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Considerations on numerical modelling for compensation of in-process metrology in manufacturing

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Abstract
The growing demands for quality and flexibility and at the same time production speed challenges conventional metrology. The future tendency is that metrology is an integrated part of the production line and thus is placed in a production environment. This is a challenge since dimensional metrology in a production environment might lead to higher uncertainties due to dynamic variations both in the conditions of the environment and in the conditions produced parts, with all the influencing factors such as temperature, vibrations, forces and humidity etc. that lies outside the requirements from todays standards referring to 20ºC and 0 N (zero forces acting on the part). However, many of these effects can be treated as systematic errors if the physical phenomena leading to the deviations can be described. Today, it is very common to compensate for the variations in temperature in a classical 1D manner where a measurand is compensated via the coefficient of thermal expansion (CTE) and the difference from the reference temperature. However, when temperature gradients and very complex part geometries exist the deformation pattern might not at all follow a linear path. Instead, more advanced three-dimensional thermomechanical numerical models should be used for predicting the deformation of the parts due to the thermal effects taking the inherent build-up of residual stresses and warpage into account. The same goes for other effects that might change the dimensions over time such as hygroscopic swelling (for polymer parts), which can be taken into account by considering numerical modelling. In the present work, different academic and industrial parts will be used as cases in order to show the advantages of using numerical simulation tools for compensation of the dynamic changes and further also highlight and discuss where the classical 1D approaches might be sufficient for a desired uncertainty.

Metrology, production environment, numerical modelling, hygroscopic swelling

1. Introduction

The growing demands for quality and flexibility and at the same time production speed challenge the conventional metrology. Hence, the metrology in production engineering should be fast, accurate and robust and should ideally be integrated inline and thus be in the production environment [1]. Dimensional metrology in a production environment might lead to higher uncertainties due to the variation in environment conditions, as stated in todays ISO standards [2]. Here the most influencing condition is the ambient temperature which in a production environment might be several degrees away from the 20ºC reference conditions. Also humidity is stated as having a major impact on the dimensions of polymer parts. The purpose of the present work is to show how 3D thermo-hygro-mechanical models together with information from a set of sensors, can be used for compensating for the length dimension measured on three different metal and polymer cases performed outside reference conditions.

2. Methodology

The overall idea of the proposed method, resembling Dynamic Length Metrology (DLM) [3], is to do simultaneous measurements of the influencing parameters such as e.g. temperature and humidity affecting the dimensions of a part over time (dynamically) together with predictions of condition-specific material characteristics, in order to compensate the measured dimensions to reference conditions, see **Fig. 1**.

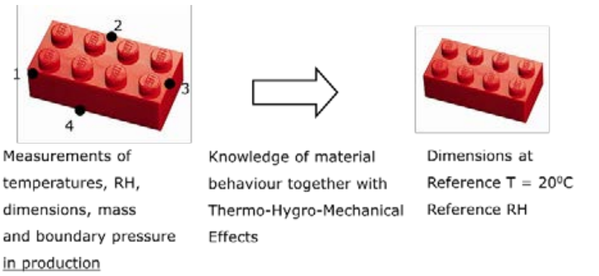

Figure 1. Illustration of the overall concept of acquring data from the measurements used as input to the numerical models for dimensional compensation.

One of the key elements of this compensation is the use of numerical simulation tools, which are applied to model the physical phenomena affecting the dimensions of a part at non-reference consitions.

2.2. Thermo-hygro-mechanical model

The numerical model in general has to solve for three different field quantities. The transient temperature field $T(x,y,z,t)$ is found by solving for heat balance, applying the heat conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1}$$

where ρ is the density, c_p is the specific heat capacity and k is the thermal conductivity. The moisture concentration field $C(x,y,z,t)$ is found by solving for mass balance utilizing Fick's second law

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) \qquad (2)$$

where D is the diffusion coefficient. Finally, the displacement field $u(x,y,z,t)$ has to be found by establishing force balance, applying the three static equilibrium equations here in tensor form

$$\sigma_{ij,i} + p_j = 0 \qquad (3)$$

where σ_{ij} is the stress tensor and p_j are body force components. The solution of these equations, together with a set of properly described boundary conditions, constitutes the bases of the thermo-hygro-mechanical analyses. The hygroscopic part of the model is not applied when metal parts are considered.

3. Applications

In the present work, different academic and industrial cases has been used for numerical in-process compensation, see **Fig. 2-4**.

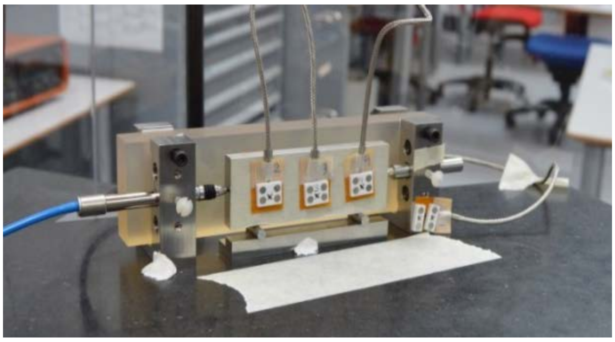

Figure 2. Setup for measuring the length of a steel gauge block, including temperature sensors.

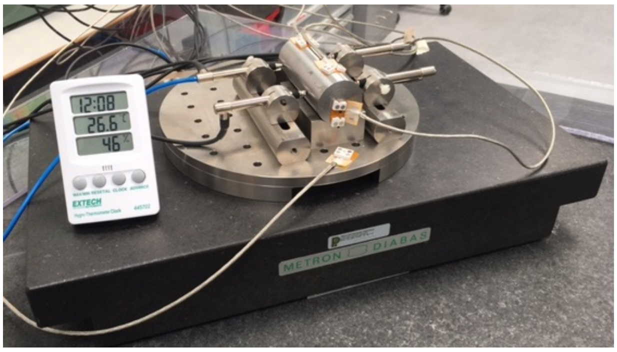

Figure 3. Setup for measuring the diameter of a steel cylinder in a non-controlled environment.

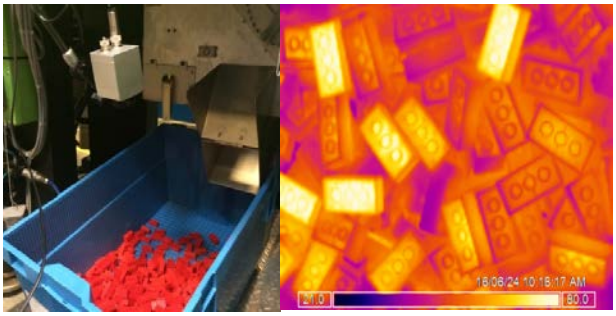

Figure 4. Photo of ABS bricks coming out of the injection moulding machine together with a thermographic image indicating temperatures ranging from 21 to 80 °C.

Comparison of uncertainties between the numerical model predictions and classical 1-D compensation has been performed in order to uncover the benefits of applying simulation tools.

4. Results

In **Fig. 5**, a typical result for compensating a Acrylonitrile butadiene styrene (ABS) brick for temperature and moisture with the applied numerical model, is shown.

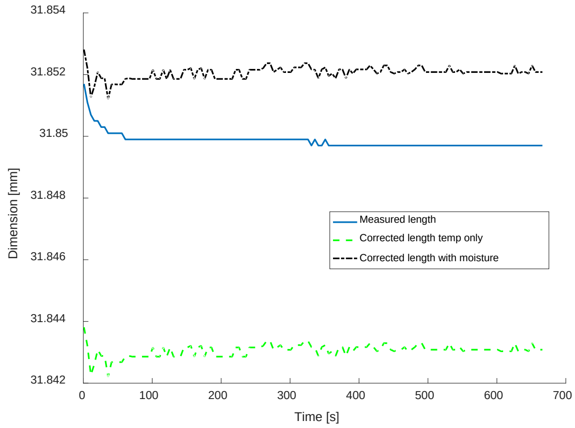

Figure 5. Results in terms of temperature and moisture uptake compensation for the ABS brick.

It is observed how the numerical is capable of taking the transient change in dimension as a result of a non-constant temperature field into account. In **Table 1**, the comparison between calculated uncertainties for the steel cylinder case, is shown as an example.

Table 1: Comparison of uncertainties obtained for the steel cylinder measurement.

	Classical 1-D /µm	**3-D num. model /µm**
Reference	0.3	0.3
Set-up	0.2	0.2
Repeatability (n = 10)	2.1	0.17
Thermal errors	2.1	0.1
U (σ = 2)	6.0	0.80

Here, it is observed how the implementation of a numerical model dramatically reduces the uncertainty, due to a more correct description of the transient thermal field as opposed to the assumption of a uniform temperature field used in classical 1-D compensation.

5. Conclussion

The 3-D thermo-hygro-mechanical model has been shown to be able to predict the transient changes in dimensions of the different parts, reducing the uncertainty for measurements performed at non-reference conditions. Numerical modelling tools have with these cases shown to be very effective and is one of the tools that has to be applied in order to satisfy the future demands for in-process metrology.

References

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