A Physical Model for a Quality Control Concept in Injection Molding

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ABSTRACT: In this work, a model is presented, which is the basis of a quality control concept for the injection molding process. Contrary to statistical methods, this model uses physical dependencies of two quality parameters on four influencing parameters. The influences of holding pressure, holding time, melt temperature, and mold temperature on part mass and dimensions are described based on the fundamental material behavior such as pvT-data or energy equation. Furthermore, the influence of viscosity changes is indirectly taken into account using the injection work. Assuming only small deviations of the influencing parameters around an optimized operating point, the four parameters are treated as being independent from each other. With this assumption, a product ansatz was chosen with different functions for each influencing factor. Applying basic algebra, the starting equation was transformed into a form that describes either the change in part mass or characteristic part dimensions as a function of the influencing factors. The final equation for the part mass contains six model parameters, whereas nine model parameters are necessary for the equation for the part length. To obtain those model parameters some systematic experiments are required. Once the parameters are known, the model is able to calculate the change of the target values when the influencing factors vary around the operating point. The model was tested experimentally with focus on dimensions using a plastic cover made of an acrylonitrile butadiene styrene (ABS) grade. For the investigated part geometry and material grade, the process behavior was described well by the model. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 124: 4926–4934, 2012

Key words: injection molding; modelling; process model

INTRODUCTION

With intensifying quality regulations and demanding product specifications in sectors such as the medical or the automotive industries, modern quality control concepts for the injection molding process are constantly gaining importance. Traditional quality control systems rely on Statistical Process Control, where the part quality is ascertained by hindsight with a simple distinction in good or poor part quality. On the one hand, this assures to a high degree that only parts fulfilling the quality requirements find their way to the customer but on the other hand generates a considerable amount of scrap and demands high personnel and testing effort. Therefore, the determination of the quality of a lot or of the production of a whole shift production is mostly based on a sampling inspection once per lot or shift and article. The injection molding process itself can only be influenced belatedly. Short term disturbances may either be unperceived or cause large numbers of rejections.

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Modern quality control concepts are aimed at ensuring the production of good quality parts directly in the injection molding process itself. Thus, personnel and testing expenses and scrap rate can be reduced significantly. As depicted in Figure 1, there are basically three approaches to closed loop controls for the injection molding process.[1] The most rudimental control circuit (I) represents a simple machine control, which adjusts the set parameters of the injection molding machine and the mold in the case of deviations caused by disturbances. The actual part quality remains unconsidered for this control mechanism. Circuit II goes one step further and differentiates between good and poor product quality by a measurement of the vital part properties and relates the machine and mold set values to the part quality by a direct product adaptive process model. In control loop III, the decision on the product quality is taken based on an analysis of correlation between part quality and measured process data. Finally, machine and mold parameters are controlled by an indirect product adaptive process model as a function of the process data.

Similar process control architectures were published by Wang et al.[2] and Gao and Yang.[3] In principle, a process control system can be built on the basis of physical models,[4–6] which tries to use physical

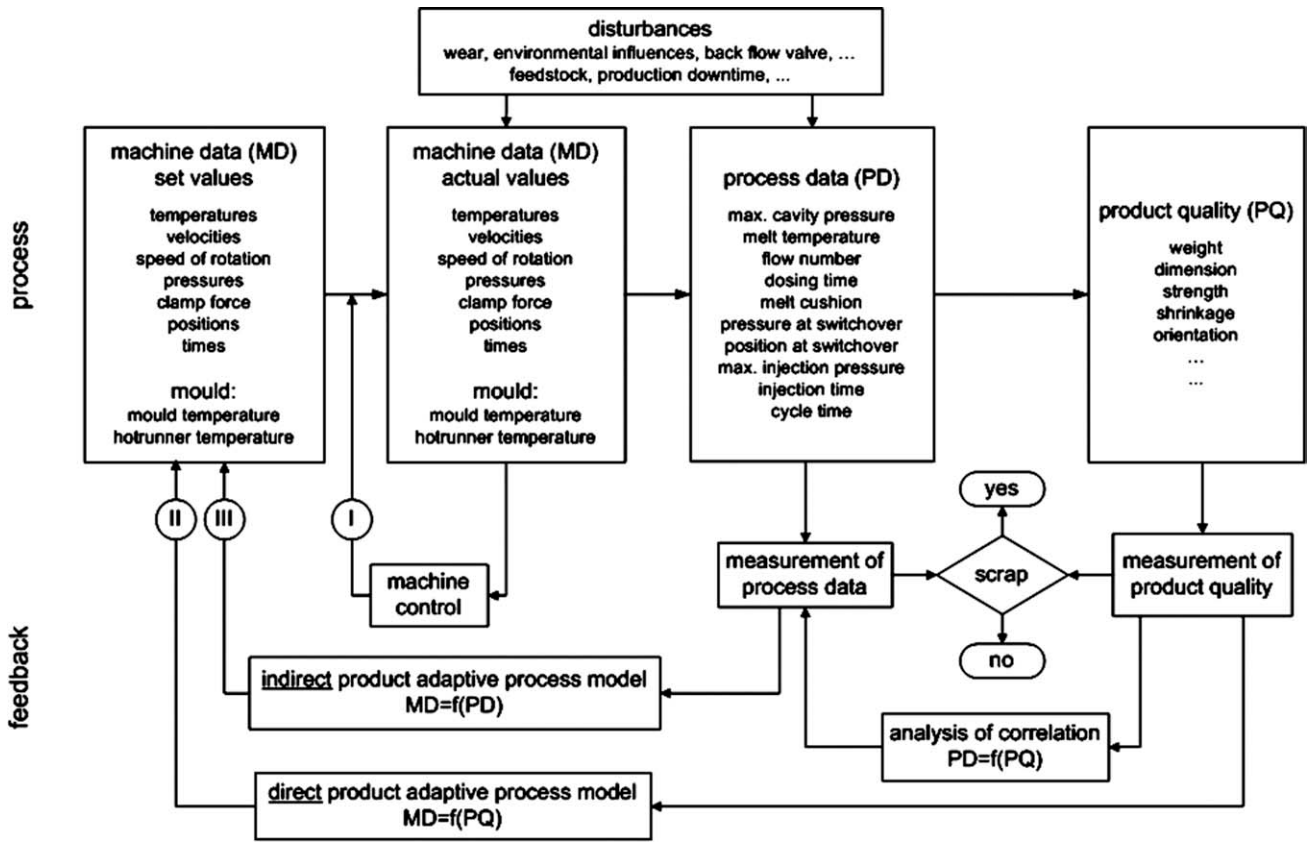

Figure 1 Strategies of closed loop controls for the injection moulding process, according to Ref. 1.

laws like energy conservation or pvT properties.[7–9] Although, in the article of Kamal et al.,[7] the quality parameter is the part weight only.

An alternative approach to process control is the use of artificial neural networks (ANNs), which has been reported widely in literature.[10–12] Additionally, various hybrid models combining physical models with ANNs were applied for process and quality control in the past.[13–17]

A comprehensive review of the intensive research activities concerning process and quality control in injection molding around the millennium was published by Chen and Turng,[18] giving a good overview of the advantages and disadvantages of the different concepts.

The presented physical model of a quality control is proposed to work after control circuit II (according to Fig. 1). Besides individual optical and functional properties specific to a certain article, a constant part mass and constant part dimensions are appropriate target values for quality surveillance and control in injection molding processes.[19]

In this research work, the relations between the two quality parameters part mass and part dimensions were investigated as functions of machine data such as holding pressure, holding time, nozzle temperature, and mold temperature. This article is an attempt to build up a process model strongly based on physical properties and relations, especially extending the quality parameters from part weight to part length based on pvT properties and energy conservation equation for a description of temperature development depending on time. Moreover, the influence of the rheological behavior is taken into account.

THEORETICAL BACKGROUND

Due to environmental or process-inherent disturbances, actual machine and process data may be subject to variations. It is obvious that this leads to changing part properties. Common pvT-control concepts try to keep part mass and shrinkage constant by providing a constant specific volume in the mold cavity at the gate seal-off point. However, in doing so, constant part dimensions and morphologic structures cannot be ensured. This is because of differing shear deformations along the flow path at same positions and times from one cycle to the other during filling and packing.[20] Equal orientation is essential for equal shrinkage and part dimensions and can only be achieved if shear rates stay locally and temporally constant from cycle to cycle. As a consequence injection time and flow rate, respectively, the injection

speed profile must be kept constant. The injection pressure may vary because of changes of melt temperature, mold temperature, and batch viscosity fluctuations. If the injection pressure shifts, the holding pressure must be adjusted to obtain a constant part mass. This may lead to relatively high flow rates in the packing phase in conjunction with short holding times and high cooling rates. Thus orientation, shrinkage, and morphology become inconsistent from cycle to cycle. The dynamics of the packing phase are affected by the melt viscosity to a high degree. An adequate parameter must be introduced to be able to incorporate the influence of viscosity into the quality control. One appropriate parameter to detect viscosity changes in the filling phase is the injection work. However, measuring of the occurring work during packing is subject to imprecision due to the very little screw movements.[21] Subsequently, a functional combination of holding pressure and injection work turns out to be well suited for the consideration of varying viscosity. Besides constant shear deformations with regard to constant thermodynamic conditions, also unvarying timing has to be implemented for all cycles, keeping the overall cycle time and its components constant.[20]

Constant part mass

The following explanations will concentrate on the relations for the part mass being the basis for the equations of the part dimensions, which will be explained thereafter. If only small deviations around an optimized operating point occur, interactions between the four parameters can be neglected and a product ansatz containing four independent functions can be formulated to describe the dependencies of the specific volume on the machine parameters[20]:

$$v_{sp} = f_1(p_h(W_i)) \cdot f_2(T_m) \cdot f_3(t_h) \cdot f_4(T_t) \quad (1)$$

where v_{sp} is specific volume; f_1–f_4, functions; $p_h(W_i)$, holding pressure as a function of injection work; T_m, melt temperature; t_h, holding time; T_t, mold or tool temperature.

After logarithmizing and subsequent differentiation eq. (1) turns to

$$\frac{dv_{sp}}{v_{sp}} = f_1(p_h(W_i)) \cdot dW_i + f_2(T_m) \cdot dT_m + f_3(t_h) \cdot dt_h + f_4(T_t) \cdot dT_t \quad (2)$$

Function f_1 contains the compressibility κ of the polymer:

$$\kappa = -\frac{1}{v_{sp}} \cdot \frac{dv_{sp}}{dp_h} \quad (3)$$

Under real process conditions κ is no mere material parameter but also dependent on mold and part geometry. For this reason, κ is substituted by the constant K_1:

$$dv_{sp} = -v_{sp} \cdot K_1 \cdot dp_h \quad (4)$$

Equation (5) introduces the coupling of injection work and holding pressure[22]:

$$\ln(p_h) = \ln(p_{h0}) + N \cdot \ln\left(\frac{W_i}{W_{i0}}\right) \quad (5)$$

with p_{h0}, holding pressure at the optimized operating point; W_{i0}, injection work at the optimised operating point; N, material-dependent and mold-dependent parameter (typically $0.3 < N < 1.5$)[20]

The injection work is defined as the integral of the injection pressure along the screw stroke multiplied by the cylinder cross section area:

$$W_i = a_{cyl} \cdot \int_{s_1}^{s_2} p_i(s_i) \cdot ds \quad (6)$$

with W_i, injection work; a_{cyl}, cylinder cross section area; p_i, injection pressure; s, screw position

After differentiation of eq. (5) follows:

$$dp_h = \frac{p_{h0}}{W_{i0}} \cdot N \cdot \left(\frac{W_i}{W_{i0}}\right)^{N-1} \cdot dW_i \quad (7)$$

With eq. (4), the coupling of filling and packing phase is finally described as:

$$dv_{sp} = -v_{sp} \cdot K_1 \cdot \frac{p_{h0}}{W_{i0}} \cdot N \cdot \left(\frac{W_i}{W_{i0}}\right)^{N-1} \cdot dW_i \quad (8)$$

Function f_2 characterizes the coherence between specific volume and melt temperature based on the relation for the coefficient of volume expansion α:

$$\alpha = \frac{1}{v_{sp}} \cdot \frac{dv_{sp}}{dT_m} \quad (9)$$

For the physical model, α is substituted by the constant K_2:

$$dv_{sp} = v_{sp} \cdot K_2 \cdot dT_m \quad (10)$$

Function f_3 contains the dependency of the specific volume on the holding time. With changing holding time, the cooling time and the temperature of the polymer at the end of packing will change too. This conjunction can be found over the equation for the cooling time:

$$t_c = \frac{s^2}{\pi^2 \cdot a_{\text{eff}}} \cdot \ln\left(\frac{8}{\pi^2} \cdot \frac{T_m - T_t}{T_d - T_t}\right) \tag{11}$$

with t_c, cooling time; s, average wall thickness of part; a_{eff}, effective thermal diffusivity at average mold temperature; T_d, demolding temperature

With t_c substituted for t_h, the temperature T_s at the end of the packing phase can be calculated:

$$T_s = T_t + \frac{8}{\pi^2} \cdot (T_m - T_t) \cdot \exp\left[-\frac{\pi^2 \cdot a_{\text{eff}} \cdot t_h}{s^2}\right] \tag{12}$$

To calculate the change of T_s due to a variation of t_h, eq. (12) is differentiated. With eq. (12) the temperature T_s is known and can be assumed as a new starting temperature for further small deviations around this temperature with changing holding time. Therefore, T_m in eq. (12) can be replaced by T_s and furthermore t_h is set to zero for this new starting temperature:

$$dT_s = -\frac{\pi^2 \cdot a_{\text{eff}}}{s^2} \cdot \frac{8}{\pi^2} \cdot (T_s - T_t) \cdot dt_h \tag{13}$$

Replacing dT_m by dT_s in eq. (10) and inserting eq. (13) into eq. (10), the following relation between specific volume and holding time can be formulated:

$$dv_{\text{sp}} = -v_{\text{sp}} \cdot K_3 \cdot (T_s - T_t) \cdot dt_h \tag{14}$$

The constant K_3 stands for:

$$K_3 = \frac{\alpha \cdot 8 \cdot a_{\text{eff}}}{s^2} \tag{15}$$

Describing the relation between specific volume and mold temperature, function f_4 can be derived from the expression for the cooling time [eq. (11)]. Partial differentiation and transformation deliver:

$$dt_h = \frac{T_m - T_s}{T_s - T_t} \cdot \frac{s^2}{\pi^2 \cdot a_{\text{eff}}} \cdot \frac{1}{T_m - T_t} \cdot dT_t \tag{16}$$

Equation 17 derives after substitution of dt_h in eq. (14):

$$dv_{\text{sp}} = -v_{\text{sp}} \cdot K_4 \cdot \frac{T_m - T_s}{T_m - T_t} \cdot dT_t \tag{17}$$

with

$$K_4 = \frac{\alpha \cdot 8}{\pi^2} \tag{18}$$

Finally, with

$$m = \frac{v}{v_{\text{sp}}} \tag{19}$$

respectively,

$$dm = -\frac{v}{v_{\text{sp}}^2} \cdot dv_{\text{sp}} = -m \cdot \frac{dv_{\text{sp}}}{v_{\text{sp}}} \tag{20}$$

with m, part mass; v, cavity volume.

Equation 2 can be written as the relation of the dependency of the part mass on the four parameters in form of a differences equation [eq. (21)], whereat m_0 is the part mass at the optimized operating point and the differences Δm, Δp_h, ΔT_m, Δt_h, and ΔT_t signify the parameter deviances.

$$\frac{\Delta m}{m_0} = K_1 \cdot \Delta p_h - K_2 \cdot \Delta T_m + K_3 \cdot (T_s - T_t) \cdot \Delta t_h + K_4 \cdot \frac{T_m - T_s}{T_m - T_t} \cdot \Delta T_t \tag{21}$$

with:

$$\Delta p_h = \frac{p_{h0}}{W_{i0}} \cdot N \cdot \left(\frac{W_i}{W_{i0}}\right)^{N-1} \cdot \Delta W_i \tag{22}$$

With introducing a fifth constant K_5 eq. (12) turns to:

$$T_s = T_t + \frac{8}{\pi^2} \cdot (T_m - T_t) \cdot \exp[-K_5 \cdot t_h] \tag{23}$$

with

$$K_5 = \frac{\pi^2 \cdot a_{\text{eff}}}{s^2}. \tag{24}$$

The eqs. (21)–(23) describe the fundament of the physical model for the part mass.[20] For keeping the latter constant ($\Delta m = 0$), the right side of eq. (21) must be zero. Provided that K_1–K_4 are known, the four functions can be adapted in the case of deviations of the machine parameters. If changes in part mass occur due to batch viscosity variations, this can be adjusted by eq. (7). For varying holding times, eq. (23) is combined with eq. 21. Whereat with unchanged sealing temperature and holding pressure, a constant part mass can be achieved.

The constants K_1 to K_5 and the exponent N have to be determined through experimental design varying one parameter at a time, while keeping the other three constant.

With ΔT_m, Δt_h, $\Delta T_t = 0$, and $\Delta p_h \neq 0$, eq. 25 for the determination of K_1 derives from eq. (21) as:

$$K_1 = \frac{\Delta m}{m_0} \cdot \frac{1}{\Delta p_h} \tag{25}$$

With Δp_h, Δt_h, $\Delta T_t = 0$, and $\Delta T_m \neq 0$. K_2 is determined by eq. (21) as:

$$K_2 = -\frac{\Delta m}{m_0} \cdot \frac{1}{\Delta T_m} \tag{26}$$

The corresponding expression for K_3 is deduced from eq. (21) and eq. (23) with Δp_h, ΔT_m, $\Delta T_t = 0$, and $\Delta t_h \neq 0$:

$$\frac{\Delta m}{m_0} = K_3 \cdot \frac{8}{\pi^2} \cdot (T_m - T_t) \cdot \exp[-K_5 \cdot t_h] \cdot \Delta t_h \tag{27}$$

In this case, at least two pairs of values (Δm_1, Δt_{h1}) and (Δm_2, Δt_{h2}) are required to solve the equation. K_5 is calculated by:

$$\frac{\Delta m_1}{\Delta m_2} = \frac{\exp[-K_5 \cdot t_{h1}] \cdot \Delta t_{h1}}{\exp[-K_5 \cdot t_{h2}] \cdot \Delta t_{h2}} \tag{28}$$

respectively,

$$K_5 = \frac{\ln\left(\frac{\Delta m_1}{\Delta m_2} \cdot \frac{\Delta t_{h2}}{\Delta t_{h1}}\right)}{t_{h2} - t_{h1}} \tag{29}$$

Subsequently, K_3 is finally defined by eq. (30), averaging eq. (27) for the two pairs of values (Δm_1, Δt_{h1}) and (Δm_2, Δt_{h2}):

$$K_3 = \frac{1}{2} \cdot \left[\frac{\frac{\Delta m_1}{m_0} \cdot \exp[K_5 \cdot t_{h1}]}{\frac{8}{\pi^2} \cdot (T_{m0} - T_{t0}) \cdot \Delta t_{h1}} + \frac{\frac{\Delta m_2}{m_0} \cdot \exp[K_5 \cdot t_{h2}]}{\frac{8}{\pi^2} \cdot (T_{m0} - T_{t0}) \cdot \Delta t_{h2}} \right] \tag{30}$$

K_4 derives from eq. (21) with Δp_h, ΔT_m, $\Delta t_h = 0$, and $\Delta T_t \neq 0$:

$$K_4 = \frac{\Delta m}{m_0} \cdot \frac{T_{m0} - T_t}{T_{m0} - T_s} \cdot \frac{1}{\Delta T_t} \tag{31}$$

The determination of the exponent N follows from eqs. (21) and (22) with Δt_h, $\Delta T_t = 0$, and ΔT_m, Δp_h, $\neq 0$. This means, experiments are carried out, in which the melt temperature is varied, and the holding pressure is adjusted to obtain a constant part mass. In doing so, the injection work is measured and N is calculated by eq. (33). With $\Delta m = 0$, the eqs. (21) and (22) deliver:

$$K_1 \cdot \frac{p_{h0}}{W_{i0}} \cdot N \cdot \left(\frac{W_i}{W_{i0}}\right)^{N-1} \cdot \Delta W_i = K_2 \cdot \Delta T_m \tag{32}$$

By using eq. 5, eq. 32 is simplified to:

$$N = \frac{K_2}{K_1} \cdot \frac{\Delta T_m}{W_{i0} - W_i} \cdot \frac{W_i}{p_h} \tag{33}$$

Constant part dimensions

If a constant part length is the more determining factor for the product quality than the constant part mass the corresponding expressions for the part dimensions can be derived from the relations between specific volume and machine parameters.

A constant part mass is related to a constant initial part volume v_0[20]:

$$v_0 = l_0 \cdot w_0 \cdot h_0 \tag{34}$$

with l_0, initial length; w_0, initial width; h_0, initial height.

If the part mass varies, the part dimensions will shift to:

$$v = l \cdot w \cdot h \tag{35}$$

In conjunction with eq. (20), eq. (35) yields

$$dm = -\frac{l \cdot w \cdot h}{v_{sp}^2} \cdot dv_{sp} = -m \cdot \frac{dv_{sp}}{v_{sp}} \tag{36}$$

Subsequently, the product ansatz for the physical model for the part dimensions is achieved:

$$l \cdot w \cdot h = m \cdot v_{sp} \tag{37}$$

After logarithmizing [eq. (38)] and differentiation [eq. (39)] of eq. (37), a differences in equation [eq. (40)] can be derived:

$$\ln(l) + \ln(w) + \ln(h) = \ln(m) + \ln(v_{sp}) \tag{38}$$

$$\frac{1}{l} \cdot dl + \frac{1}{w} \cdot dw + \frac{1}{h} \cdot dh = \frac{1}{m} \cdot dm + \frac{1}{v_{sp}} \cdot dv_{sp} \tag{39}$$

$$\frac{\Delta l}{l} + \frac{\Delta w}{w} + \frac{\Delta h}{h} = \frac{\Delta m}{m} + \frac{\Delta v_{sp}}{v_{sp}} \tag{40}$$

As on one hand, the dimensions Δl, Δw, and Δh are coupled, and on the other hand, defined by Δm and Δv_{sp} the eqs. (41)–(43) are valid for an isotropic, respectively, and anisotropic cube[2]:

$$\frac{\Delta l}{l} \approx \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \quad \text{respectively} \quad \frac{\Delta l}{l} = K_l \cdot \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \tag{41}$$

$$\frac{\Delta w}{w} \approx \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \quad \text{respectively} \quad \frac{\Delta w}{w} = K_w \cdot \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \tag{42}$$

$$\frac{\Delta h}{h} \approx \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \quad \text{respectively} \quad \frac{\Delta h}{h} = K_h \cdot \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \tag{43}$$

K_l, K_w, and K_h represent constants for each of the three spatial directions taking into account anisotropy. The subsequent deductions will only be performed for the part length l. The relations for width and height are deduced analogously.

Applying eqs. (42) and (43) in eq. (40), the following expression can be formed:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ -\frac{\Delta v_{sp}}{v_{sp}} + (K_w + K_h) \cdot \sqrt[3]{\frac{\Delta v_{sp}}{v_{sp}}} \right\} \quad (44)$$

Starting from this basic relation [eq. (44)], the dependencies of the part length on $\Delta p_h(W_i)$, ΔT_m, Δt_h, and ΔT_t can be found by the earlier mentioned physical coherences for the specific volume.

By eq. (4), the dependency of part length on holding pressure can be written as:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ \kappa \cdot \Delta p_h - (K_w + K_h) \cdot \sqrt[3]{\kappa} \cdot \sqrt[3]{\Delta p_h} \right\} \quad (45)$$

κ, K_w, and K_h are substituted by the constants A and B:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ A \cdot \Delta p_h - B \cdot \sqrt[3]{\Delta p_h} \right\} \quad (46)$$

with

$$A = \kappa \quad (47)$$

and

$$B = (K_w + K_h) \cdot \sqrt[3]{\kappa} \quad (48)$$

For the relation between part length and melt temperature, eqs. (44) and (9) yield:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} + \left\{ \alpha \cdot \Delta T_m - (K_w + K_h) \cdot \sqrt[3]{\alpha} \cdot \sqrt[3]{\Delta T_m} \right\} \quad (49)$$

With the constants C and D follows:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} + \left\{ C \cdot \Delta T_m - D \cdot \sqrt[3]{\Delta T_m} \right\} \quad (50)$$

with

$$C = \alpha \quad (51)$$

and

$$D = (K_w + K_h) \cdot \sqrt[3]{\alpha}. \quad (52)$$

The influence of the holding time on the part length is introduced by eq. (14).

This leads to:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ \frac{\alpha \cdot 8 \cdot a_{eff}}{s^2} \cdot \Delta t_h - (K_w - K_h) \cdot \sqrt[3]{\frac{\alpha \cdot 8 \cdot a_{eff}}{s^2}} \cdot \sqrt[3]{\Delta t_h} \right\} \quad (53)$$

By introduction of the constants E and F eq. (53) is simplified to:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ E \cdot \Delta t_h - F \cdot \sqrt[3]{\Delta t_h} \right\} \quad (54)$$

with

$$E = \frac{\alpha \cdot 8 \cdot a_{eff}}{s^2} \quad (55)$$

and

$$F = (K_w - K_h) \cdot \sqrt[3]{\frac{\alpha \cdot 8 \cdot a_{eff}}{s^2}} \quad (56)$$

The relation between part length and mold temperature follows with eq. (17):

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ K_4 \cdot \frac{T_m - T_s}{T_m - T_t} \cdot \Delta T_t - (K_w - K_h) \cdot \sqrt[3]{K_4 \cdot \frac{T_m - T_s}{T_m - T_t}} \cdot \sqrt[3]{\Delta T_t} \right\} \quad (57)$$

Equation 57 is reduced to:

$$\frac{\Delta l}{l} = \frac{\Delta m}{m} - \left\{ G \cdot \Delta T_t - H \cdot \sqrt[3]{\Delta T_t} \right\} \quad (58)$$

with

$$G = \frac{\alpha \cdot 8}{\pi^2} \cdot \frac{T_m - T_s}{T_m - T_t} \quad (59)$$

and

$$H = (K_w - K_h) \cdot \sqrt[3]{\frac{\alpha \cdot 8}{\pi^2} \cdot \frac{T_m - T_s}{T_m - T_t}} \quad (60)$$

The constants A to H are obtained by experimental design variating one parameter at a time. As each of the equations 46, 50, 54, and 58 contain two variables, two pairs of variates are necessary for the determination of the constants. However, experiments showed that for B, D, F, and H very low values are obtained, affecting the results not more than by the 16th position after decimal point. Thus B, D, F, and H can be neglected and the constants A, C, E, and G can be easily calculated applying equations 46, 50, 54, and 58.

On this condition the exponent N [eq. (62)] of the physical model for the part length is achieved by the eqs. (5), (46), and (50):

$$-A \cdot \frac{p_h}{W_i} \cdot N \cdot \Delta W_i = C \cdot \Delta T_m \quad (61)$$

TABLE I
Set Data for the Evaluation of the Physical Model

Holding pressure (bar)	Nozzle temperature (°C)	Holding time (s)	Mould temperature (°C)
270	250	2	60
280	255	3	65
290	**260**	**4**	**70**
300	265	5	75
310	270	6	80

$$N = -\frac{C}{A} \cdot \frac{\Delta T_m}{\Delta W_i} \cdot \frac{W_i}{p_h} \tag{62}$$

EXPERIMENTAL

The applicability of the physical model was validated by practical experiments in which the dependencies of the part length, which is the important quality parameter of the investigated part, on the parameters holding pressure, holding time, melt and mold temperature were investigated. For reasons of adjustability and reproducibility, the nozzle temperature was chosen as setting parameter in place of the melt temperature. The applied experimental design implemented the variation of one parameter at a time, keeping the other three constant. Table I shows a roundup of the data set of the experiments. Each parameter was varied by two equidistant steps below and above the central point (bold). The overall cycle time stayed unchanged for all experiments.

The experiments were carried out on a plastic cover for a washing machine (Fig. 2) made of a standard ABS grade (Novodur P2H-AT by Ineos Group Ltd., UK). The investigated test series were injection molded on a hydraulic injection molding machine with knee lever system (ENGEL ES330/80H, Engel Austria GmbH, Schwertberg, Austria).

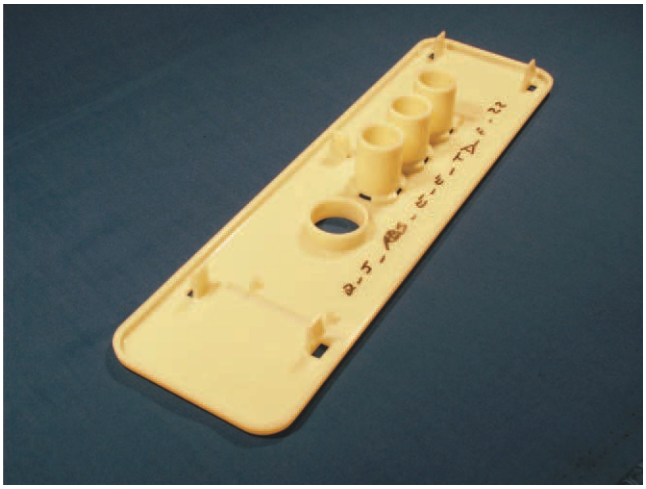

Figure 2 Plastic cover, ABS. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The measurements of the parts were taken manually. The part mass was weighed using a special accuracy weighing machine with a minimum resolution of 0.001 g. For the investigations on the part dimensions a representative length on the part had to be found. As the measurement of the length was performed by hand using a slide gauge (minimum resolution 0.01 mm), the distance between the recesses at the positions of two snap in joints (1 and 2 in Fig. 3) were chosen. These recesses offered

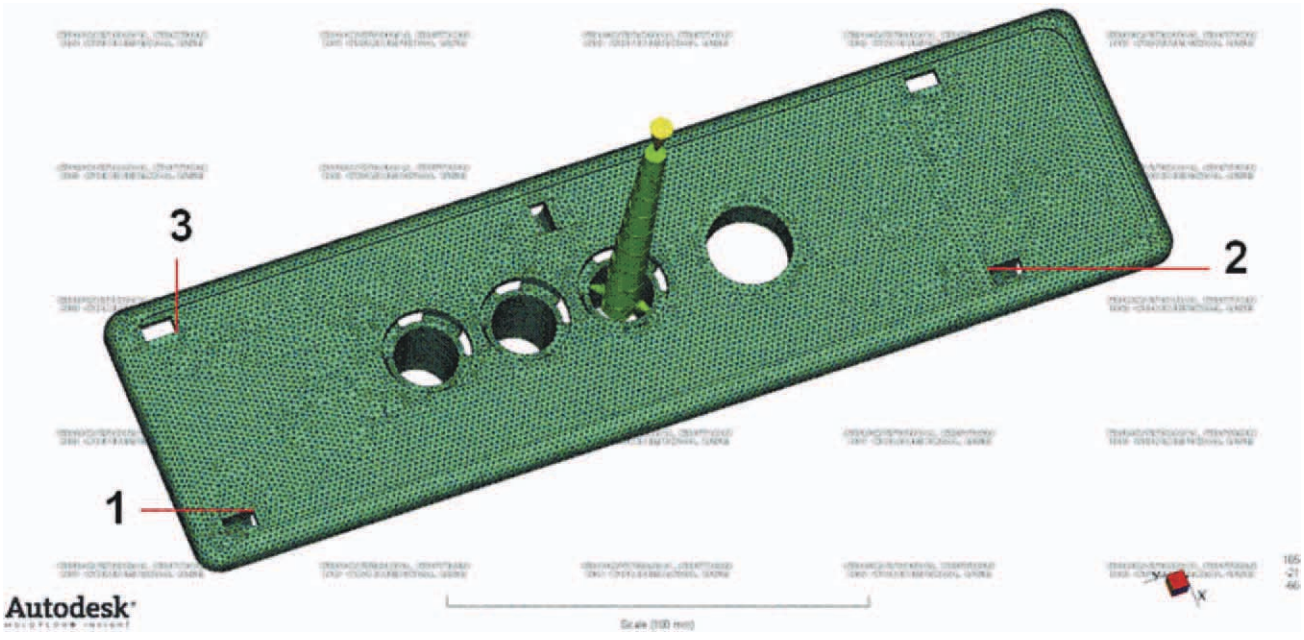

Figure 3 Measuring positions for the part length (1 and 2). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

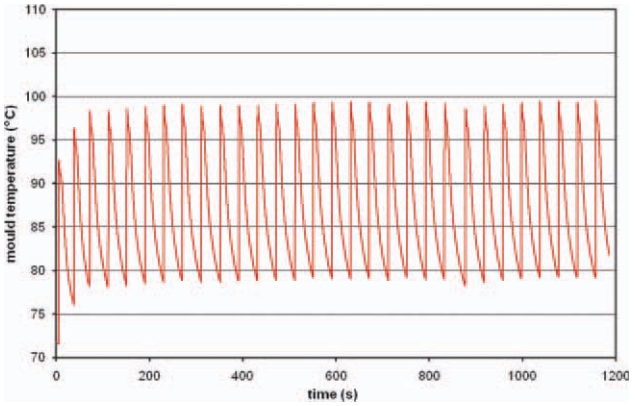

Figure 4 Build-up of mould temperature over 30 cycles. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

a good repeatability for the positioning of the slide gauge.

The physical model concentrates on changes in the part dimensions due to shrinkage, whereas warpage is not taken into account. Thus, warpage had to be eliminated from the part before measurement. This was implemented in using a simple auxiliary support with plane seating and a weight.

To reassure similar conditions for the production of each test series a consistent experimental routine was applied. Before production restarts, a 1-h waiting time was adhered to allow a homogenous heating of machine and mold. Furthermore, a condition of thermodynamic equilibrium was indispensable for the reproducibility of the experiments. Thus, a quantity of 60 parts was produced for each set of parameters and only the last 15 were used for measurement. Figure 4 shows an example of the build-up of the mold temperature over a range of the first 30 cycles.

Measurement of the parts directly after production turned out to be impractical. The residual heat of the parts and a noticeable static charge did not allow repeatable weighing. Therefore, a resting time of 16 h was adhered to. This lead to a conditioning of the temperature of the parts to room temperature and a decrease of the static charge. Furthermore, the influence of postshrinkage on the dimensional measurements was also reduced.

TABLE II
Complete Set of Constants for the Physical Model for the Part Length

A	1,8901E-04	Bar^{-1}
B	3,3845E-17	$Bar^{-1/3}$
C	1,1107E-04	$°C^{-1}$
D	5,5114E-19	$°C^{-1/3}$
E	5,9170E-03	s^{-1}
F	2,0079E-16	$s^{-1/3}$
G	−4,4141E-04	$°C^{-1}$
H	−1,1774E-16	$°C^{-1/3}$
N	−3,3969E-01	(/)

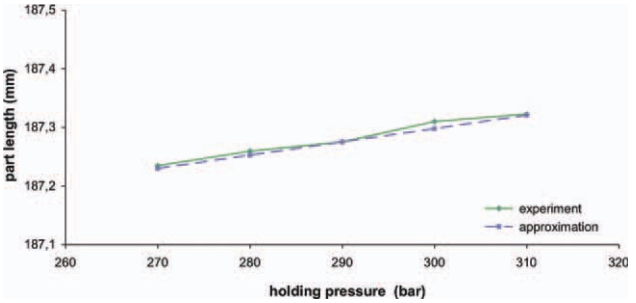

Figure 5 Part length versus holding pressure. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RESULTS AND DISCUSSION

After measurement and analysis of the produced test parts, the constants of the physical model were computed from the obtained functional runs. Table II shows a summary of the resulting constants for the model for the part length. Here also, the negligible constants B, D, F, and H are stated.

Subsequently, these constants were used to recalculate the experimental results to assess the accuracy of the underlying model. Due to the linear character of the applied physical coherences, the approximation yielded linear curves. In the following Figures 5–8, the dependencies of the part length on the four investigated parameters holding

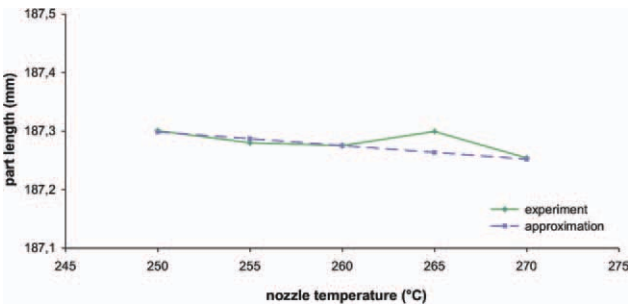

Figure 6 Part length versus nozzle temperature. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

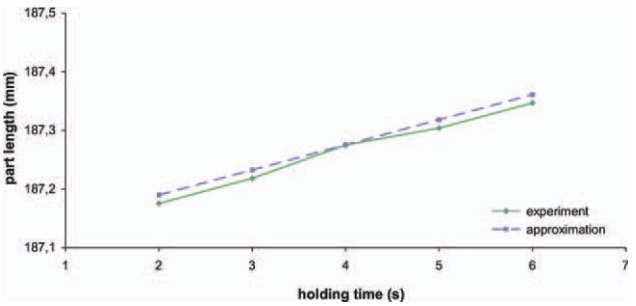

Figure 7 Part length versus holding time. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

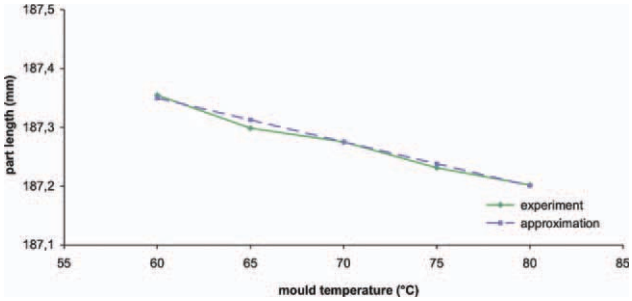

Figure 8 Part length versus mould temperature. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

pressure, nozzle temperature, holding time, and mold temperature are displayed. The comparison between real and calculated values only showed little deviations with an average value of 0.01 mm. The maximum difference of 0.04 mm was observed for the part length at 265°C nozzle temperature (Fig. 6).

As one can see, the assumption of linear relations in a narrow range around the central point of the experiments can be accepted in very close approximation. However, care must be taken if the observed window of set parameters, respectively, the occurring deviances are wider, especially, for relations such as between part properties and holding time (Fig. 7), which generally show nonlinear coherences.

CONCLUSIONS

This work shows that the investigated physical model of a quality control concept for injection molding and its underlying formulae are able to describe the behavior of part length as a function of holding pressure, nozzle temperature, holding time, and mold temperature in very good accordance with reality. However, the presented results are specific to the used machine and mold and to the material and the production environment. So, further experimental work should be performed to secure the model on a broad base. For practical implementation, the injection molding machine has to be provided with appropriate measuring and control elements. The quality parameters of the part must be assessed directly after demolding. So, it has to be ensured that particularly the weighing equipment is not affected by vibrations, temperature, and static charge caused by the production environment. Furthermore, not each of the investigated set parameters might be appropriate to be applied in an actual control loop. The control system behavior might set limits to the rapidity and accuracy of adjusting the set data, especially the temperature parameters. A practicable strategy appears to be keeping holding time and mold temperature constant and controlling the process with the pressure during filling and packing.[21]

The presented work shows considerable potential for the application of the physical model. Yet, it involves much experimental effort to gain the required constants. In the course of the performed investigations additional research effort has been done to clarify the possibility of determining the constants by simulation.[23] The related results indicate that the extent of experiments can be reduced to a high degree without compromising the accuracy of the model. A further advantage offered by the use of a simulation programme is the possibility of performing the investigations ex ante in an early stage of the product development, when potential modifications in part or mold design are still possible.[24]

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