Precision Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Predicting the reference length of polymer parts with micrometer uncertainty measured under non-reference conditions[☆]

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A R T I C L E I N F O

Keywords:
Metrology for polymers
Product validation
Moisture uptake
Creep phenomena

A B S T R A C T

Today, dimensional validation of polymer parts with micrometer level accuracy is performed long time after production because the part needs time to “settle” (which for some polymer materials takes weeks). However, manufacturing industry requires the measurements to be performed before part stabilization, to reduce the waiting time for quality control without compromising the level of accuracy. This work proposes an analytical solution for predicting the reference length of a classical 32 mm polymer part with an uncertainty of less than 10 µm when measured at non-reference conditions. Creep, moisture uptake and temperature are here the main issues to consider for polymer parts. The present study focuses on the dimensional changes governed by moisture uptake and creep with model parameters separately obtained by experimental studies combined with numerical simulations. Finally, the obtained analytical solution is used to predict the reference length of stabilized and non-stabilized polymer parts measured continuously over two months. The prediction shows good agreement with the reference values for settled parts at reference conditions.

1. Introduction

Modern manufacturing technologies involve manufacturing of polymer parts with dimensional tolerances of a few micrometers, and this is also the case in the production of critical components for industries such as automotive, toys, aerospace, medical, etc. Examples of such parts produced today are toy bricks or internal parts of insulin pens, where very tight tolerances and dimensional control is required in order to have the right functionality of final the product. The polymer industry is constantly facing cost-effectiveness requirements, which call for more effective process control. However, it is critical to come up with innovative ways of integrating high accuracy in the quality inspection right after production. Such quality inspection provides feedback for potential adjustment of the manufacturing process parameters if a product starts to deviate from the prescribed tolerances. Hence, moving the quality control from the metrology lab as close to the production line as possible allows for a reduction in scrapped parts and hence improves the return from the production.

A substantial effort has been carried out recently to optimize the injection moulding process to achieve tighter industrial tolerances. The optimization is performed by correlating quality control criteria to process parameters [1]. Chen and Turg [2] adjusted the holding pressure by measurement of the final product weight and configured an automated quality inspection and tuning proces. Lopez et al. [3] investigated the effect of packing time, packing pressure and injection temperature on the weight of a moulded polymer part. Manaf and Yan [4] used an observation system to find surface defects for optimizing the pressing force and moulding temperature. Vagelatos et al. [5] optimized an injection moulding process by monitoring defects in products. Sasaki [6] investigated the effect of ejection force on surface roughness. Coates and Speight [7] showed the dependency of hydraulic pressure and melt pressure to the weight of polymer parts. However, dimension is the most widely used quality control variable in process optimization. Here, shrinkage taken in a general sense plays a major role. There are three types of shrinkage occurring in injection moulded polymer parts 1) In-mould (solidification inside the mould) 2) as-mould (right after mould opening) 3) post-mould (residual stress) [8]. The effect of in-mould and as-mould shrinkage on final dimension has been investigated in literature by correlating measured dimensions to different process parameters such as mould deformation and friction between polymer surfaces [9], holding pressure and injection velocity [10], die gap [11], mould temperature and holding pressure [12] as well as pressure decay during the moulding cycle [13].

Another very influencing factor on dimensions of a polymer part is moisture uptake. The moisture from the ambient humid air diffuses into the polymer structure. The water molecules have two different states in

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[☆] This paper was recommended by Associate Editor Gorka Aguirre.

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https://doi.org/10.1016/j.precisioneng.2018.07.003
Received 23 February 2018; Received in revised form 19 June 2018; Accepted 16 July 2018

Please cite this article as: Mohammadi, A., Precision Engineering (2018), https://doi.org/10.1016/j.precisioneng.2018.07.003

Nomenclature

c	Moisture concentration
c_{sat}	Equilibrium moisture content
$c_{sat}^{50\%}$	Equilibrium moisture content at 50 %RH
c_{sat}^{rh}	Equilibrium moisture content at arbitrary %RH
D	Diffusion coefficient
E	Young's modulus
E_n	Normalized error
$l_{measured}$	Measured length of the workpiece
$l_{reference}$	Length of workpiece at reference conditions (measured or predicted)
L	Nominal length
u	Uncertainty component
U	Combined standard uncertainty
w_m	Measured weight of a part
w_d	Measured dry weight of a part
x,y,z	Spatial coordinates in a Cartesian coordinate system
β	Coefficient of moisture expansion
δl^{cr}	Length variation due to creep
δl^{rh}	Length variation due to moisture uptake
ε	Strain
η	Newtonian viscosity
ρ	Density
σ_{ij}	Stress tensor
σ_0	Predefined constant stress
τ	Retardation time

the polymer material: “Free” and “Bounded”. “Free” or “unbound” is the state when the water molecules are placed in the voids and non-porous part of the polymer material. “Bounded” molecules make chemical bonds with hydrogen in the polymer chains [14–16]. The “bounded” state can change the mechanical properties such as elastic modulus, shear strength, flexural modulus, fracture toughness, yield stress, coefficient of thermal expansion, glass transition temperature and viscoelastic behavior [17–19] of the polymer part. Moisture causes swelling which is quantified by the Coefficient of Hygroscopic Swelling (CHS) or Moisture Expansion Coefficient (CME). Ma et al. [20] measured the CME value for an epoxy moulding compound at three different temperatures and different relative humidities. They found that the CME is constant for different relative humidities but it is linearly increasing with temperature. Park et al. [21] measured the CME for temperatures between 25 °C and 180 °C. They found that the CME is highly dependent on temperature especially at higher temperature ranges such as 100 °C - 180 °C.

This short literature review shows that optimization of the injection moulding process depends on the method of quality inspection. However, there is a lack of quality control methods which include the effect of shrinkage as well as measurement conditions (temperature, moisture and probe force) for dimensional measurements and this is necessary for a modern quality inspection. This is addressed in the present work, where the dimensions at reference conditions of polymer parts are predicted before stabilization. A coupled 3D hygro-mechanical model is applied to simulate the deformation path of a polymer part as a result of moisture and post-mould shrinkage (which from now on will be attributed viscoelastic creep as a result of the residual stress field in the injection moulded part). This 3D finite element model should be able to capture the warpage in the part as a result of the non-uniform nature of the moisture concentration field. In a previous study warpage was the main reason for including 3D thermomechanical analyses for capturing the thermal effects for dimensional measurements on non-acclimatized polymer parts [22]. The simulation outcome is simplified to a more practical 1-D equation which can be used directly to predict the dimension at reference state based on the measured quantities without the need to perform heavy 3-D finite element (FE) calculations. The different influencing effects are characterized with the help from experiments, which then are used to back out the material properties entering the analytical model and numerical solutions. An overall uncertainty is estimated based on all the influencing factors. Finally, a validation of the prediction against reference measurements is presented.

2. Methodology

2.1. Calculation of the reference length

As mentioned in the introduction, the dimensions of a moulded part decreases slowly after injection moulding due to creep effects, with fluctuations due to the influence of temperature and moisture as shown schematically in Fig. 1. The length is measured after the part has been ejected from the injection moulding machine, as indicated by the time t_1 in Fig. 1 (the 1-D point to point dimension of a part will from now on be denoted “length” and will be the only measure used in the present work).

Several days or weeks after (at time t_2), the polymer part has settled; no more creep or moisture will affect the length of the part (if the relative humidity is constant). At this point in time conventional metrology can be performed in a temperature and moisture controlled environment in order to check if the part meets the specified tolerances. It is the length at this particular point in time that the obtained prediction algorithm should be able to calculate, based on the measurements performed at time t_1.

Creep is an intrinsic phenomenon of injection moulding and its effect on dimension decays gradually over time. The injection moulding

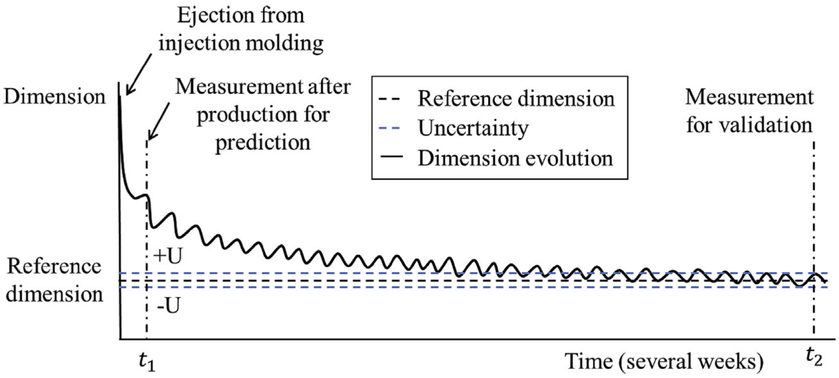

Fig. 1. Schematic of dimensional variation of a polymer part after injection moulding.