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Innovative thermal error correction of a vertical machining centre spindle head

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Abstract

This paper presents the research undertaken at Bridgeport Machines Limited in the implementation of Thermal Compensation on a range of Vertical Machining Centres.

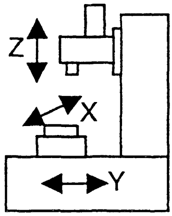
A significant portion of the inaccuracy on a machined component is attributable directly to the thermal distortions in the Machining Centre structure. There are three principal sources of inaccuracies related to thermal distortions, two of which are directly related to the machining process and the third is related to the environment. This paper concentrates on the thermal distortions resulting from the heat generated within the spindle assembly.

1 Introduction

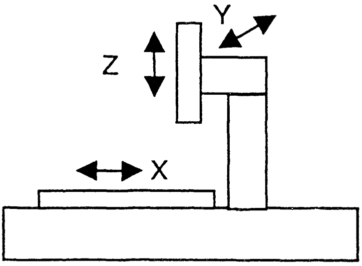
The Manufacturing Industry demands continuous improvement of the accuracy and repeatability achieved on machined components. Structural deformations due to thermal stresses, characteristics of all machine structures, have previously been identified as the largest sources of error on the machined components.

The eventual implementation of the ISO230-3 Test Code for Machine Tools Part 3 – Evaluation of Thermal effects will further highlight the errors related to thermal distortions when compared to the positional accuracy specified on a machine tool [1]. Previous research into the instruments used for collection of data and the typical distortions experienced by machine tool structures is well documented [2].

Bridgeport Machines Limited design and manufacture a range of metal cutting machines including Horizontal and Vertical Machining Centres. There are six models, in the Vertical Machining Centres range, with the X axis strokes ranging from 500mm to 2000mm and with two generic types of construction. The first, referred to as "C type" construction, accounts for over ninety percent of machines by volume. This type of construction consists of a machine bed with a saddle for Y axis motion incorporating the table assembly for X axis motion. The machine bed also supports a column carrying the spindle head for the vertical Z axis. The second is a "Bridge-type" construction used for machines with large axis strokes. The bridge carries a saddle for Y axis motion which houses the spindle head assembly for the vertical Z axis . The table for X axis motion, in this arrangement is fully supported on the machine bed.



"C type"



"Bridge-type"

All machine tool users are affected by errors in accuracy and repeatability due to thermal distortion of machine tool structure. The Mould and Tool makers, the high volume producers, the small batch precision component manufacturers and the users of 4&5th Rotary axes each experience the errors in their unique way.

It should be noted that a significant portion of the components using the machining process are unaffected by the errors. This is usually as a result of the features being machined on the component having a relatively large tolerance from its datum position and in other cases machining cycle is relatively short between the setting of datum on the component and completing the machining operation.

There are three separate sources of thermal errors on the machining centre. The first is related to the Spindle Assembly, the second is related to the axis positioning arrangement and the third is related to the environmental influence. This paper is restricted to the reduction of errors attributed to the Spindle assembly, but below is a brief summary of the other two.

Machining Centres use the ballscrew, in addition to principal purpose of axis movement, to provide positional measurement. The design specifies for the ballscrews to be stretched to negate any localised expansion of the ballscrew. This stretch is sufficient to offset average temperature rise in a ballscrew of two degrees Kelvin. The Machining Centres can also be specified with linear scales for positional measurement, this arrangement is independent of any thermal load on the ballscrew. The errors due to the environment depend on a large number of external factors. Research is being undertaken to identify and subsequently reduce the level of distortion experienced by the structure due to the environment. The final solution will be a combination of changes to the design of the machine structure and provision of guidance and appropriate information to the user in terms of the machine location for minimum distortions.

2 Design Philosophy

The first priority is to minimise, through appropriate design, any thermally induced errors. The subsequent step is to eradicate the remainder, as much as possible, through application of compensation techniques.

The introduction of any measures are subject to additional product cost, the degree of changes to machine structure and implications to the service support of existing and future installations. The Machining Centres are marketed in segments where competitive advantage is exercised through a balance between the product specification and product cost.

3 Implementation

The reduction in errors due to thermal deformation of the spindle assembly was achieved by design changes and subsequently implementing a compensation technique to the remainder of the error which was still at a significantly high portion.

The type of compensation technique applied is an indirect method [3] using a number of temperature measurements on the structure and calculating the error based a mathematical model.

The constraints in the number of inputs available on the control coupled with cost of the installation limited the number of measurement points to four. The locations of the four points on the structure were selected based on investigation of the thermal gradient within the structure. There were also constraints regarding the location of the measuring points as the spindle assembly had to remain unchanged for uniformity with an existing large number of machines already installed.

The machine control resolved the temperature measured in half degree increments and the PLC programme calculated and applied the error based on the mathematical model every 15 seconds.

The mathematical model for the machine was based on the best fit between the temperature gradients and the expansion of the structure. The objective was for one model to fit all the machines which were identical in specification. In practice it was found that there were wide variations between machines of identical specifications. A calibration cycle was devised to modify the mathematical model to suit each machine based on the temperature rise and the distortion. The initial model was derived from warm-up and a cool down cycle and checked for

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compliance with various duty cycles consisting of spindle being on and off at varying intervals and spindle speeds.

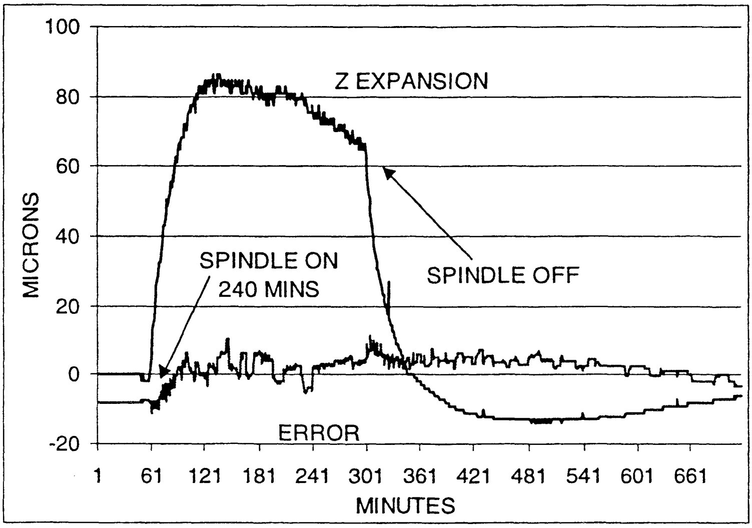

Figure 1
Z axis Expansion
The cycle is as specified in ISO230-3 with the spindle on the maximum spindle speed of 6000 rpm for a period of 4 hours followed by a cool down period. The compensated residual error is within a 20 micron band.

The design changes to the "C type" construction Machining Centres included a number of steps. Firstly an insulating motor mounting plate, made from nylon, was introduced to the assembly. Design changes made to the head cover to increase the volume of warm exhaust air from the drive belt and spindle motor. This was subsequently followed with a re-specified motor design exhibiting lower heat generation and improved ventilation with axial discharge fan replacing the existing radial discharge fan. Finally for spindles with maximum spindle speeds of 10,000 rpm, bearings with ceramic balls and reduced pre-load were introduced to further reduce the amount of heat generated.

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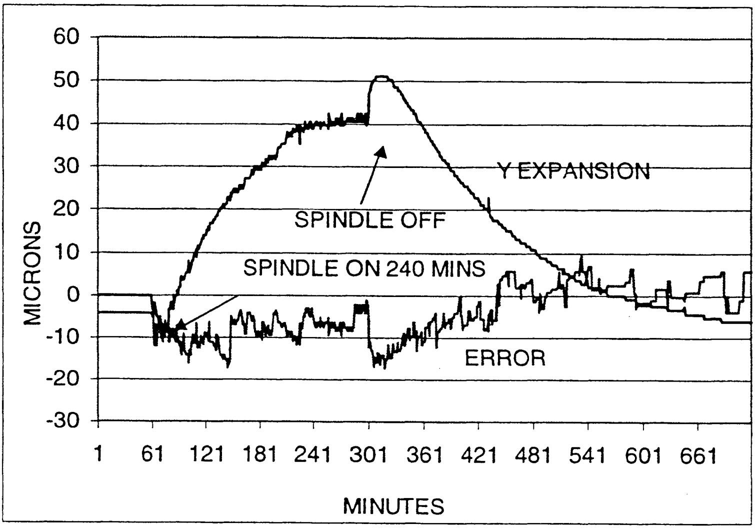

Figure 2
Y axis Expansion
The expansion measurements are for the same machine as for Figure 1 and were collected during the same test. Again the residual error is within a 20 micron band as specified in ISO230-3
The error in the X axis is relatively insignificant due to the symmetrical nature of the head design.

The products with a "bridge-type" construction was designed with an integral spindle motor assembly incorporating a sealed liquid circuit to exchange the heat generated in the motor to the atmosphere through a forced draft radiator. This structure exhibited excessive thermal distortions, as high as 110 microns in the Z direction and 45 microns in the X direction. The distortion in the Y direction was minimal due to the symmetric nature of the design.

Implementing the philosophy of minimising the error, a chiller was incorporated in the liquid heat transfer circuit replacing the forced draft radiator. This specification of the chiller controlled the temperature of the liquid to a constant temperature and this reduced the distortion in the Z direction from 110 microns to 35 microns. The distortions in the X direction were also reduced to insignificant levels.

The head structure was then introduced with three temperature measurement points one of which was placed as near to the spindle bearings as possible. The compensation through a mathematical model was applied to the machine, with the result that the accuracy of the machine was maintained to within 5 microns under wide range of load conditions.

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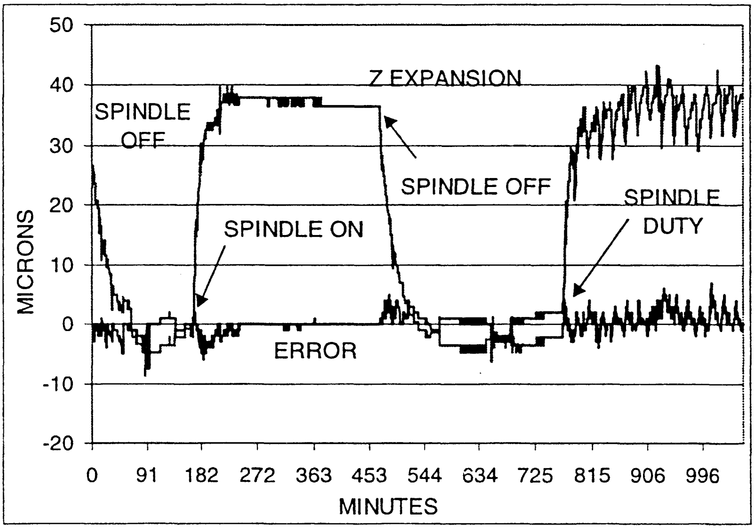

Figure 3
Z axis Expansion
The compensated error in the Z direction is well within a band of 10 microns. The cycle consisted of a period of cooling down from a warm spindle. This was followed by the spindle being run at 15000 rpm for 5 hours and then spindle stopped for the next 5 hours. Finally the spindle was set on a 5 hour duty cycle with the spindle alternating between being on for 20 minutes at 15000 rpm and stopped for the next 20 minutes.
The distortion in both X and Y axis is insignificant. This is a machine with "bridge-type" construction incorporating an integral spindle motor design.

4 Innovative approach for temperature measurement and compensation

The compensation technique applied calculates the expected error at an instant in time based on a number of spot temperature measurements and a mathematical model. A new type of temperature measurement system has been developed to give an "average" temperature of a structure. With this average temperature, the expansion of the structure is calculated by multiplying the temperature rise with the length of the structure and the coefficient of thermal expansion of the material.

A temperature measuring device has been developed in conjunction with Dr Johannes Heidenhain GmbH, under their European Patent number 0 349 738 B1 (08.06.89). This strip temperature measuring system, in effect, gives an infinite number of measuring points over its length and has been installed on the head structure to measure the expansion in the Y direction.

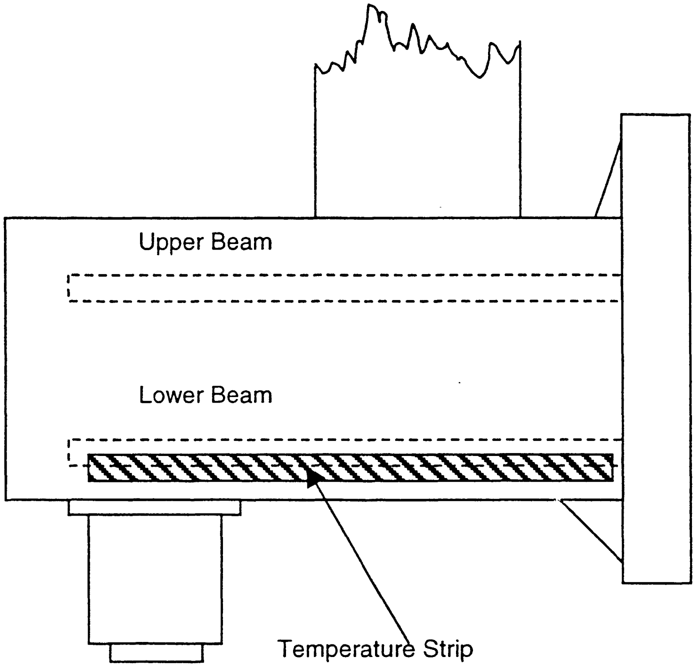

Figure 4
The innovative temperature measuring strip is fitted inline with the lower beam of the head structure. The strip provides an average rise in temperature of the head along its measuring length

The head structure design incorporates two horizontal beams supporting the spindle assembly at one end. The strip temperature measuring system is being installed along the bottom of the two beams of the head structure and is used to compensate for the expansion in the Y direction. This new method has to date been installed in three machines. The calculated compensation value now based on the actual temperature, length and coefficient of expansion of the material therefore does not require calibrating between various machines of similar specification even though they may exhibit different temperature gradients.

The expansion in the Y direction due to differential in temperatures between the two beams tends to tilt the spindle from the vertical. The spot temperature on the top beam is used to calculate the tilt. The calculated expansion applied is independent of the position on the structure. However additional research is being undertaken to incorporate the error due the tilt of the spindle taking into account the tool length and position on the structure.

The Graph below gives the end result of using a strip temperature measuring system on the head

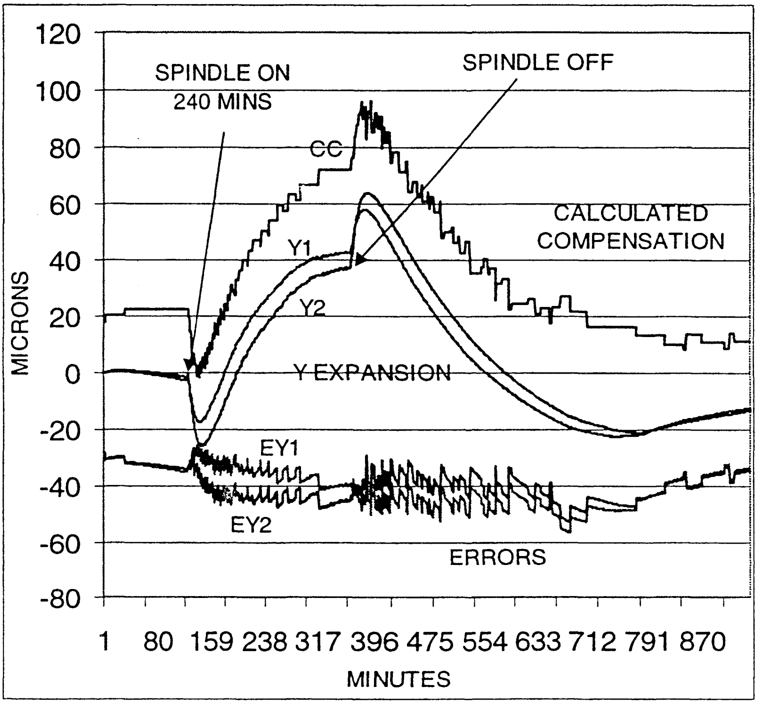

Figure 5
Y axis expansion
Y1 upper Y direction expansion; Y2 lower Y direction expansion 100 mm below Y1; EY1 error at Y1; EY2 error at Y2; CC calculated compensation.
The duty cycle is similar to that specified in figure 1.
The combination of using a strip temperature measuring device and modelling the tilt through spot measurement gives excellent correlation between the measured expansion and the calculated compensation value

5 The Installed Base

The various techniques of minimising the thermal distortions and compensating utilising a mathematical model have been implemented by Bridgeport Machines on its range Vertical Machining Centres for past 18 months.

There are a large number of cases which demonstrate that the philosophy adapted by the company provides a cost effective benefit through more accurate machining by the manufacturing industry.

The benefits to the Mould Makers has been the ability to machine more accurate moulds requiring reduced amount of subsequent machining operation or hand finishing on the blends between various features machined at different times. The improved accuracy between male and female forms gives improved "shutout" in the mould. Typically the machining cycle times for moulds can range from a number of hours to several tens of hours.

The Toolmakers typically require confidence in the accuracy of the machine on single one off tools machined over a number of days. The number of re-datumings required for the same tool to compensate for Z expansion is reduced and the accuracy in the Y direction significantly improved.

The volume manufacturer who is normally monitoring the process at regular intervals needs less frequent updates to ensure the component is maintained within its specification.

The users of rotary 4&5th axes usually experience twice the error that is generated by the thermal expansion on the component when machining on two faces rotated through 180 degrees. A customer producing aircraft structural components requiring 4&5th axes to produce specified features could not produce small volumes accurately with cycle times of several hours each. After installation of the compensation system, the accuracy improved through reduction in variability between a cold and a hot machine, producing machined components within the specification.

One user, producing low volume components for the motor racing industry complained that while the machined component was accurate, the surface appearance was unacceptable. The compensation is normally applied every 15 seconds and the steps can be as big as 3 microns which could be seen as lines on the component. To reduce the "tramline" marks on the machined component, the calculated compensation was applied in 0.1 micron steps and thus producing an acceptable surface finish.

6 Conclusion

Bridgeport Machines is a market leader in the production of Vertical Machining Centres with a very diverse range of customers in every sector of manufacturing industry. The techniques developed and applied to its product have proved acceptable to the industry. Future research is continuing in all three areas of, the spindle assembly, the axis arrangements and the environmental effects, to quantify and reduce the errors due to thermal stresses within the machine structure.

References

1. International Standard ISO/CD 230-3
Test Code for Machine Tools Part 3 – Evaluation of Thermal Effects

2 A. Statham, A Martin, D.M.S. Blackshaw, Assessing the thermal distortion caused by spindle rotation of a machining centre using draft standard ISO/DIS 230-3, Proceedings of third Landamap Conference 1997.

3 J.P. Allen, S.R. Postlethwaite and D. G. Ford., Practical application of thermal error correction, Proceedings of third Landamap Conference1997 pages359-368