Thermal Analysis for Condition Monitoring of Machine Tool Spindles

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Abstract. Decreasing tolerances on parts manufactured, or inspected, on machine tools increases the requirement to have a greater understanding of machine tool capabilities, error sources and factors affecting asset availability. Continuous usage of a machine tool during production processes causes heat generation typically at the moving elements, resulting in distortion of the machine structure. These effects, known as thermal errors, can contribute a significant percentage of the total error in a machine tool. There are a number of design solutions available to the machine tool builder to reduce thermal error including, liquid cooling systems, low thermal expansion materials and symmetric machine tool structures. However, these can only reduce the error not eliminate it altogether. It is therefore advisable, particularly in the production of high value parts, for manufacturers to obtain a thermal profile of their machine, to ensure it is capable of producing in tolerance parts. This paper considers factors affecting practical implementation of condition monitoring of the thermal errors. In particular is the requirement to find links between temperature, which is easily measureable during production and the errors which are not. To this end, various methods of testing including the advantages of thermal images are shown. Results are presented from machines in typical manufacturing environments, which also highlight the value of condition monitoring using thermal analysis.

1. Introduction

It is the primary goal of machine tool manufacturers and maintenance teams to bring their machine tools in to a state where they can consistently produce parts to within a specified tolerance. Within manufacturing, especially the aerospace industry, part tolerances have tightened considerably over recent years. These tight tolerances require high levels of repeatability and accuracy from the machine tools used to produce these parts. The sources of error responsible for affecting these machine performance parameters can be split into three main areas; geometric, non-rigid and thermal errors.

Geometric errors are mechanical errors due to the setup of the machine. Once a machine has been built to within a predefined tolerance it generally remains in this state unless crashed. There will be some change in machine condition over a long period of time due to wear of moving elements, but this can easily be monitored with periodic testing suggested in ISO 230/2 [2].

Non-rigid errors are those that occur as the mass distribution changes either from moving axes or work-piece change during machine operation. Load errors are typically smaller then geometric errors but where significant can be predicted and therefore compensated. The finite stiffness of the machine and wear can also cause vibration which requires periodic monitoring to ensure it does not become a problem.

Thermal errors are frequently the biggest problem faced by production engineers as they can account for around 70% of the total positional error of a machine tool [1]. They arise from a combination of internally generated heat and environmental influences, which unless controlled can result in large positional errors as will be seen later in this paper.

The requirement of machine tool builders and users to understand and quantify there machine tool thermal errors has resulted in the production of an international standard for thermal error testing. ISO 230 part 3 'Determination of thermal effects' specifies test procedures for determining thermal effects caused by a variety of heat inputs resulting in the distortions of a machine tool structure or the positioning system [3].

The purpose of this paper is to assess the practical implementation of these tests as part of a machine tool condition monitoring method.

2. Current Industry Practice

Many solutions exist for the machine tool builder to reduce thermal errors that can be applied at the design stage including; symmetric machine tool structures to allow for a uniformed thermal growth and therefore better prediction of thermal error . Liquid circulation cooling systems, which pump chilled oil, water or other coolant around the moving elements to extract some of the heat generated. Low thermal expansion coefficient materials may be applied if they maintain other key material properties. Where this is not a viable option, the machine can be designed so that the direction of thermal growth is away from the thermal datum so as to limit the affect on tool part accuracy. However, design effort together with cooling systems can be prohibitively expensive and without proper condition monitoring, may not fully eliminate thermal errors over longer periods.

The aforementioned standard for assessing machine thermal effects describes three main tests:

- Environmental Temperature Variation Error (ETVE) test
- Thermal Distortion Caused by Rotating Spindle test (spindle heating test)
- Thermal Distortion Caused by Linear Motion of Components test (axis heating test)

An ETVE test can be performed to assess the effect of environmental temperature changes on the machines positional accuracy. A spindle heating test can be conducted to identify the effects of the internal heat generated by rotation of the spindle(s) and the resultant temperature gradient along the structure and the distortion of the structure observed between the work-piece and the tool. An axis heating test can be carried out to identify the effects of internal heat generated by the driving system components, such as the ballscrew, nut and support bearings, on the distortion of the machine tool structure observed between the work-piece and the tool. [3]

The standard suggests using non contact measurement sensors to measure the linear and angular displacement of the spindle relative to the work-piece as it rotates, while monitoring the temperature of the machine structure near the spindle nose, the machine ambient temperature and the spindle ambient temperature. An example setup used in the ISO standard can be seen in figure 1.

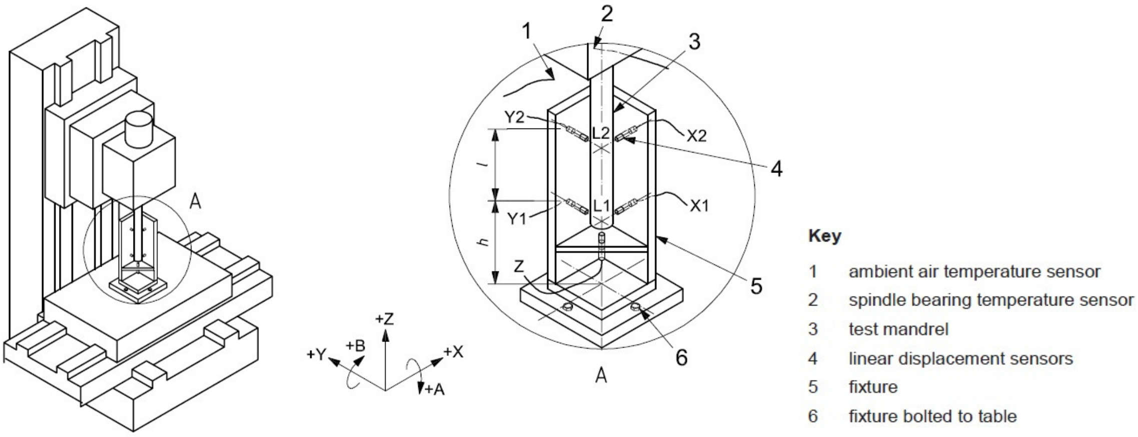


Figure 1. Typical setup for ETVE or spindle heating test [3].

Non-contact measurement sensors such as capacitive or eddy current sensor are recommended for thermal testing however, many machine tool users and service teams don't have access to this type of technology and so may use indictor clocks or other contact probe method. This involves a simple routine that measures the displacement of the spindle relative to the work piece, usually performed every 15 minutes, and requires the spindle to be stopped in order to take the measurement.

The measurement of the temperature and error components is only the first step towards the goal of improving the accuracy of machine tools. The other important step to take is the correction of these errors in real-time such that the effect of the errors on the accuracy is minimised. [4] This correction comes in the form of applied thermal compensation to the CNC controller. Many modern CNC machine tools offer thermal compensation system solutions. These are usually based on a simple linear error to temperature relationship, with the temperature data being fed into the controller from a single sensor. Sensibly the temperature sensor is usually positioned close to the main heat source, such as the spindle nose, close to bearings or reading oil and coolant temperatures.

3. Thermal Condition Monitoring

The process of performing the thermal tests described in the previous section provides useful information on the thermal behaviour of the machine tool. In the case of the machine tool builder it allows them to setup thermal compensation in the controller before it is delivered to the customer. Once the customer has received their machine tool they may wish to perform their own thermal analysis with the machine in a new environment to establish any residual thermal error that requires monitoring.

Performing these thermal tests periodically can aid in the prediction of service life for things such as bearings and chiller units. The effectiveness of a chiller system can degrade over time, through the results of these thermal tests the point at which in tolerance parts will no longer be achievable can be predicted and service time planned, for the installation of a new chiller system.

However, in reality it is not always practical to free up a machine to allow thermal testing to be conducted. Depending on the scope of the tests to be completed it could take from a couple of days to a week to complete. It is common for manufacturers to wait until they are producing out of specification parts before they have their machine thermally tested. This can lead to long periods of downtime while the problem is identified and replacement parts ordered and fitted. The next section of this paper offers a possible solution to this problem and is based on real test results from a machine in industry.

4. Test Case Study

Machine A is a medium size vertical turning lathe used in the aerospace industry and is situated in an environment that has excellent temperature control to ±1ºC. The purpose of the testing was to provide a full thermal profile of the machine to ISO 230/3 to allow condition monitoring to take place. The test results in figure 1 are from a spindle heating test, as described earlier in this paper. Figure 2 shows a CAD representation of Machine A's configuration, including axes of travel.

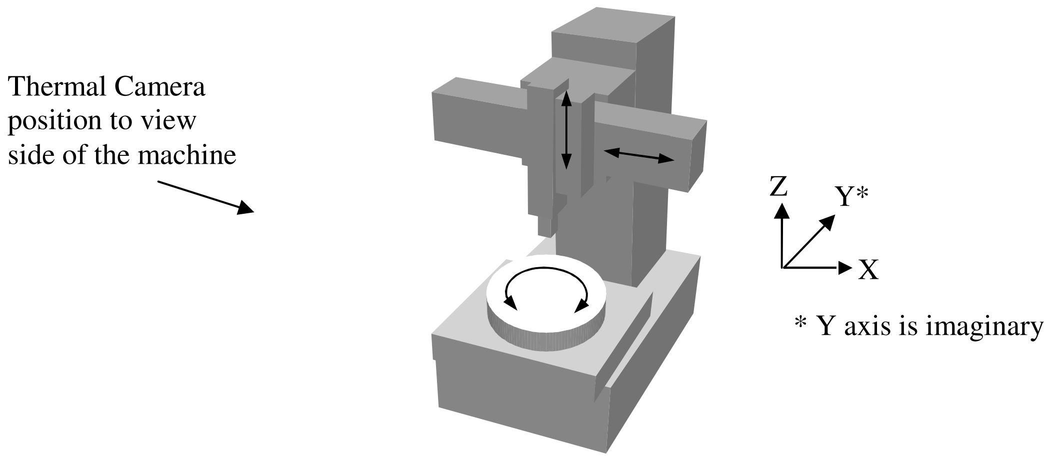
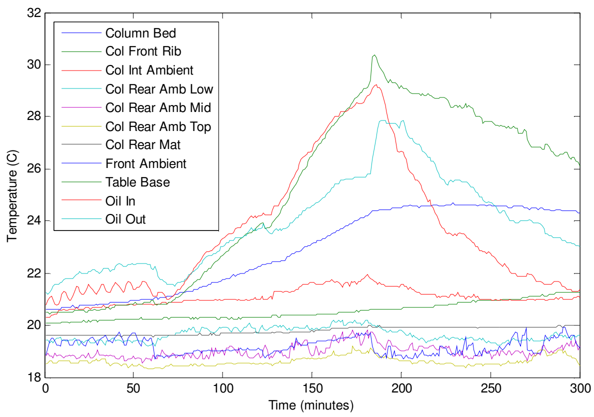


Figure 2. CAD representation of Machine A configuration.

The standard suggests either a constant or variable speed for heating of the spindle and also advises that, in situations where machine processes are known it is advantageous to simulate these processes as close as possible during testing. In this case, the processes were not known so a spindle speed step test was employed. The spindle was run at 60rpm for the first hour, 180rpm for the second hour, and 360rpm for the third hour and then left to cool. Eddy current non-contact measurement sensors were used to measure the spindle displacement and surface mountable temperature sensors were used in areas of thermal interest to measure temperature. A thermal imaging camera was also used to monitor the flow of heat through the machine structure, the position of which can be seen in figure 2. This location was chosen so the flow of heat in to the bed and column could be monitored.



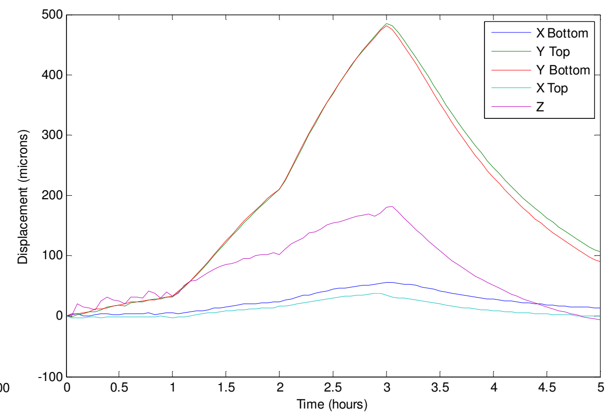


Figure 3a. **Figure 3b.**

Error and temperature plots from a spindle heating test.

Figure 3b shows a large error in the Y direction of nearly 500µm. Due to the configuration of the machine in question, this error could be ignored as it only has a second order effect on part accuracy. The main concern from these results was the Z axis displacement of 180µm during the 3 hour test, as this would directly impact part accuracy.

From figure 3a it can be seen that the temperature at the base of the table heats up in a similar profile to that of the error in the Z axis. This is to be expected, as the internally generated heat from the bearings flows into the large steel table and bearing housing, the expansion of which results in a Z axis displacement. The correlation between the temperature and displacement, shown in figure 4a is only sufficiently accurate between 1 and 3 hours of the test. As the error over the first hour is very small it can be ignored for the purpose of this exercise. When the spindle is stopped after 3 hours and the machine begins to cool, the heat in the table is slow to diminish compared to the displacement error. This means that the link between this temperature and the error is poor overall, but valid as an indicator of error while the table is running.

In figure 4b, the temperature has been plotted against the displacement data and a trend line fitted to show the linear correlation, y=13x -210. The plot shows the hysteresis of the data is approximately 10 µm from the linear fit. Therefore, anytime during the test a temperature reading can be taken from the base of the table and the Z error estimated using the formula to within 10µm.

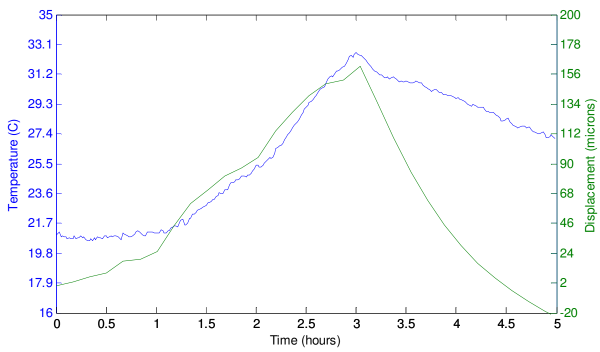


Figure 4a.
Correlation between temperature and error.

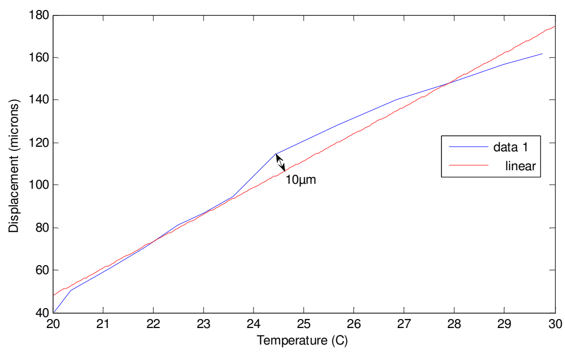


Figure 4b.
Temperature against displacement.

In order to improve monitoring accuracy during other speeds and spindle inactivity additional temperatures were investigated. Looking back at figure 3a the temperature of the oil feed back into the chiller unit appears to have a much quicker temperature reduction once the spindle is stopped than the temperature at the base of the table. Figure 5 indicates the temperature of the oil feed and the Z axis error, during the 5 hour heating and cooling test and as can be seen, there is a much better correlation during the cooling phase.

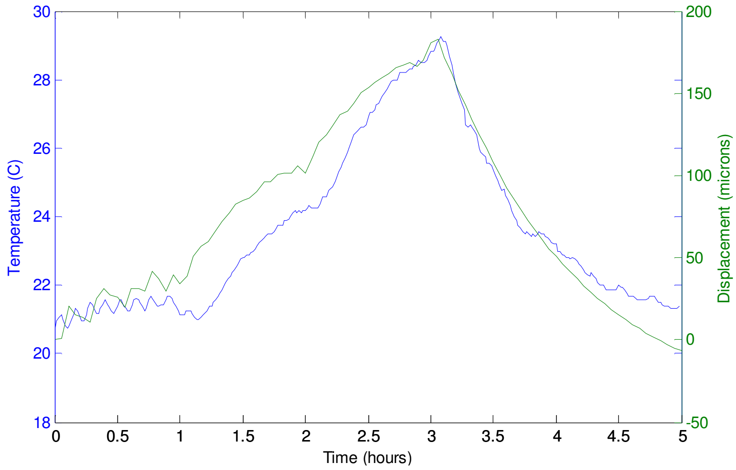


Figure 5. Correlation between oil feed temperature and error.

The data in figure 5 can be split into a heating phase (any time the spindle is running) and a cooling phase (any time the spindle is stopped). As before, these two sets of data can then be plotted against each other to form the temperature displacement plots seen in figure 6a & b. Due to the non linear behavior of the data, instead of fitting a linear trend line, 4th and 3rd order polynomial curves were used respectively.

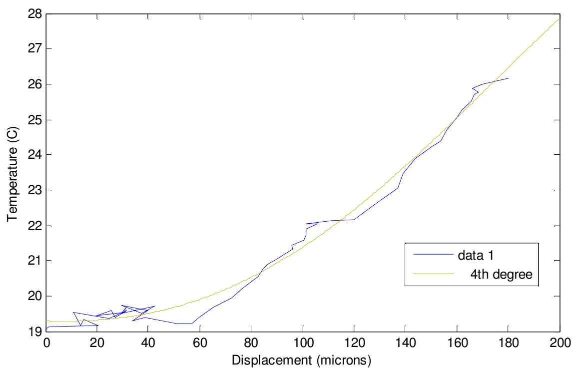


Figure 6a.

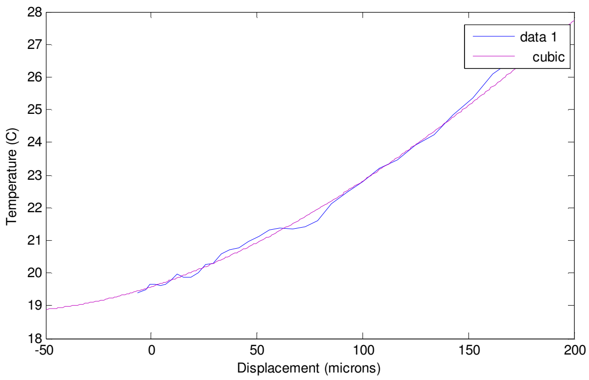


Figure 6b.

Temperature against displacement during heating and cooling phases.

From the heating phase in figure 6a, the following equation was derived:

$$y = (-4.7 \times 10^{-9})x^4 + (1.3 \times 10^{-6})x^3 + 0.00014x^2 + 0.0022x + 19 \text{ ……….. } (1)$$

From the cooling phase in figure 6b the following equation was derived:

$$y = (-1.6 \times 10^{-7})x^3 + 0.00013x^2 + 0.021x + 20 \text{ ………... } (2)$$

Using this information and by monitoring the temperature of the oil feed to the chiller unit an estimation of the Z axis error can be calculated at any time during the test. If this method was transferred to a production process these calculated Z axis errors could be fed back into the CNC controller and compensated for.

4.1. Thermal Imaging

The use of thermal imaging during testing can also provide comprehensive data about the flow of heat through the structure of the machine tool by way of the high spatial resolution of temperature information. One drawback of thermal imaging is it can have poor accuracy, usually in the order of ±2ºC. Methods exist to improve this accuracy, including applying masking tape (with a known emissivity of 0.95) to areas of thermal interest and averaging the images to reduce noise [7]. Accurate surface mountable temperature sensors in the field of view of the camera can also be used to adjust emissivity to improve accuracy. Figure 5 shows thermal images taken at different periods during the spindle heating test from Machine A.

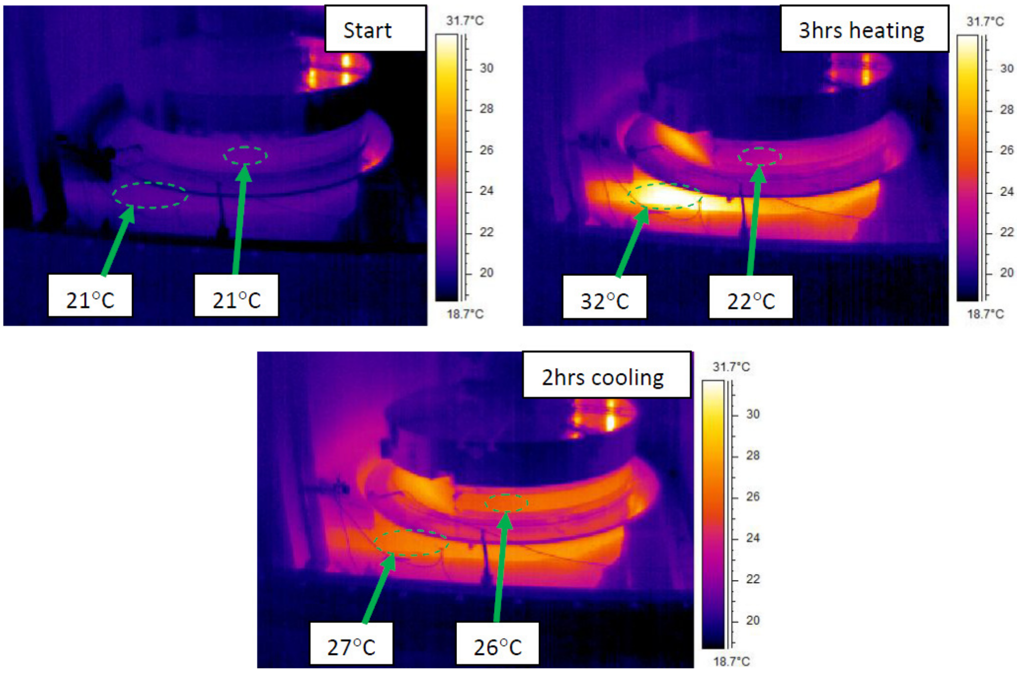


Figure 7. Thermal imaging at various times of a heating and cooling test.

To facilitate processing large amounts of data that can be acquired, Matlab software has been developed to aid in the processing of the large amounts of data that can be acquired. This allows a sequence of thermal images, captured using a Flir ThermaCam thermal imaging camera to be loaded into Matlab directly. A number of functions enhance the usability of the images, including image averaging to reduce pixel noise, alignment of images and extraction of the temperature data as adjustable groups of pixels at discrete points. Figure 8(right) shows a thermal image with 7 points of interest identified, the function then plots the temperature at these 7 points for every image over the duration of the test (see Figure 8 left).

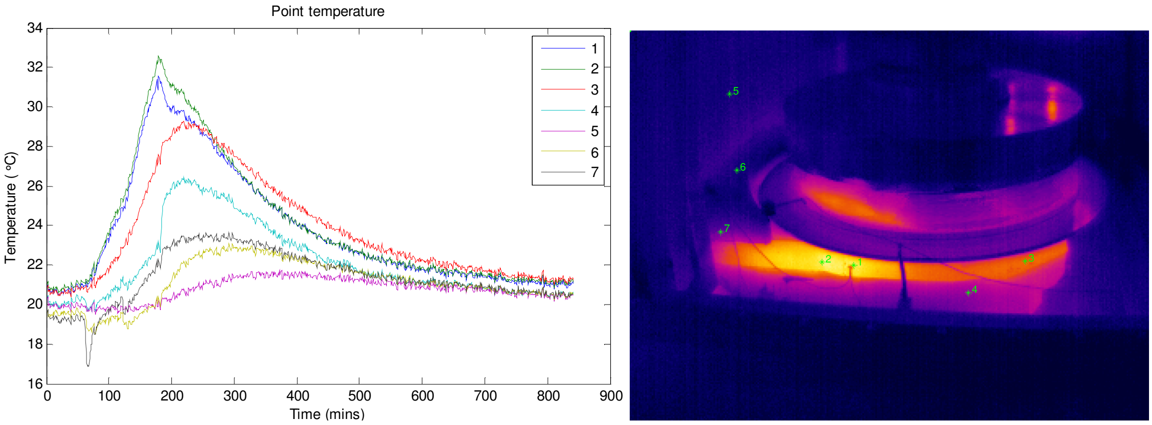


Figure 8. Thermal data extracted from images using Matlab.

In addition, instead of simply selecting spot temperatures, a line may be drawn on the thermal image, providing multiple sets of point data efficiently or data for the average temperature of the line over the duration of the test. Using this information a spot or line temperature can be identified that correlates best with the thermal error in the machine.

As seen with the data gathered from Machine A, it may not always be possible to determine one spot or line temperature that correlates well enough with the error during heating and cooling to use the data in a compensation method. However, through the use of thermal imaging the flow of heat into the structure can clearly be seen. When Machine A is stopped the localised heat from the spindle bearings begins to flow into the column to the left of the table, indicated by the sequence of images in figure 7. This flow of heat into the column is a significant contributor to the decline of Z axis displacement error as the tool continues to move away from the table long after the spindle has stopped.

In this situation it may be possible to use several temperature points to establish an estimation of the error at any one time. In figure 8, at point 6 the temperature in the column remains stable until the spindle is stopped. As a result of this the Matlab software can be used again focusing in on the temperature of the column as can be seen in figure 9 (right).

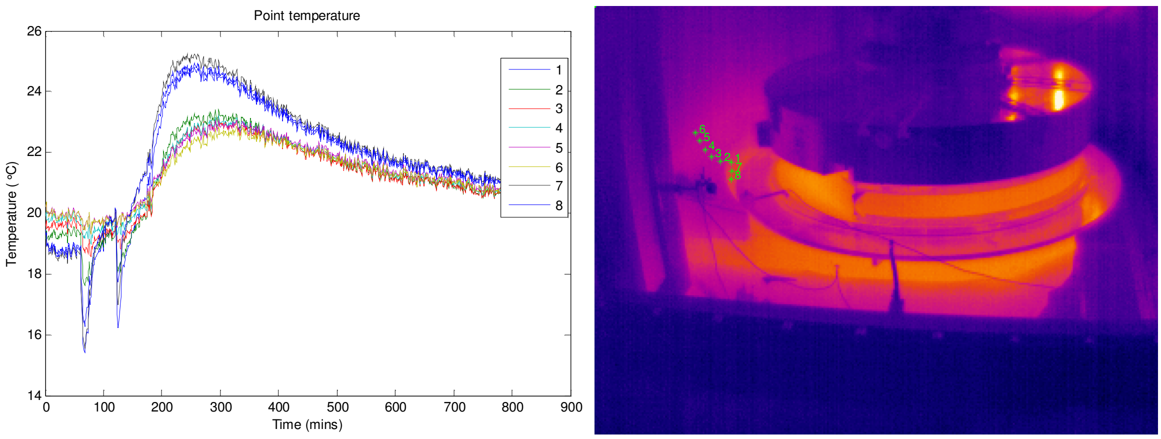


Figure 9. Thermal data extracted from images using Matlab.

Through analysis of the above plot the following equation was derived as a function of three temperature points:

$$Y = T_1^* - T_2 - T_6 + 40 \qquad \text{......................} (3)$$

* T_1 is taken from data in figure 8

This resulted in the significantly improved correlation between temperature and displacement being established shown in figure 10.

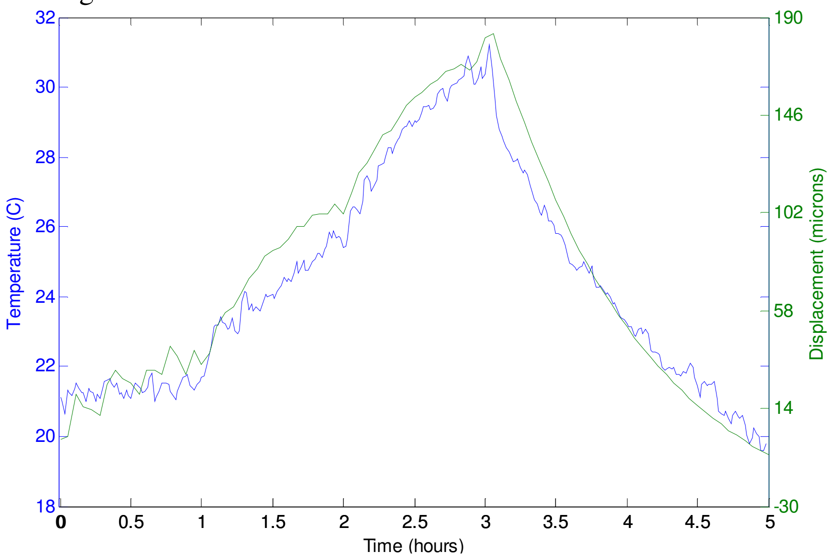


Figure 10. Correlation between function of thermal temperature and error.

Figure 11 shows the temperature plotted against the Z axis displacement for the entire heating and cooling test and low order polynomial fitted curve. The accurate fitting enables the single derived equation to be used to estimate the error whether the machine is heating or cooling. This is useful in cases where it is not always known whether the spindle is running or not to change the fitting parameters.

From figure 11 the following parameters for the equation was derived:

$$y = (-0.11)x^3 + 7.4x^2 - 140x + 730 \text{ ....} (4)$$

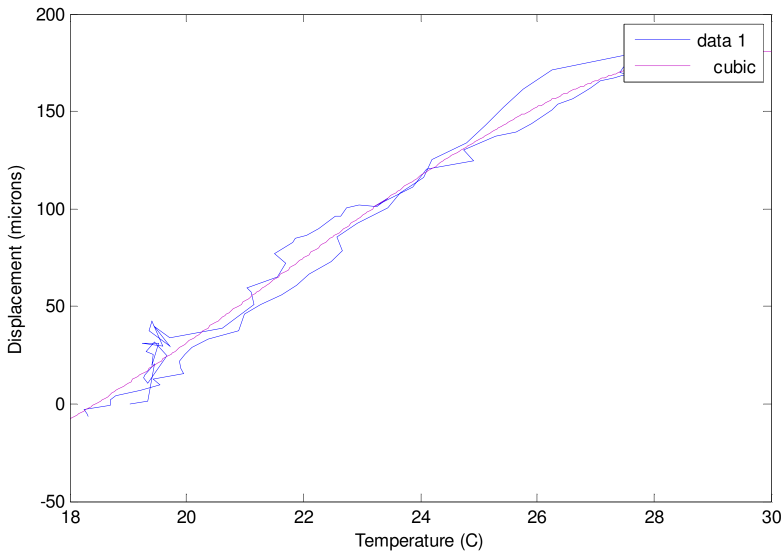


Figure 11. Temperature against displacement for combined heating and cooling phases.

Figure 13a shows the difference between the calculated error using equation 4 and the residual error. There is a maximum deviation between measured and calculated error of approximately 40µm at a displacement of 200µm, therefore a possible maximum error at any one time of 20%.

In applications where a more accurate estimation is required it may still be necessary to split the heating and cooling phases of the test in order to obtain equations for each:

From the heating phase in figure 12a, the following equation was derived:

$$y = (0.066)x^3 - 5.4x^2 + 160x - 1530 \quad \ldots\ldots\ldots\ldots (5)$$

From the cooling phase in figure 12b the following equation was derived:

$$y = (-0.25)x^3 + 17x^2 - 360x + 2430 \quad \ldots\ldots\ldots\ldots (6)$$

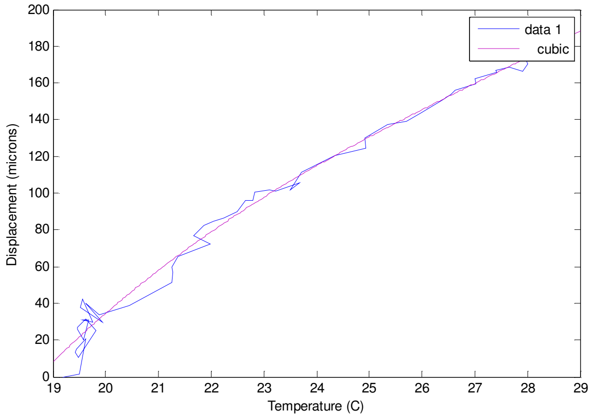


Figure 12a.

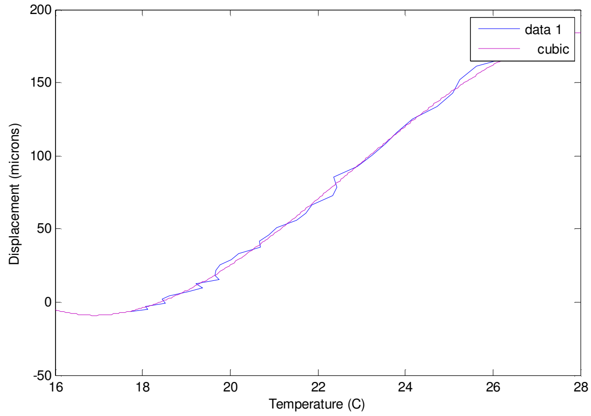


Figure 12b.

Temperature against displacement during heating and cooling phases.

Figure 13b shows the difference between calculated and residual error using equations 5 and 6. There is a much better correlation between measured and calculated of 95% and a residual error of just 10µm equivalent.

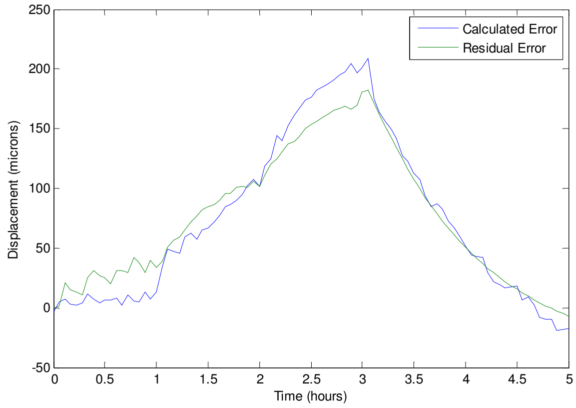


Figure 13a.

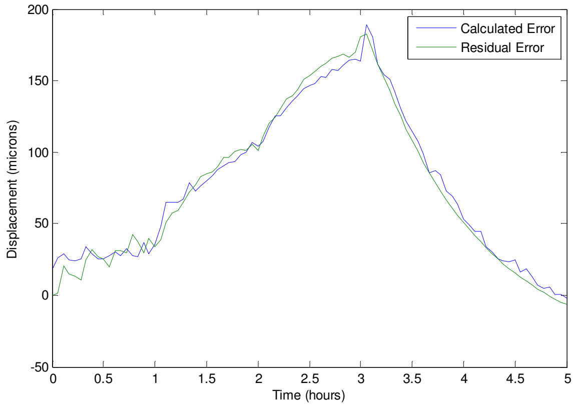


Figure 13b.

Comparison of calculated error and residual error.

If this method was used during a specific production cycle using surface mountable temperature sensors at a number of locations, then during normal operation the temperature at the most appropriate locations could be monitored to provide a good estimation of the displacement error at any one time. This information could be fed back into the CNC controller and the error compensated. It would also be able to alert the operator if the spindle exceeds a predefined level so appropriate action can be performed before tolerances could be exceeded, potentially reducing cost in concessions and rework for high value parts.

The temperature sensors used during this testing are direct to digital utilising 1-wire communication for easy connection to controller or PC via USB or serial ports. Their cost is approximately £2 per sensor which allows for a large number of sensors to be used without the need for high capital investment.

4.2. Error Prediction from speed

It is often not practical to perform tests for all operating conditions and for as yet undefined processes. This section explains a method for estimating the error for situations where information on processes is not available. In this case study no process information was available and therefore a standard spindle heating test was conducted. The plots in figure 14 show the measured displacement for each of the spindle speeds. It is quite often the case that for errors caused by internal heat sources, that the error exhibits an exponential profile. A single exponential function, eqn 7, was used to fit a curve to the data for each speed.

$$e_x = \alpha\left(1 - e^{-bt}\right) \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

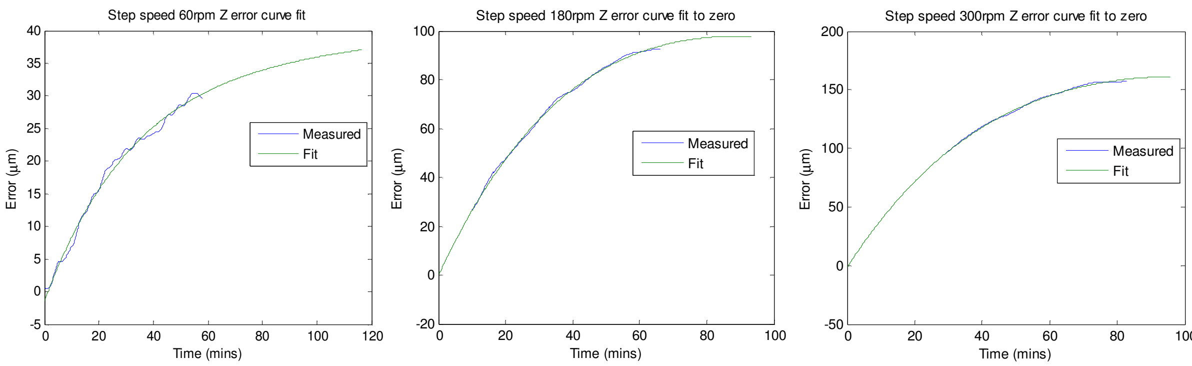


Figure 14. Displacement plots for 3 spindle speeds.

As can be seen in each of the plots in figure 14 the fit is very good and the calculation extends past the test data to the point at which the error has saturated. From this data the following table was extracted:

Table 1. Maximum spindle displacement and different speeds.

Speed (rpm)	Maximum Error (µm)	Time (minutes)
60	38	120
180	98	90
300	162	80

Figure 15 indicates a linear correlation between the spindle speed and the maximum Z axis error. This allows the machine user to estimate the magnitude of the Z axis error for any spindle speed. It also allows them to establish the approximate time required to reach this error. This would be beneficial for the user when calculating the required warm up cycle of a machine to ensure any residual error is kept within production tolerance bands.

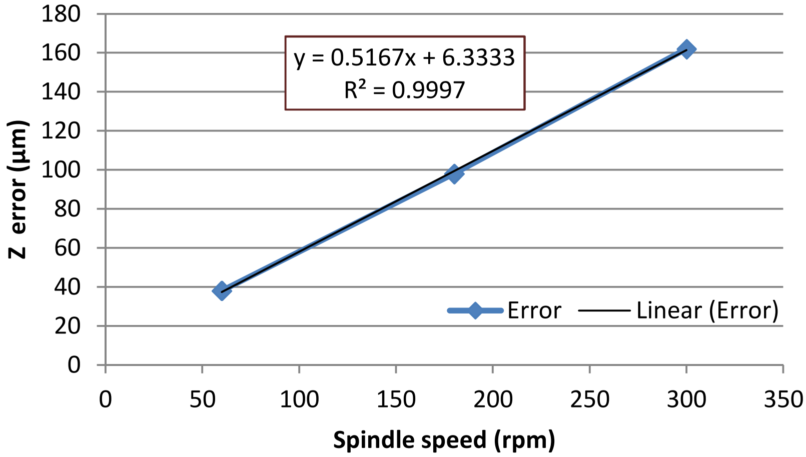


Figure 15. Correlation between spindle speed and Z axis error.

5. Conclusions

Using the test methods described in ISO230 part 3 "determination of thermal effects", combined with thermal imaging sequences, data can be obtained to establish a thermal profile of a machine tool in it's operational environment. The errors seen as a result of these tests are the residual thermal error in the machine tool and it is these errors that require monitoring to establish the condition of the machine.

This paper describes a methodology, based on standard thermal tests, for predicting error from temperature to monitor the condition of the machine. Low cost surface mountable temperature sensors coupled with thermal imaging provide data during initial thermal benchmark testing. This is used to estimate thermal error during normal production processes. Although testing maybe required ensuring that the correlation between temperature and error remains stable, this can be done in a relatively short period of time compared to a full thermal analysis.

Using an optimised selection of temperature positions from the thermal imaging data, a correlation between temperature and error of 80% was achieved enabling good condition monitoring. Separating the heating and cooling condition, a very accurate correlation of 95% was achieved but this would require additional knowledge about the spindle activity.

The testing and data processing methods used in the case study were for Z axis error, but are easily transferrable to not only other linear errors, but also tilt errors.

Acknowledgements

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