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Dimensional measurements with submicrometer uncertainty in production environment

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Abstract

The work concerns a laboratory investigation of a method to achieve dimensional measurements with submicrometer uncertainty under conditions that are typical of a production environment. The method involves the concurrent determination of dimensions and material properties from measurements carried out over time. A laboratory set-up was developed comprising a pair of electronic probes mounted on a Zerodur block featuring near zero thermal expansion. Three temperature sensors, data acquisition system, and a temperature regulated plate for heating the workpiece were implemented. Investigations with synchronous measurements of length and temperature during cooling from 25 °C to 20 °C were carried out, using two calibrated gauge blocks as workpieces, i.e., a steel gauge block and a tungsten carbide gauge block. Each measurement was repeated 9 times. Coefficients of thermal expansion (CTE) for the two gauge blocks along with their uncertainties were estimated directly from the measurements. The length of the two workpieces at the reference temperature of 20 °C was extrapolated from the measurements and compared to certificate values. The investigations have documented that the developed approach and laboratory equipment allow traceable length measurements with expanded uncertainties (k=2) below 1 µm.

Keywords: Dimensional measurements, Measurement uncertainty, Production Environment

1. Introduction

The work concerns a method to achieve dimensional measurements with submicrometer uncertainty under conditions that are typical of a production environment, i.e. when the workpiece temperature differs from the reference temperature of 20°C. The method involves the concurrent determination of dimensions and material properties from measurements carried out over time. The work describes an experimental investigation of the method through development, implementation and validation of a laboratory setup. Focus has been placed on determination of the actual values of the workpiece coefficient of thermal expansion (CTE) directly from length and temperature measurements.

2. Experimental set-up and methodology

The experimental set-up consists of a Zerodur block, two electronic length probes and three contact temperature sensors, as shown in Figure 1. The Zerodur block acts as a thermally stable reference frame for the length measurements. The length probes have a resolution of 0.01 µm and a MPE value of 0.07 + 0.4L, where MPE is in µm and L in mm. The temperature sensors (T_1, T_2, T_3) with a calibration expanded uncertainty of 0.02 °C, are attached on the front side of the workpiece while a fourth sensor is attached to the Zerodur block. A data acquisition system using Labview has been used to collect length and temperature data at a frequency of 2 samples per second.

The set-up is aligned so that the probes measure the centre distance between the parallel planes of the workpiece which is supported by two cylindrical pins positioned at its Airy points. Two 100 mm calibrated gauge blocks, one made of steel and a second one of tungsten carbide, were used as workpieces in this investigation. A heating system encompassing a power unit, a heating plate provided with a thermocouple, and controlled through a PLC, has been used for heating the workpiece to a given start temperature. A start temperature of approximately 25°C was used in the experiments.

Figure 1. Experimental set-up.

The temperature of the workpiece is considered as the weighed reading of the 3 sensors considering the length they cover out of the total length (30, 40 and 30% for T_1, T_2 and T_3, respectively). In this investigation, temperature differences for the sensors readings have reached 1.8 °C. Once the workpiece gauge block had reached the required temperature on the heating plate, it was placed in the measuring set-up, and thereafter length and temperature signals were collected over time. Zeroing of the length probes was done using the second calibrated gauge block used at ambient temperature and after full thermal stabilisation. The workpiece gauge block was left to naturally cool down to the ambient temperature, which was measured on the Zerodur frame with an average of 19.8°C and a range of 0.1°C. The down cooling process lasted approximately 3 hours. Each gauge block was measured 9 times.

3. Experimental data and calculations

Length-temperature curves were obtained for each workpiece gauge block. Figure 2 shows the results for the tungsten carbide gauge block using the steel gauge block as reference.

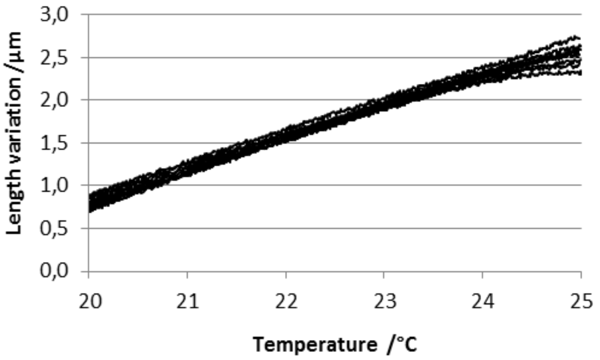

Figure 2. Length-temperature results from 9 measurements on the tungsten carbide block.

The length-temperature curves were fitted to a second order polynomial model, equation 1, from which a CTE value was calculated. An uncertainty for the CTE was calculated according to equation 2.

$$L = a_0 + a_1(T - T_0) + a_2(T - T_0)^2 \qquad \text{eq.1}$$

$$u(\alpha) = \sqrt{\sum_{j=0}^{2}\left\{\left(\frac{\partial \alpha}{\partial a_j} u(a_j)\right)^2\right\}} \qquad \text{eq.2}$$

The length of the workpiece was calculated as a function of the reference length according to equation 3 as described in [2]. Here: L_s is the length of the reference gauge block at 20 °C extracted from its calibration certificate, α_w is the measured CTE of the workpiece gauge block, α_s is the CTE of the reference gauge block from the certificate, θ_w is the deviation in temperature from 20 °C of the workpiece gauge block, and θ_s is the deviation in temperature from 20 °C of the reference gauge block. The uncertainty associated to this length is calculated according to equation 4, where u_{DE} is the uncertainty associated with the CTE of workpiece and reference, and u_{TM} is the uncertainty associated with the temperature measurement. The expanded uncertainty was calculated with k=2.

$$L_W = \frac{L_S(1+\alpha_S\theta_S)+d}{(1+\alpha_W\theta_W)} \qquad \text{eq.3}$$

$$u_c^2(L_w) = [1 + (\alpha_S\theta_S - \alpha_w\theta_w)]u^2(L_S) + \\ +u^2(d) + u_{DE}^2(L_w) + u_{TM}^2(L_w) \qquad \text{eq.4}$$

3 Results

The E_n value normalised with respect to the estimated uncertainty was computed according to ISO 17043 [3], equation 5. Here, L_w is the value obtained from eq. 3 while U_w is the expanded uncertainty of the calculated length, L_{ref} is the value obtained from the calibration certificate, and U_{ref} the uncertainty of the length indicated in the certificate. Table 1 shows the results from the conducted investigation. E_n values lower than 1 for both gauge blocks indicate agreement between values obtained from measurements and calibrated values.

$$E_n = \frac{|L_W - L_{ref}|}{\sqrt{U_W^2 + U_{ref}^2}} \qquad \text{eq.5}$$

Table 1 Comparison of calculated and reference values

	Steel	Tungsten carbide
Reference lenght [mm]	1000.000138	100.000389
U_{ref} [µm]	0.052	0.043
Calculated length [mm]	100.000201	100.000561
U_w [µm]	0.45	0.45
E_n	0.14	0.38

5. Conclusions

A set-up for accurate measurement of length dimensions in a production environment has been developed. Two gauge blocks made of steel, and tungsten carbide, respectively have been used in an investigation using one gauge block as workpiece and the other one as reference. Their CTE and uncertainty values have been calculated using a second order polynomial model. Their lengths at 20°C have been calculated from the measurements. An uncertainty of 0.45 µm has been achieved for both gauge blocks. The measurements are in agreement with the reference values stated in the gauge block certificates. The technique can be applied to achieve dimensional measurements with submicrometer uncertainty under conditions that are typical of a production environment, i.e. when the workpiece temperature differs from the reference temperature of 20°C.

Acknowledgments

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