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PHD THESIS BOOKLET

ANALYSIS OF DEFORMATIONS OF
PROTOTYPE INJECTION MOULD INSERTS

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1 INTRODUCTION

The global plastics production exceeded 400 million tons in 2022. Injection moulding is a main contributor in this by processing approximately one third of the entire quantity. Injection moulded products became inseparable parts of modern life. The development of injection moulding is continuous because 3D parts with nearly arbitrary geometry can be manufactured with it in large volumes. An important characteristic of injection moulding machines is that the required clamping force can exceed 1000 tons that is required to prevent mould opening during production. Cavity pressure can exceed several hundred bars during the moulding process. The mould opening force, caused by the cavity pressure is primarily dependent on the number of cavities, the wall thickness of the product and its projected surface, the structure of the product surface and the length of the flow path. It is also dependent on the injection moulded material and the resulting moulding parameters. The combination of mechanical loads coming from the cavity pressure and the clamping force and the thermal load coming from the injected hot melt and the tempering of the mould act simultaneously on the injection moulds and they cause a significant amount of deformation. Mould deformations can lead to product quality issues like dimensional errors. The dimensional variations of the cavities coming from mould deformation also influence the cavity pressure distribution and the resulting shrinkage and warpage of the products. The cyclically occurring deformations can also be a source of the fatigue failure of the mould components. It is clear that mould deformations are important both from a product quality and a mould design point of view.

Another emerging trend in the moulding industry is the application of low-volume prototype injection moulds, typically manufactured by an additive technology. These 3D printed polymeric moulds provide an excellent opportunity to check the injection mouldability of a product geometry in a real-life production environment before the lengthy and costly large-volume mould making. Prototype mould inserts also allow the flexible customisation of product geometries opening the way for injection moulding in low-volume and customised part production. This is definitely a novelty as injection moulding is traditionally considered as a large-volume technology that is economically feasible only when millions of identical parts have to be manufactured. The biggest flaw of polymeric prototype moulds is that the stiffness, the strength and the thermal conductivity of the applicable mould insert materials falls behind that of conventional mould steels and these material properties are also heavily dependent on the mould temperature. Another significant problem of polymeric moulds is creep which is amplified by the elevated temperatures during moulding. The limited heat extraction capacity of polymeric moulds also have to be considered when designing the moulding process as it causes significant cooling time increase. The decrease of the cooling speed also changes the frozen layer and the remaining space for the melt in the

cavity. However, if the operational behaviour of polymeric moulds can be measured and modelled, it can enhance the application of polymeric low-volume moulds.

Based on the earlier statements, the main objective of my PhD thesis is the analysis of the operational deformations of prototype mould inserts by measurement and then by simulations. To achieve this, I compare the operational behaviour of different prototype mould inserts under the same injection moulding conditions and highlight the main differences in their deformations and thermal states. I present the how the modern and comprehensive metrology can help to fine tune the moulding parameters to increase the lifetime of prototype moulds. I also show how cavity pressure measurement and strain measurement can be used to monitor product quality. Following the experimental work, I elaborate a coupled simulation method that allows a more accurate modelling of the mould inserts' deformations and thermal state compared to the commercially available injection moulding simulation softwares. It is my emphasised goal to make my modelling method capable to model the time and temperature dependent of polymeric moulds because the commercially available injection moulding softwares currently are not able to do that. I also validate my results with the measured temperature and strain curves to prove the adequacy of my models.

2 CRITICAL ASSESSMENT OF THE LITERATURE, AIMS OF THE PHD THESIS

In my literature review, I presented the different Rapid Tooling techniques and compared the operational characteristics of the injection mould inserts made by these techniques with those of conventional steel inserts. Among the direct RT techniques, I focused on the inserts made by additive technologies (LPBF – laser powder bed fusion for metallic materials, FDM – fused deposition modeling, SLA – stereolithography, SLS – selective laser sintering and PolyJet for polymeric materials).

Based on the literature review, the lifetime of polymeric mould inserts is typically in a few tens of cycles range due to the significantly lower strength and stiffness, compared to steel inserts. Polymeric mould inserts are also sensitive to elevated temperatures occurring during operation. On the other hand, the design freedom of additive technologies also has to be emphasised compared to conventional machining. If the limited lifetime of polymeric moulds can be enhanced, their application can be more widespread in the future. In order to achieve this, a comprehensive state monitoring method is necessary, which allows the proper setting of the moulding parameters and thus increase the life expectancy of moulds. To elaborate such a monitoring system, I made a thorough review of the already existing metrology in injection moulds. A comprehensive measurement system, that allows the simultaneous measurement of strain, cavity pressure and temperature is non-existent in the literature.

I reviewed the already existing analysis methods of injection mould deformations and found that only few research case studies are available. Commercial injection moulding simulation softwares can simulate the operational displacements of mould inserts, but there are a number of simplifications that negatively affect the accuracy of the results. I highlighted three of these simplifications that are relevant for my PhD thesis. The first is that the finite element modelling algorithm only calculates nodal displacements until the melt is frozen at a given point. After that, the nodal displacements of the analysed mould inserts are considered to be constant, neglecting the shrinkage and the warpage of the injection moulded part as it cools. Also, there is significant heat transfer in the cooling stage between the moulded part and the mould inserts that results in the thermal expansion of the mould insert. This effect is neglected in the existing algorithms. The second fundamental limitation of the already existing modelling method is that it only analyses parts directly in contact with the injected melt. However, in reality only a part of the operational mould deformation is caused by the melt pressure. In the case of high melt pressures and mould housings with low stiffness, so-called "breathing" occurs which is the bending of the mould housing plates. This phenomenon has to be avoided because it causes early failure of the mould components and it makes the distribution of the clamping force uneven. The finite rigidity of the mould components, surrounding the cavity inserts cannot be considered

in the currently existing injection moulding simulation software. The third limitation is specific for polymeric mould inserts as the injection moulding simulation can only consider the mould insert material as homogenous, isotropic and linear elastic with constant material parameters (Young's modulus and Poisson's ratio). This assumption is valid in the case of conventional mould materials (steel, aluminium, brass). However, low-volume polymeric moulds are gaining popularity in the injection moulding industry as well as overmoulding to polymeric inserts. In these cases, the linear elastic material model is an inaccurate assumption as it does not consider the temperature and time dependence of the material properties. The linear elastic material model also neglects the creep tendency of the mould insert materials, which is further amplified at elevated temperatures. These limitations have to be addressed to create a novel and more accurate modelling method for polymeric moulds and mould inserts.

Based on the literature review I set the following objectives in my PhD thesis.

- I set the foundations of the comprehensive state monitoring of low-volume polymeric injection moulds. This state monitoring method allows the measurement of operational temperatures, strains and cavity pressures.
- I perform the injection moulding experiments for the mould inserts manufactured by the most common polymeric additive technologies. I compare these polymeric mould inserts to a reference machined aluminium mould insert to create a database of measurement results.
- I apply my state monitoring method to set the injection moulding parameters to increase the lifetime of the mould inserts and to enhance the dimensional accuracy of the moulded products.
- I analyse the correlations between the cavity pressure integral and the product mass and thickness in the case of the aluminium mould insert. I also analyse the correlation between the strain integral and the product properties in the case of polymeric mould inserts.
- I analyse the applicability of high-energy (gamma) radiation post treatment in the case of photopolymer moulds. I prove that high-energy radiation increases the stiffness and reduces the creep compliance of the photopolymer and it enhances the applicability of this material in the field of prototype moulds.
- I elaborate a coupled simulation approach that is based on linking injection moulding simulation with thermal and mechanical finite element simulations. This coupled simulation approach allows the modelling of the operational behaviour of polymeric mould inserts. I validate the strain and temperature results of the simulations with my measurements and prove the adequacy of the modelling method.

3 MATERIALS USED AND METHODS APPLIED

3.1 Test mould geometry and the analysed mould insert materials

I designed a novel test mould to analyse the operational behaviour of mould inserts manufactured by conventional and additive technologies. The mould and the injection moulded product are presented in Figure 1. The injection moulded product was a 65 x 55 x 2 mm plate with 4 mm radii at the two corners of the plate at the end of the flow length. The radius was required because this way the machined aluminium mould insert could be produced only with milling and drilling. The test mould also allows the variation of the gate geometries by using different gate inserts. In my measurements, I uniformly used an edge gate insert.

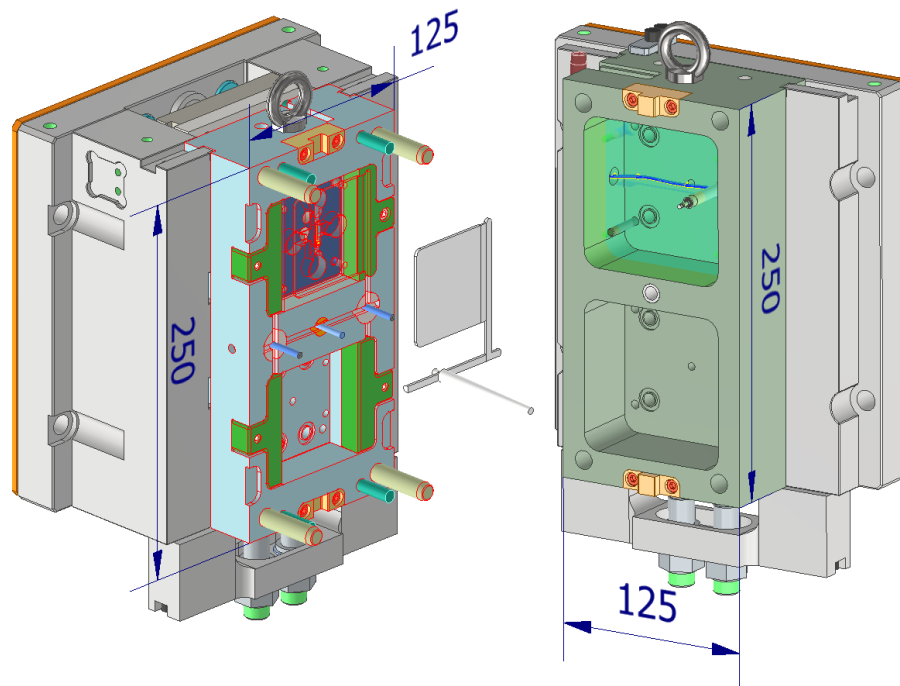


Figure 1. The moving half and the fixed half of the test mould and the injection moulded product.

I placed eccentrically a piezoelectric direct pressure sensor in the fixed mould half. This geometry allows the measurement of cavity pressure both near the gate and far from the gate only by rotating the fixed half mould insert by 180°. The piezoelectric pressure sensor was located by a bushing in the fixed half of the mould. I measured cavity pressure uniformly at the far from the gate location during the moulding tests.

The moving side cavity insert is presented in detail in Figure 2. The four slots at the back of the moving side mould insert allow the placing of four separate strain gauges that can measure strains both in the parallel and in the perpendicular directions of the melt flow. The slot at the centre of moving side cavity insert hosts a thermocouple that measures the temperature at the back of the mould insert. The wires of the strain gauges and the thermocouple are taken out of the test mould through the dedicated holes in the washer under the mould insert and in the mould housing. During the injection moulding tests, I measured strains in the near the gate and the far from the

gate slots by two linear strain gauges. Each strain gauge was linked to the data collector unit in a half bridge arrangement.

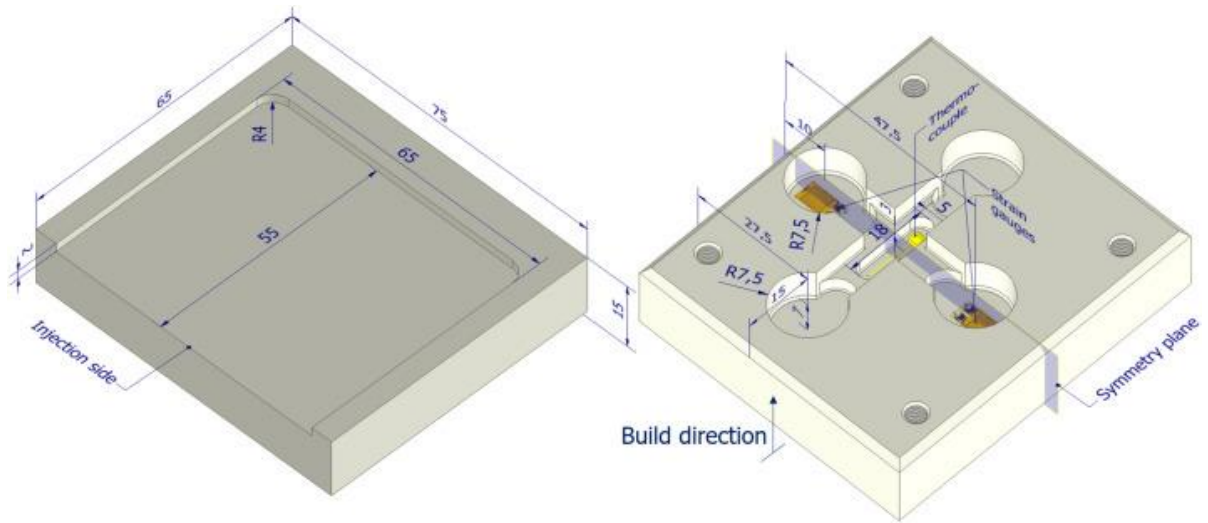


Figure 2. The moving side mould insert with the strain gauges and the thermocouple.

The injection moulded material and the analysed prototype mould insert materials are listed in Table 1. The injection moulded materials was Tipplen H145F polypropylene homopolymer.

Analysed materials		
Injection moulded material	Tipplen H145 F (PP)	MOL Zrt.
Mould insert material 1	RGD835 - VeroWhite (photopolymer)	Stratasys Ltd.
Mould insert material 2	EN AW5754 O/H111 (aluminium)	Amari Kft.
Mould insert material 3	Z-ABS (ABS)	Zortrax S.A.
Mould insert material 4	PA 2200 (PA12)	EOS GmbH.
Applied sensors		
Temperature measurement (thermocouple)	Platinum Resistance Temperature Detector M222	Heraeus GmbH.
Temperature measurement (thermal imaging camera)	FLIR - A325sc	FLIR Inc.
Piezoelectric pressure sensor	RJG Piezo 6159	RJG Inc.
Strain gauge	KMT-LIAS-06-3-350-5EL	Kaliber Méréstechnika Kft.

Table 1. The analysed materials and the applied sensors.

During the injection moulding tests I analysed four different prototype mould insert materials. These materials were the following.

- Aluminium is the traditional material of prototype injection mould making. It has adequate strength and stiffness and it is easily machinable. However, it has a major drawback which is the typically one order of magnitude higher thermal conductivity, compared to conventional tool steel. This is not desirable for injection mould making because the moulding parameters set for the aluminium prototype

mould have to be reconsidered fundamentally when the large volume steel mould is made. The variations in the thermal conductivity also cause fundamental differences in the moulding process. These differences can be found in the freezing of the outer layers of the product, the freezing of the gate and the speed of the heat extraction in the cooling phase.

- The VeroWhite mould insert was printed by an Objet Alaris 30 printer (Stratasys Inc) which operates by the Material Jetting additive technology. The VeroWhite photopolymer shows excellent strength and stiffness among the unfilled polymers. Its main limitation is the relatively low glass transition temperature that limits its applicability in prototype injection mould making.
- The moving side cavity insert was also printed from Zortrax Z-ABS. The main reason for the material selection was the high glass transition temperature (108°C). Another reason for the selection was the incompatibility of ABS with the injection moulded PP material. The third reason was that fused filament fabrication (FFF) is the most popular and most widely available additive technology nowadays. There is a whole range of different commercially available filaments and printers.
- Selective laser sintering (SLS) is a promising technology in prototype injection mould making because it allows the printing of materials with high strength and stiffness. SLS is typically applied when printing high-performance parts. According to this, I used the PA2200 (polyamide 12 powder) manufactured by EOS GmbH. This material is suitable for parts that have to withstand high mechanical and thermal loads.

3.2 The applied moulding parameters and the measurement method

The applied moulding parameters during the measurements are listed in Table 2. The varying parameter was the holding pressure. The melt temperature was set according to the technical data sheet of the material. It was chosen to be the lowest value of the recommended processing temperature range to reduce the heat load acting on the mould insert. The injection speed, the injection pressure limit and the clamping force were minimised and the idle time between the cycles was introduced to reduce the mechanical and thermal loads acting on the mould inserts. This way the lifetime of the mould inserts can be improved.

Varying parameters		
Holding pressure (constant operating parameters)	[bar]	75 bar (10 cycles)
Holding pressure (analysis of the effect of increasing holding pressure)	[bar]	From 50 bar increased in 25 bar steps, maximally 300 bar
Constant parameters during the moulding experiments		
Product volume (with edge gate and cold runner) (based on 3D model)	[cm ³]	12.6
Injection speed	[cm ³ /s]	15
Mould temperature	[°C]	Ambient – no tempering applied
Clamping force	[t]	5
Switchover volume	[cm ³]	26
Injection pressure limit	[bar]	500
Holding time	[s]	15
Dose volume	[cm ³]	40
Decompression volume	[cm ³]	4
Residual cooling time	[s]	30
Idle time	[s]	~250
Melt temperature	[°C]	190

Table 2. The applied moulding parameters during the injection moulding experiments.

The measured quantities were the following: the strains of the mould inserts as functions of time (in the near the gate and far from the gate slots), the cavity pressure as function of time, the volumetric temperature of the mould insert as function of time, measured by the thermocouple and the surface temperature of the mould insert as function of time, measured by the thermal imaging camera in the open state of the mould, in the idle time between the cycles. I also measured the thickness and the mass of the injection moulded plates. The strain gauges and the thermocouple were glued into their slots by a cyanoacrylate adhesive: 3M Scotch-Weld Plastic & Rubber Instant Adhesive PR100. During the main moulding tests, I only changed the material of the moving side mould insert. The other mould inserts were made from EN AW 5754 O/H111 aluminium.

Both the fixed and the moving sides of the test mould are assembled in Figure 3. I performed the injection moulding experiments with the presented test mould. I also scanned the mould inserts and the injection moulded products using a GOM ATOS Core 5M 3D scanner. I measured the thickness of the injection moulded plates using a Mitutoyo Digimatic micrometer and measured their masses using a Radwag PS 600.R2 laboratory scale.

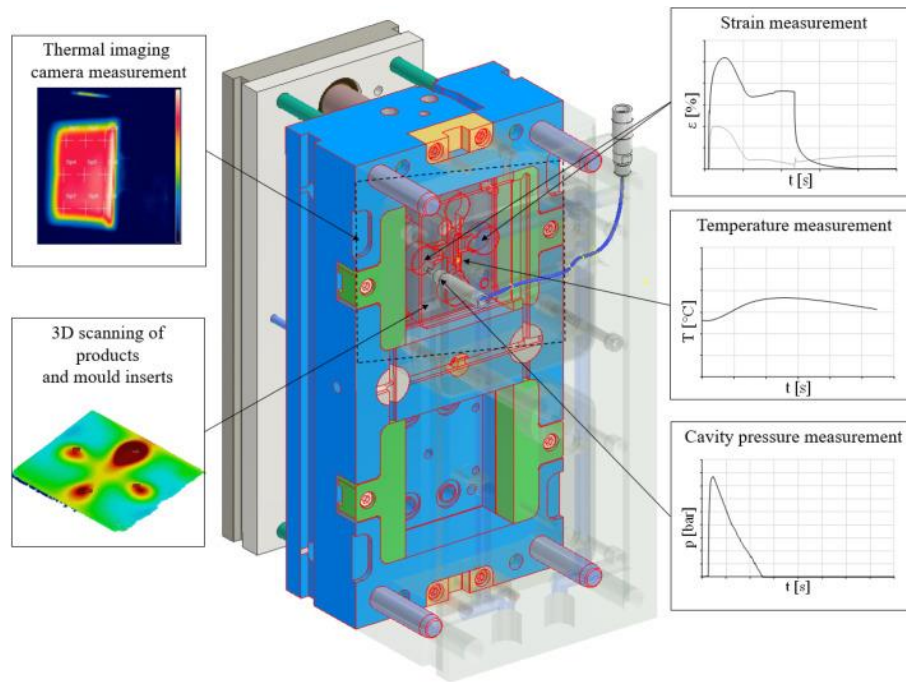


Figure 3. The test mould, the measured quantities and the measurement locations.

3.3 Material tests

Creep testing

I performed Creep Time Temperature Superposition (TTS) tests on a dynamic mechanical analyser (DMA) to test the creep behaviour of the polymeric mould insert materials. Creep testing was performed on rectangular specimens with dimensions of 4 x 10 x 59 mm. The tests were performed in three point bending arrangement and the support span was 50 mm. The applied test parameters are listed in Table 3.

Applied parameters	Unit	Value
Bending stress	[MPa]	5
Furnace time	[min]	10
Creep time	[min]	30
Recovery time	[min]	30
Minimal temperature	[°C]	30
Maximal temperature	[°C]	90
Temperature increment	[°C]	5
Measurement atmosphere	Air	

Table 3. Parameters of the DMA Creep TTS tests.

Dynamic mechanical analysis

I analysed the temperature dependence of the stiffness of the polymeric mould materials using DMA measurements in Multi-Frequency – Strain mode. The measurements were performed in Dual Cantilever arrangement. The rectangular test specimens were 4 x 10 x 50 mm. The analysed temperature range was 25 – 105 °C, the load frequency was 1 Hz, the heating speed was 3 °C/min and the load amplitude was 15 µm.

4 SUMMARY

In my PhD thesis, I elaborated a novel comprehensive state monitoring system for prototype injection moulds. I also created a novel modelling method to analyse the operational thermal and deformational state of injection moulds.

I elaborated the comprehensive measurement system of a mould insert printed by PolyJet technology. I measured the operational strains in two points at the back of the moving side cavity insert. I also measured cavity pressure by a direct piezoelectric pressure sensor built into the fixed side cavity insert. The comprehensive state monitoring also contains temperature measurements. The volumetric temperature of the moving side cavity insert was measured by a thermocouple and the surface temperature of the mould insert was measured by a thermal imaging camera in the idle time between the cycles, in the open state of the mould.

With this test mould, I carried out a series of injection mouldings into an epoxy-acrylate insert made with PolyJet technology. During this injection moulding series I analysed the behaviour of the mould insert both under constant operating conditions (thus repeatability) and under increasing holding pressure. Alongside the operating characteristics, I also measured the size of the moulded products and the dimensions of the mould inserts. I also investigated the effect of the injection moulding method on operational strains, pressures and temperatures. By applying time-controlled, pressure-limited filling, the problem of changing switching point due to the thermal expansion of the insert can be eliminated. On the other hand, this injection moulding method also imposes a higher pressure and thermal load on the mould insert compared to conventional volume-based switchover.

After that, I analysed the effect of high-energy (gamma) irradiation on the stiffness, the creep compliance and the temperature dependence of the mechanical properties of an epoxy-acrylate photopolymer. I found that high-energy irradiation increased the stiffness, reduced the creep compliance and increased the glass transition temperature of the photopolymer material. This is caused by the increase in the cross-link density. Following the material tests, I performed injection moulding tests with the mould inserts irradiated with different doses. The mould insert that received the highest irradiation dose suffered the lowest operational strain. Irradiation reduced the operational deformations of the mould inserts substantially. This way, I proved the positive effect of high energy irradiation on the applicability of the photopolymer mould inserts.

Following that, I analysed the applicability of fused filament fabrication in prototype injection mould making because it is a popular and relatively low-cost technology. I found that by printing with a higher infill rate, the printed mould inserts can be applied in low-volume injection moulding. I also introduced the strain integral, which is the area under the measured strain-time curves and correlated this with product weight and thickness. The strong linear relations demonstrated the applicability of the method in product quality monitoring. After that, I used selective laser sintering to print a mould insert from a polyamide 12 powder material. I also carried out a series

of injection moulding experiments with this mould insert and investigated the correlations between the product properties (mass and thickness) and the strain integral. The product properties showed a strong correlation with the strain integral in this case as well.

After that, I presented the modelling methods of prototype injection mould inserts. I used the Core Shift simulation available in the injection moulding simulation software (Moldflow) to model the deformations of the mould inserts. I identified the strengths and the limitations of the Core Shift method. Based on the latter, I developed a new coupled simulation workflow that links injection moulding simulation with transient thermal and mechanical simulations. This more general approach is capable to predict both the operational temperature distribution and the deformations with suitable accuracy for the analysed aluminium and polymer tool inserts. Injection moulding simulation software is used to mesh the mould block geometry and calculate the time-dependent pressure load. The results are then used in a transient thermal simulation, where the time-dependent temperature distribution of the mould block is determined as the product cools down. The calculated transient temperature field and the transient pressure field obtained from the injection moulding simulation are then used as inputs for a mechanical simulation. In addition, I carried out creep tests on the previously used insert materials on a DMA machine. I determined the storage modulus and loss factors of the mould materials in order to take into account the temperature dependence of stiffness. After the material tests, I modelled the creep of the insert materials using finite element mechanical simulation. The material model, based on the Prony-series approximation of the creep modulus can reproduce the creep measured in a three-point bending arrangement with sufficient accuracy in the small deformation range. By modelling the creep tests, I also calibrated the Prony-series parameters of the insert materials, which were then used in the model of the tool inserts.

In conclusion, my comprehensive state monitoring system made it possible to investigate both the thermal and mechanical characteristics of the tool insert during operation. Injection moulding measurements were carried out for a wide range of prototype mould materials and possible additive manufacturing technologies. I found a link between operational strains, cavity pressures and the characteristics of the injection moulded products. I successfully investigated post-treatment options for cross-linked photopolymer materials to increase the stiffness of the inserts and to improve their stiffness and creep resistance even at elevated temperatures. Additional material tests were performed to determine the temperature-dependent creep properties and stiffness for polymeric insert materials. I presented a possible method for modelling the creep of polymer mould insert materials under small deformations. I validated the model and presented the limits of its applicability. I have developed a novel modelling method based on the one-way coupling of injection moulding simulation and finite element thermal and mechanical simulations. The method can be used to model operational temperatures and strains of both metal and polymer mould inserts. Measurement results were used to validate the computational models and to demonstrate their adequacy. Both the developed measurement and modelling methods can be applied in practice.

5 THESES

1. scientific thesis:

I have developed a comprehensive state monitoring system to measure the in-mould behaviour of mould inserts made with conventional and additive manufacturing technologies. The measurement system is capable to predict the failure of tool inserts and characterise the dimensional accuracy of the products and the repeatability of the injection moulding cycle. The state monitoring system consists of strain gauge deformation measurement of the inserts, cavity pressure measurement, thermocouple volumetric temperature measurement and thermal camera surface temperature measurement. In addition to operational state monitoring, the measurement system is complemented by 3D scanning of the manufactured products and mould inserts, as well as geometric and mass measurements on the products. The applicability of the system was demonstrated by testing mould inserts made from aluminium, epoxy-acrylate, ABS and PA12.

Scientific publications related to the thesis: [1-5,9]

2. scientific thesis

The state monitoring system is capable to determine the required idle time after the injection moulding cycle for a given injection moulding parameter set to increase the mould insert lifetime and improve the dimensional accuracy of the injection moulded products. The strain measurement is used to monitor the recovery of the viscoelastic deformation after mould opening, and the temperature measurement is used to determine the time required for the insert to cool below the glass transition temperature. I verified this statement by injection moulding experiments performed by mould inserts made of Vero White-RGD835, RGD 720 (Stratasys Inc.), Z-ABS (Zortrax) and PA2200 (EOS GmbH).

Scientific publications related to the thesis: [1-5,9]

3. scientific thesis

For products manufactured with aluminium mould inserts, product mass and thickness are linearly related to the integral of the mould cavity pressures for a given holding time, melt temperature and mould temperature. The relationships between the integral of the cavity pressure curves and the product mass and thickness are given by the following equations:

$$m_{termék} \approx c_1 \cdot \int_{t=utónyomáskezdeté}^{t=utónyomásvége} p_{üreg}(t) dt + m_1 \quad (1)$$

$$w_{termék} \approx c_2 \cdot \int_{t=utónyomáskezdeté}^{t=utónyomásvége} p_{üreg}(t) dt + w_1 \quad (2)$$

where: $m_{product}$ [g] and $w_{product}$ [mm] are the mass and the thickness of the products, c_1 [g/(bar·s)] and c_2 [mm/(bar·s)] are fitted parameters depending on the mould material, local mould geometry and the load case. The p_{cavity} [bar] is the cavity pressure, m_1 [g]

and w_1 [mm] are the static product mass and product thickness that can be measured at theoretically 0 pressure integral (volumetric filling of the cavity).

I verified my statement by injection moulding experiments performed by injection mould inserts made from EN AW 5754 O/H111 aluminium alloy.

Scientific publication related to the thesis: [6]

4. scientific thesis

High-energy (γ) irradiation significantly reduced the operational strains of additively manufactured photopolymeric injection mould inserts. The reduction of operational strains was dependent on the dose rate. The reduction of operational strains is caused by the increase in the modulus of elasticity and the reduction of the creep compliance.

Due to this, the operational deformations of the mould inserts stabilised in the residual cooling time even when higher holding pressures (250-300 bar) were applied. Injection moulding experiments were carried out on mould inserts made from RGD835 – VeroWhite (Stratasys Ltd.) photopolymer resin that was subjected to 0-200 kGy irradiation doses from a ^{60}Co radiation source. I also carried out material tests: conventional DMA in temperature sweep mode, DMA Creep Time Temperature Superposition tests and Shore D hardness tests.

Scientific publications related to the thesis: [7]

5. scientific thesis

I elaborated a simulation method that allows the modelling of mould inserts made from unreinforced materials. The modelling method is based on the one-way coupling of injection moulding simulation, thermal and mechanical finite element simulations.

The finite element meshing of the mould and the calculation of the transient pressure field is carried out in the injection moulding simulation software. These results are then imported into a finite element simulation software where a coupled thermo-mechanical simulation is performed. The transient temperature field of the analysed mould block is calculated in the thermal simulation that is also an input of the latter mechanical simulation. The transient pressure field is represented by multiple lists of nodal forces in the mechanical simulation which is used to calculate the operational deformations of the mould inserts. The presented one-way coupling method is only applicable when the mould inserts suffer small deformations. It means that mould deformations do not change the shape of the cavity significantly throughout the entire injection moulding cycle.

The presented one-way coupling also allows the modelling of polymeric mould inserts by using the generalised Standard-Solid model. The creep modulus of the polymeric mould materials can be approximated by Prony-series. I proved my thesis with injection moulding experiments performed by mould inserts made from EN AW 5754 O/H111, Vero White-RGD835, Z-ABS (Zortrax) and PA2200 (EOS GmbH.)

Scientific publications related to the thesis: [6,8,10]

6 LIST OF MY SCIENTIFIC PUBLICATIONS

1. **Krizsma Sz. G., Kovács N. K., Kovács J. G., Suplicz A.:** In-situ monitoring of deformation in rapid prototyped injection molds. *Additive Manufacturing*, 42, 102001/1-102001/8 (2021) [10.1016/j.addma.2021.102001](https://doi.org/10.1016/j.addma.2021.102001) **IF=11.632 D1**
2. **Krizsma Sz. G., Suplicz A.:** Comprehensive in-mould state monitoring of Material Jetting additively manufactured and machined aluminium injection moulds. *Journal of Manufacturing Processes*, 84, 1298-1309 (2022) [10.1016/j.jmapro.2022.10.070](https://doi.org/10.1016/j.jmapro.2022.10.070) **IF=6.2 D1**
3. **Krizsma Sz., Suplicz A.:** Analysis of the applicability and state monitoring of material extrusion–printed acrylonitrile butadiene styrene injection mould inserts with different infill levels. *Materials Today Communications*, 35, 106294/1-106294/ (2023) [10.1016/j.mtcomm.2023.106294](https://doi.org/10.1016/j.mtcomm.2023.106294) **IF=3.8 Q2**
4. **Krizsma Sz. G., Suplicz A.:** Additív gyártástechnológiával előállított fröccsöntő szerszámbetétek üzem közbeni deformációinak vizsgálata. *Polimerek*, 7, 155-160 (2021)
5. **Krizsma Sz. G., Suplicz A.:** State-monitoring and product quality measurement of additively manufactured injection mould inserts. *IOP Conference Series: Materials Science and Engineering*, 1246, 012020/1-012020/8 (2022) [10.1088/1757-899X/1246/1/012020](https://doi.org/10.1088/1757-899X/1246/1/012020) **Q3**
6. **Krizsma Sz. G., Suplicz A.:** Monitoring and modelling the deformation of an aluminium prototype mould insert under different injection moulding and clamping conditions. *Results in Engineering*, 20, 101556/1-101556/13 (2023) [10.1016/j.rineng.2023.101556](https://doi.org/10.1016/j.rineng.2023.101556) **IF=6 Q1**
7. **Krizsma Sz., Mészáros L., Kovács N. K., Suplicz A.:** Expanding the applicability of material jetting–printed photopolymer prototype injection moulds by gamma irradiation post-treatment. *Journal of Manufacturing Processes*, **IF=6.2 D1, minor revision.**
8. **Krizsma Sz., Széplaki P., Suplicz A.:** Coupled injection moulding simulation–thermal and mechanical simulation method to analyse the operational behaviour of additively manufactured polymeric injection moulds. *Results in Engineering*, 23, 102558 (2024) [10.1016/j.rineng.2024.102558](https://doi.org/10.1016/j.rineng.2024.102558) **IF=6 Q1**
9. **Krizsma Sz., Suplicz A.:** Prototípus fröccsöntő szerszámok üzem közbeni állapotfelügyelete és termékminőség vizsgálata. XXXI. Nemzetközi Gépészeti Konferencia (OGÉT), Temesvár, Románia. 2023.04.17. - 2023.04.20., 323-328 (2023)
10. **Krizsma Sz., Suplicz A.:** Comprehensive Measurement and Simulation of Prototype Injection Moulds. *Defect and Diffusion Forum Chapter 4: Defect Identification and Fault Analysis* (2024)