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State-monitoring and product quality measurement of additively manufactured injection mould inserts

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Abstract. Additive technologies represent a state-of-the-art and innovative way in today's mould making. They allow production of both metallic and polymeric moulds with relative simplicity and flexibility compared to conventional machining. Despite its possible benefits, this area is scarcely researched. In our work, we analysed in-mould applicability of epoxy-acrylate inserts manufactured by PolyJet technology. We created a comprehensive state monitoring method to quantify important process parameters like cavity pressure, strain and temperature of the inserts. We analysed the effect of holding pressure on the resulting cavity pressure and strain of the insert. We showed that strain of the insert gradually increased after the cycles and we identified characteristic segments of the injection moulding cycle on the strain-time curves. We also applied surface temperature measurements using a thermal imaging camera. The purpose of this measurement was to determine necessary delay time between cycles allowing inserts to cool below heat deflection temperature, so early failure could be prevented. By using thermal imaging camera, we measured cavity surface temperature distribution and demonstrated the effect of low thermal conductivity of the insert material. We also measured thickness and weight variation of injection moulded products to show the effect of holding pressure and mould deformation on final product quality. As we applied higher holding pressures, product mass and average product thickness grew.

1. Introduction

Additive manufacturing (AM) technologies have already revolutionised part making. They are capable of producing functional parts in small series and manufacturing low-volume moulds for well-established plastic processing technologies like injection moulding [1-3]. Materials for AM technologies include metals, thermoplastic and non-thermoplastic polymers. Thermoplastic polymers can be printed from filament that is melted by a heated nozzle at the printer head (Fused Deposition Modeling, FDM) or thermoplastic polymer powder particles are melted and bound together by a high energy laser (Selective Laser Sintering, SLS) [4]. Non-thermoplastic polymer parts can be printed by curing resin using an UV lamp (PolyJet) or laser (Stereolitography, SLA). Metal parts are printed from powder similarly to SLS, that technology is called Direct Metal Laser Sintering (DMLS). [5] Application of additively manufactured mould inserts offers much desired flexibility in mould making. Complex geometries can be manufactured, like conformal cooling channels [6-8]. Research has already been made to analyse the effect of additively manufactured mould inserts on final injection moulded product properties like dimensional accuracy or crystallinity and resulting mechanical properties [9-11]. Yet, only few research papers are available on comprehensive state monitoring of additively manufactured inserts during their in-mould use. [12-13]

In our research we manufactured mould inserts by PolyJet technology from an epoxy-acrylate photopolymer resin. After that we carried out an injection moulding series to measure operational strains, cavity pressures and surface temperature distribution of the inserts. We measured the effect of holding pressure on resulting strains and cavity pressure. We also analysed the thermal state of the insert and showed the effects of low thermal conductivity.

2. Materials and methods

2.1. Materials

Injection moulded material was *Tipplen H145F* (polypropylene homopolymer) manufactured by *MOL Group Public Limited Company*. We chose this material grade because of its low required processing temperature, and good MFI value. Processing and mechanical properties of the material are listed in table 1.

Table 1. Material properties of *Tipplen H145F*. [14]

Physical property	Typical value
Melt flow rate (MFR) (at 230 °C and 2.16 kg) $\left(\frac{\mathrm{g}}{10\ \mathrm{min}}\right)$	29
Recommended processing temperature (°C)	190 - 235
Flexural modulus (GPa)	1.8
Module of elasticity (in tension) (GPa)	1.99
Tensile stress at yield (MPa)	38
Tensile strain at yield (%)	8

Mould inserts were manufactured by PolyJet using an *Objet Alaris 30* printer (*Objet Geometries Ltd.*). The material was an UV curable epoxy-acrylate photopolymer resin (*VeroWhitePlus RGD835, Stratasys Ltd.*). Important physical properties of the material are listed in table 2.

Table 2. Material properties of *VeroWhitePlus (RGD835)*. [15]

Physical property	Typical value
Tensile Strength (MPa)	50 - 65
Elongation at break (%)	10 - 25
Modulus of elasticity (GPa)	2 - 3
Flexural modulus (GPa)	2.2 - 3.2
Heat Deflection Temperature (at 0.45 MPa) (°C)	45 - 50
Shore Hardness (D Scale)	83 - 86

2.2. Mould inserts and mould

For injection mouldings we used a steel mould housing fitted by additively manufactured mould inserts. Figure 1 shows the moving half of the mould and the ejection system a) the stationary half of the mould b) and the product with its main dimensions c). Cavity inserts in both mould halves and the washers underneath them were made of *VeroWhitePlus (RGD835)*.

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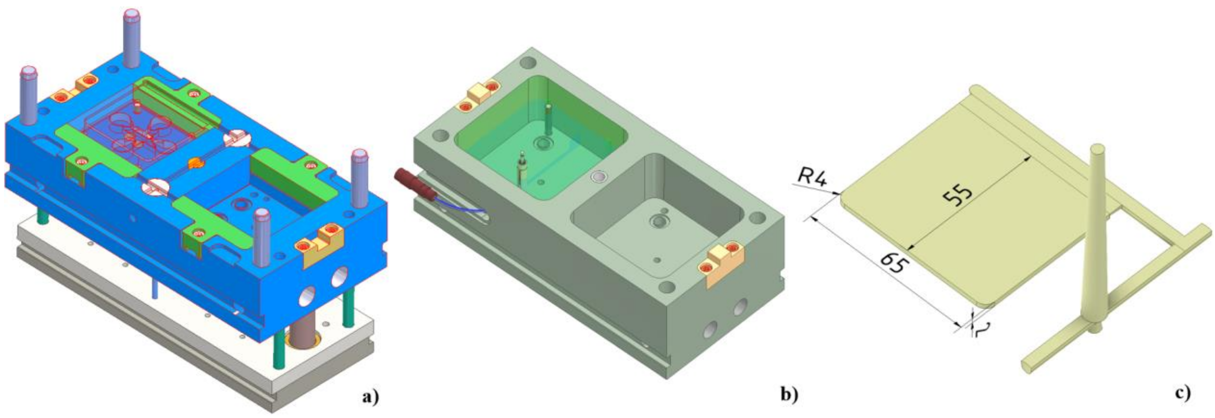

Figure 1. The applied mould: moving half a), stationary half b) and the injection moulded product c).

We injection moulded using an *Arburg Allrounder 270 S 400-170* injection moulding machine (*Arburg GmbH*). Cavity pressure was measured by an *RJG Piezo 6159* piezoelectric direct pressure sensor and its data was collected by a *Como Injection 2869B* unit (*Kistler AG.*). Strains were measured using *KMT-LIAS-06-3-350-5EL* strain gauges (*Kaliber Műszer- és Méréstechnika Kft*) and their data was collected by a *Spider 8* unit (*Hottinger Baldwin Messtechnik GmbH*). Surface temperature of the moving side cavity insert was measured in the delay time between cycles, using a *FLIR A325sc* thermal imaging camera (*Teledyne FLIR LLC.*). Positions of the two strain gauges and the thermal imaging camera are illustrated in figure 2.

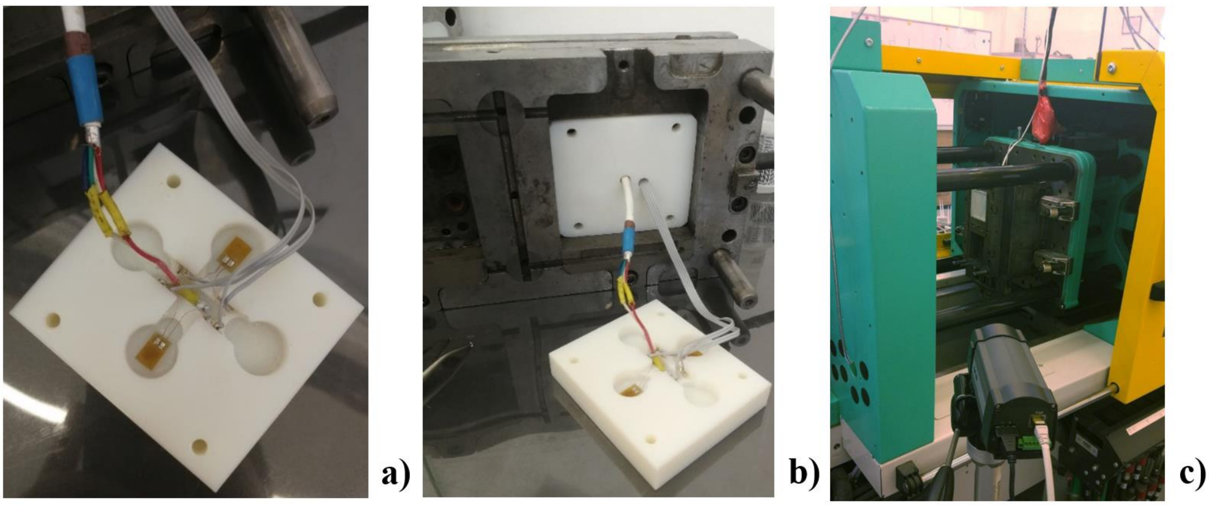

Figure 2. The moving side mould inserts a), b) and the thermal imaging camera location c).

2.3. Injection moulding parameters

The applied injection moulding parameters (constant throughout the cycles) are shown in table 3. As can be seen, melt temperature was chosen approximately in the middle of the recommended processing temperature range. Injection speed, clamp force and injection pressure limit were lowered to protect the inserts from high loads. Long holding time and residual cooling time are needed because heat extraction from the injection moulded product is slow due to low thermal conductivity (approximately. 0.15 - 0.3 $\frac{W}{\mathrm{m} \cdot \mathrm{K}}$) of the inserts. Also, long delay time is necessary for the cooling of cavity surface after part ejection.

Table 3. Applied injection moulding parameters.

Melt temperature (°C)	Injection speed $\left(\frac{cm^3}{s}\right)$	Clamping force (kN)	Injection pressure limit (bar)	Holding time (s)	Residual cooling time (s)	Delay time (s)
210	15	50	500	15	30	~300

Injected melt volume was gradually increased by lowering the switchover point from 35 cm^3 to 27 cm^3 using 2 cm^3 steps. Complete volumetric filling was reached at 26 cm^3. In cycles 1-6, no holding pressure was applied. After reaching complete volumetric filling in the 6th cycle, we started applying holding pressure. In the 7th and 8th cycles, we applied 50 bars holding pressure and its magnitude was increased by 25 bar steps in every second cycle. The aim was to analyse the effect of holding pressure on cavity pressure and resulting strain of the moving half cavity insert. Creep of the epoxy-acrylate material was expected to become more dominant as holding pressure increased.

3. Results and discussions

The presented state monitoring method can quantify main mechanical and thermal parameters of the mould inserts during injection mouldings. In this section, relevant results are presented.

3.1. Strain and cavity pressure results

We measured strain in two locations as can be seen in figure 2. One strain gauge was glued into the near-gate slot, the other into the far-gate slot at the back of the moving side cavity insert, using a cyanoacrylate adhesive (*3M Scotch-Weld Plastic & Rubber Instant Adhesive PR100*). Strain results for near-gate gauge are shown in figure 3.

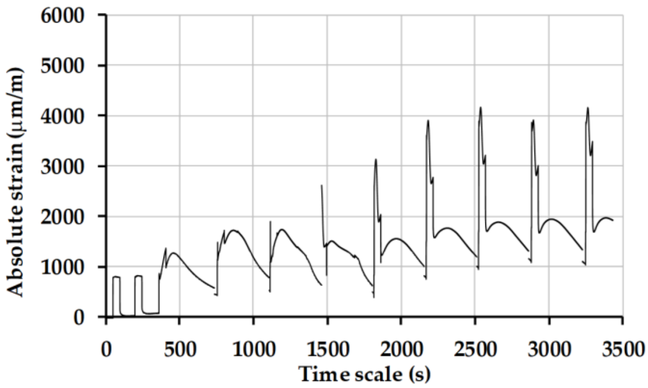

Figure 3. Measured strain results of the gauge near-gate.

In the first two cycles, melt only filled the runner and the gate. Partial filling of the cavity began in the 3rd cycle, therefore the near gate gauge measured a bell-shaped strain-time curve. In the 4th and 5th cycles we increased injected melt volume and it caused an increase on the corresponding strain curves of the near-gate gauge. In the 6th cycle we reached complete volumetric filling but still no holding pressure was applied. The first segment of the 6th cycle's strain curve is missing because strain measurement was started with a delay. From the 7th cycle, the effect of elevated holding pressure can be seen, as maximum points of strain curves show an increasing tendency due to more dominant creep of epoxy-acrylate material in the holding phase. After part ejection, viscoelastic deformation component decreases in the delay time. Figure 3 also demonstrates the importance of delay time when using polymeric injection mould inserts.

Strain curves corresponding to the 7th - 11th cycles have a similar shape. To show the change in strain comparably in each cycle, relative strain was introduced. Relative strain is the difference of measured strain in the current cycle and residual strain after the previous cycle. Relative strain curves of the near gate gauge in the 8th, 10th and 11th cycles are presented in figure 4 with the main segments of the injection moulding cycle.

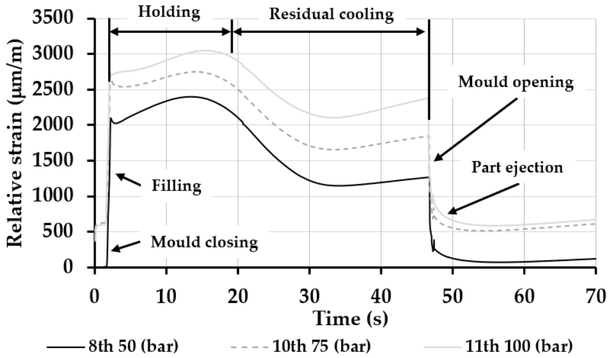

Figure 4. Relative strains near-gate at different holding pressures.

A steep increase is seen during filling but maximum is reached only in the holding phase. This is caused by viscoelastic deformation component of the epoxy-acrylate material. After holding pressure is not applied, strain decreases to a lower, near constant value in residual cooling time. Mould opening and part ejection are indicated by a steep decrease as the cavity has free space to spring back. Figure 4 also shows the effect of increasing holding pressure, as the curve corresponding to the 11th cycle (100 bar holding pressure) shows significantly higher relative strain than that of the 8th cycle (50 bar holding pressure).

Viscoelastic behaviour of mould inserts causes delay between cavity pressure and resulting strain. It can be best observed in figure 5 that shows near-gate relative strains and cavity pressure as function of time. We present near-gate relative strains in figure 5 because we also measured direct cavity pressure there. Cavity pressure maximum is almost immediately reached at the end of the filling phase, but maximal strain is reached only in the holding phase with a significant delay (~11 seconds). In figure 5 the effect of holding pressure on resulting cavity pressure is also illustrated. At 50 bar holding pressure, cavity pressure dropped to zero at 18 seconds, while at 100 bar only a change in the slope of the cavity pressure curve can be observed at 20 seconds. Due to higher holding pressure, cavity pressure can be maintained longer since pressure loss from maximal injection pressure at switchover is lower.

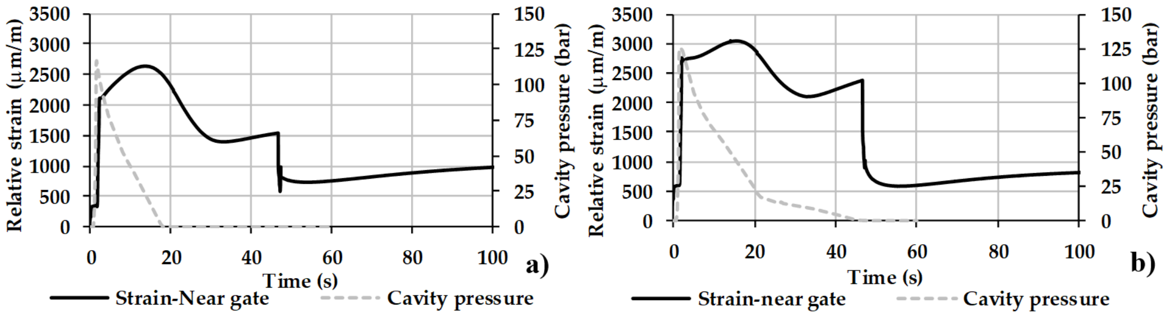

Figure 5. Measured strain results of the gauges and the cavity pressure curves in cycle 7 (50 bar holding pressure) a) and in cycle 11 (100 bar holding pressure) b).

3.2. Thermal imaging camera results

We measured surface temperature distribution of the moving side mould insert to observe cooling of the cavity in delay time. Since HDT of epoxy-acrylate material is low (shown in table 2.) it is vital to allow the cavity surface to cool down between cycles. Figure 6 shows the thermal camera image of a short shot in the 3rd cycle a) and the surface temperature-time curves of the analysed points b). In the thermal camera image, low thermal conductivity of the insert material can be clearly seen as the contour of high temperature zone is almost identical to the actual short shot product. It proves that heat is stuck under the product, and it is not dispersed in the whole cavity. Effect of low thermal conductivity can also be seen in the cooling diagram of the insert. Temperature in the points that are not touched by the melt (P4, P7 and P8) do not change significantly even if they are very close to the higher temperature zone.

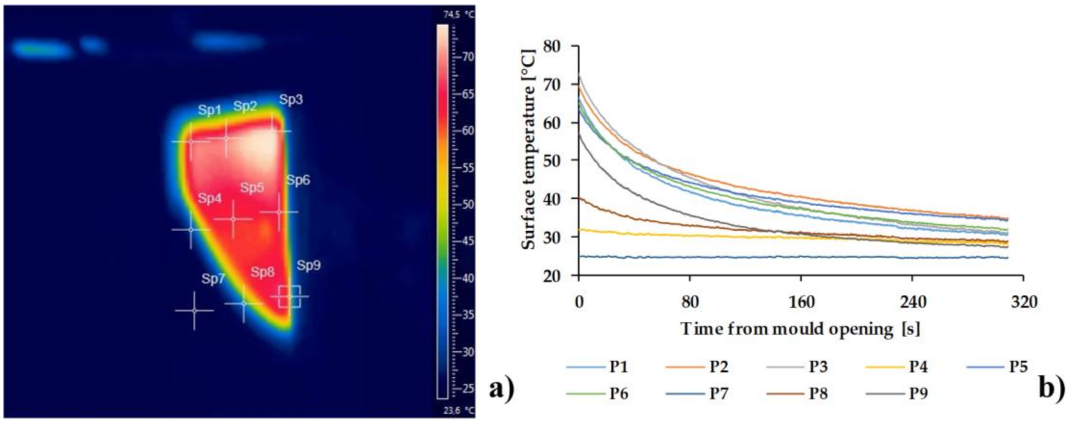

Figure 6. Surface temperature distribution of the mould insert in cycle 3 (short shot) at mould opening a) and the surface temperature-time curves of the characteristic points of the cavity.

Temperature of the cavity midpoint (P5 point in figure 6 a)) is shown as a function of time in figure 7. It can be seen that both minimal and maximal surface temperature values increase over the cycles. In the 1st and 2nd cycles, the melt only filled the runner and in the 3rd cycle it still did not reach the centre of the cavity (P5 point). From the 4th cycle on, the melt reached the centre point and gradual heating of the insert is clearly shown. In the 4th cycle maximal surface temperature (at mould opening) was 63.6 °C and minimal surface temperature (at the end of delay time) was 34.6 °C. Maximal value increased to 83.2 °C and minimal value to 46.8 °C in the 10th cycle. Exponential cooling curves can be observed between the maximal and minimal values. After the 11th cycle we kept longer delay time that resulted in lower cavity surface temperature, reaching 39.9 °C at 4021 seconds.

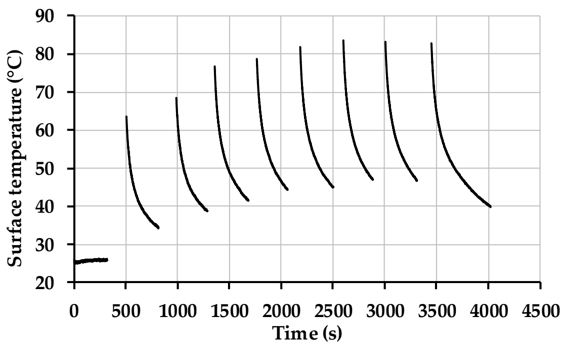

Figure 7. Surface temperature at the centre of the cavity as function of time.

Figure 8 shows cavity surface temperature distribution at mould opening a) and at the end of delay time b). At mould opening, surface temperature distribution correlates well with the filling pattern. It is clear that high temperature zone is identical to the entering location of the melt and cavity surface temperature decreases gradually along the flow length. At the start of the flow length (P3 point) surface temperature is 84 °C (at mould opening) while at the end of the flow length (P7 point) it is only 73.7 °C. Both temperature and pressure loads are higher at the start of the flow length (P3 point) therefore it is a critical part of the mould. However, at the end of delay time high temperature zone is located at the centre of the cavity (P5 point, 45 °C) as the outer surfaces of the insert tend to cool faster because they contact the steel mould housing.

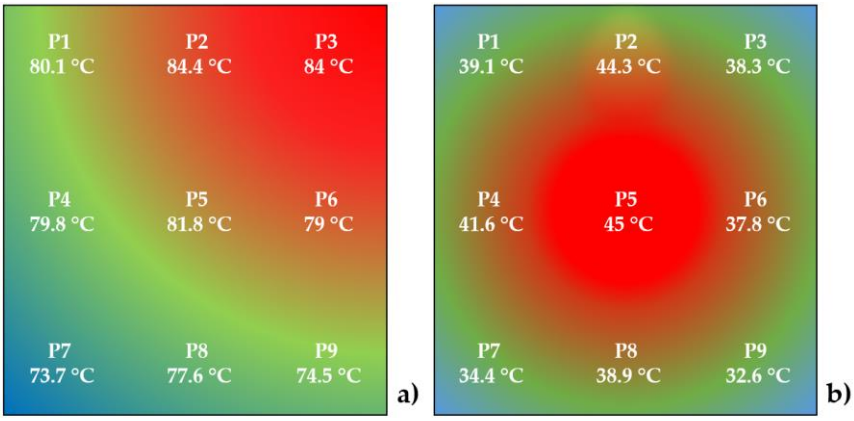

Figure 8. Surface temperature of the cavity at mould opening a) and at the end of delay time b) in the 7th cycle.

3.3. Product weight and dimension

We also measured product mass and thickness and the results are shown in figure 9. Product thickness was measured in 5 points using a *Mitutoyo Digimatic* micrometre and the average of the values with their standard deviation are shown in figure 9. The 1st and the 2nd cycles are not indicated in figure 9 as only the runner and the gate were filled. As the cavity was gradually filled in the 3rd-6th cycles both product mass and average product thickness increased from 1.21 g to 5.25 g and 1.60 mm to 1.74 mm, respectively. In the 6th cycle, complete volumetric filling was reached but no holding pressure was applied. From the 7th cycle, the effect of increasing holding pressure is shown as both product mass and thickness grew. In the 12th cycle, average thickness was closest to the nominal value of 2 mm as it reached 1.90 mm with a standard deviation of 0.15 mm. In our experiment we managed to improve product thickness and mass by applying higher holding pressure.

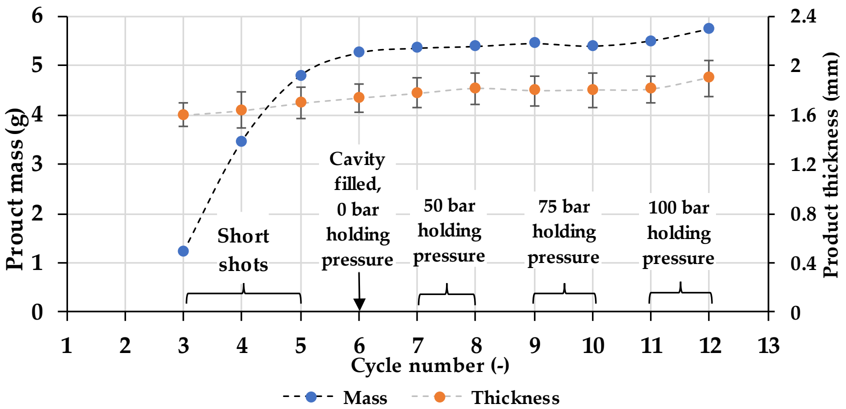

Figure 9. Product mass and average thickness.

4. Summary

In this research paper we analysed the applicability of PolyJet printed epoxy-acrylate injection mould inserts. We created a comprehensive measurement system where we measured strains, cavity pressure and surface temperature of the mould inserts. We presented strain-time curves measured by the two gauges at the back of the moving side insert. We identified the effect of increasing injected melt volume on the strain of the inserts. After reaching complete volumetric filling we also measured the effect of increasing holding pressure on strain of the insert and cavity pressure. On the strain-time curves we identified characteristic segments (mould closing, filling, holding, residual cooling time, mould opening and part ejection) of the injection moulding cycle. During our injection moulding series, we left significant delay time between cycles to allow cavity surface to cool below the epoxy-acrylate material's HDT temperature. In these delay times we measured cavity surface temperature of the inserts by thermal imaging camera and experimentally showed the effect of low thermal conductivity of the insert material. Our injection moulding series was terminated when the fixed side cavity insert failed. After injection mouldings we measured product mass and thickness and found a positive correlation with applied holding pressure.

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References

[1] Bagalkot A et al 2019 *Rapid Prototyping Journal* **25/9** 1493-1505
[2] León Cabezas M A et al 2017 *Procedia Manufacturing* **13** 732-737
[3] Boros R et al 2019 *Express Polymer Letters* **13/10** 889-897
[4] Lupone F et al 2021 *Express Polymer Letters* **15/2** 177-192
[5] Keresztes Z et al 2019 *Periodica Polytechnica Mechanical Engineering* **63** 195-200
[6] Kuo et al 2020 *The International Journal of Advanced Manufacturing Technology* **107** 1223-1280
[7] Park H.-S. et al 2017 *Procedia Manufacturing* **10** 48-59
[8] Zink B et al 2019 *International Communications in Heat and Mass Transfer* **108** 104297
[9] Tábi T et al 2016 *Journal of Thermal Analysis and Calorimetry* **123** 349–361
[10] Kovács N K et al 2011 *Műanyag és Gumi* **48** 269-272
[11] Mendible G A et al 2017 *Rapid Prototyping Journal* **23/2** 344-352
[12] Krizsma Sz et al 2021 *Polimerek* **7/5** 155-160
[13] Krizsma Sz et al 2021 *Additive Manufacturing* **42** 102001
[14] *Tipplen H145F* technical data sheet: (https://www.molgroupchemicals.com/userfiles/products/68/68_tds_hu.pdf) (2022.01.10.)
[15] *VeroWhitePlus (RGD835)* technical data sheet: (https://support.stratasys.com/en/materials/polyjet/vero-family) (2022.01.10.)