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Precise length measurement at non-standard temperature

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Abstract
Length measurements are to be made at standard temperature 20°C, otherwise errors due to thermal expansion of workpieces and scales will occur. In production environments this cannot always be granted. DIN EN ISO 15530-3 describes a technique to correct the measurement error by referring to a calibrated reference workpiece. We have investigated this approach theoretically and experimentally and present some results.

Measurement, Quality assurance, Thermal error, Workpiece

1 Introduction

Geometric measurements are affected by temperature changes because of the material-specific temperature expansion of workpiece and instrument. For that reason the environmental conditions have to be tightly controlled for precision measurements. In real-world applications, especially in production environments, it is often not possible or economically not affordable to control the environment to the standard temperature of 20°C that is required by the relevant national and international standards. This problem is even more demanding for many developing countries situated in areas with hot climate.

In principle this problem can be solved as far as the temperature distribution is known and a model of the measurement system is available. However, the complexity of a cmm with 3 axes is quite demanding, as 21 degrees of freedom have to be controlled. Only the manufacturer of the cmm has access to the required data. Software modules for correction of thermal errors are available for high-end cmms.

Our measurement strategy is based on DIN EN ISO 15530-3 [1] and can be applied without special mathematical or engineering skills. A single selected workpiece is calibrated and applied as a reference for checking the conformity of all other produced parts of that type. Thermal effects then only affect the geometrical difference between the reference part and the serial part. This difference typically is much smaller than 1mm and only this length difference will change by an index of thermal expansion in the order of 10^{-5} (relative), resulting in an absolute deviation in the order of less than 1µm.

2 Theory

Let l_{20} be the length of a workpiece measured at standard temperature and l the length of that same workpiece measured at some temperature T = 20°C + ΔT. With the coefficient of thermal expansion α we get equation 1:

$$l = l_{20}(1 + \alpha \cdot \Delta T) \quad (1)$$

In general the workpiece and the scale will have different temperatures so that we can write equation 1 for both of them, identifying them with the index “wp” or “sc”, respectively:

$$l_{sc} = l_{20sc}(1 + \alpha_{sc} \cdot \Delta T_{sc})$$

$$l_{wp} = l_{20wp}(1 + \alpha_{wp} \cdot \Delta T_{wp})$$

This leads to the correction formula:

$$l_{20wp} = l_{wp} \frac{1+\alpha_{sc} \cdot \Delta T_{sc}}{1+\alpha_{wp} \cdot \Delta T_{wp}} \quad (2)$$

If the temperatures and the coefficients of thermal expansion were precisely known, a correction of the thermal error is possible. Instead of this we refer to the calibrated workpiece with nominally the same geometry, made from the same material (Figure 1) and measured under the same non-standard temperature and end up with the following simple formula:

$$l_{20\,wp} = \frac{l_{20\,rwp} \times l_{wp}}{l_{rwp}}$$

With: l_{20rwp}: known calibration value
l_{rwp}: measured value at temperature T

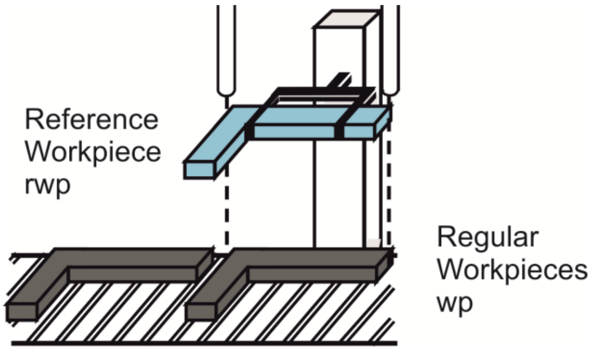

Figure 1. Serial test in production referring to a calibrated reference workpiece rwp

3 Experiments and Simulation Calculations

We tested this approach experimentally with a number of workpieces, ranging from simple end gauges to complex shaped test workpieces (Figure 2). Using a cmm Werth VideoCheck HR without internal temperature compensation for the measurements we varied the room temperature between 16°C and 24°C. In all cases the resulting errors were in the order of only a few µm.

To overcome the limited variation range of the temperature control of the cmm we added an experiment at 40°C, using a precision optoelectronic probe (Heidenhain SP25, Figure 3). Though the error due to thermal expansion in this case was more than 80µm, we were able to correct it to less than 2µm.

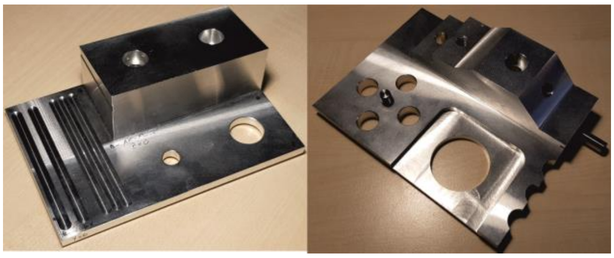

Figure 2. Complex shaped test workpieces used for our experiments

We simulated the temperature distribution resulting from heat exchange between workpiece and surrounding air using the software ANSYS. Workpieces with complex shape show local temperature gradients that lead to inhomogeneous deformation. Because of the similarity of reference and serial workpiece, however, the difference between both will stay small.

An in-depth error analysis according to GUM can be found in [2]. Considering realistic assumptions we estimate the expanded uncertainty of a length measurement of a workpiece with about 100 mm length to 5µm. The analysis of the error budget shows that the main error contributions are the measurements of the actual lengths of workpiece and reference workpiece and variations in material properties in serial production.

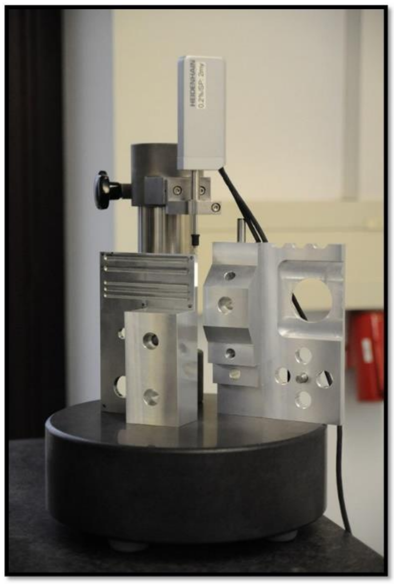

Figure 3. SP25 probe with different workpieces

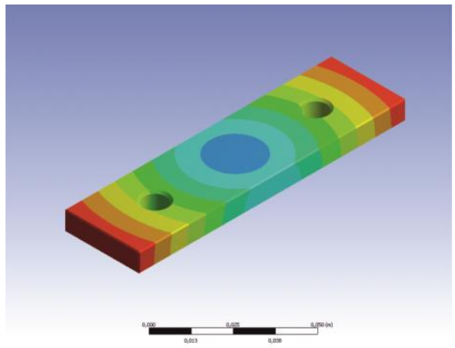

Figure 4. Colour-coded display of the temperature distribution of a workpiece caused by heat exchange with the ambient air

It has to be emphasized that the technique proposed here is limited to homogeneous workpieces. Workpieces made from multi-materials or showing extreme temperature gradients may exhibit large warpage errors that can neither be corrected by our simple approach nor by the more sophisticated correction modules offered by cmm manufacturers

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References

1. N.N.: ISO 15530-3: Geometrical product specifications (GPS) -- Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement -- Part 3: Use of calibrated workpieces or measurement standards (2011)

2. D. Sumin, R.Tutsch: Precise linear measurements using a calibrated reference workpiece without temperature measurements. Journal of Sensors and Sensor Systems, 7, 609-620, (2018)