Novel Coupled Simulation Method and Comprehensive Metrology to Enhance the Application of Prototype Injection Moulds

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Novel coupled simulation method and comprehensive metrology to enhance the application of prototype injection moulds

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Abstract Injection moulding is the most diverse and dynamically developing polymer processing technology. Conventional injection moulding is economically viable only in large-volume part production. However, there is an ever-growing demand for more customised, low-volume plastic products, which is called mass customization. This need can be served by the hybridisation of injection moulding with additively manufactured, low-volume injection moulds (produced for example from thermoset resins by PolyJet technology). In our work, we elaborated a novel state-monitoring and modelling method to analyse the mechanical and thermal characteristics (strains and temperature distribution) of these polymeric injection mould inserts during operation. The results of the modelling method were successfully validated by the actual injection moulding experiments, proving the adequacy of the modelling method.

Introduction

The application of low-volume prototype injection moulds is a novel and rapidly evolving field of polymer processing. Additive manufacturing allows the direct production of prototype moulds and mould inserts in a single technological step. Polymeric moulds and mould inserts offer an excellent opportunity to verify the mouldability of a product geometry in real-life operating conditions, before the expensive large-volume mould is made. They also make feasible the flexible production of small and customized product batches with the variation of different, additively manufactured mould inserts [1].

A major disadvantage of low-volume, polymeric injection moulds is the limited strength and stiffness of the insert material. Polymeric moulds can show even two orders of magnitude lower stiffness and one order of magnitude lower strength compared to conventional tool steels. Thermal conductivity is typically two orders of magnitude lower compared to metallic tool materials while the specific heat is higher. This results in the slow cooling of these polymeric inserts and heat also spreads moderate in them. The mechanical and thermal properties of the polymeric mould materials are also heavily temperature dependent. Another important characteristic of these materials is their tendency to creep, especially at elevated temperature. Due to the limited heat extracting capacity of the polymeric moulds, the cooling speed of the product changes, which influences the frozen layer thickness and the resulting free space for the polymer melt.

Case studies are already available on the application of additively manufactured polymeric moulds made from thermoset resins. Whlean et al. [2] machined a mould housing from aluminium and they inserted mould inserts in it, printed by stereolitography (SLA) from a high-temperature (HT) resin. They moulded 20 clips when the polymeric mould insert failed. Wick-Joliat et al. [3] applied digital light processing (DLP) to print mould inserts for ceramic injection moulding (CIM). They concluded that the surface quality of the moulded parts was excellent due to the high-resolution printing and the mould inserts were suitable for CIM. Giorleo et al. [4] also manufactured mould inserts from a special HT resin by Material Jetting (MJ) technology. They proved that building orientation has a profound effect on the surface quality and the failure mechanism of the mould inserts. They also proved that the mould inserts manufactured by MJ are also suitable for micro injection moulding due to the low build layer thickness and the resulting dimensional accuracy of the products. Bogaerts et al. [5] also applied MJ to print prototype injection mould inserts from Digital ABS. They concluded that the high-temperature zones that occur during operation fundamentally determine the lifetime of the polymeric moulds. To prevent early failure, they recommended the thermal imaging camera measurement of the mould inserts to track high-temperature zones. Bagalkot et al. [6] showed the failure mechanism of the polymeric moulds by three case studies. They also printed the mould inserts by MJ from Digital ABS. The first stage of the failure is the appearance of micro cracks and burn marks on the mould insert surface. The second stage of failure is the spread of the cracks, which results in delamination and final failure of the part. Cracks typically occur in sharp corners or holes for the ejector pins. Davoudinejad et al. [7] proved experimentally that thermal aging deteriorates the lifetime of thermoset photopolymer injection moulds.

The combination of modern metrology and additively manufactured prototype moulds can deliver outstanding results. Gülcür et al. [8] applied computer tomography (CT) to analyse dimensional deviations of micro injection moulded parts. The parts were made by an MJ printed mould insert, made from Vero PureWhite photopolymer resin. Their measurement system allows the continuous tracking of product dimensional stability. Storti et al. [9] applied thermal imaging camera measurements to set the injection moulding parameters to avoid overheating and early failure of a polymeric mould insert. They also applied finite element thermal simulation to optimize the conformal cooling circuit layout of the mould insert. They successfully validated the transient temperature results of their thermal simulations by the thermal imaging camera measurements. Kovács et al. [10] also applied injection moulding simulation to optimise the conformal cooling channel layout of their polymeric mould insert, manufactured by MJ from FullCure 720 photopolymer resin. They validated their simulation results with thermal imaging camera and thermocouple temperature measurements. Davoudinejad [11] applied transient thermal simulation to model the thermal stresses in a vat photopolymerisation printed mould insert. Their model accurately predicted the critical (high temperature) locations in the mould insert. Mendible et al. [12] created a comparative study of a direct metal laser sintering printed mould made from bronze, a PolyJet printed mould made from DigitalABS and a conventional machined mould made from stainless steel. Both metallic moulds endured 500 cycles, while the PolyJet printed insert failed after 116 cycles.

The international research community has already elaborated methods to analyse the operational characteristics of polymeric prototype moulds. Measurement is typically limited to temperature while simulations are mainly limited to thermal modelling. Cavity pressure or strain measurement in polymeric injection moulds is hard to find in the literature. A comprehensive monitoring system that allows the simultaneous measurement of operational strain, cavity pressure and temperature is a definite novelty. This article presents such a measurement system. This article also outlines a new coupled simulation approach to model both the thermal and the deformational state of polymeric injection mould inserts.

Materials and methods

A two-cavity mould housing was applied, and the upper cavity was fitted with the photopolymer mould insert in the moving side. The injection moulded product was a plate with dimensions of 65 × 55 × 2 mm and the cavity was filled through a 1 mm thick edge gate, along the 55 mm long side. The two cylindrical runner inserts in the moving half of the mould shut off the lower cavity. The moving side cavity insert was fitted with two strain gauges: one at the near the gate and one at the far from the gate slot (KMT-LIAS-06-3-350-5EL, Kaliber Kft, Hungary). Strain signal was collected by a Spider8 unit (Hottinger Baldwin Messtechnik GmbH., Germany). The volumetric temperature was also measured by a thermocouple at the back of the mould insert by a thermocouple (M222 PT 100, Heraeus GmbH., Germany). and its data was collected by a Ahlborn Almemo 8990-6 unit (Ahlborn Mess und Regelungstechnik GmbH., Germany). The surface temperature of the mould insert was measured by a FLIR – A325sc thermal imaging camera in the open state of the mould. The test mould is presented in Figure *1* with its characteristic dimensions.

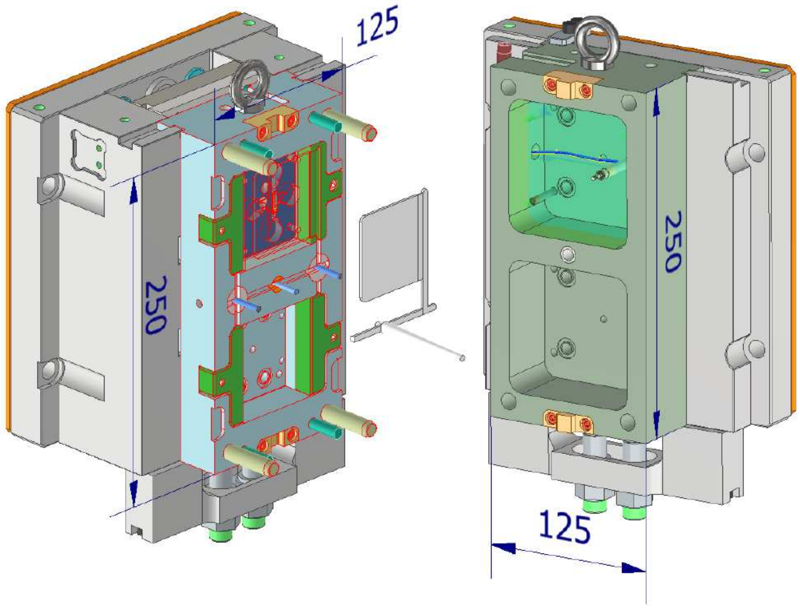

Figure 1. The test mould.

The moving side mould insert was printed from RGD835 (VeroWhite) photopolymer resin by an Objet Alaris 30 printer. The important mechanical and thermal properties of the photopolymer is listed in Table *1*.

Table 1. Mechanical and thermal properties of RGD835 (VeroWhite).

Property (Unit)	Value
Tensile strength (MPa)	50-65
Elongation at break (%)	10-25
Modulus of elasticity (GPa)	2-3
Thermal conductivity (W/(m·K))	0.2
Coefficient of thermal expansion (1/K)	$75\cdot10^{-6}$
Glass transition temperature (°C)	52-54

The injection moulded material was a polypropylene-homopolymer (Tipplen H145F, Mol Group Plc.) and its relevant mechanical and processing properties are listed in Table *2*. This PP grade has outstanding melt flow rate and low recommended processing temperature that make it ideal for injection moulding into polymeric moulds.

Table 2. Mechanical and processing properties of Tipplen H145F polypropylene.

Property (Unit)	Value
Melt flow rate (MFR) at 230 °C and 2.16 kg (g/10 min)	29
Flexural modulus (GPa)	1.8
Modulus of elasticity (GPa)	1.99
Recommended processing temperature (°C)	190-235

The injection moulding machine was an Arburg Allrounder Advance 270S 400-170 (Arburg GmbH., Germany) with a screw diameter of 30 mm. The injection moulding parameters are listed in Table *3*. The moulding parameters were set to avoid excessive pressure load on the insert. To achieve this, the injection speed and the pressure limit was set as low as possible. The melt temperature was also decreased to the lowest value of the recommended processing temperature range and the clamping force was also minimized. Relatively long residual cooling time was applied because the heat transfer from the melt to the mould insert is relatively slow because of two reasons. First, the low injection pressure and holding pressure results in poor heat transfer from the melt to the mould. Second, the thermal conductivity of the mould insert material is two orders of magnitude smaller, compared to a conventional tool steel grade, which results in the localized heating of the cavity surface area. During the injection moulding series, 10 cycles were injection moulded at 75 bar constant holding pressure to characterize the reproducibility of the moulding process. After that, the holding pressure was increased from 50 bar to 300 bar in 25 bar steps, in every second cycle. This segment of the moulding series was to characterize the reproducibility of the moulding cycles.

Table 3. The injection moulding parameters.

Parameter (Unit)	Value
Clamping force (t)	5
Dose volume (cm^3)	40
Switchover point (cm^3)	25.5
Injection speed (cm^3/s)	15
Injection pressure limit (bar)	500
Holding pressure (bar)	50 to 300
Holding time (s)	15
Residual cooling time (s)	30
Idle time (s)	250
Melt temperature (°C)	190

Results and discussions

Injection moulding tests

The injection moulding series started with 75 bar constant holding pressure, where 10 cycles were moulded. The measured operational strains at this pressure are presented in Figure 2. A sharp increase can be seen in the operational strain in the filling phase, where the elastic deformation of the photopolymer mould material is dominant. The filling phase lasts for approximately 1 second. After that, switchover happens into the holding phase, where the injection pressure drops to the pre-set holding pressure. Pressure drop from the maximal injection pressure at switchover (~320 bar) to the 75 bar holding pressure also causes a gradual decrease in the operational strain. The increase in the operational strain from 8 seconds can be attributed to the gradual heating of the mould insert. Heating causes three simultaneous phenomena, which are the following. First, the stiffness of the mould drops. Second, the creep of the material becomes more dominant at elevated temperature and third, the thermal expansion of the mould insert occurs. The result of these three effects is the increase in strain the late holding phase and during the entire residual cooling time. After the residual cooling time is over, the clamping force is removed, the mould opens and the part is ejected that results in a small, stepwise increase in the operational strain. During the idle time (from 45 seconds to 300 seconds) the mould insert cools down that results in the decrease of the thermal strain and the viscoelastic deformation of the mould also diminishes. The strain curves show minimal scatter that proves the stability and the reproducibility of the moulding process.

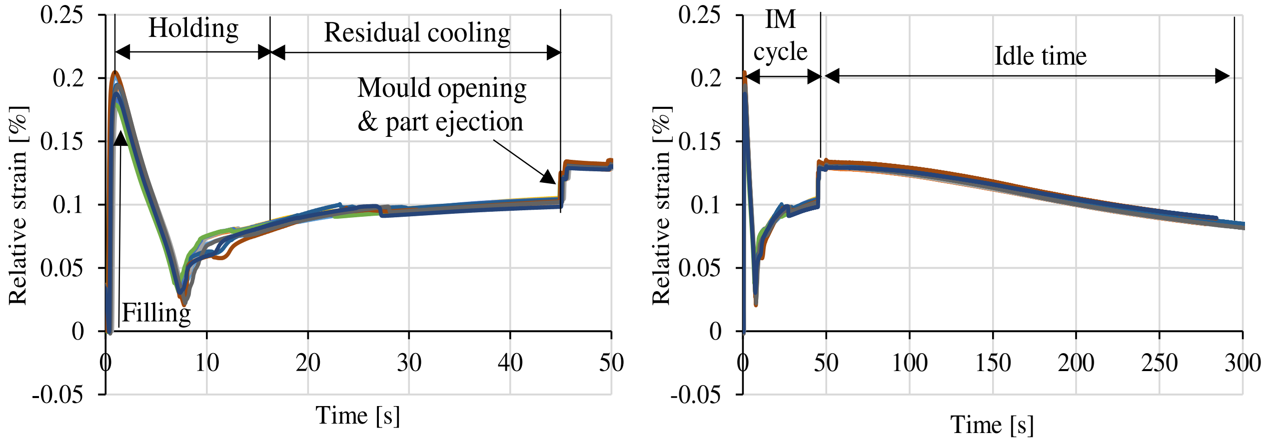

Figure 2. The relative strain results at 75 bar holding pressure.

Following the repeatability test at 75 bar, the holding pressure was increased from 50 bar to 300 bar in 25 bar steps, in every second cycle. The strain results of this section are presented in Figure 3. Increasing the holding pressure resulted in elevating operational strain especially in the holding and later in the residual cooling phase. It is because the elevating holding pressure resulted in the gradual overfilling of the cavity. Higher holding pressure also causes a rise in the operational temperature of the mould insert because of the increased amount of injected melt and the more intense heat transfer between the melt and the cavity wall. The combination of the increasing pressure load in the holding phase and the more intense heating of the mould insert results in elevating deformations coming from creep. This can be clearly observed at the 250 - 300 bar holding pressure range, where the operational strains increase in the late holding and residual cooling phases and even exceed the maximal strain measured at the switchover from filling to holding. These segments are highlighted in Figure *3*. The stepwise decrease at mould opening and part ejection also becomes higher at elevating holding pressure due to the overfilling of the cavity.

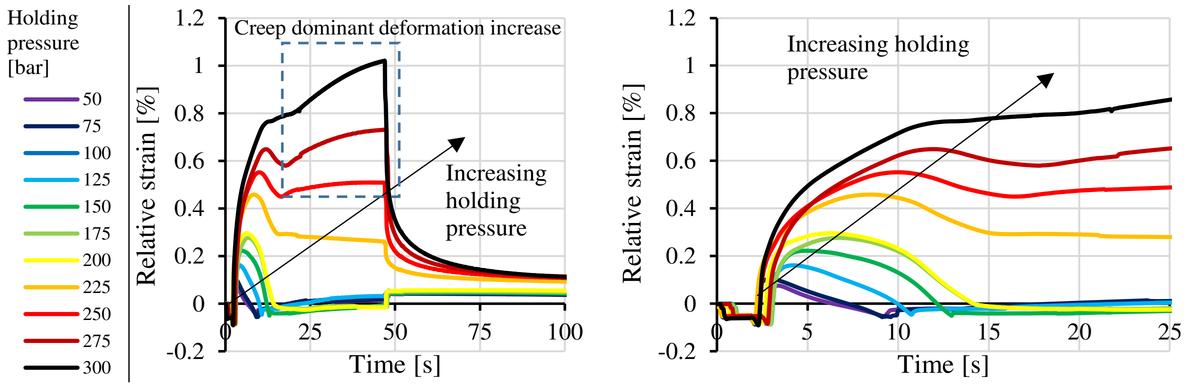

Figure 3. The relative strain results at increasing holding pressure.

Cavity pressure curves, measured at the increasing holding pressure section can be seen in Figure 4. Similar tendencies can be observed that were found for the strain results. Gradual overfilling caused the cavity pressure maximum to increase and significant residual pressure also remained in the late holding phase and in the residual cooling phase. Cavity pressure stabilised at nearly constant holding pressure that is the clear indication of the gradual overfilling of the cavity. The cavity pressure curve corresponding to 300 bar holding pressure is detached from the other curves because the 5 t clamping force was insufficient to keep the mould closed during the moulding cycle.

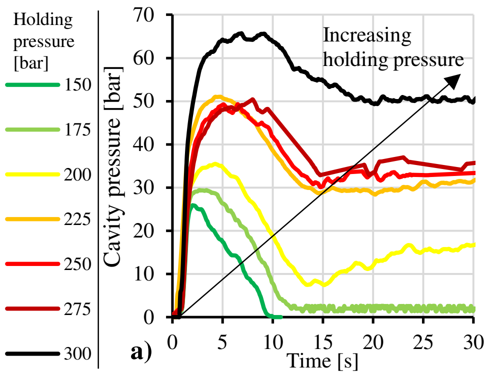

Figure 4. The cavity pressure results at increasing holding pressure.

The volumetric temperature of the mould insert is presented in Figure *5*. Gradual heating of the mould insert can be observed cycle-to-cycle and maximal volumetric temperature is reached at the maximal, 300 bar holding pressure. This is because of two reasons. First, the intensity of the heat transfer between the melt and the cavity wall is primarily dependent on the pressure between the two contacting parts and second, the product mass and the resulting amount of injected melt is also increased by the elevating holding pressure.

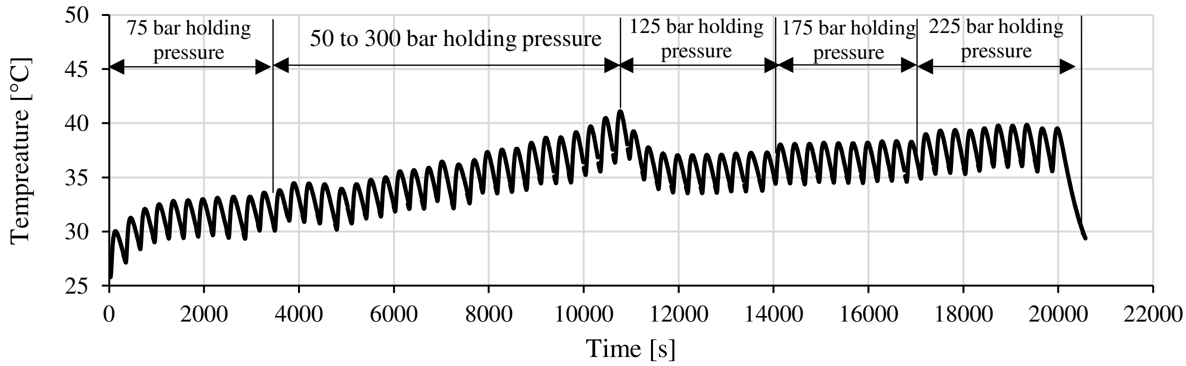

Figure 5. The volumetric temperature of the mould insert measured by the thermocouple.

Mould insert material testing

Dynamic mechanical analysis (DMA) measurements were performed to characterize the temperature dependent stiffness of the mould insert material. DMA measurements were carried out on a TA Instruments Q800 machine. The storage modulus and the loss factor were measured in the temperature sweep mode of the DMA apparatus, with a load frequency of 1 Hz and a load amplitude of 15 µm. The test arrangement was dual cantilever. The analysed temperature range was from 27 °C to 105 °C that completely covers the entire possible application range of a polymeric mould insert. The measured storage modulus and the loss factor data are shown in Figure 6. The storage modulus drops from the ~ 2200 MPa value at room temperature to ~1000 MPa at 53 °C and to 100 MPa at 65 °C. This significant decrease in the stiffness also proves that the recommended operational temperature range of the mould insert has to be kept below its glass transition temperature with a proper safety margin. Operating the mould insert above its T_g temperature results in severe deformation and early failure that has to be avoided.

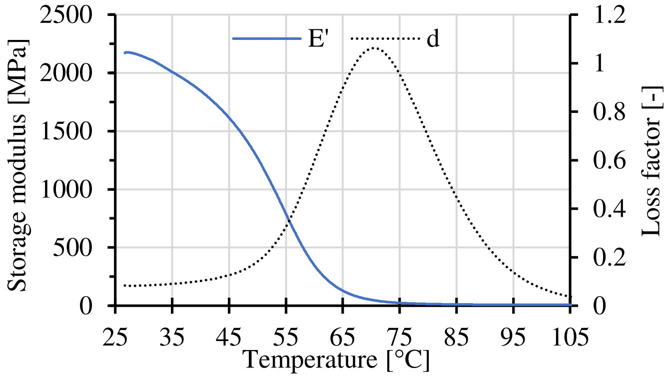

Figure 6. The storage modulus and loss factor of the VeroWhite material.

Coupled simulation method to model the thermal and mechanical behaviour

The coupled modelling workflow is presented graphically in Figure 7. First, an injection moulding simulation was built in Autodesk Moldflow to model the moulding cycle and calculate the operational pressure load acting on the mould insert. The injection moulding simulation model contains the finite element mesh of the mould that is fixed throughout the entire modelling process. The analysis sequence was Fill + Pack + Warp and the moulding parameters were set according to the actual measurements. The time stepping of the transient modelling is set in the injection moulding simulation and this time stepping is applied later in the thermal and mechanical simulations as well. The injection moulding simulation model also has to be prepared to be exported to ANSYS using the built-in “mpi2ans” macro. This requires two separate studies: one that only contains the mesh of the moulded part and one that contains the mesh of the analysed mould block and the part. After running the injection moulding simulation, the mesh of the mould block and the product and the transient pressure data can be exported from Moldflow using the earlier mentioned macro. The transient pressure data is represented as a set of text files that contain the nodal forces acting on the cavity surface nodes in each analysed time step.

Following the successful export of the mould mesh and the transient pressure results, the mesh can be imported to ANSYS Workbench, where a transient thermal simulation has to be set up. This model contains the mould block and the product. Transient thermal modelling requires the specific heat capacity, thermal conductivity and density data of each material included in the analysis. In the present model, it was assumed that the product cools down freely from the melt temperature in the holding and residual cooling phases and the cooling product transfers heat to the surrounding mould components that causes the mould block to heat. The transient temperature field (which is a list of element temperature data in each time step) can be exported from the transient thermal simulation. The results of the transient thermal simulation can be validated by volumetric temperature measurement inside the mould (for example by building in thermocouples or thermowires) or by surface temperature measurement, using a thermal imaging camera.

The final phase of the coupled simulation is mechanical modelling. This model requires the mould mesh, the transient pressure and temperature data from the injection moulding simulation and the transient thermal simulation. In the case of polymeric mould insert material, further required inputs are the time and temperature dependent mechanical properties (modulus of elasticity, Poisson-ratio and creep compliance) that can be determined by material testing, for example by DMA measurements. This model can calculate the operational deformation of the analysed mould components and the results can be validated by operational strain measurements.

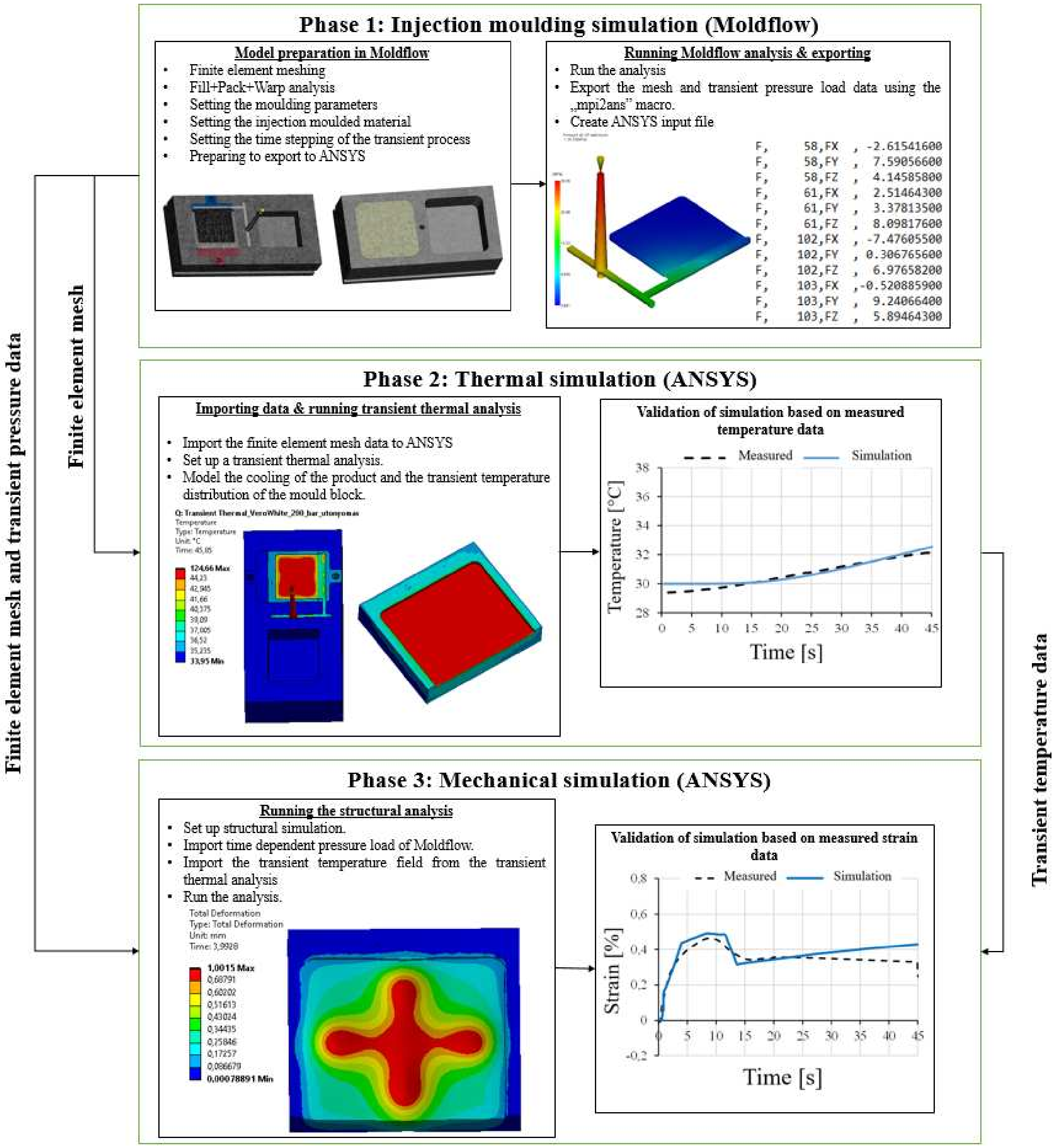

Figure 7. Workflow of the coupled simulation method.

Comparison of the measured and the simulated volumetric temperature is presented in Figure 8 for two different holding pressure values (200 bar and 300 bar). There is an adequate match between the measured and the simulated temperature-time curves, which proves the accuracy of the modelling method. Due to the low thermal conductivity of the mould insert material, the heated zone is localised mainly around the cavity surface. The back of the mould insert, where the thermocouple is located only heats by approximately 2 °C during the 45 seconds of the moulding cycle. On the other hand, the cavity surface can heat even by 30 °C. As it was shown in Figure 5, the volume of the mould heats further in the idle time, due to the low thermal conductivity and high specific heat. The temperature change at the back of the mould during one complete cycle (idle time included) is approximately 5 °C.

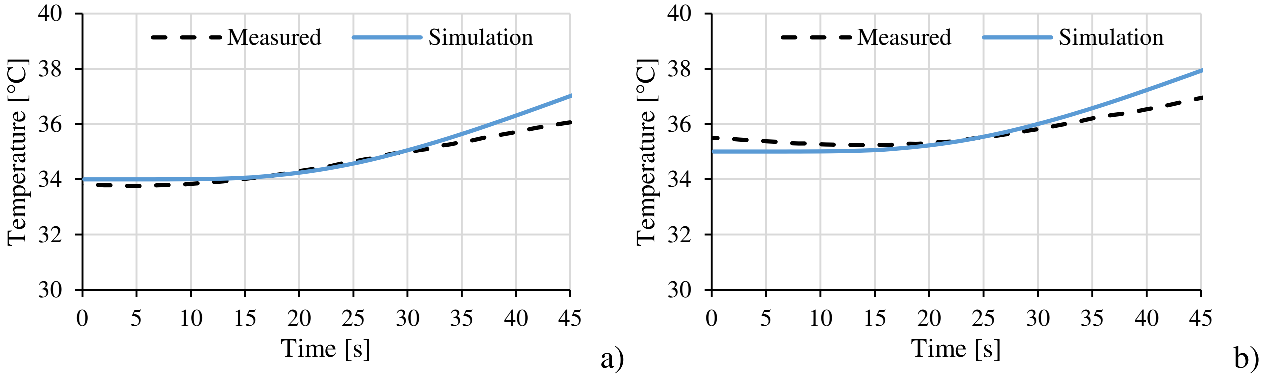

Figure 8. Comparison of the measured and the simulated mould insert volumetric temperature a) 200 bar holding pressure, b) 300 bar holding pressure.

Comparisons of the measured operational strains with the simulation results are presented for two analysed holding pressures (200 bar and 300 bar) in Figure 9. There is a good match between the measured and the simulated values, which proves the adequacy of the modelling method even at different values of the analysed load range.

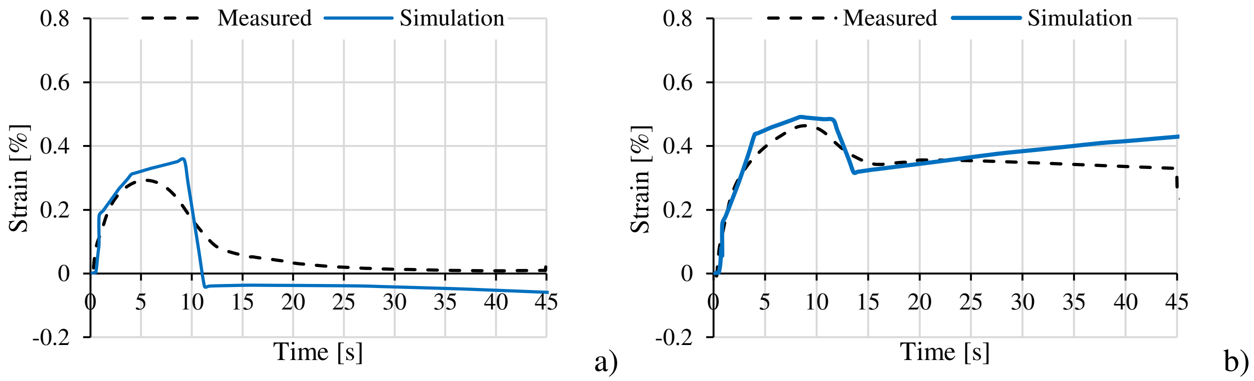

Figure 9. Comparison of the measured and the simulated mould insert strain a) 200 bar holding pressure, b) 300 bar holding pressure.

Summary

In this article, a new measurement system was presented to simultaneously monitor the thermal and mechanical state of additively manufactured mould inserts. The state monitoring system consists of strain gauges, a cavity pressure sensor, a thermocouple and a thermal imaging camera. This way, the mechanical and thermal characteristics of the mould can be measured comprehensively. The operational deformations, cavity pressure and temperature curves were presented in detail. The relations between deformation, pressure load and thermal state were highlighted. After that, a novel coupled simulation approach was outlined that consists of the one-way coupling of injection moulding simulation with finite element thermal and mechanical simulations. The coupled simulation method was presented in-depth and the simulation results were compared with the measured results. Sufficient accuracy of the modelling method was proved as the measured results and the simulation results showed good agreement. The outlined modelling method can be applied to model the thermal and mechanical state of polymeric mould inserts or part inserts. This way, the injection moulding process can be modelled and designed more accurately that helps the more widespread use of low-volume polymeric injection mould or part inserts.

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References

[1] K. Kumar, D. Zindani, J. P. Davim: Rapid prototyping, rapid tooling and reverse engineering, De Gruyter, Berlin (2020)

[2] C. Whlean, C. Sheahan: Using additive manufacturing to produce injection moulds suitable for short series production. Procedia Manufacturing, 38, pp. 60–68. (2019)

[3] R. Wick-Joliat, M. Tschamper, R. Kontic, D. Penner: Water-soluble sacrificial 3D printed molds for fast prototyping in ceramic injection molding. Additive Manufacturing, 48, 102408. (2021)

[4] L. Giorleo, B. Stampone, G. Trotta: Micro injection moulding process with high temperature resistance resin insert produced with material jetting technology: Effect of part orientation. Additive Manufacturing, 56, 102947. (2022)

[5] L. Bogaerts, M. Faes, J. Bergen, J. Cloots, E. Vasiliauskaite, F. Vogeler, D. Moens: Influence of thermo-mechanical loads on the lifetime of plastic inserts for injection moulds produced via additive manufacturing. Procedia CIRP, 96, pp.109-114. (2021)

[6] A. Bagalkot, D. Pons, D. Symons, D. Clucas: Categorization of failures in polymer rapid tools used for Injection Molding. Processes, 7(1), 17. (2019)

[7] A. Davoudinejad, M. R. Khosravani, D. B. Pedersen, G. Tosello: Influence of thermal ageing on the fracture and lifetime of additively manufactured mold inserts. Engineering Failure Analysis, 115, 104694. (2020)

[8] M. Gülçür, P. Wilson, M. Donnelly, K. Couling, V. Goodship, J. Charmet, M. A. Williams, G. Gibbons: X-ray computed tomography for predictive quality assessment, 3D visualisation of micro-injection mouldings and soft-tool deformation, Materials & Design, 227, 111741. (2023)

[9] B. A. Storti, V. Sobotka: A numerical framework for three-dimensional optimization of cooling channels in thermoplastic printed molds. Applied Thermal Engineering, 238, 121988. (2024)

[10] J. G. Kovács, F. Szabó, N. K. Kovács, A. Suplicz, B. Zink, T. Tábi, H. Hargitai: Thermal simulations and measurements for rapid tool inserts in injection molding applications. Applied Thermal Engineering, 85, 44-51 (2015)

[11] A. Davoudinejad, M. Bayat, D. B. Pedersen, Y. Zhang, J. H. Hattel, G. Tosello: Experimental investigation and thermo-mechanical modelling for tool life evaluation of photopolymer additively manufactured mould inserts in different injection moulding conditions. The International Journal of Advanced Manufacturing Technology, 102, pp. 403–420. (2019)

[12] G. A. Mendible, J. A. Rulander, S. P. Johnston: Comparative study of rapid and conventional tooling for plastics injection molding. Rapid Prototyping Journal, 23(2), pp. 344 – 352. (2017)