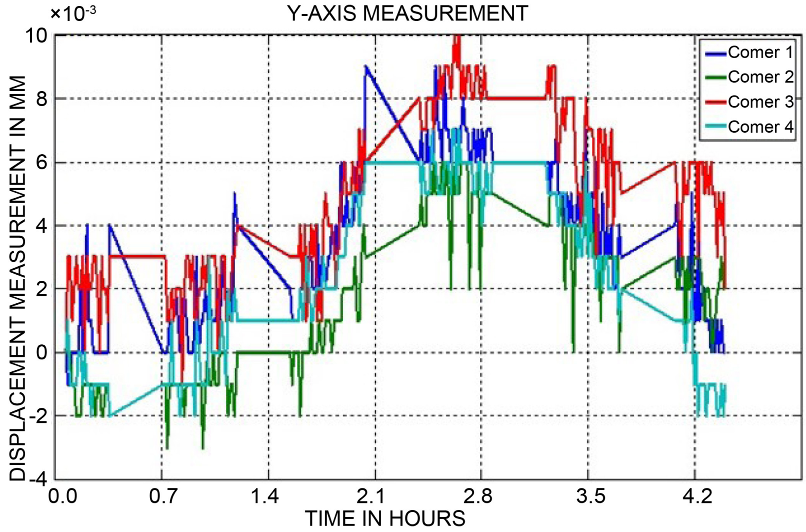


Figure 3. Deviation measurement for regular heating in the Y-axis.

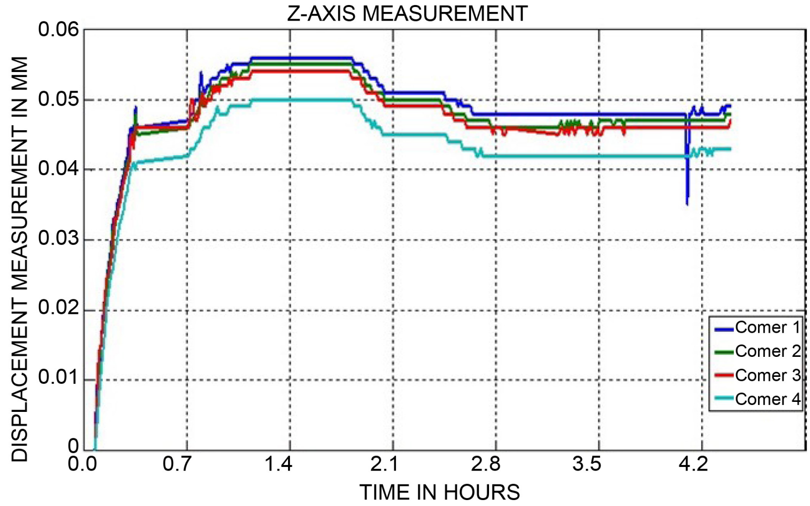


Figure 4. Deviation measurement for regular heating in the Z-axis.

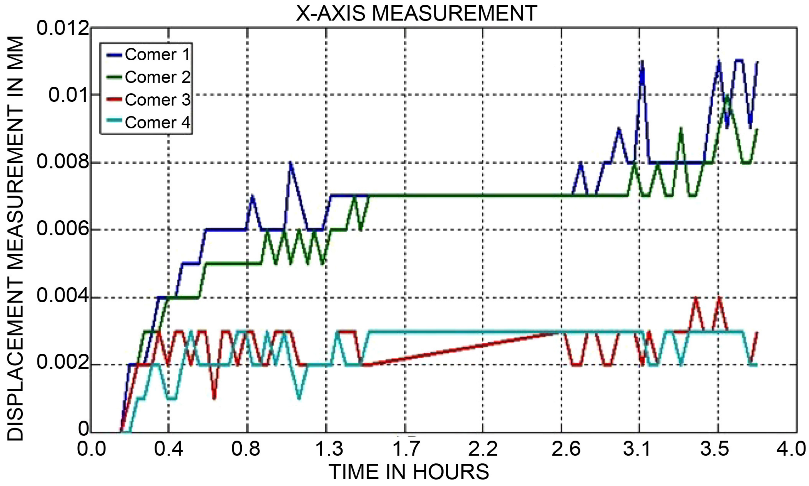


Figure 5. Continued deviation measurement in X-axis.

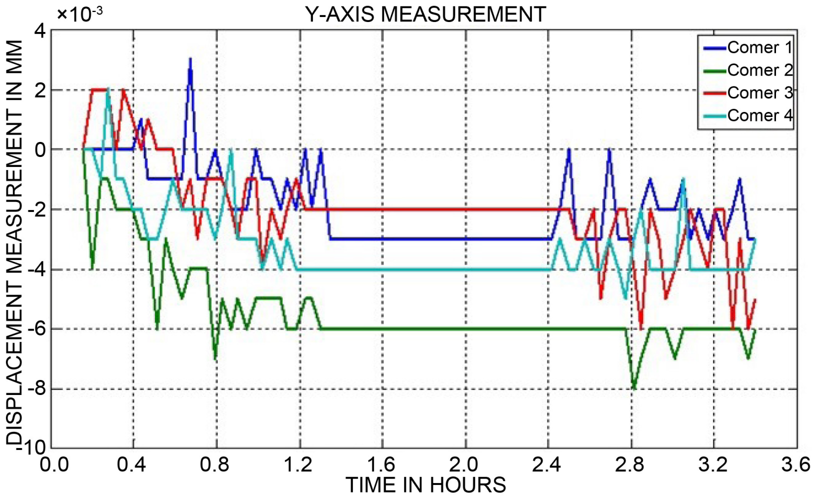


Figure 6. Continued deviation measurement in Y-axis.

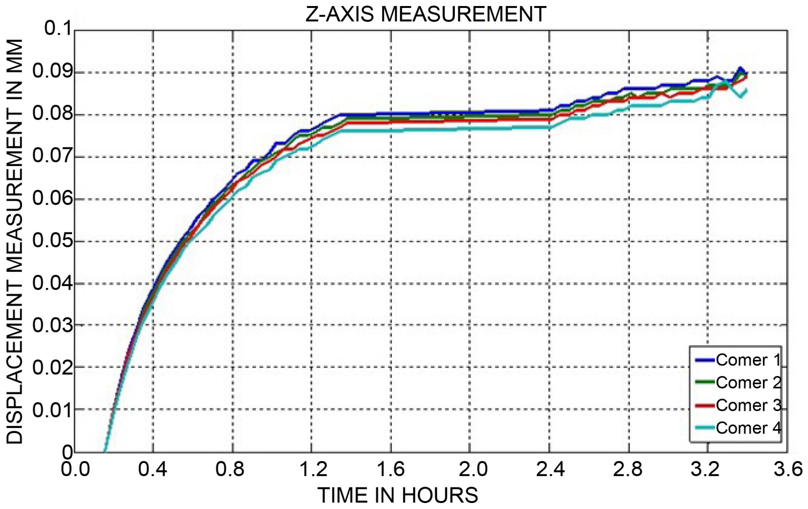


Figure 7. Continued deviation measurement in Z-axis.

from an emergency stop and operated to probe the granite block rapidly for four hours. Rapid heating meant the Z-axis, consisting of the Z-axis motor and spindle, was moved repeatedly upwards and downwards ten times before each probe cycle. From the results in the graphs below, the machine gradually got soaked with the new temperature, and the Z-axis motor temperature rose marginally to 27.25˚C. Due to the automatic temperature settings of the machine floor, the ambient temperature gradually dropped from 22˚C to 19˚C after 2 hours. This change had almost no effect on the temperature of the Z-axis motor, which remained at 27.37˚C at the end of the four hours.

The maximum deviation on the X-axis is 8 microns and is derived at the first and second corners, just after 3 hours and 30 minutes of probing, as seen in **Figure 9**.

At about the same time, the Y-axis experienced a maximum of 8 microns deviation from the original datum points after 3 hours and 30 minutes of probing.

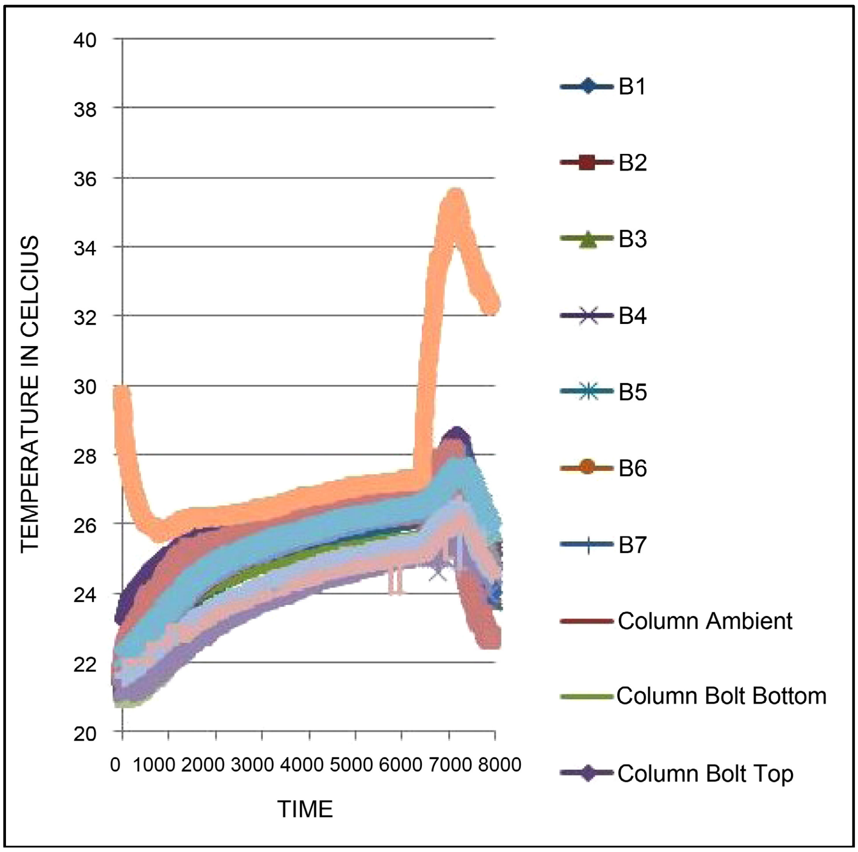


Figure 8. Temperature graph of machine components heating and cooling during idle run.

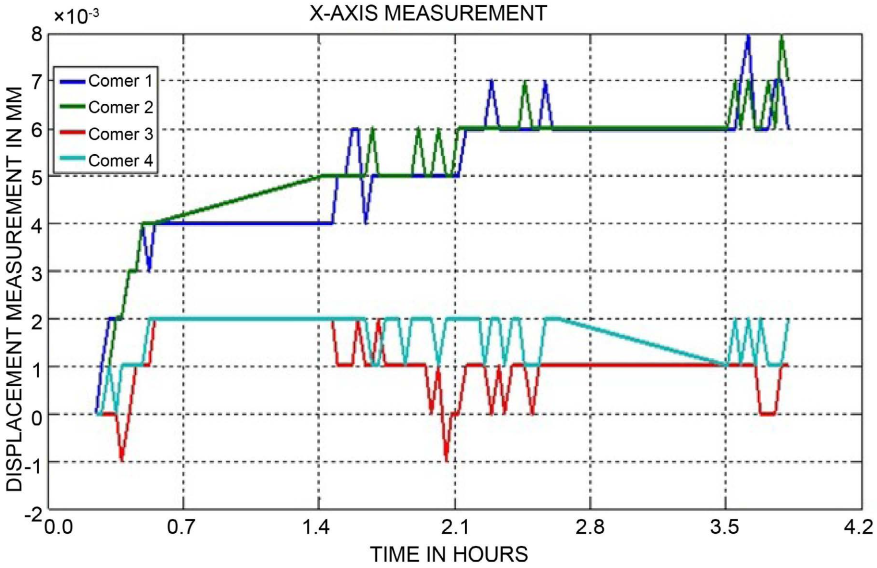


Figure 9. Deviation measurement in Rapid Z-Axis heating for X-Axis.

See **Figure 10**.

On the Z-axis, however, the deviation measurement was 30 microns, just under 45 minutes of probing and climaxed at almost 60 microns on all four corners

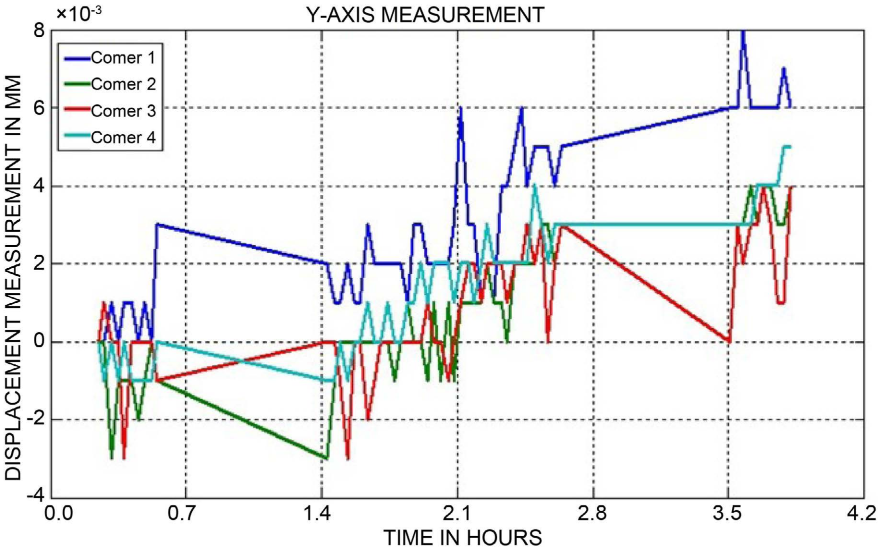


Figure 10. Deviation measurement in rapid Z-Axis heating for Y-Axis.

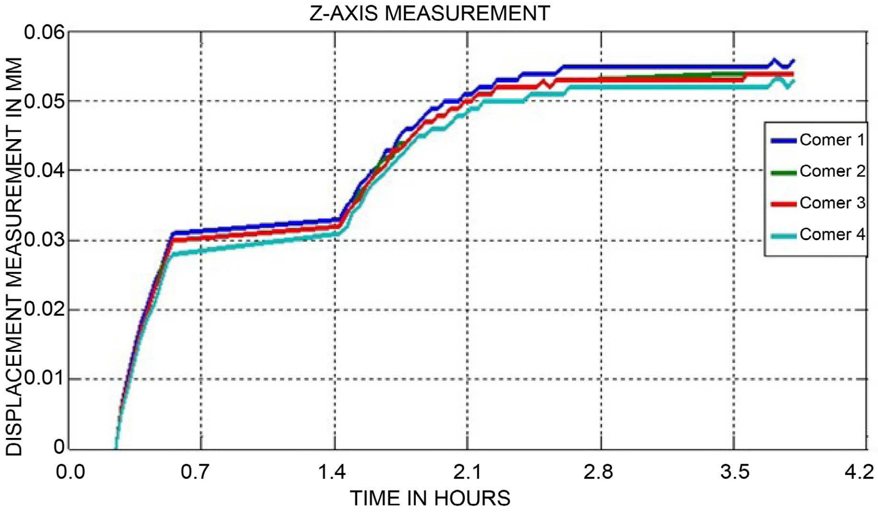


Figure 11. Deviation measurement in rapid Z-Axis heating for Z-Axis.

at the end of 4 hours.

Z-Axis Rapid Heating (Continuation after Machine Stopped)

As with many machines and systems, certain factors not inherent in the system's composition could lead to minor or significant malfunctions/breakdowns. After four hours of probing, the machine part programme failed, and the machine automatically stopped while the temperature sensors kept sampling and recording the temperature of the various components. As a result of the undue stoppage, the machine was restarted after the ambient temperature was raised to 31˚C, and rapid Z-axis heating/probing continued.

At this stage, the X-axis mostly showed a 7-micron deviation but had a maximum of 8 microns seen at the first corner after 1 hour and 42 minutes, as captured in Figure 12. The first corner also showed a maximum deviation of almost

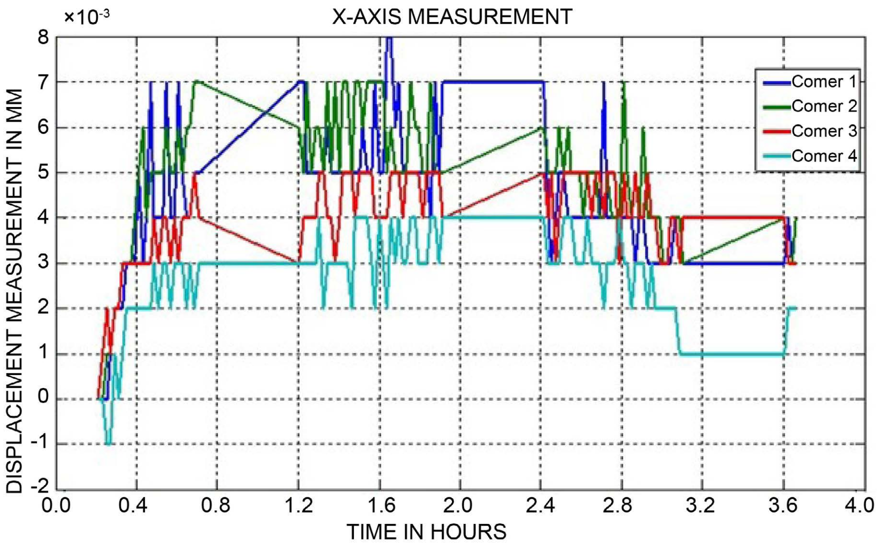


Figure 12. Continued deviation measurement in rapid heating for X-axis.

5 and 8 microns on the Y-axis. On the Z-axis, however, the maximum deviation measurement was 90 microns, occurring after 3 hours and 42 minutes on all four corners. The graphical representation of the results obtained is shown in Figures 12-14.

3. Analysis

3.1. Temperature Analysis

Twenty-four temperature sensors measured the temperature of the various components in real-time from start to finish of the experiment and for an additional 2 hours of cooling. The machine tool's three most thermally affected components are the Z-axis motor, the column bolt and the Z-ball nut. The effect of varying the ambient environment temperature is shown in this experiment to affect machine tool accuracy due to the varying degrees of spindle/tool expansion and other key machine components.

Furthermore, it has been discovered that starting machine operations with temperatures slightly higher than the ambient temperature makes the Z-axis motor faster and more thermal stable. However, higher temperatures introduce more errors due to expansion. As a measure in industry, error correction mechanisms could be incorporated to cover these errors, but again, this may lead to more power consumption for an entire machine process.

At cooling, with the machine completely shut down, the automatic temperature setting of the machine floor dropped the ambient temperature to 19˚C, thereby bringing the temperature of the Z-axis motor to 32.25˚C from 35.35˚C in two hours. The column bolt top and the Z-ball nut also showed significant temperature responses, as depicted on the temperature graph, with both components rising to 28˚C. The Z-axis is the most thermally affected because it accounts for most of the machine's rigorous motions. In addition to friction, electric

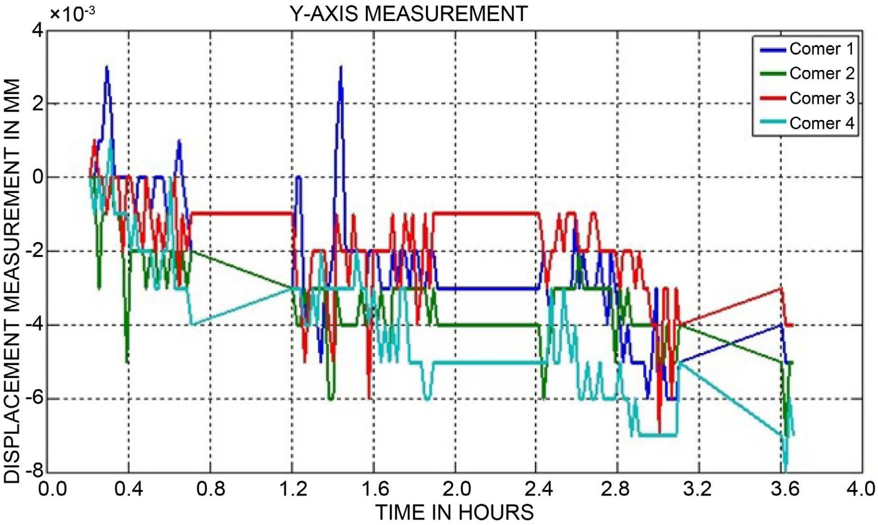


Figure 13. Continued deviation measurement in rapid heating for Y-axis.

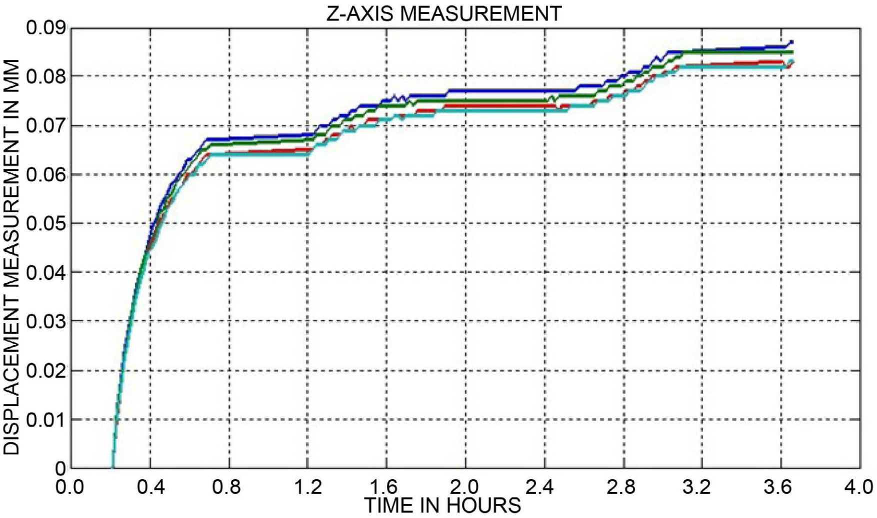


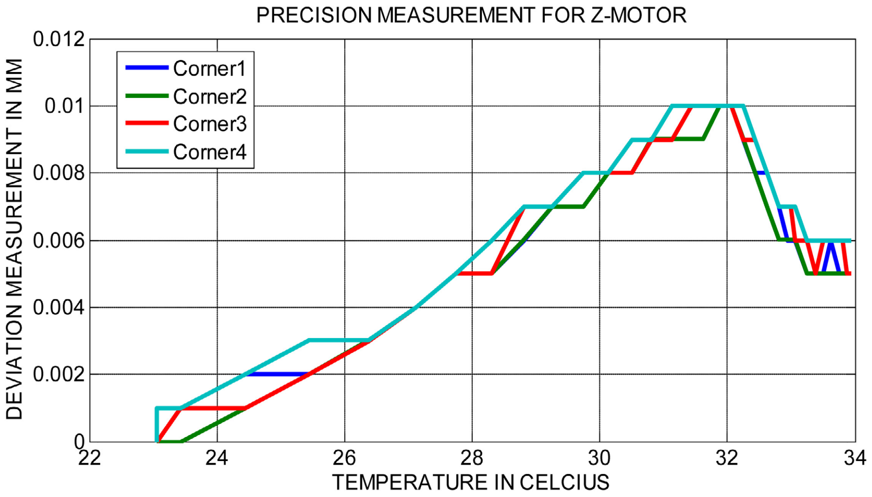
Figure 14. Continued deviation measurement in rapid heating for Z-axis.

power is drawn, and increased ambient temperature raises its operating temperature.

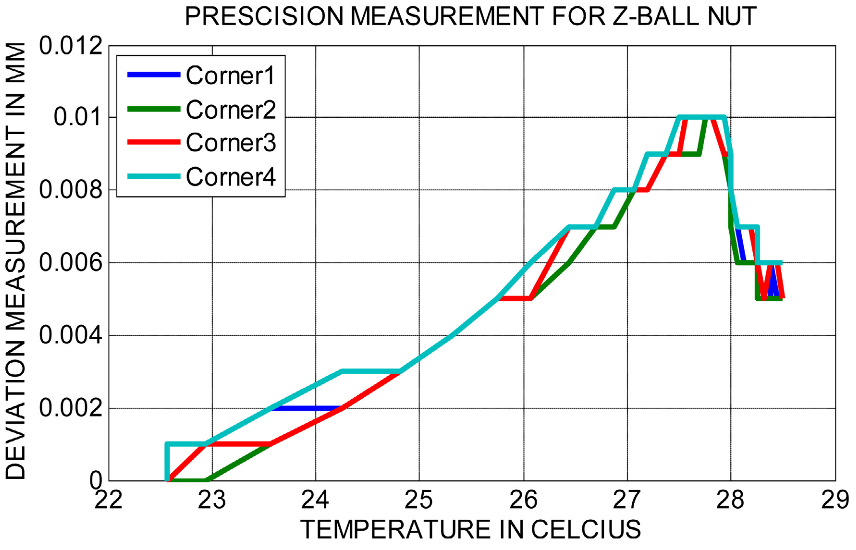
3.2. Correlation of Temperature with Dimensional Deviation

The several experiments of dimensional deviation with time carried out above and the accompanying temperature graphs show the effect and errors associated with increased temperature above the normal operating conditions of the machine as well as the machine floor with time. While it is important to know the deviation with time due to thermal expansion, it is equally essential to understand how much deviation is derived within some degree of change in temperature as a measure of standard in precision marking. Having this knowledge will show the required temperature of the z-motor needed to attain a particular precision part. It will also enable effective monitoring/manipulation and control of operating temperatures on the machine and machine floor for the desired results. Figure 15(a) and Figure 15(b) show the correlation of deviation measurement with temperature. Since MATLAB deals with quantities as vectors and temperature and deviation are of different vector sizes, it was better to make them equal to obtain a deviation plot against time, as shown in Figure 15(a) and Figure 15(b).

The correlation values are measured given a fluctuating ambient temperature of the machine floor between 19˚C and 31˚C since many machine floors are imperfect in keeping floor temperatures constant over an entire machining period. This results in different temperature ranges for the z-motor (the primary component being considered due to its apparent workload). Correlation values are produced by matching the deviation measurement obtained at a particular



(a)



(b)

Figure 15. (a) Correlation of deviation measurement with temperature for the Z-motor; (b) Correlation of deviation measurement with temperature for Z-Ball Nut.

machining time to the exact temperature measured by the sensor on the Z-motor. It measures the maximum probable expansion (error) derivable from the machine over time. From the graph of correlation for Z-motor in **Figure 15(a)**, it can be seen that an approximately one-micron deviation is added to the initial datum measurements when machining below or around a machine floor ambient temperature of 22˚C as well as within two hours from the start of a machining process. This is because the temperature rise in the Z-motor is insufficient to translate into much expansion on the spindle and tool where the errors are recorded. Subsequently, measurements beyond two hours of light machining or increased ambient temperature above 24˚C to a maximum of 31˚C yield an addition of approximately 2 microns deviation per 2˚C rise in temperature of the Z-motor, which had now become soaked with high temperatures over time.

4. Conclusions

This paper buttresses the point that although the parts of a machine tool may be made from highly thermal stable alloys, a degree rise in ambient temperature could sometimes introduce errors in high-precision parts. The results obtained from probing over time show a gradual rise in deviation measurement due to temperature rise from continuously operating the machine tools. These expansions occur in different proportions on all axes due to the heat added to the spindle from the Z-motor and friction. A careful look at the machine tool shows that increased temperature affects the Z-axis most since it operates mainly throughout the entire time. This is corroborated by the Z-axis and temperature graphs, where the Z values soar above all other components. The different temperature scenarios for the machine floor show the extent to which manipulations of the floor temperatures could be made. By keeping the temperature at specified limits, the expansion of machine components can be minimized to attain the desired part measurement. Most of the expansions are not coherent as a result of temperature fluctuations. Upon attainment of thermal stability of the z-axis motor (which is vital before beginning machining a part) and keeping ambient temperature constant at around 22˚C, machining errors are significantly reduced. The most critical factor affecting the accuracy of probe cycles is the ambient temperature of the machine floor, which, if manipulated, can considerably impact the temperature of the motors and electronics either positively or negatively.

Finally, it is possible to predict the temperature at which a particular degree of precision may be achieved, given a good understanding of manipulating the machine floor temperature with the machine’s gradual heating or rapid heating. Also considered is the predictability of other factors, such as tool type and proficiency of the operator. Therefore, it is pertinent for engineers seeking high-precision machining to combine all temperature factors for the machine and machine floor to determine what can best be achieved within cost considerations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Moore, W.R. (1970) Foundations of Mechanical Accuracy. Moore Special Tool Company, Bridgeport, 143.

[2] Putz, M., Richter, C., Regel, J. and Bräunig, M. (2018) Industrial Relevance and Causes of Thermal Issues in Machine Tools. *1st Conference on Thermal Issues in Machine Tool*, Dresden, 21-23 March 2018, 127-142.

[3] Arumun, J. and Abiola, S. (2023) Evaluation of Machine Tool Thermal Stability against Dimensional Accuracy. *International Research Journal of Engineering and Technology*, **10**, 932-938.

[4] Brecher, C., Esser, M. and Witt, S. (2009) Interaction of Manufacturing Process and Machine Tool. *CIRP Annals - Manufacturing Technology*, **58**, 558-607. https://doi.org/10.1016/j.cirp.2009.09.005

[5] Nicolescu, M. and Rashid, A. (2013) Machining Dynamics. Lecture at KTH, Autumn Semester.

[6] Hedderich, J. (2015) Thermal Stability in Machine Tools. Master's Thesis, Royal Institute of Technology, Stockholm. https://www.semanticscholar.org/paper/Thermal-stability-in-machine-tools-Hedderich/b15a735a97d85db674cf66d34d4376f164737d63

[7] Uddin, M.S., Ibaraki, S., Matsubara, A. and Matsushita, T. (2009) Prediction and Compensation of Machining Geometric Errors of Five-Axis Machining Centers with Kinematic Errors. *Precision Engineering*, **33**, 194-201. https://doi.org/10.1016/j.precisioneng.2008.06.001

[8] Mekid, S. and Jedrzejewski, J. (2009) Thermal problems in Machine Tools Design and Operation. In: Mekid, S. Ed., *Introduction to Precision Machine Design and Error Assessment*, CRC Press, Boca Raton. https://doi.org/10.1201/b15822

[9] Mayr, J., Jedrzejewski, J., Uhlmann, E., *et al.* (2012) Thermal Issues in Machine Tools. *CIRP Annals - Manufacturing Technology*, **61**, 771-791. https://doi.org/10.1016/j.cirp.2012.05.008

[10] Voight, I., Winker, S., Werner, R., Bucht, A. and Drossel, W.G. (2018) Thermal Error Compensation on Direct Drive Based on Latent Heat Storage. *1st Conference on Thermal Issues in Machine Tool,* Dresden, 117-126.

[11] Srinivasa, N., Ziegert, J.C. and Mize, C.D. (1996) Spindle Thermal Drift Measurement Using the Laser Ball Bar. *Precision Engineering,* **18**, 118-128. https://doi.org/10.1016/0141-6359(95)00053-4

[12] Schwenke, H., Knapp, W., *et al.* (2008) Geometric Error Measurement and Compensation of Machines—An Update. *CIRP Annals - Manufacturing Technology*, **57**, 660-675. https://doi.org/10.1016/j.cirp.2008.09.008

[13] Bryan, J. (1990) International Status of Thermal Error Research. *Annals of the CIRP*, **39**, 645-656. https://doi.org/10.1016/S0007-8506(07)63001-7

[14] Abukhshim, N.A., Mativenga, P.T. and Sheikh, M.A. (2006) Heat Generation and Temperature Prediction in Metal Cutting: A Review and Implications for High-Speed Machining. *International Journal of Machine Tools & Manufacture*, **46**, 782-800. https://doi.org/10.1016/j.ijmachtools.2005.07.024

[15] Kuznetsov, A.P., Koriath, H.J. and Dorozhko, A.O. (2018) The Methods for Controlled Thermal Deformation in Machine Tools. *1st Conference on Thermal Issues in Machine Tool*, Dresden, 21-23 March 2018, 117-126.

[16] Brecher, C. and Hirsch, P. and Weck, M. (2004) Compensation of Thermo-Elastic Machine Tool Deformation Based on Control internal Data. *CIRP Annals - Manufacturing Technology*, **53**, 299-304. https://doi.org/10.1016/S0007-8506(07)60702-1

[17] Archenti, A., Österlind, T. and Nicolescu, M. (2011) Evaluation and Representation of Machine Tool Deformations. *Journal of Machine Engineering*, **11**, 105-117.

[18] Arumun, J. and Eronu, E. (2023) Low-Cost 4-20 mA Loop Calibrator. *Journal of Flow Control Measurement & Visualization,* **11**, 49-63. https://doi.org/10.4236/jfcmv.2023.113004