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Accurate measurements in a production environment using dynamic length metrology (DLM)

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J. H. Hattel^a, H. N. Hansen^a, K. Mohaghegh^b, M. Meftahpour^b, J. Meinertz^b, C. Meinertz^b^aDepartment of Mechanical Engineering, Technical University of Denmark, Produktionstorvet 425, DK-2800 Kgs. Lyngby, Denmark^bMetrologic ApS, Håndværkersvinget 10, DK-2970 Hørsholm, Denmark* Corresponding author. Tel.: +45 45254760. E-mail address: ldch@mek.dtu.dk**Abstract**

This paper gives an update on current work concerning the development of the method of Dynamic Length Metrology (DLM) to obtain accurate traceable measurements directly in the production. Three case studies are described dealing with diameter measurements with sub-micrometer uncertainty on metallic parts, and dimensional measurements on polymer parts, where the achievable uncertainty of after molding predictions is of a few micrometers.

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Keywords: Metrology; low uncertainty; production environment.**1. Introduction**

The importance of metrology as a fundamental tool adding value in manufacturing is clearly documented in [1] and [2]. Conventional length metrology for traceable accurate measurements requires costly temperature controlled facilities, long waiting time for part acclimatisation, and separate part material characterisation. Due to the increasing need for measurements directly in the production, investigations under nonstandard conditions have been carried out, e.g., as reported in [3-5]. This work concerns a new approach intended for process control called Dynamic Length Metrology (DLM). The method is developed to achieve, directly in a production environment, sub-micrometre accuracy on metal parts, or micrometre accuracy on polymers parts. The new method consists in simultaneously to measure all quantities affecting dimensions of a part over time (dynamically), using a series of sensors and references, and thereafter apply analytical and numerical modelling of the thermo-mechanical effects to concurrently predict condition-specific material properties and

part dimensions at any point, time, temperature, moisture, etc. In principle, if all systematic errors and all influencing factors and their effect on the measurands are known, e.g., temperature [6], it is possible to develop a metrological model calculating the corrected length at standard conditions, i.e., 20 °C, zero measuring force, 50% relative humidity, etc. An estimation of the uncertainty of the measurement U can be obtained following the guidelines in the GUM [7], dimensional values and their uncertainties being the final result of the analysis. Table 1 compares conventional length metrology with the DLM approach. In terms of requirements, DLM can conceptually be implemented at different levels:

- Stand-alone unit complete of sensors and software;
- Solution complete of sensors and software for use with a measuring fixture in the production;
- Solution complete of sensors and software for use with a Coordinate Measuring System (CMS) in the production.

Preliminary investigations have indicated that the approach is viable [8-12].

Table 1: Main requirements in conventional vs. Dynamic Length Metrology.

Requirements to accurate measurements in conventional length metrology	Requirements to accurate measurements in Dynamic Length Metrology
- Costly temperature controlled facilities - Long waiting time for part acclimatization - Separate part material characterization	- Directly in production environment - Dynamic multi-sensoring system - Reference frame and artefacts - Mathematical and numerical modeling

2. Dynamic length metrology - DLM

The DLM approach is presented for the case of a simple length measurement that follows the comparator method [6], using a metrology frame and a reference artefact made of low expansion materials. The general expression (1) to calculate the length of the workpiece at standard conditions $l_{w,s}$ contains the length of the reference artifact l_r and the length difference δl_m between the reference artifact and the workpiece. Under nonstandard conditions, the difference in length also comprises the expansion of the workpiece due to different sources: $\sum f_i$, i.e., temperature, force, humidity and any other relevant factor.

$$l_{w,s} = l_r + \delta l_m - \sum f_i \quad (1)$$

When specifically dealing with metal parts, temperature only is considered, see equation (2). After zeroing the length probe using the reference artefact, concurrent measurements of length and temperature are carried out over time during cooling down, or heating up, of the workpiece, toward the temperature of the ambient, which may be different from 20 °C. The measured data are used to estimate the workpiece length difference by calculating an apparent coefficient of thermal expansion (CTE) α^* of the part during measurement, which is a condition-specific value depending on workpiece geometry.

$$l_{w,s} = l_r + \delta l_m - l \times \alpha^* (T - 20) \quad (2)$$

The method involves calculating and minimizing the difference δl_m by finding the optimum values of the model parameter α^* which are in accordance with the actual measurements. As a result, length measurements compensated to standard conditions are obtained. The better the approximation of the model is to the measured length variation of the workpiece, the more accurate will be the prediction.

Simple analytical formulas, such as equation 1, may not be sufficiently accurate to describe objects with complex geometries that are subject to transient and non-uniform conditions. By combining the measurements with numerical simulations, the behavior of the workpiece can be better

characterized, yielding lower measurement uncertainties. Three case studies showing applications of the DLM approach to steel rods, ABS bricks, and POM tubes, are described in the following paragraphs.

3. DLM on steel rods

Dynamic Length Metrology has been applied to the measurement of a Ø40 mm cylindrical medium carbon steel workpiece outside a metrology laboratory. The workpieces have been heated up, to simulate the heat generation of a cutting process, cleaned and placed on the measurement set-up made out of Invar (CTE of 1.6 ppm/°C) shown in Fig. 1. Two diameters are measured by four inductive probes provided with cylindrical tips. The workpiece is placed and aligned using a V-block so that diameter measurements can start around 3-4 minutes after the simulated manufacturing. The temperature was measured using five temperature sensors. Three sensors measure the workpiece surface temperature (two on the cylinder generatrix, aligned with the length probes, and one on the rod bottom surface), one sensor measures the set-up temperature, and a fifth sensor the ambient temperature. A Zerodur cylinder (CTE=0±0.050 ppm/°C) was used as reference, having a calibrated diameter with an expanded uncertainty (k=2) of $U = 0.3 \mu\text{m}$. An acquisition system to collect data with a frequency of 1 Hz was used. 15 different rods have been measured during this experiment.

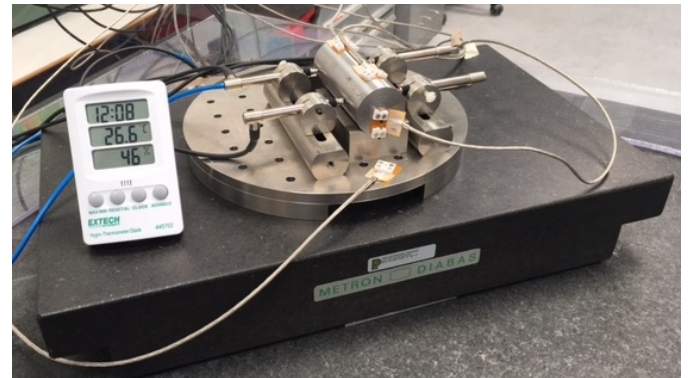


Fig. 1. DLM setup for cylinder diameter measurement.

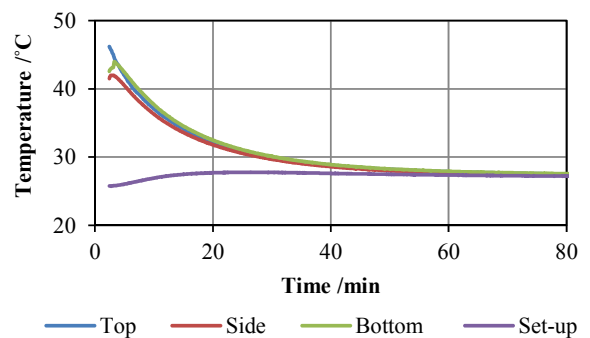


Fig. 2. Dynamic temperature measurements on a steel rod.

Each workpiece was measured for a period of approximately two hours. The ambient temperature was in the range 25-26 °C and the workpiece was heated to a maximum of 50 °C. Simultaneous measurements of diameters and

temperatures were collected, e.g., the temperatures shown in Fig. 2.

The raw data were processed analytically by fitting the length and temperature signals to a linear fit, the slope of which can be interpreted as an apparent coefficient of thermal expansion α^* . This coefficient depends on the workpiece geometry, the temperature sensors' position, and the temperature transient behavior during cooling. This coefficient was used to calculate the diameter at standard conditions. The more data are acquired, in terms of time, the more precise is the prediction.

The predicted diameter, using equation 2, is shown in Fig. 3. The diameter will converge to a value with a small variability in approximately 20 minute: this is an indication that the model has reached a stable prediction, as shown in Table 2. The computed apparent CTE is also converging to a stable value over the same period of time. Figure 3 also shows a comparison, for a single DLM measurement, of the measured diameter, the predicted one, and the calibrated value. It was concluded that the model compensates for most of the thermal effect within 20 minutes.

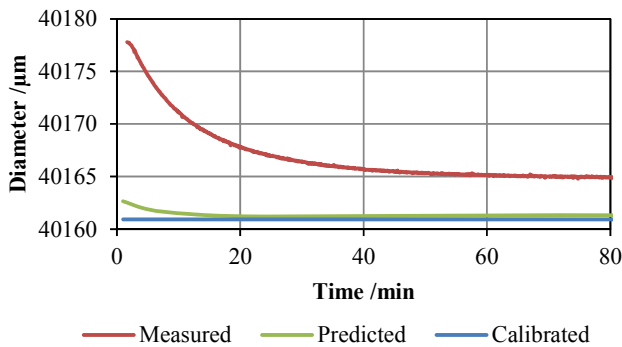


Fig. 3. Measured, analytically predicted, and calibrated diameter values vs. measurement time. Uncertainties: see Table 2.

Table 2: Bias and expanded uncertainty ($k=2$) vs time for analytical solution.

Time /min	Predicted diameter /mm	CTE ppm/°C	Systematic error (bias) /μm	Expanded Uncertainty /μm
1	40162.6	8.3	1.7	19.7
5	40161.9	10.3	1.0	10.7
10	40161.5	11.1	0.6	6.0
20	40161.2	11.8	0.3	2.0
40	40161.2	11.8	0.3	1.7
60	40161.3	11.7	0.3	1.6
80	40161.3	11.7	0.4	1.6
100	40161.2	11.7	0.3	1.6

Table 2 shows the results of diameter prediction, indicating that an error of 0.3 μm and an uncertainty of 2 μm can be achieved within 20 min using the analytical solution. In order to obtain sub-micrometre uncertainties, numerical simulation must be applied: a thermal model of the workpiece and set-up is defined and thermal properties and boundary conditions are optimized to match the numerical result of the temperature field with the corresponding measured values. Successively a thermomechanical model leads to the calculation of the displacements due to temperature variations [9]. Figure 4 depicts an example of simulated temperature field across the

rod and the fixture, and Table 3 shows the results of the prediction. In this case, very low errors and uncertainties can be achieved at a very early stage. This shows that the numerical simulation is needed in order to fulfill the requirement of a sub-micrometre uncertainty directly under production conditions.

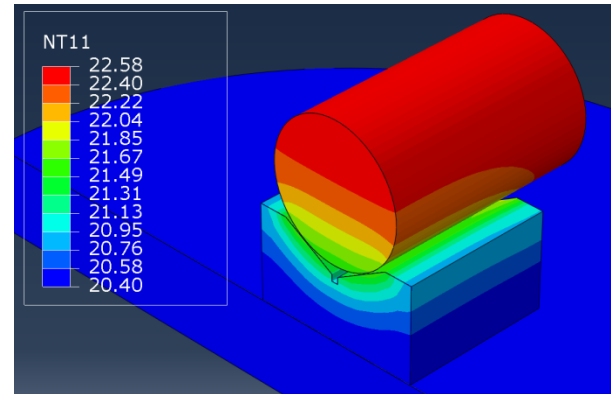


Fig. 4. Modelled temperature field.

Table 3: Systematic error and expanded uncertainty vs time for numerical solution.

Time /min	Predicted diameter /μm	Systematic error /μm	Expanded Uncertainty /μm
3	40161.5	0.55	0.77
5	40161.5	0.56	0.77
10	40161.0	0.10	0.80
20	40160.6	-0.30	0.95
40	40160.7	-0.19	0.96
60	40160.9	-0.02	0.91
80	40160.9	-0.02	0.88

4. DLM on ABS bricks

Polymer components are to a great extent produced by injection molding, a process that generates parts with high initial temperature and low moisture content. In the initial period after production, polymer parts are subject to an acclimatization transition to reach equilibrium with the ambient. Moreover, other dimensional instabilities can occur over a longer period of time, such as relaxation of residual stresses and crystallization. In this and in the next section, two examples are presented where DLM is applied to industrial polymer parts with different geometries and materials. As the dimensional stabilization of polymers may require many weeks, the experiments involve a preliminary, extended measuring phase, necessary to understand all the instabilities occurring over the short and long term after production, together with laboratory tests to analyze the behavior of the selected parts. The outcome of this first phase allows for the definition of a prediction model that uses as input short time measurements performed just after production and gives as output the dimension of the polymer parts at stable and standard conditions.

The selected part has a prismatic hollow shape and is made of Acrylonitrile Butadiene Styrene (ABS), which is an amorphous polymer. The principal length, with a nominal

value of 32 mm, was measured using the Invar set-up shown in Fig. 5, equipped with inductive probes, with the possibility to measure up to 8 parts simultaneously.

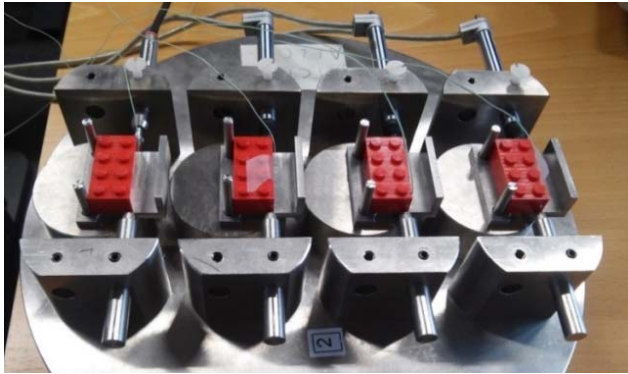


Fig. 5. Measuring set up for ABS bricks.

4.1. Preliminary characterization of ABS

Preliminary tests were performed to assess the thermal behavior of the parts during cooling when exposed to given boundary conditions [10]. The parts were heated up uniformly on a heating plate to simulate the conditions at ejection, and length and temperature variations were measured simultaneously upon cooling. Length at standard conditions could be estimated performing a linear regression of length variation as function of temperature. In order to minimize the uncertainty of the predicted length, a measurement time longer than 1 minute, i.e., approximately 10 % of the cooling time, is required. A vertical temperature gradient is generated due to a preferential direction of heat exchange through the fixture support by conduction, as compared to the natural convection of the free surfaces. The vertical location of the temperature sensor induces a systematic error when the temperature is not measured as close as possible to the measured dimension. A more formal thermal analysis performed with numerical simulations of the temperature field and the heat flow through the polymer part (Fig. 6) lead to the definition of a correction factor to compensate for this systematic effect, allowing more freedom in the selection of the temperature sensor location.

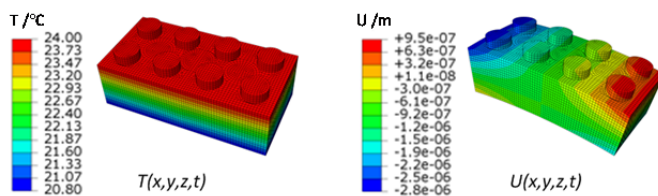


Fig. 6. Thermomechanical simulation of ABS brick: Temperature field T and displacement field U .

A preliminary analysis on the hygroscopic behavior of the ABS brick was performed using a climate chamber to investigate the moisture uptake due to changes in the ambient conditions and the consequent hygroscopic swelling [11]. A proportional increase of mass and length was observed, and a coefficient of moisture expansion (CME) was defined for the

given measurand. The compensation of the moisture expansion for the calculation of the length at stable and standard conditions presents a difficulty: the current ambient conditions, i.e. the ambient relative humidity, cannot be considered in the compensation unless complete equilibrium is achieved, and the material is in a saturated condition, which occurs several hours after molding. On the other hand, the gain in mass after the ejection leads to a relative result, unless the initial water content is known. The introduction of the hypothesis of a completely dry material after ejection allows the definition of a prediction algorithm that considers the moisture expansion as a systematic increase of dimensions, due to the total uptake of water under reference ambient conditions.

Further monitoring of the brick dimensions during the first two months following production showed decreasing trend which terminated within 15 days after production, as shown in Fig. 7. This long time shrinkage can be represented by an exponential decay, in accordance with the assumption of a viscoelastic creep due to residual stress relaxation [12]. Since the shrinkage shows an asymptotic trend, the reference conditions shall be fixed at an instant after the stabilization.

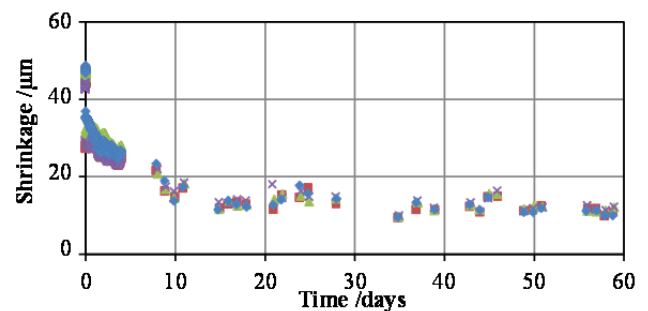


Fig. 7. Post moulding length monitoring: exponential shrinkage occurs within the first 15 days. Symbols refer to four different parts.

Another relevant dimensional instability occurring in polymer parts consists of deformation due to the contact force applied by the inductive length probe. The polymeric material can be considered purely elastic as the stresses and the contact time are limited. Due to the shallow contact area between the brick and the spherical tip of the probe the elastic deformation can be calculated from the Hertz theory of contact between solids [13].

4.2. DLM measurements on ABS brick

Based on the preliminary investigations described above, a formula was developed to predict the dimension of the bricks from measurements within 20 minutes after moulding. The formula contains four contributions which affect the length of the newly produced part as follows:

- Thermal expansion: temperature and length measurements are combined together with the value of the CTE in a complex formula accounting for the influence of the location as the temperature sensor;

- Moisture expansion: a systematic increase of dimension is applied considering the initial condition as a completely dry material;
- Shrinkage: an exponential decrease is applied to determine the dimension at any time after production;
- Elastic deformation: compensation of the elastic deformation due to the force applied by the probe.

The thermal expansion formula is based on numerical simulations while the three other contributions are based on fitting experimental data.

A series of tests was performed to validate the described formula carrying out measurements just after production, without acclimatization and stabilization of the parts, and comparing the predictions with reference measurements under controlled and stable conditions. The developed algorithm yielded a prediction of dimensions with a systematic error of $4.1 \mu\text{m}$ and an expanded uncertainty of $7.5 \mu\text{m}$. Since $100\text{--}200 \mu\text{m}$ are common tolerance values for polymer parts of this kind, it was concluded from the investigation that DLM measurements carried out over 20 minutes directly after production can replace conventional measurements in a metrology laboratory after full acclimatization.

5. DLM on POM tube

5.1. Preliminary characterization of POM

Polyoxymethylene (POM) is a semi-crystalline polymer with a glass transition temperature below ambient temperature; hence, post molding crystallization can occur and can affect dimensions. In particular a reduction of dimensions, proportional with the increase of the crystallinity, is expected.

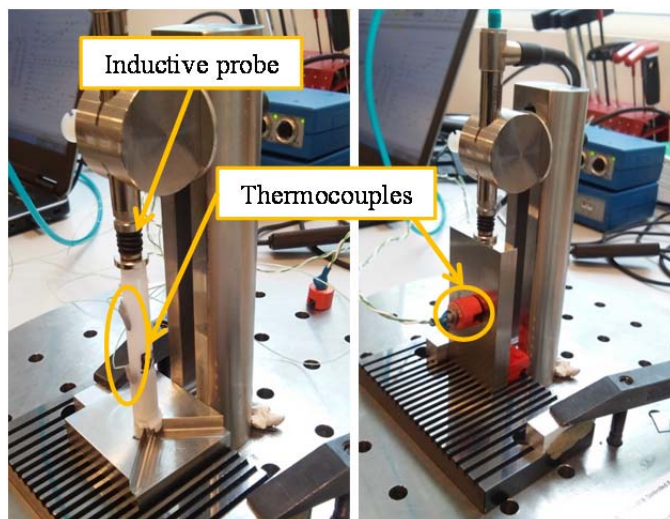


Fig. 8. Set up for concurrent measurement of length and temperature of a POM tube(left); probe zeroing with gauge block (right).

The investigated component was a tubular shape element with nominal length of 59 mm. The length was measured in a column shape fixture, made of Invar, equipped with an inductive probe, see Fig. 8. A grade 1 steel gauge block was

used to zero the set-up. The temperature of the part was measured directly on its surface using type K thermocouples. The change in weight due to moisture absorption/desorption was measured using a scale with resolution of 0.1 mg.

The parts were directly collected from the injection molding machine and the initial weight was measured as soon as possible (approximately 3 minutes after ejection). The parts were placed in the fixture when still warm. Length and temperature variations were simultaneously and continuously measured till the complete cooling, which occurred approximately 15 minutes after molding, obtaining a cooling curve relating temperature and length as shown in Fig. 9. Successively, length, temperature and weight of the tubes were measured at intervals of 1 hour for the first three days and of 1 day for the following week. The final two measurement points were obtained after 6 and 12 weeks from production.

A linear regression of the initial cooling curve, shown in Fig. 9, allows for the calculation of an apparent CTE as the slope of the regression line. An average expanded uncertainty of $10 \text{ ppm}/^\circ\text{C}$ ($k=2$) was estimated considering several parts: it corresponds to approximately 9 % of the CTE value [14].

The weight W presents an initial increase over time during the first 9 hours, till equilibrium with the ambient is achieved, and follows a power law model [14].

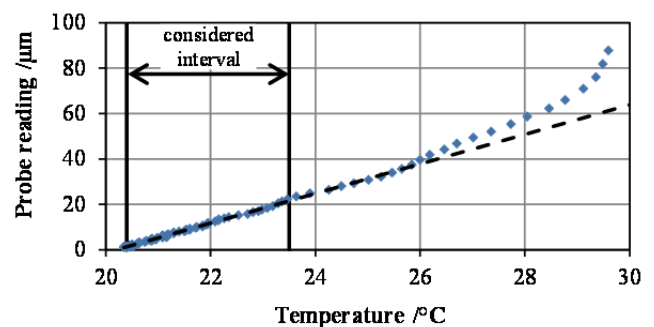


Fig. 9. Cooling curve of a POM tube. The CTE is determined from the dashed regression line over the indicated interval [14].

Such model can be used to predict the weight under equilibrium conditions from measurements in the first minute after molding. The measurements performed during the first week after production, in particular the change of weight and length consequent to different ambient humidity, are used to define a value for an apparent CME. Due to the uncontrolled conditions used to calculate the CME, its value shows a high variability among different parts, leading to a 22 % relative expanded uncertainty ($k=2$).

A compensation of moisture and thermal expansion has been implemented using the two abovementioned coefficients (CTE, CME) and the knowledge of the weight at reference condition. After such compensation, the dimension of all parts considered present a decrease (Fig. 10) over time, occurring even after many weeks from production. This long term trend matches a logarithmic model which can be used for determine the length of the component at any time after production, from a measurement at a given time. The logarithmic decrease,

differently from the ABS parts, can be assigned to a post molding crystallization.

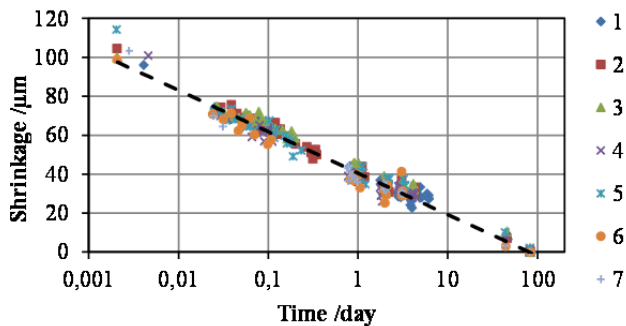


Fig. 10. Logarithmic post molding length decrease of 7 POM tubes. The logarithmic regression is indicated with a black dashed line [14].

5.2. DLM measurements on POM tube

The prediction model defined on the basis of the abovementioned consideration contains:

- Thermal expansion: CTE and the length at reference temperature condition are obtained using information directly from measurements in production;
- Moisture expansion: the model of the initial weight gain and the CME have been defined using long term tests (few hours the first and few days the second) which cannot be practically implemented in a production and shall be considered as a separated test;
- Shrinkage: a logarithmic decrease, defined from a long investigation, is applied;
- Elastic deformation is disregarded: due to the large contact area achieved using a flat probe tip.

A validation stage followed the preliminary investigation. Measurements on 4 tubes, performed just after production over a short time (30 min), were used as input to the model described above to predict the length of the parts after a long time from production (6 and 12 weeks). An expanded uncertainty ($k = 2$) of the predicted length was estimated to $11 \mu\text{m}$, considering contributions from measurements of length, weight and temperature, and contributions from the uncertainty of the model parameters. The values of the predicted length are consistent with reference measurements, with $U = 3.5 \mu\text{m}$ ($k=2$), performed under stable standard conditions [14].

6. Conclusions

This work concerns the method of Dynamic Length Metrology (DLM) to obtain accurate traceable measurements directly in the production. A number of investigations are described dealing with diameter measurements with sub-micrometer uncertainty on metallic parts, and dimensional measurements on polymer parts, where the achievable uncertainty is of a few micrometers. The metal tests have shown that the numerical simulation is needed in order to fulfill the requirement of a sub-micrometre uncertainty for

measurements directly under production conditions. The tests on polymer parts have shown that DLM nicely can account for the influence of temperature on dimensions but a material characterization cannot be avoided, because moisture absorption and shrinkage take place over longer times. Two applications of DLM to polymer parts yielded expanded measurement uncertainties ($k=2$) of $7.5 \mu\text{m}$ for a 32 mm long ABS part and $11 \mu\text{m}$ for a 59 mm long POM part.

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