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Position measurement in CNC machines: rotary encoder versus linear transducer, how to cope with the thermal problems

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Abstract

The paper is focused on a very special problem in the field of thermal effects on CNC machines and represents another contribution to the question of whether a rotary encoder-ballscrew system can be equal to a linear transducer for position measurements in CNC machines. The answer given in the paper is based on a large number of tests, which were performed on a specially equipped CNC-machining centre and a turning centre. The results show that the thermally effected positioning errors of a ballscrew system are influenced by a large number of parameters, so that software compensation needs very sophisticated measures, if it is possible at all.

1 Introduction

The question of thermal effects on the accuracy of machine tools is rapidly gaining interest. One of the reasons is certainly the new ISO 230-3 [1] and the fact that thermal errors are becoming a part of machine acceptance tests.
The thermal effects on the feed drive and the position measurement system in CNC machines is a question which is discussed worldwide and which is the object of a research program at the Department of Production Engineering at the Technical University of Graz, Austria [2].
Even though the physical phenomena of friction, heat generation, heat transfer, material expansion etc. are obvious, the discussion of how to cope with the thermal effects in CNC machines is an endless one.

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2 Goal of investigations

If a ballscrew rotary encoder system is used for position measurement, it must be realised that the ballscrew represents the scale (and not the rotary encoder!). Which means that the main heat source, the pretensioned nut, is travelling along the scale - with variable speed and changing length of motion according to the parameters of the machining process. So a constant ballscrew temperature can never be assumed. On the contrary: the very local heat-input can cause remarkable temperature gradients.
The central question is, to what extent software compensation of the thermally effected ballscrew expansion and contraction is practicable, if permissible at all. Generally it must be stated, that compensation can only be applied to systematic, reproducible influences. Nonreproducible random errors cannot be subject to compensation and have to be treated as positioning uncertainty. Thus the problem can be reduced to the question, of how far the thermal load of the ballscrew-nut-unit causes systematic, reproducible and predictable errors.

3 Test equipment

The tests were performed on an EMCO VMC600 vertical machining centre and a VOEST WNC500S turning centre, both at the CNC laboratory of the Department of Production Engineering at Technical University Graz, Austria.
The machining centre has two tables which are mounted on the bed while the column travels along the x-axis (Fig.1). Both the x-axis and the y-axis have been equipped with rotary-encoder-ballscrew measuring systems and linear transducers in parallel. It is possible to switch from one system to the other by means of the keyboard. So either one or the other system can be activated alternatively and without delay.

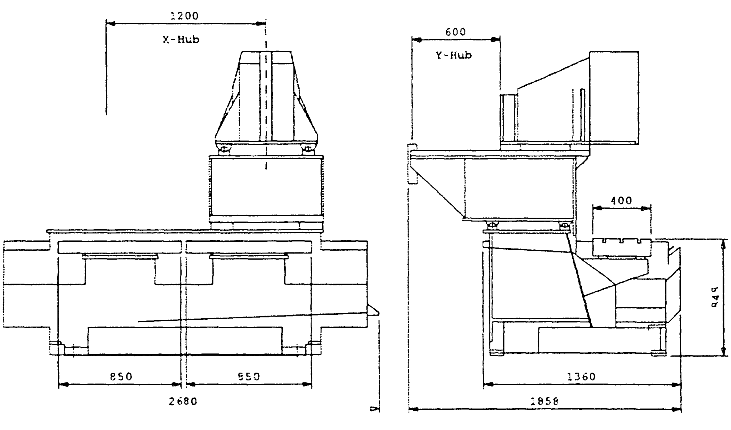

Figure 1: Test bed

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The laser beam of the laser interferometer which is used as length reference is situated symmetrically between the ballscrew and the linear transducer to minimise the Abbe-offsets and thus the effects of yaw on positioning errors (Fig.2). The temperatures were measured by thermal imaging and by means of surface probes.

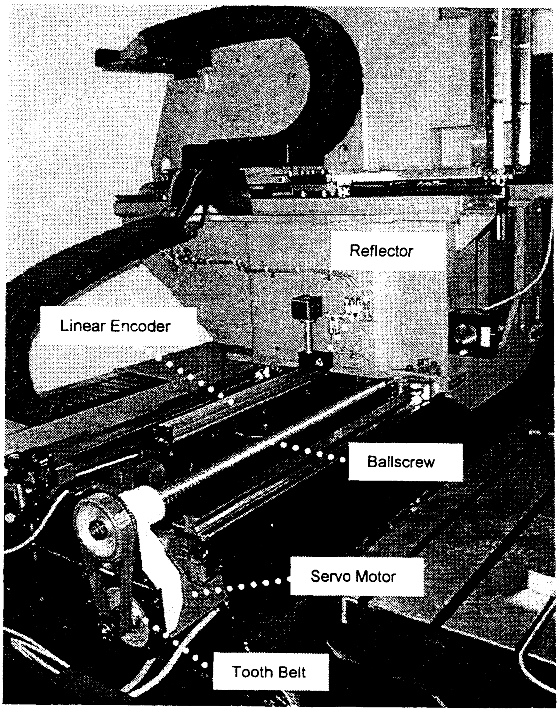

Figure 2: Drive components and position measurement systems

4 Test cycles and results

It is obvious that the ballscrew and the nut are heated up as a result of friction under motion. Therefore the postioning errors, shown in Fig. 3 could be estimated predictibly, when running a 12 hour-test-cycle, travelling the column up and down all along the x-axis with a feed rate of 24 m/min. The expansion of the ballscrew causes a linear pitch error according to an average ballscrew temperature. The linear positioning error of the linear transducer corresponds to a temperature increase of the machine bed of 5°C, which was measured during the 12 hours of testing. Up to now the thermal effects could easily be compensated. The NC programs for the test cycles had been carefully chosen and correspond on one hand to extreme loads (rapid traverse motion), and on the other hand to technologically determined feed rates of real machining processes.

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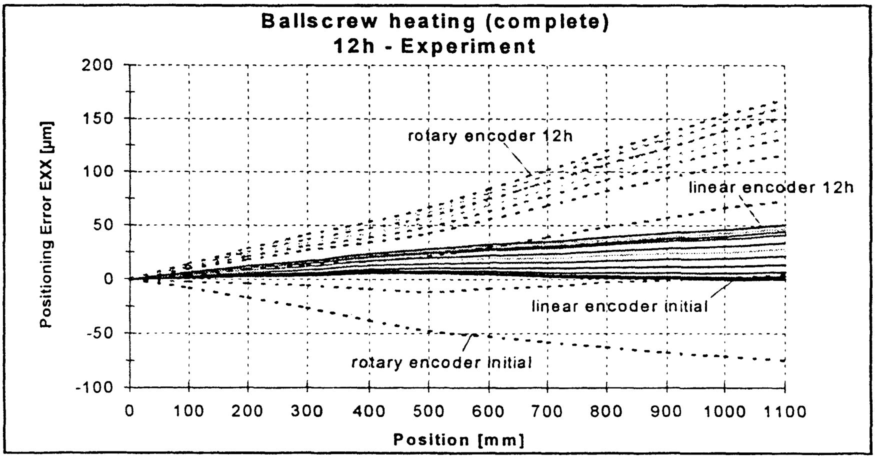

Figure 3: Positioning error, 12 hours full length traverse motion

As Fig. 4 shows, position measurements were performed at the beginning of each test cycle, after 2 hours and after 6 hours. Each measurement was performed once with the linear transducer and thereafter with the ballscrew rotary encoder system, over the entire length of travel.

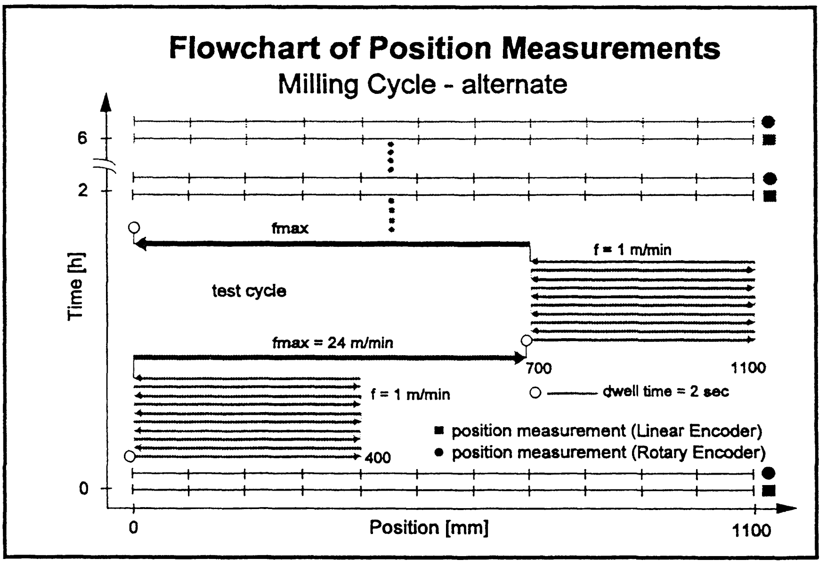

Figure 4: Test procedure

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The following examples are just two out of a multitude of test runs. They feature drilling cycles on the left and on the right table. Fig. 5 and Fig. 6 represent the respective positioning errors, obtained by laser-interferometer. The diagrams reflect the very local thermal influences very clearly. Even though the geometric

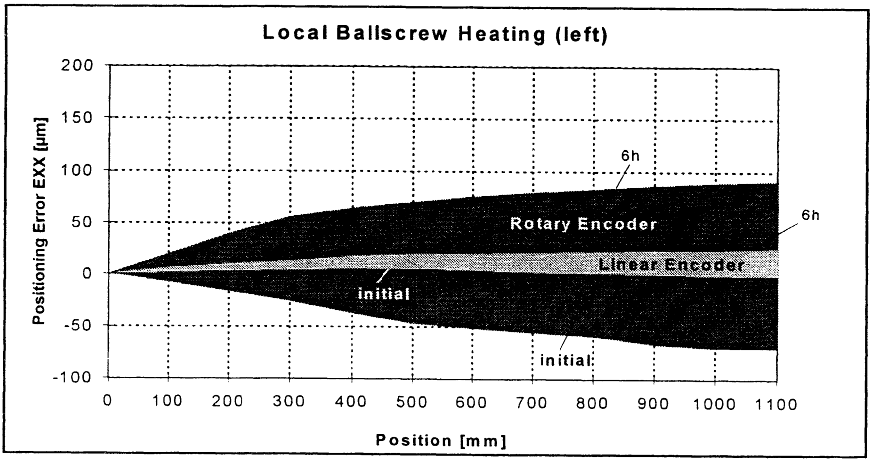

Figure 5: Positioning error – drilling cycle on the left table

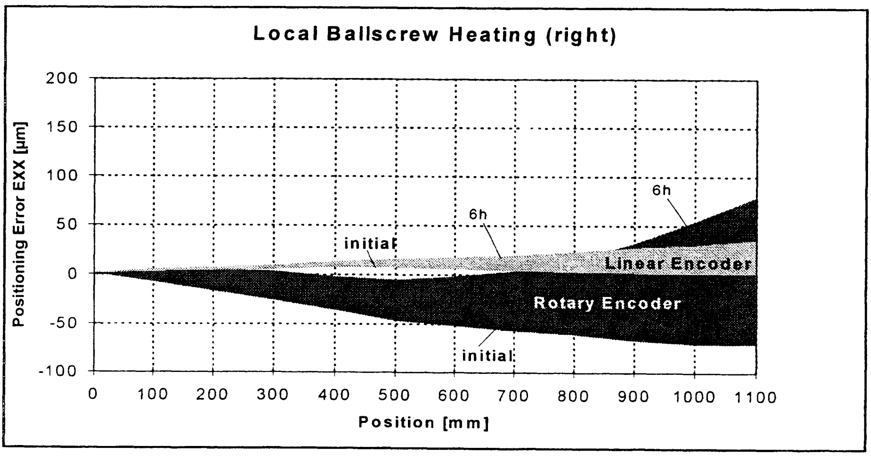

Figure 6: Positioning error – drilling cycle on the right table

parameters are deterministic ones, the user of the machine has to treat them as random errors. The dark areas indicate the ranges of positioning uncertainty. Comparing the linear transducer and the rotary encoder ballscrew system the result cannot surprise: the linear scale is not influenced by any machining parameters. It has an average temperature all over its length and does not show any temperature gradients. The resulting positioning error is a linear one. It follows the machine temperature and shows the expansion coefficient of glass.

In addition to such geometrical influences as location and length of traverse motion, technological parameters, e.g. the feed rate, influence the thermal behaviour. Thus a drilling operation using rapid traverse motion between the drilling positions results in distinctly different temperature distributions and positioning errors than a milling operation with technologically determined slow feed rates. Fig. 7, presenting a pendulum milling operation utilising both tables, may prove this.

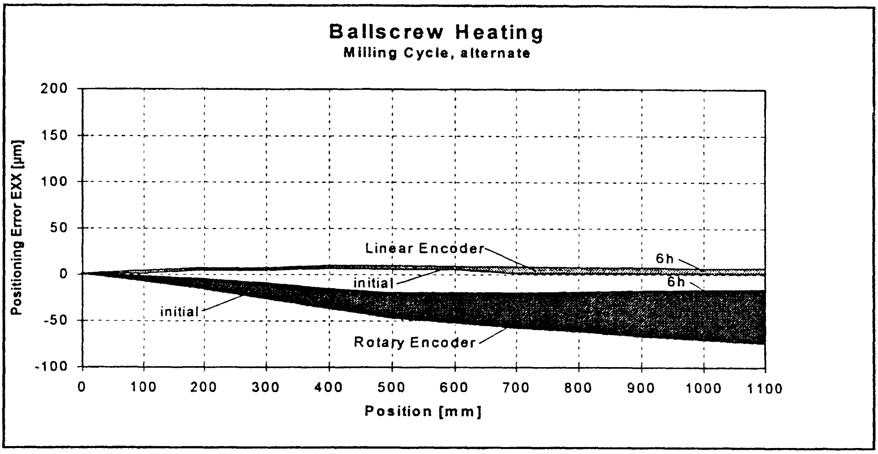

Figure 7: Pendulum milling

5 Ballscrew Temperatures

The main source of heat is the pretensioned ballscrew-nut unit. On the ballscrew local temperature maxima of more than 50°C were measured. The thermal image of Fig. 8 shows the temperature profile on the left end of the ballscrew corresponding with the positioning measurements shown in Fig. 4. This may provide evidence of a never-constant ballscrew temperature.

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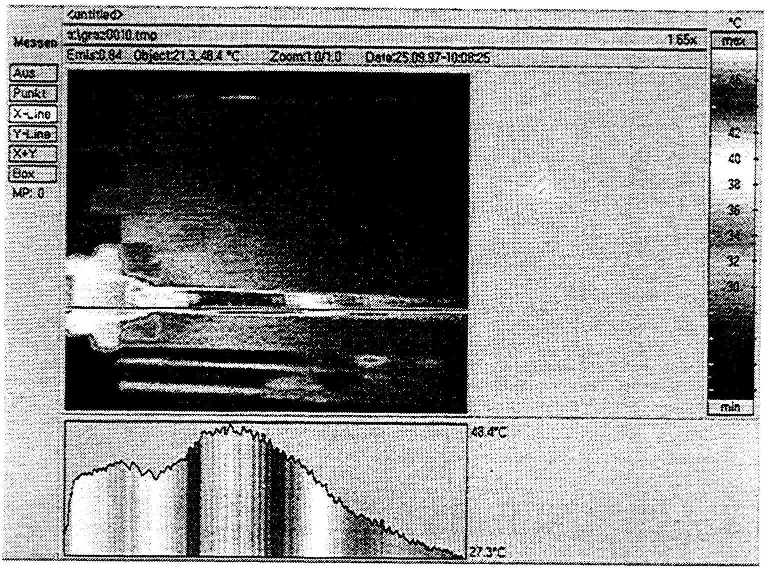

Figure 8: Thermal image : ballscrew temperatures, drilling cycle, left table

All measurements are just snapshots. A real machining cycle is composed of a sequence of heating-up and cooling-down phases. This renders the problem to a highly complex nonstationary problem even though the time constant of a cooling down phase could be measured (see Fig. 9 and 10).

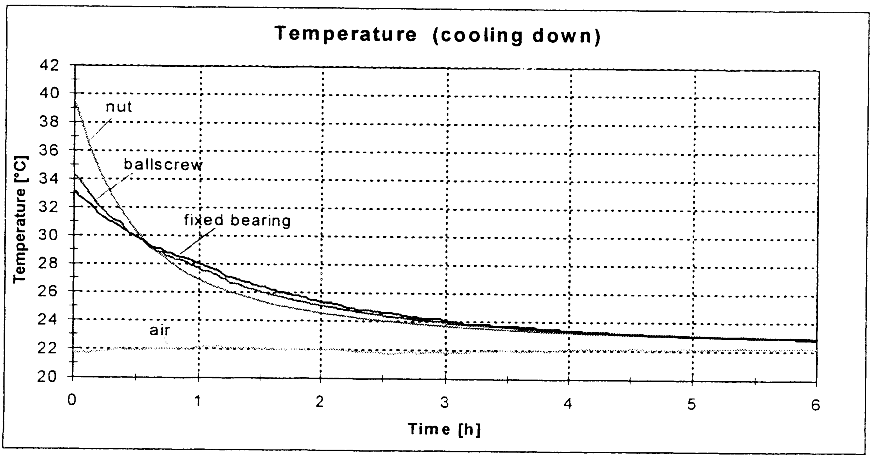

Figure 9: Cooling down phase

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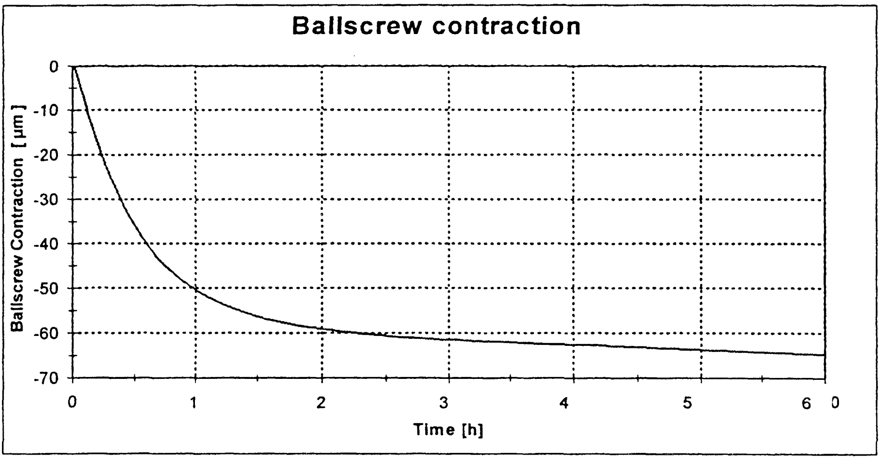

Figure 10: Cooling down, ballscrew contraction

6 Direct comparison - the turning centre

The most direct comparison of the behaviour of a linear transducer and a rotary ballscrew measuring system is offered by a turning centre.
The classic design of a CNC-lathe consists of a linear transducer on the x-axis and a ballscrew-rotary-encoder system on the z-axis. This design was sufficient as long as lathes were designed for turning processes only. But now the question arises: can this traditional design still meet today's demands on turning centres for precise milling and boring operations?

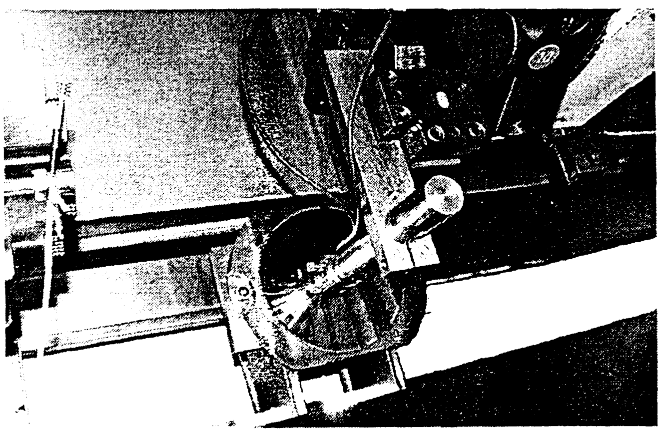

Figure 11: Test setup turning centre

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An optimal comparison of the two measuring principles can be obtained by running long term circle tests in the z-x- plane by means of a HEIDENHAIN KGM cross grid encoder and by watching deformation and shift of the resulting plots as shown in Fig. 11. The results can be easily predicted: the z-position and the z-diameter of the circles can be assumed to shift by duration of test, the x-position and the x-diameter should not be effected. And in fact: Fig. 12 shows the circles obtained with the KGM and Fig. 13 the shift of the circles over time and at different feed rates.

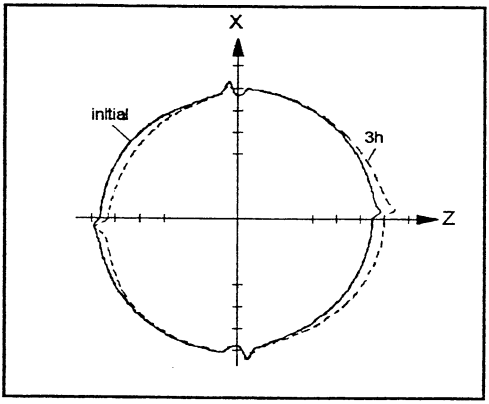

Figure 12: Long term circle test

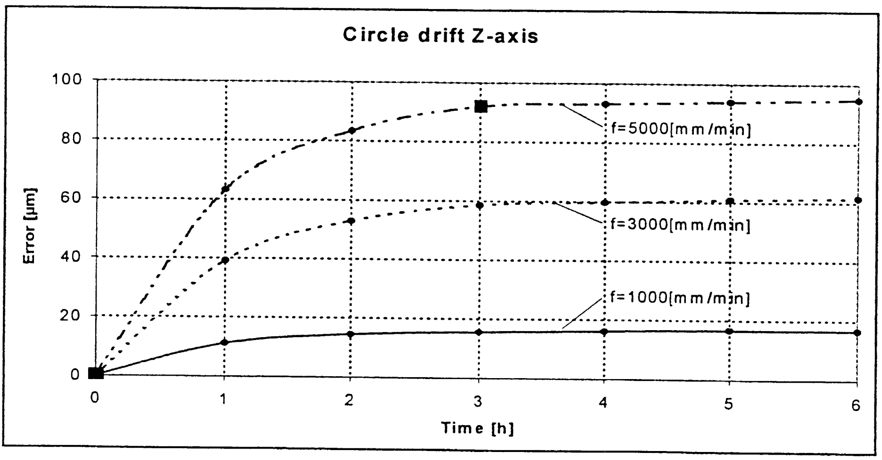

Figure 13: Circle drift

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7 Conclusions

From the results of the tests we can deduct the following conclusions.

1. The temperature variation and therewith the thermally determined positioning errors using a rotary-encoder-ballscrew system are influenced by geometrical as well as by technological parameters of the respective machining process. In addition, the influence of time, which means the sequence of heating-up and cooling-down phases of the ballscrew, brings the problem to such a degree of complexity that software compensation of the ballscrew pitch error requires very sophisticated measures. Their reliability seems to be questionable.

2. The temperature variation and therewith the thermally determined positioning errors of a linear transducer are highly reproducible and could therefore, if needed, easily be compensated based on a simple temperature measurement. Different machining cycles have no influence.

3. ISO 230-3 (and ISO 230-2) should be updated in order to utilise the latest results of research. The warming-up procedure of the machine before starting the test cycles should be clarified. The question of where to place the material temperature sensors of the laser interferometer should be treated as well.

4. The thermal effects of a rotary encoder ballscrew measuring system must be taken into account when designing turning centres. Can the traditional design, combining a linear transducer at x and a ballscrew at z meet the demands of precise milling and boring operations ?

References

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2. Frank A., Ruech F., Thermal errors in CNC machine tools, focus : ballscrew expansion, *Proc. of the MTTA seminar "sharing tomorrow's technology today"*, Warwick, Loughborough, Manchester, 1998.