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Evaluation of Machine Tool Thermal Stability against Dimensional Accuracy

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Abstract - *Monitoring of energy consumption patterns on machine tools over variable workloads for a machine in operation is important in improving production. This paper seeks to relate machine thermal stability with dimensional accuracy. Machine tool signal acquisition and processing techniques are applied over three set of experiments in idle, runtime and production modes using a CNC machine tool; Fanuc RoboDril Model α-T14iDe. The same work piece and same workshop floor temperatures are maintained with critical discussion on outcomes. The study uses analytical methods to monitor and evaluate thermal stability in the machine tool and how it affects dimensional or measurement accuracy. It established the fact that it is important to bring up a machine tool to its thermal stability before any operation if high dimensional accuracy is deserved.*

Key Words: Machine Tool, Thermal Stability, Dimensional Accuracy.

1. INTRODUCTION

Manufacturing takes about half of the total world's primary energy consumption and a large part of this energy is consumed by machine tools [1]. The course of action toward energy efficiency in the manufacturing sphere is constantly being driven by machine tool users looking for regimes of low operational costs. Deliberate monitoring of machine operation to ensure efficient production processes will minimize wastages. Having adequate knowledge about the amount of energy consumption by machine tools forms the basis for optimizations of machine tools' measurement accuracy and monitoring.

The global manufacturing industry is driven by machine tools which aid in the production of other industrial equipment and machinery. Bawa, (2004) defines machine tools as power-driven machines capable of holding and supporting the work tool and at the same time directing and guiding the cutting tool or job or both to perform various metal cutting operations for providing different shapes and sizes [2]. The machining process is characterized by three basic elements namely, the workpiece, tool, and Chip or swarf [3].

Machine tools may be divided into conventional types and computer numerical controlled (CNC). This project is concerned with the CNC machine type [4]. A machining centre is a sophisticated CNC machine that can perform multiple machining operations in the same setup with a variety of tools. Vertical Machining centres (VMC) and Horizontal Machining Centres (HMC) are the two types of CNC machine centres we have and are based on the orientation of the spindle. VMCs are the most widely used machine centres designed for operations in the X-Y motions to a desired depth [5]. A third type of machining centre is the universal machining centre which incorporates both a vertical and horizontal spindle in one machine, making them able to machine all surfaces of any workpiece [6].

Shaohua et al [2012], uses a multi-component approach that takes into account the energy monitoring of nearly all components of a machine tool [7]. However, Kordonowy, (2003) argued that this methodology poses great difficulties in the accurate measurement and monitoring of energy efficiency and utilization [8]. He emphasized that constant energy consumption is independent of machining, whereas, the variable energy consumption which is the cutting power consumed during the machine operation, is dependent on machining.

The components that draw the most power are the rotating spindle, servo motor, and cooling devices [9]. Others are the hydraulic unit, cutting oil pumps, and other peripheral devices. Most energy monitoring methodologies are very superficial, only taking into account the measurement of the machine cutting power with torque sensors or dynamometers which is not efficient or adequate. Another major issue of contention is that of the different definitions of the machine tools given by different bodies looking at it from different perspectives, as is the case with the CECIMO and NACE.

2. SIGNAL AQUISITION

The consequence of the many sources and mechanisms of energy demand in machine tools and the robust auxiliary metrology tools, no doubt require the use of a multi-sensor systems approach in the acquisition and monitoring of process flow signals [10]. These multi-sensor systems encounter several technical issues such as the derivation of effective down-sampling methods required to extract the most vital signals representative of desired measured parameters (Diaz et al, 2009). The seemingly complex nature of machine tools makes signal acquisition and analysis a challenging task.

The signal acquisition follows the procedure itemised below. Probing for accuracy under three thermal energy measurement scenarios:

(A) Keeping the machine tools in the idle state for 24 hours and subsequently running in production mode to probe a stable granite block at intervals of 6 minutes for 4 hours. This is to determine (measurement) accuracy with each probe

cycle, in the three axes to identify the deviation resulting from the effect of heat on the ball screw as a result of the prolonged production mode of the machine.

(B) Probing granite block in production mode for Z-axis accuracy, at intervals of 6 minutes for 4 hours, with the incorporation of temperature sensors. This is done after the machine is completely shut down for 16 hours. The probing cycles are required to determine the effects of thermal energy on the machine tool from its cold state to a period when the temperature of key components has reached thermal stability while in production mode.

(C) The Z-axis motor is moved in ten quick motions upwards and downwards to rapidly heat the motor, to see if this could bring the machine and especially the motor faster to thermal stability than the procedure in (b). This is followed by a probe of the granite block and rapid motion of the Z-axis motor again. This sequence is carried out for 4 hours and incorporates temperature sensors to monitor the temperature of the various components in real time.

3. EXPERIMENTS

3.1 Experiment One

A granite block is probed for machine dimensional accuracy to determine the response to heating of the machine tool over a long operating period. Fanuc RoboDril Model α-T14iDe which incorporates a Renishaw probing tool is used. See Fig -1. The machine tool was kept in an idle state for 24 hours and subsequently operated in production mode to probe the granite block at intervals of 6 minutes for 4 hours at a workshop temperature of 25Co

The dimensional values in the X, Y, and Z axis positions of each corner of the granite block were extracted and MATLAB was applied to graphically show the deviation from the original datum points for each axis and at the various corners. Block datum is given in Table 1.

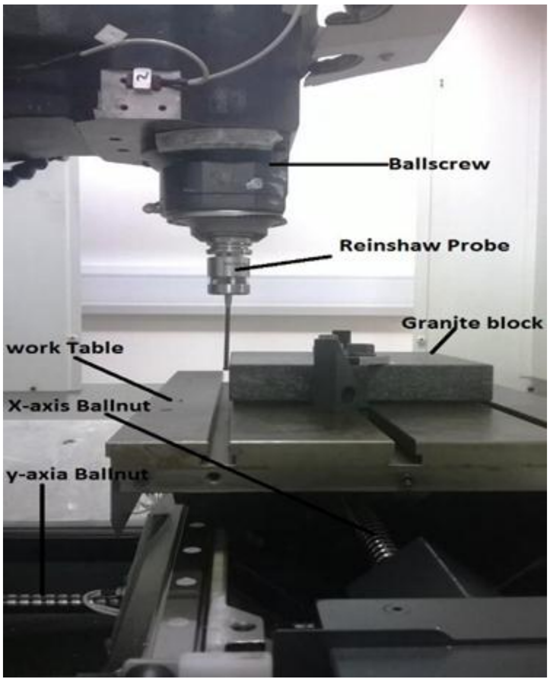

Fig -1: Probing with RoboDril CNC Machine Tool

Table 1. Datum positions for granite block

CORNER1	CORNER2	CORNER3	CORNER4
92239	92255	92312	92329
X - .0100	X .0890	X .9400	X .8440
Y - .0160	Y .5310	Y .4270	Y - .1170
Z - .0250	Z - .1090	Z - .0230	Z .0520

Result and Analysis of Experiment One

The plot of probe data showed some significant deviation in measurement from the initial datum points. See chart 1, 2, and 3.

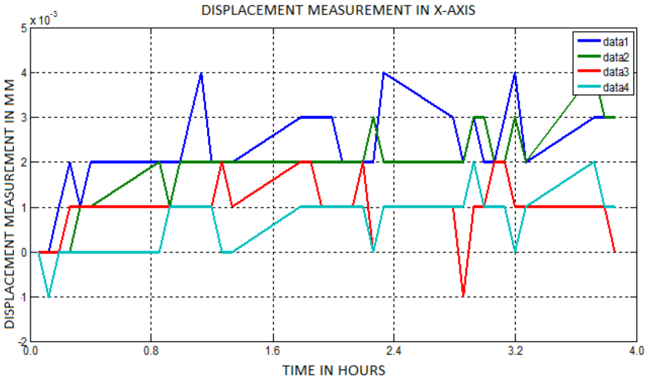

Chart -1: Experiment 1 - Displacement in X-Axis

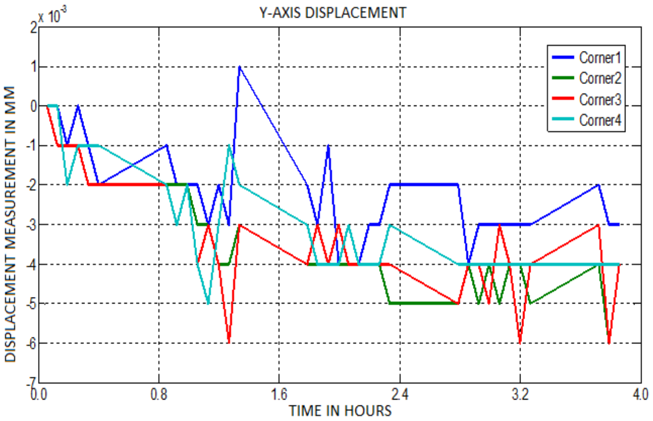

Chart -2: Experiment 1 - Displacement in Y-Axis

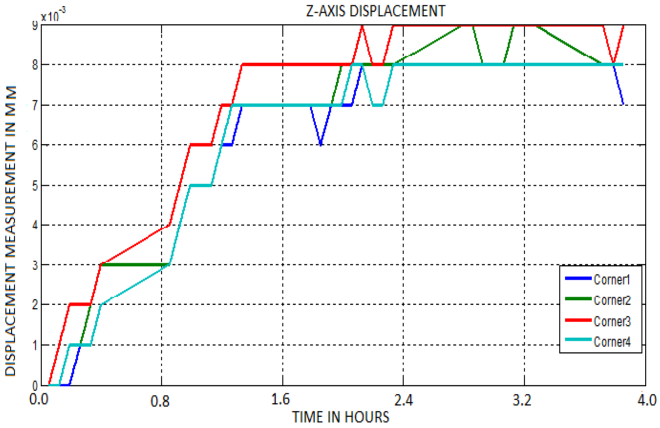

Chart -3: Experiment 1 - Displacement in Z-Axis

While these deviations may not be visible to the human eyes, their presence may constitute a challenge in the manufacture of parts requiring tight tolerances as these deviations could manifest as significant cumulative errors. From the results, it is seen that the maximum deviation is on the z-axis.

This is probably because the heat is transferred to the ball screw and then to the tool, which could lead to machining errors as a result of the expansion. The Machine tool reaches thermal stability eventually.

Though the various axes arrived thermal stability at different times, it took the Z-axes the longest time of about two and a half hours.

3.2 Experiment Two

Probing the granite block for dimensional accuracy using the same machine tool and workshop temperature with the incorporation of 24 temperature sensors (see Fig -2) and it runs for 6 hours.

This second experiment sought to go further in not just determining the deviation of dimension from the datum over prolonged machine usage, but also to determine the thermal energy emitted by key operating components with time, such as the machine column, column Bolt, Spindle, spindle Motor, Z-axis Motor, etc. A total of 24 sensors are used for temperature measurement. A temperature software, 'TempSpy' samples the signals every 30 seconds.

This procedure was performed in three stages after the machine was left completely shut down for 16 hours:

(a) Probing granite block in production mode every 6 minutes for 4 hours and 20 minutes.

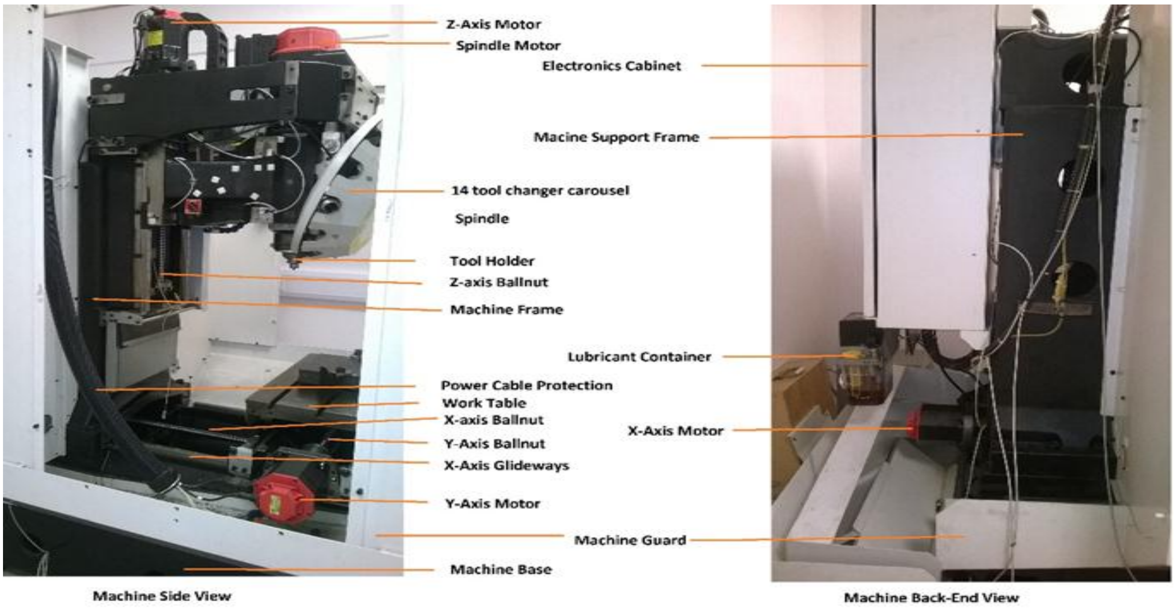

Fig -2: Arrangement of Temperature Sensors on Robodrill

(b) The machine was then placed on the emergency stop and completely shut down for about 1 hour to observe the rate of cooling and heat dissipation from the machine components, and

(c) The machine was taken off the emergency stop and then powered to production mode to probe the granite block for 45 minutes, as in stage one.

Result and Analysis of Experiment Two

A two-dimensional graphical plot of displacement measurement in microns against time is obtained for the three axes (X, Y, and Z) at the four corners of the block using MATLAB.

(a) Analysis of Stage One

The X and Y axes had a little rise in measurement deviation with time but quickly stabilized while the Z-axis, on the other hand, showed a steady rise in measurement deviation with probe time. This axis is majorly affected by the heating of the Z-motor and explains the very visible rise in measurement deviation. It shows the effect of temperature on measurement accuracy, see Chart 4, 5, and 6.

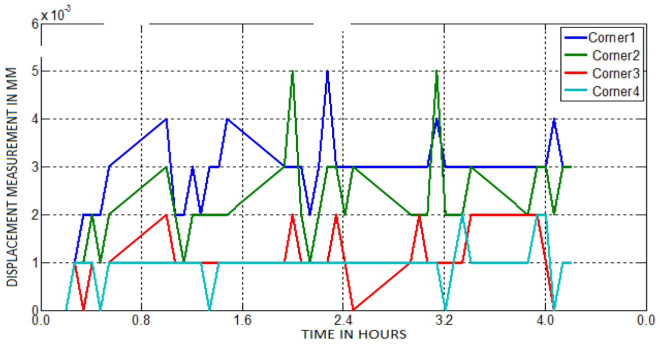

Chart -4: Experiment 2 - Displacement in X-Axis

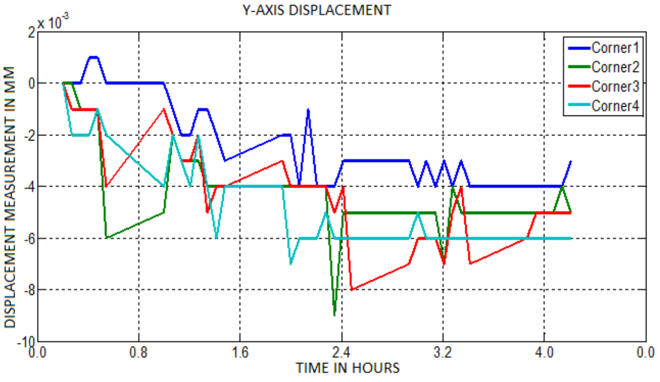

Chart -5: Experiment 2 - Displacement in Y-Axis

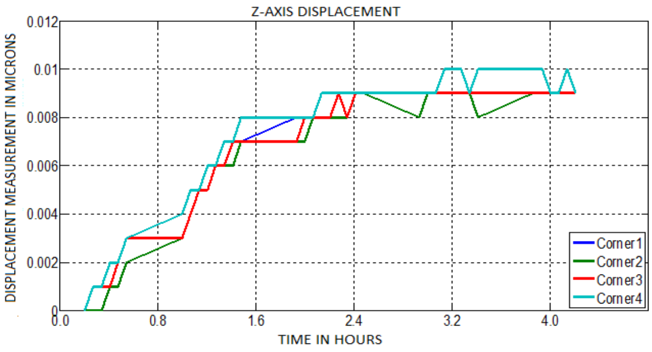

Chart -6: Experiment 2 - Displacement in Z-Axis

(b) Analysis of Stages Two and Three

The results of measurement deviation are shown in Chart 7, 8, and 9. The x-axis experiences a maximum deviation of 2 microns throughout the period. In the y-axis, the maximum deviation is 5 microns. The Z-axis showed consistency in probing cycles at the four corners.

At this point, there is more expansion of the Z-axis components which are fully soaked with the high temperature, as objects tend to cool for a much longer time than they get heated up. The Z-axis motor experiences a greater thermal effect and heat retention for a longer time as compared with other components of the machine.

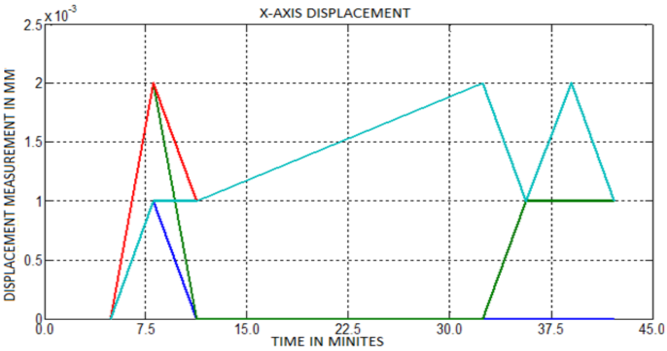

Chart -7: Experiment 2: X-Axis Displacement for Probing Cycle

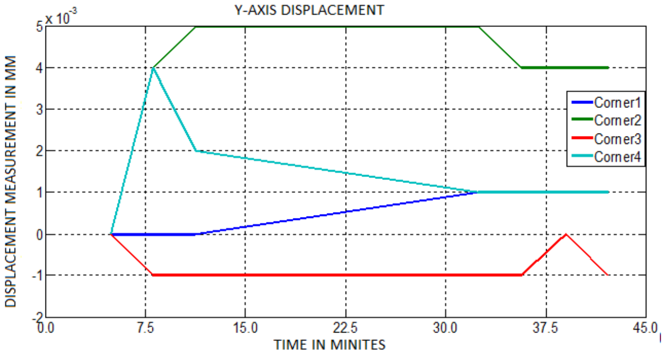

Chart -8: Experiment 2: Y-Axis Displacement for Probing Cycle

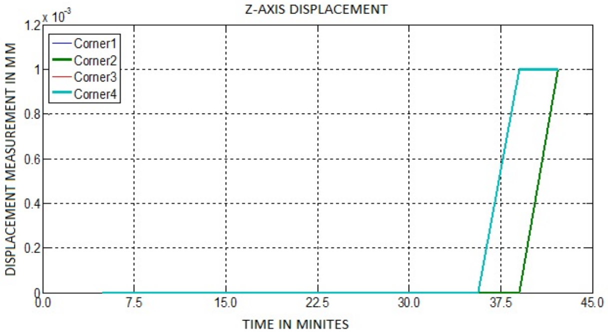

Chart -9: Experiment 2: Z-Axis Displacement for Probing Cycle

(c) Temperature Analysis of Experiment two

The temperature analysis of the machine tool in this experiment is captured by 24 different sensors affixed to different parts of the machine tool. They capture the temperature data in real-time at a sampling time of 30 seconds and then analysed it by the TempSpy software. The graph of Chart 10 indicates the sensor locations and the temperature measurement throughout probing. It gives an insight as to how the machine warms up, the component generating the greater heat and those most affected by heat, the rate of cooling, and the thermal stability region. The sensors monitored the machine from a cold state which is the initial temperature before start-up. This temperature rose gradually with very unstable ripples which took 2 hours to attain thermal stability. The most substantial rise is noticed in the z-axis motor, which rose exponentially above the average machine stable temperature of 22.5Co to a peak of 30.37Co as the most thermally affected component within the experiment period. Other components worthy of mention are the column bolt and Z-ball nut whose temperatures were 23.8oC and 22.9oC respectively at a machine thermal stability of 22.5oC.

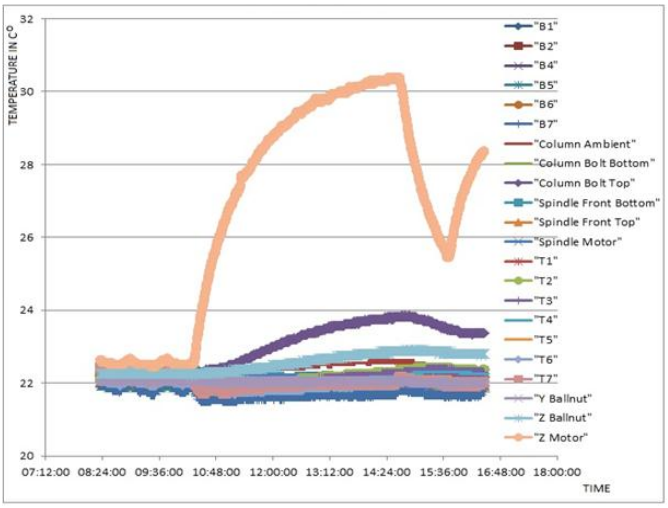

Chart -10: Experiment 2: Robodrill Temperature Data

3.3 Experiment Three

Probing the same granite block, using the same machine tool at the same workshop floor temperature for dimensional accuracy, whilst rapidly heating the machine z-axis motor to attain thermal stability. Rapid heating is achieved by moving the Z-axis motor in ten quick upward and downward motions through the use of machine codes. Earlier procedures showed a gradual heating up of the Z-axis motor but here it is rapid heating to ascertain which the two would make for a quick arrival at thermal stability.

Result and Analysis of Experiment Three

MATLAB plot for the X, Y, and Z axis for all four corners of the granite block is examined. In the Y-axis, the maximum deviation was minus 8 microns. The negative value of the deviation measurement in the Y axis is an indicative motion of the probe tool in negative Cartesian coordinates only. The Z-axis experiences a steady rise in deviation from the start of the experiment. A tremendously significant deviation at all four corners.

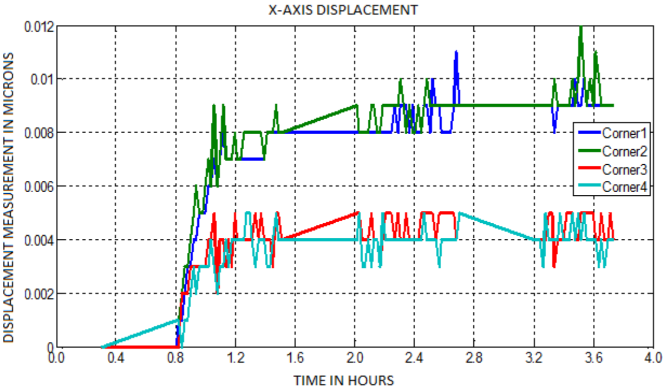

Chart -11: Experiment 3: X-Axis Displacement

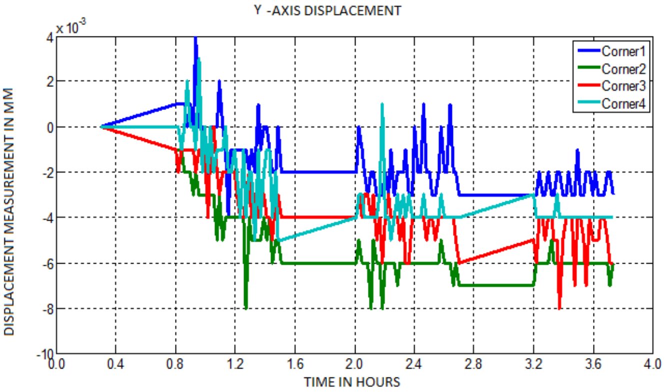

Chart -12: Experiment 3: Y-Axis Displacement

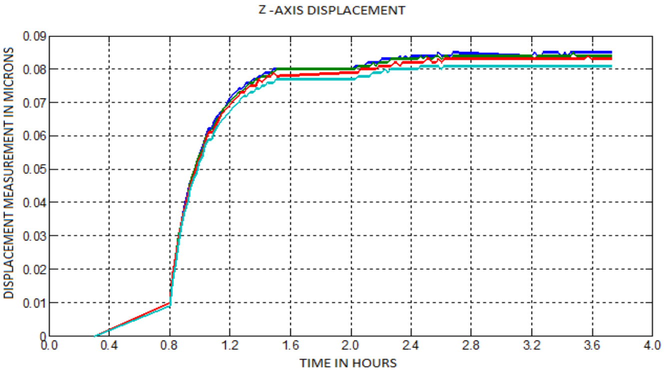

Chart -13: Experiment 3: Z-Axis Displacement

Temperature Analysis of Experiment Three

At the initiation of the probing/Z-axis heating sequence, the temperature of all the components increased steadily as shown in Chart 14.

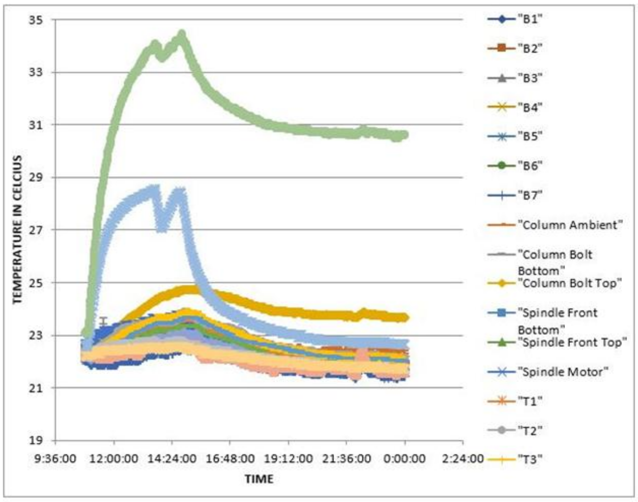

Chart -14: Experiment 3: Robodrill Temperature Data

The machine components attained thermal stability at about 3 hours of probing. There was however a significant rise in three components of the Z-axis. These components are the z-axis motor, the Z ball nut, and the column bolt top. The temperature of the motor rose and a drop in temperature to 33.5 Co is seen at 3 hours of machining time. This is due to a failure in the machine part programme, resulting in a temporary crash. This was resolved and the probing process continued for the next 1 hour. After the z-axis motor reached its stabilized temperature in 4 hours, the Robodrill CNC machine was placed on emergency stop and shut down completely.

4. CONCLUSIONS

It is established that it is important to first carry out warm-up cycles for a machine tool before it goes into full operation mode. For better efficiency, studies would be carried out to determine the most effective and sufficient way to carry out these warm cycles required to bring each machine to thermal stability. This has several advantages such as the ability to detect any probable errors that may arise during machine operation and to mitigate against such, to bring the machine to its stable temperature wherein it can operate effectively and efficiently without any adverse effects to the tool itself, workpiece, operators and the immediate environment. This is also important for machining over a given period. Graphical results of deviation with time buttressed the fact that the deviational measurement showed small deviations at the onset of experimentation but throughout machining, there is a steady rise in deviation measurement to point (thermal stability) where it becomes relatively constant on all four corners. This is indicative that warm-up cycles are important as machining a workpiece before thermal stability could lead to dimensional errors.

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