

Applying additively manufactured lattice structures in injection overmoulding to produce high-performance hybrid components

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ABSTRACT

Additive manufacturing (AM) enables the rapid production of prototype injection moulds and complex reinforcement structures for injection overmoulding. In this study, an injection mould insert was produced by vat photopolymerisation and used to overmould fused filament fabricated (FFF) cellular reinforcement structures printed from carbon fibre-reinforced polyamide. Rib, grid and gyroid reinforcement geometries with different relative densities were placed in the mould cavity and overmoulded with polypropylene. During injection moulding, the operational deformation and temperature of the additively manufactured mould insert were monitored, while cavity filling was analysed through a glass window using a high-speed camera. The reinforcement inserts increased mould deformation and fill time, especially for more complex geometries, while the thermal state of the mould remained nearly unchanged. The resulting hybrid structures were evaluated under quasi-static, dynamic and thermomechanical loading. Reinforcement geometry strongly affected mechanical performance: the best-performing grid structure increased flexural stiffness by 74%, while the rib structure increased impact strength by 107% compared to neat injection moulded polypropylene. Dynamic mechanical analysis proved that lattices improved the thermomechanical performance of the parts. The proposed approach demonstrates that additively manufactured cellular reinforcements can be effectively integrated into injection overmoulding to produce lightweight hybrid components with locally tailored mechanical performance.

1. Introduction

The appearance of additive manufacturing (AM) allows the rapid and customised production of parts and tools and is expected to gain even more importance in the future [1,2]. AM is increasingly applied to produce moulds for conventional processing technologies like injection moulding, which increases the speed and efficiency of product development by the cost-effective production of physical prototypes. The most common polymeric additive technologies in prototype mould making are thermoset photopolymer-based: material jetting (MJ) and vat photopolymerisation processes like stereolithography (SLA) and digital light projection (DLP). Reinforcement inserts can be manufactured by both resin-based (thermoset) and filament-based (thermoplastic) additive technologies. Fused filament fabrication (FFF) allows the printing of parts even from high-performance thermoplastic matrix composites, like carbon fibre-reinforced polyamide. FFF also allows the printing of hybrid structures and different graded-infill geometries [3,4].

Resin-based additive technologies are already applied in printing prototype moulds which are present in special applications like micro injection moulding. Gülçür et al. [5,6] printed micro injection moulds by MJ from VeroPureWhite resin and compared it to a machined aluminium mould. They found that the low thermal conductivity of the polymer mould led to slower solidification of the product, which reduced maximal injection pressure and reduced pressure overshoots compared to the aluminium mould. This led to a more stable injection moulding process with the photopolymer mould. Lantada et al. [7] applied DLP to print micro injection moulds with microtextured fractal surfaces. They printed the resin inserts, which they coated by nickel using electroforming. After this, they removed the resin from the inside using ultrasonic agitation. They injection moulded polycarbonate and polymethyl-methacrylate, and checked the surface quality of the mould insert and the products by scanning electron microscopy (SEM). They concluded that the proposed mould making and injection moulding process allows the replication of the finest surface details (down to 100 µm). Menezes et al. [8] printed micro injection moulds from three

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different resins: Anycubic White, Monoprice Clear and Formlabs Clear. They found that the Formlabs Clear resin withstood more than 500 injection moulding cycles and they were able to eject all parts from the cavity when sidewall waviness was minimised to $1.9 \pm 0.4 \mu\text{m}$ and the interlocking angle to $1.9 \pm 0.8^\circ$. Convery et al. [9] applied SLA to print micro injection moulds with small features ($100 \mu\text{m} \times 200 \mu\text{m}$) from Formlabs Clear and High Temp resins. They managed to injection mould more than 500 parts from polystyrene without significant damage to the mould. Surace et al. [10] also applied SLA and printed micro injection moulds from Formlabs Grey and High Temp resins. They managed to injection mould 30 parts with 92% reproducibility with the Grey insert and with 98% reproducibility with the High Temp insert. Zhang et al. [11] used DLP to print micro injection moulds from a photopolymer resin (EnvisionTEC HTM 140 V2). They printed cylindrical mould cavity geometries with a diameter of $200 \mu\text{m}$ and a depth of $200 \mu\text{m}$, and injection moulded polyethylene in four production runs in more than 80 cycles in each run with dimensionally stable products. Farooque et al. [12] concluded in their review that the most important process parameters of injection moulding that determine product quality are injection pressure and speed, melt and mould temperature, holding pressure and time, and residual cooling time. Bagalkot et al. [13] also concluded that injection pressure, injection speed and mould temperature are the key process parameters which influence the lifetime of MJ-printed moulds. Yang et al. [14] developed a new resin formulation (release-agent retaining resin) for vat photopolymerisation. They printed mould inserts from their special resin and managed to produce and demould more than 100 parts with good quality from their AM moulds.

Modern metrology has spread in the injection moulding industry. The application of temperature and cavity pressure sensors is already a well-established practice. These sensors allow in-line quality monitoring and process adjustment when they are combined with modern data analysis tools [15]. Zhang et al. [16] applied the combination of a charge-coupled device (CCD) camera and a thermal imaging camera to monitor the injection moulding process and detect mould failure and product defects. They printed injection moulds from the Formlabs Rigid10K resin by SLA and added different colourings to the printed resins. They applied a method based on image segmentation and bounding box detection and monitored the failure of the soft tool inserts and the injection moulded part defects. Research articles are already available on the application of experimental glass moulds which are ideal for the analysis of cavity filling and the possible filling defects [17–19]. Baruffi et al. [20] also applied an experimental mould with a glass window to visualize melt flow in a surface-structured micro injection mould. They applied a high-speed thermal camera to monitor the filling process and the heat exchange between the injected melt and the mould housing. They used these data to set up correlations between mould temperature and melt temperature and the accuracy of the micro feature reproduction. Babenko et al. [21] also applied a high-speed thermal imaging camera to measure the surface temperature of a steel micro injection mould. They applied the measurements to calibrate the heat transfer coefficients in injection moulding simulations. They found that increasing the heat transfer coefficients in the simulations from the default values improved the accuracy of the calculations. Guerrier et al. [22] performed injection moulding tests with an induction coil-heated injection mould with a glass window. They analysed the temperature distribution of the heated mould insert during production and compared the measured temperature–time curves with their injection moulding simulation and coupled electromagnetic–thermal simulation. The measured results showed good agreements with their finite element simulations, which validated their modelling method.

Cellular structures also appeared in injection moulding in the form of reinforcing product inserts which are overmoulded [23]. Verma et al. [24] printed body-centered cubic (BCC), face-centered cubic (FCC) and Kelvin-type lattice structures from 316 L stainless steel and overmoulded polyaryletherketone (PAEK) on the printed structure. They performed tensile testing of the overmoulded specimens and analysed their failure

modes by using optical microscopy and scanning electron microscopy on the fracture surfaces of the specimens. They also created finite element models of the tensile tests and their models showed excellent correlations with the measurements. They proved that hybrid structures of metal lattice overmoulded with a polymer show excellent mechanical performance. Oliveira et al. [25] proved that alongside lattice structures, the surface structuring of additively manufactured reinforcing part inserts is also a solution to increase the bonding strength between the part insert and the overmoulded polymer. Pokkalla et al. [26] printed triangular lattice structure sheets from maraging steel using laser powder bed fusion (LPBF). They also printed polyamide 6.6 sheet preforms reinforced with long carbon fibres by material extrusion and applied compression moulding to bond the metallic sheets with the fibre-reinforced polymer sheet. They machined tensile test specimens from the compression moulded sheets and performed tests on them. They also created a finite element model of the tensile tests and validated their results successfully. Smith et al. [27] also applied compression moulding to overmould ultra-high molecular weight polyethylene (UHMWPE) on FFF-printed polyether ether ketone lattice structures. They analysed five different FFF-printed structures (triangular, grid, gyroid, honeycomb and octahedral) and they tensile tested the different hybrid structures. Their results are highly relevant for the medical industry because of the potential applicability of these high-performance joints in medical devices. Another interesting research direction is the application of lattice structures in injection moulds, which allows the lightweighting of the moulds and increase their cooling efficiency. Šakalys et al. [28] applied LPBF to print porous injection mould inserts with BCC lattices from steel and compared the dimensional stability and operational temperature of the porous mould insert to the solid reference insert. They achieved a 21.86% and a 23.95% reduction of weight on the fixed and moving side mould inserts, respectively. Dimensional measurements proved that injection moulding 1500 cycles with polyoxymethylene did not change the dimensions of the porous inserts. However, the thermal performance of the porous insert was worse than that of the solid insert, therefore they concluded that the improved cooling of these new inserts has to be a future research focus. Park et al. [29] created a similar study, where they redesigned a solid mould block to a hollow lattice structure. They applied finite element analysis to benchmark the different lattice geometries. They chose a hybrid lattice structure comprising of diamond-shape and octet truss structures and achieved a weight reduction of 79% compared to the solid mould block. They injection moulded more than 400 cycles with polyvinylchloride (PVC) without any damage to the lightweight mould. Shen et al. [30] studied the potential in the conformal cooling of AM metal moulds by creating BCC lattice structure-reinforced cooling layers around the cavity surface. They managed to reduce cooling time between 38.6% and 66.1% and decrease the maximal temperature deviation on the cavity surface from 8.5 K to 6 K. However, they also showed that the pressure required for the circulation of the coolant water increased. Mercado-Colmenero et al. [31] designed an injection mould with conformal cooling channels arranged in a structure inspired by lattice design. Their lattice-based cooling arrangement showed excellent efficiency and reduced cycle time compared to conventional, drilled cooling channels.

The reviewed literature demonstrates that polymeric additive technologies (SLA, DLP and PolyJet) are already applied in injection mould making because of their flexibility, versatility and the dimensional stability of the printed moulds. Advanced metrology can also be used to monitor the injection moulding process and validate injection moulding simulations. Cellular structures also appeared in injection moulding as experimental, lightweight moulds and as reinforcing part inserts for hybrid polymer–metal joints.

However, the combined investigation of behaviour during processing, in-line process monitoring and mechanical performance of injection-overmoulded hybrid structures reinforced with additively manufactured cellular architectures is still limited in the literature. Our

study focuses on the application of FFF-printed, carbon fibre-reinforced PA6.6 cellular reinforcement structures in injection overmoulding. We overmoulded polypropylene (PP) onto the reinforcement structures with different cellular geometries, and analysed the effects of the different reinforcement geometries on the quasi-static, dynamic and thermo-mechanical behaviour of the hybrid structures. We also applied in-line process monitoring methods to investigate the operational deformation, thermal behaviour and filling characteristics of the AM mould insert.

2. Materials and methods

2.1. Preparation of the injection mould insert

The injection mould insert design is presented in Fig. 1. During the injection moulding tests, we injection moulded standard three-point bending test and Charpy impact test specimens (according to ISO 178 and ISO 179) with dimensions of 4 mm × 10 mm × 80 mm. We chose the bar-shaped specimen geometry because it is suitable for multiple, highly standardised material tests, which characterise the quasi-static, dynamic mechanical and thermomechanical performance of the different hybrid structures. The cavity was filled through a fan gate with a 125° angle and a thickness of 0.9 mm in the cross section where the melt enters the cavity. We also fitted two strain gauges and a thermowire in the slot at the back of the mould insert to monitor the operational deformation and temperature of the injection mould insert.

The injection mould insert was printed from Formlabs Clear V5 resin. Its main material properties are listed in Table 1 based on the technical datasheet [34] and the manufacturer's documentation [35]. The resin has sufficient strength and stiffness for prototype injection mould making. Its heat deflection temperature and glass transition temperature are suitable but significant idle time have to be kept between the cycles to prevent the overheating and early failure of the mould insert (Fig. 2).

The injection mould insert was printed on a large-format and state-of-the-art MSLA printer: Form4BL (Formlabs Inc., United States). We selected the orientation of the mould insert as a compromise between minimising the area of each individual printed layer (to minimise warpage) and ensuring sufficient contact area for the support structure to prevent the detachment of the printed part from the printer plate. A dense support structure was applied on the back of the mould insert to prevent detachment, while the front surface and the cavity area were not

Table 1

Mechanical and thermal properties of the Formlabs Clear V5 resin (post-cured for 15 min at 60 °C).

Properties	Unit	Typical value
Ultimate tensile strength	MPa	60
Tensile modulus	MPa	2750
Elongation at break	%	8
Flexural strength	MPa	103
Flexural modulus	MPa	2750
Notched Izod impact strength	J/m	29
Heat deflection temperature (0.45 MPa)	°C	69
Glass transition temperature	°C	95
Thermal conductivity (for V2 resin)	W/(m·K)	0.28
Specific heat	J/(kg·K)	1800 (at 25 °C)
Coefficient of thermal expansion	1/K	~114·10 ⁻⁶

filled with supporting beams because the remnants of the support structure later have to be removed by manual sanding. The finest resolution available in the slicer software (0.25 mm) was used.

2.2. Preparation of the PA 6.6 CF reinforcement inserts

The reinforcement inserts were printed from eSun PA-CF filament which is a PA 6.6 polymer matrix reinforced with 20% carbon fibre (eSun Industrial Co., Shenzhen, China). Filament diameter is 1.75 mm and its main material properties are listed in Table 2 in accordance with the technical datasheet of the manufacturer [36]. The filament was dried for 12 h at 70 °C in a Sunlu FilaDryer S4 unit (Sunlu International Inc., China) due to the hydrophilic nature of the PA 6.6 matrix.

We analysed five different reinforcement insert geometries: two grids with 25% and 35% relative density, two gyroids with 25% and 35% relative density and a flat insert with longitudinal ribs, which we specifically designed for bending. The triangular grooves increase the connection interface between the reinforcing insert and the over-moulded material. The grid and the gyroid reinforcement inserts are presented in Fig. 3 and Fig. 4, respectively, and the rib insert is shown in Fig. 5. We chose the grid and the gyroid geometries because they are commonly applied in fused filament fabrication. They can be manufactured from a wide range of different thermoplastic filaments and these structures have already proved in practice their applicability as product infills.

The reinforcement inserts were printed on a BambuLab X1E FFF

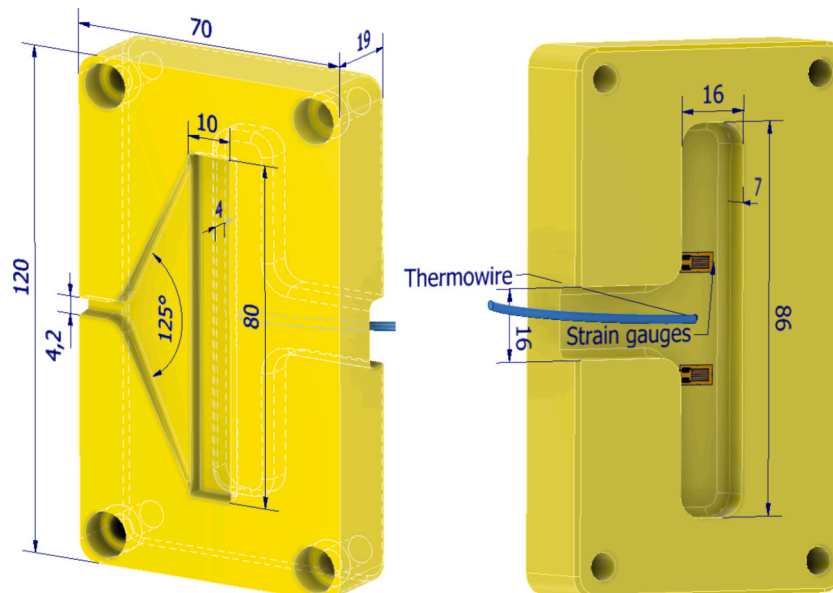


Fig. 1. The applied injection mould insert design.

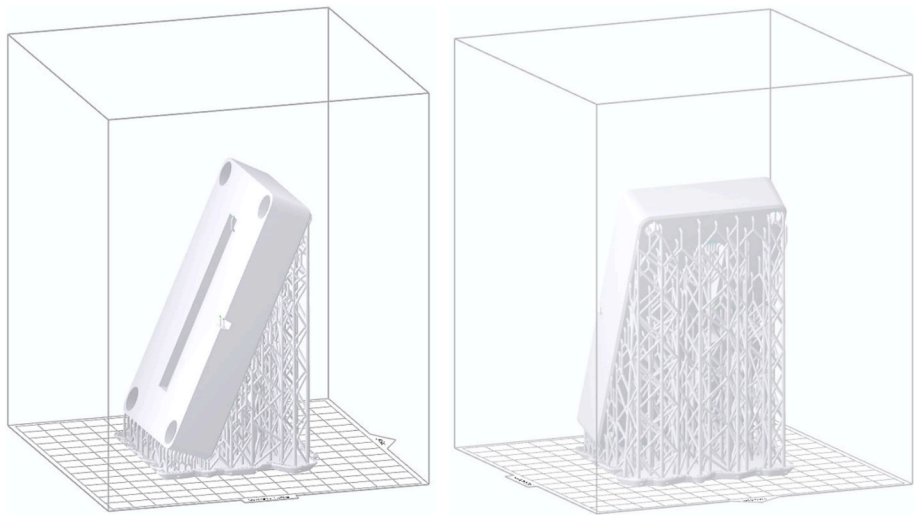


Fig. 2. The orientation of the injection mould insert on the printer build platform.

Table 2
Mechanical and thermal properties of eSun PA-CF.

Properties	Unit	Typical value
Tensile strength	MPa	140
Elongation at break	%	10.61
Flexural strength	MPa	140
Flexural modulus	MPa	4363
Heat deflection temperature (0.45 MPa)	°C	155

printer (BambuLab Inc., Shenzen, China). The printing parameters of the

reinforcement inserts were: a nozzle temperature of 290 °C, a printer bed temperature of 100 °C and a chamber temperature of 60 °C. The printer nozzle was stainless steel and its diameter was 0.6 mm. Printing speed varied between 30 mm/s and 100 mm/s based on the recommended speed range.

2.3. The injection moulding tests

Fig. 6 shows the experimental mould with the glass window and the AM mould insert. The injection mould insert was equipped with two strain gauges (KMT-LIAS-06-3-350-5EL, Hungary) and a thermowire

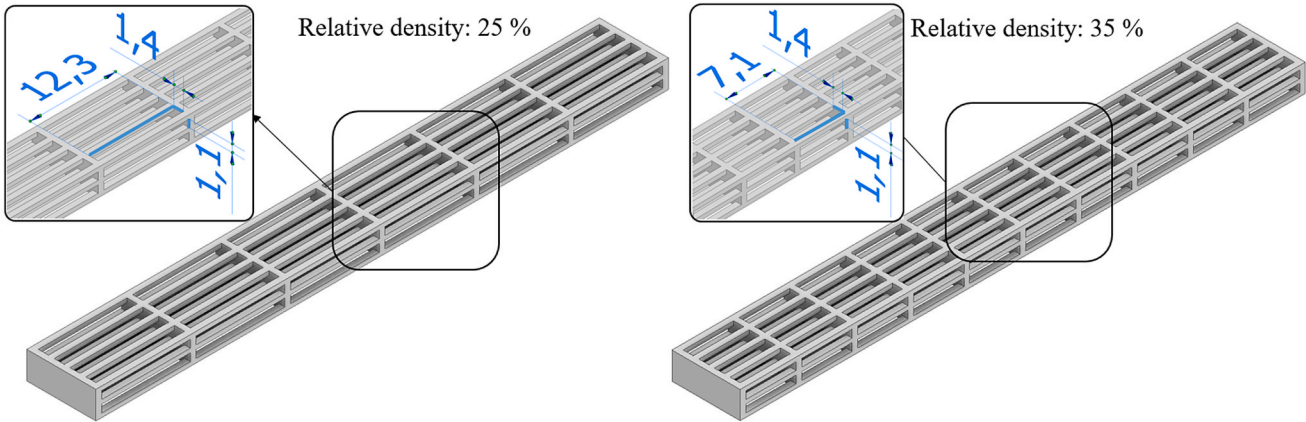


Fig. 3. The rectangular grid reinforcement inserts with different relative densities.

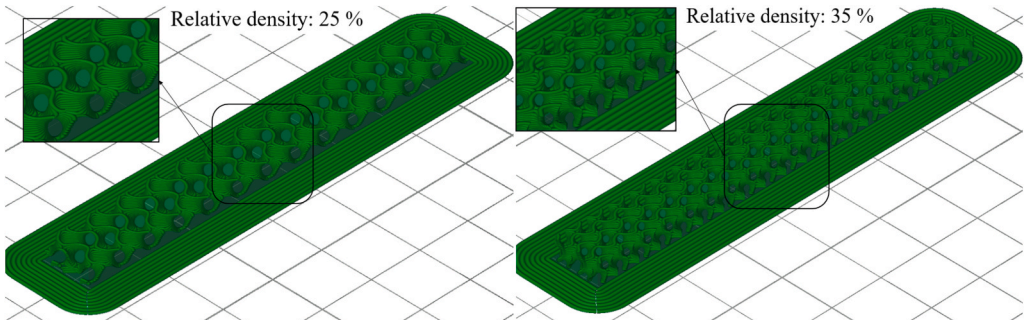


Fig. 4. The gyroid structured reinforcement inserts with different relative densities.

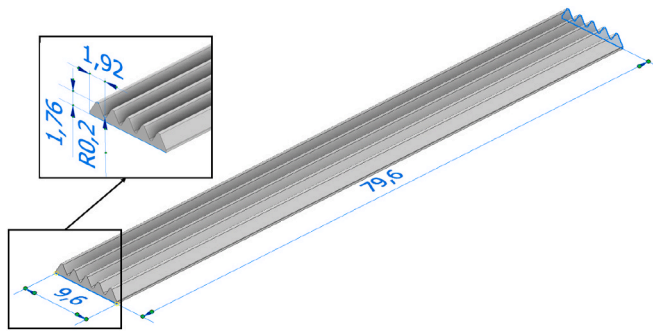


Fig. 5. The rib reinforcement insert with its characteristic dimensions.

(Ahlborn NiCr-Ni thermowire T 190–0, Ahlborn Mess- und Regelungstechnik GmbH, Germany) at the back of the insert. We also monitored the injection moulding process in-line with a Keyence VW-9000 high-speed camera (Keyence Corporation, Japan) to analyse the fill pattern and the deformations of the reinforcement insert during the injection moulding cycle. A Spider 8 signal amplifier unit (Hottinger Baldwin Messtechnik GmbH, Austria) registered the strain data, and an Ahlborn Almemo 8990–6 data collector unit (Ahlborn Mess- und Regelungstechnik GmbH, Germany) gathered the temperature data. The dimensional accuracy of the injection mould inserts were checked by 3D scanning, with a GOM ATOS Core 5 M scanner (Carl Zeiss GOM Metrology GmbH, Germany). Fig. 7 shows the measurement arrangement.

We injection moulded a dedicated polypropylene homopolymer grade (Tipplen H145F) manufactured by MOL Group Plc. (Hungary). We injection moulded 10 cycles without reinforcement inserts and 10 cycles with each of the five different reinforcement inserts. The injection moulding tests were carried out with an Arburg Allrounder 470E 1000–290 electric injection moulding machine (ARBURG GmbH, Germany). The screw diameter of the machine is 30 mm. The injection moulding parameters are listed in Table 3. We chose time-regulated switchover instead of the conventional volume-regulated method because the inclusion of the different reinforcement inserts also changes

switchover volume. We also set an injection pressure limit to avoid excessive load on the inserts. We set residual cooling time relatively long to allow the injection moulded part to reach ejection temperature. A long idle time is also necessary for the polymeric injection mould inserts to cool down. During idle time, the mould was kept open and cooling by compressed air was applied to reduce its temperature faster.

2.4. Material testing and analysis

2.4.1. Three-point bending

Three-point bending tests were performed in accordance with ISO 178 on five specimens on each hybrid structure by using a Zwick Z005 universal testing machine (Zwick GmbH., Germany). The rectangular test specimens were 4 mm × 10 mm × 80 mm and a standard span of 64 mm was applied. As recommended by ISO 178, the specimens were tested in the flatwise orientation; therefore, the flexural load was applied in the thickness direction. The crosshead speed was 1 mm/min and loading was applied until the standard deflection of 6 mm (1.5 times the height of the test specimen) was reached. Flexural strain was calculated automatically from the measured crosshead displacement according to Eq. (1).

$$\varepsilon_f = \frac{6 \cdot s \cdot h}{L^2} \quad (1)$$

where ε_f [-] is the flexural strain, s [mm] is the cross-head displacement, h [mm] is the thickness of the specimen and L [mm] is the standard span. The tests were performed at room temperature.

2.4.2. Charpy impact test

The Charpy impact test was performed in accordance with ISO 179 on five unnotched specimens of each structure. The specimens were 80 mm × 10 mm × 4 mm. The specimens were tested in the edgewise orientation, as recommended by ISO 179 for most materials; therefore, the impact load was applied in the width direction. Together with the flatwise three-point bending tests, the two test configurations provided complementary information on the mechanical response and failure behaviour of the hybrid structures under loading in the thickness and width directions. The tests were performed on a Resil Impactor Junior (Ceast Inc., Italy) testing machine equipped with a 15 J hammer. A standard span of 62 mm was applied.

2.4.3. Dynamic mechanical analysis (DMA)

Dynamic mechanical analysis was performed according to ISO 6721. Two specimens were analysed from each geometry in accordance with the standard. The specimens were tested in dual cantilever arrangement on a Q800 dynamic mechanical analyser (TA Instruments Inc., United States). The analysed temperature range was 25–160 °C, heating speed was 3 °C/min, load amplitude was 15 μm and loading frequency was 1 Hz.

2.4.4. Optical microscopy

The fracture surfaces of the Charpy impact test specimens were analysed by optical microscopy. The microscope was a Keyence VHX-5000 (Keyence Corporation., Japan). We performed the analysis to investigate the failure mechanisms of the hybrid structures and to identify inhomogeneities (air traps, contaminations and weld lines) in the injection overmoulded parts.

3. Results and discussion

3.1. Dimensional accuracy of the SLA-printed injection moulds

The dimensional stability of the as-printed and the post-cured injection mould insert is presented in Fig. 8 and Fig. 9, respectively. The dimensional accuracy of printing is suitable for rapid tooling. SLA

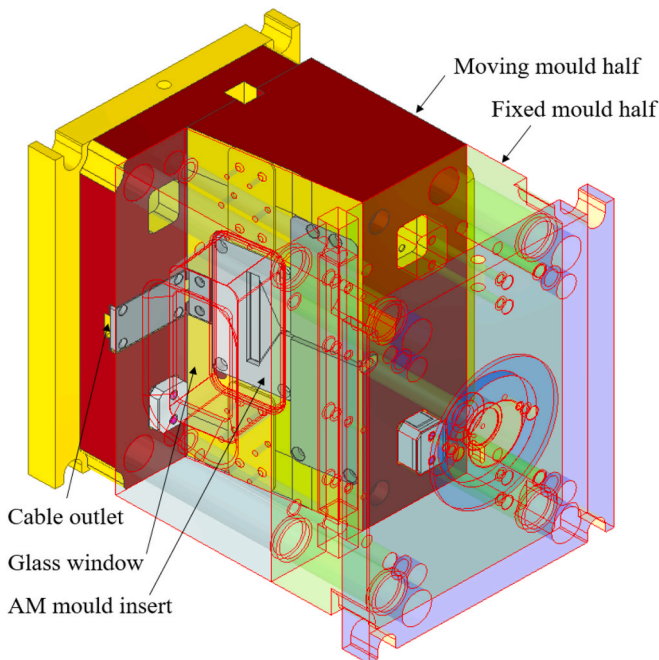


Fig. 6. The experimental injection mould with the glass window and the location of the AM mould insert.



Fig. 7. The measurement arrangement.

Table 3

The injection moulding parameters during the overmoulding experiments.

Processing parameters	Unit	Value
Clamping force	[tons]	60
Dose volume	[cm ³]	20
Injection rate	[cm ³ /s]	15
Injection pressure limit	[bar]	300
Switchover time	[s]	3
Holding pressure	[bar]	150
Holding time	[s]	7
Residual cooling time	[s]	40
Screw rotation speed	[m/min]	20
Back pressure	[bar]	60
Delay time between the cycles (idle time)	[s]	200
Melt temperature	[°C]	210

printing requires some post-machining, especially the removal of the remnants of the support structure. Maximal dimensional deviations occur at the back of the injection mould insert, which decreased after post-curing. This is highly beneficial for the applicability of the resin in injection mould tooling. The maximal size deviation on the clamping surface of the post-cured insert varied between -0.19 mm and $+0.12$ mm, which allows proper mould closing and prevents the occurrence of flash during injection moulding. The sides of the injection mould insert also showed dimensional deviations between -0.03 mm and $+0.06$ mm, which allows the proper fitting of the polymeric injection mould

insert into the metal mould housing. The 3D scanning highlighted that the Clear resin is suitable for rapid tooling because of its dimensional stability.

3.2. Overmoulding tests on the different reinforcement inserts

The operational deformations of the mould insert were monitored during the injection moulding series. Fig. 10 a) shows the strain of the mould insert during injection moulding neat PP, and Fig. 10 b) shows strain during overmoulding onto the rib reinforcement insert. Relative strain is the change in strain from the start of the current injection moulding cycle. The reinforcement insert increased operational deformation by almost ten times (from $0.025\% \pm 0.004\%$ to $0.23\% \pm 0.003\%$) because cavity volume decreased considerably. The shape of the strain curves are also slightly different when no reinforcement insert was included and when the rib insert was overmoulded. Mould closing occurs as a small dip as the clamping force compresses the insert. Cavity filling causes a stepwise increase when the melt is injected at high speed and high pressure. When there was no reinforcement insert, strain increased further in the holding phase and maximal strain was reached. On the other hand, when the rib reinforcement insert was overmoulded, strain dropped sharply after the cavity was filled. It is because the injection pressure limit (300 bar) was reached during filling but the holding pressure was only 150 bar (Fig. 10 c)). The sharp drop in injection pressure also causes the steep drop in the strain of the mould insert.

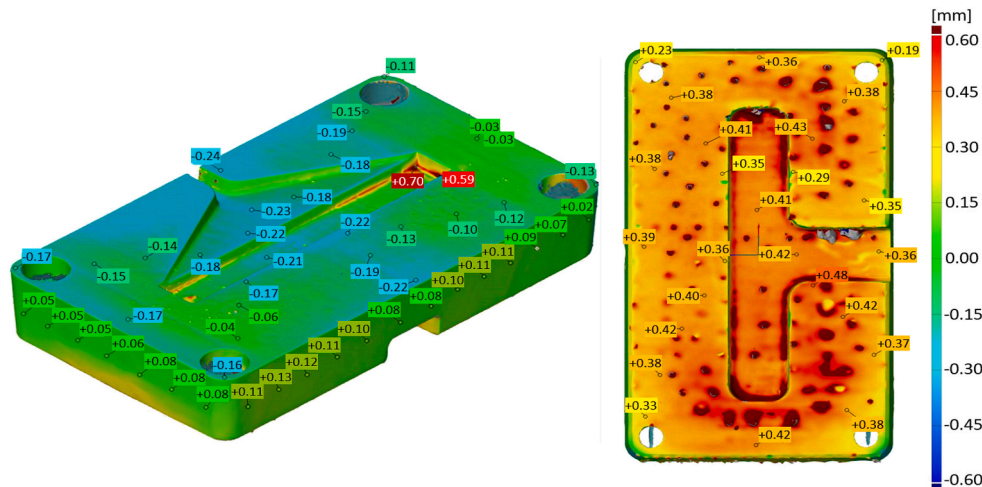


Fig. 8. The dimensional accuracy of the as-printed injection mould insert.

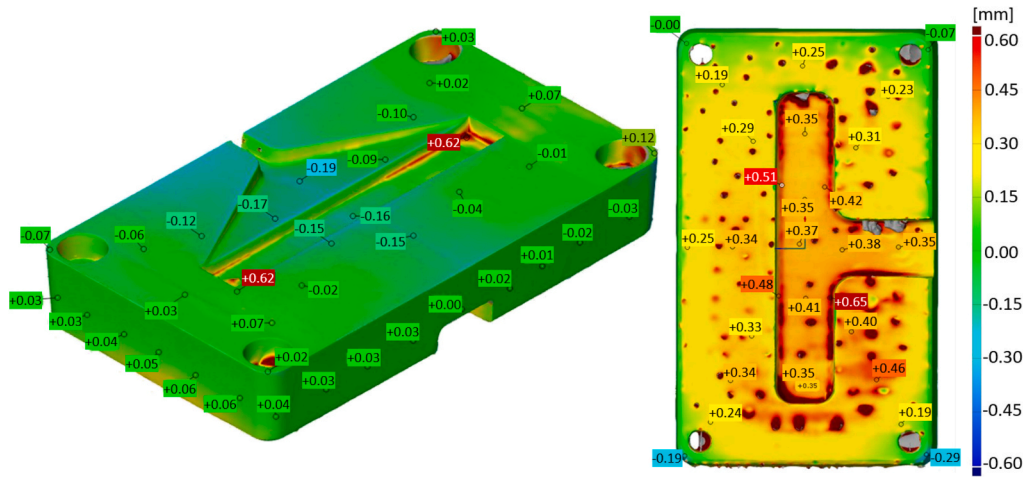


Fig. 9. The dimensional accuracy of the post-cured injection mould insert.

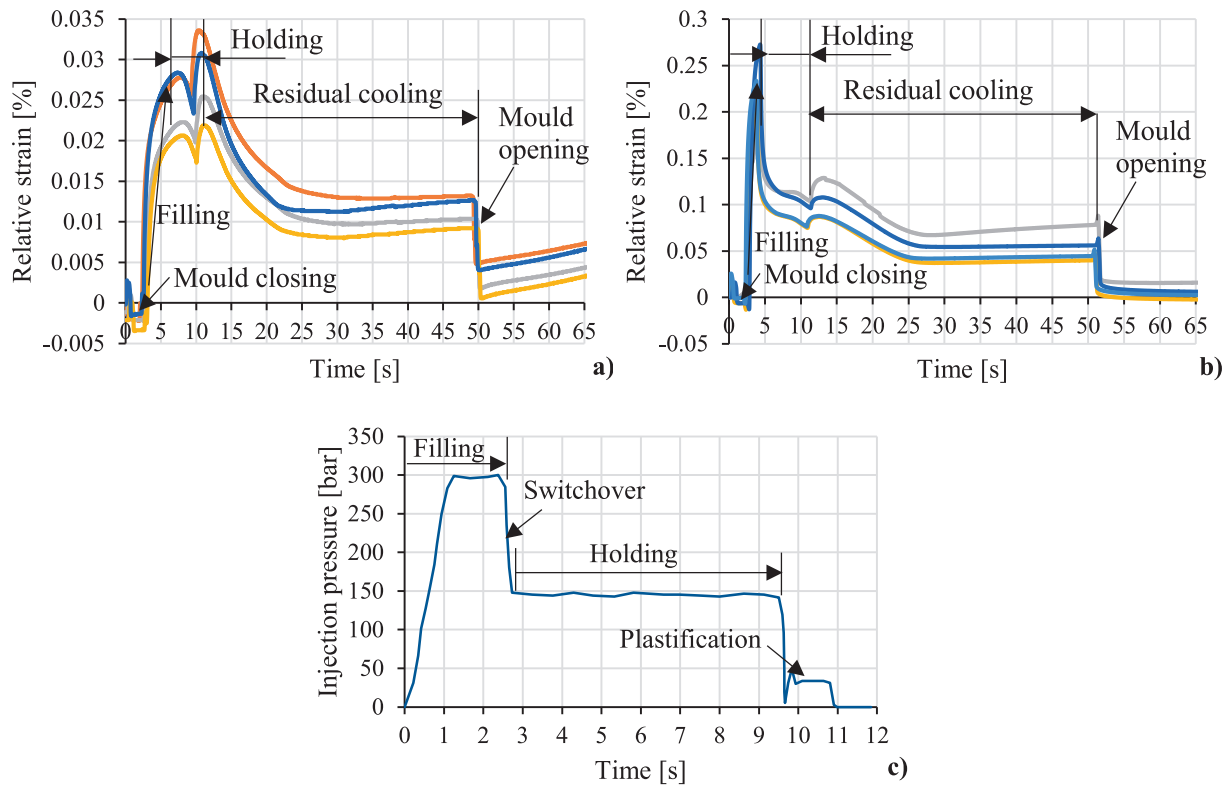


Fig. 10. Operational strain of the injection mould insert when no reinforcement insert was included a) and when overmoulding on the rib reinforcement insert b). Injection pressure as function of time when overmoulding on the rib reinforcement insert c).

The operational strain of the mould insert is shown in Fig. 11 a) and b), when the grid reinforcement inserts with 35% infill and 25% infill, respectively, were overmoulded. The shape of the strain curves are fundamentally similar to the curves which were measured during the overmoulding on the rib reinforcement insert. A higher infill ratio resulted in increased strain of the mould insert because of the decrease in free cavity volume. The operational behaviour of the gyroid reinforcement inserts was similar. Fig. 12 a) shows the strain of the injection mould insert during overmoulding on the gyroid reinforcement insert with 35% infill while Fig. 12 b) shows the strain of the gyroid insert with 25% infill. Maximum strain values of $0.22\% \pm 0.003\%$ and $0.19\% \pm 0.004\%$ were measured during overmoulding on the grid insert with 35% infill and 25% infill, respectively. The gyroid inserts produced

decreased maximal operational strain of $0.20\% \pm 0.002\%$ and $0.18\% \pm 0.002\%$ during overmoulding on the reinforcement insert with 35% and 25% infill, respectively. The overmoulding process is stable and repeatable in all cases because the strain curves show minimal scatter. The overmoulded products also showed dimensional stability. These prove the adequacy of the time-regulated and pressure-limited injection moulding method.

The operational temperature of the injection mould insert was also measured in the idle time between the cycles, during the open state of the mould. The thermal imaging camera is an excellent tool, which can help increase the lifetime of polymeric injection mould inserts because it is an easy-to-install, contactless measurement method which gives real-time information for the setting of injection moulding parameters. A

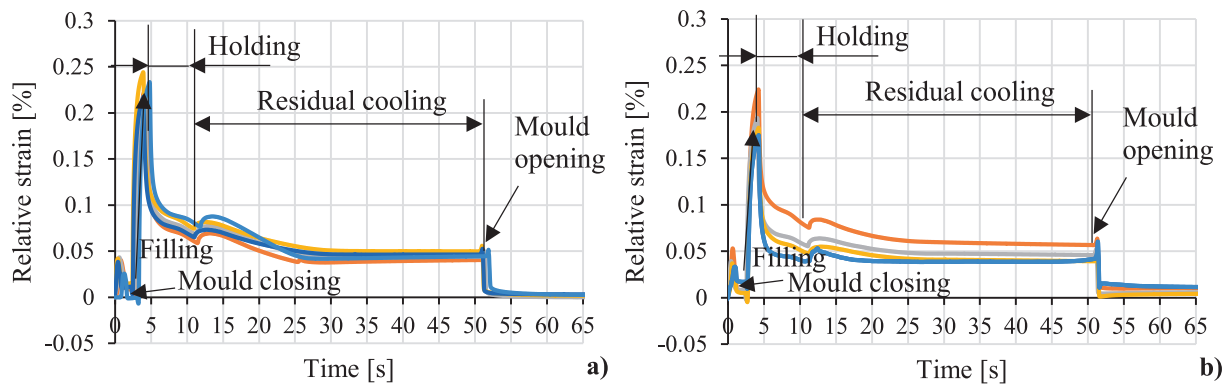


Fig. 11. Operational strain of the injection mould insert during overmoulding on the grid reinforcement insert with 35% infill a) and 25% infill b).

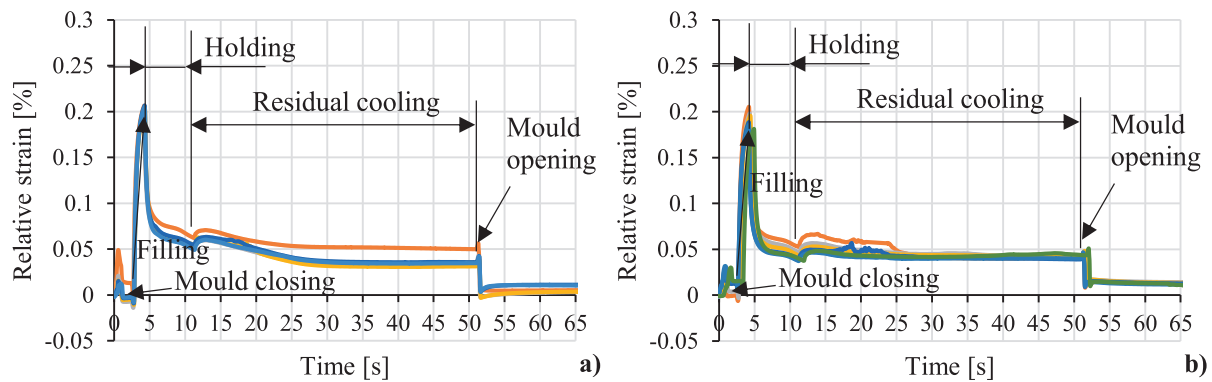


Fig. 12. Operational strain of the injection mould insert during overmoulding on the gyroid reinforcement insert with 35% infill a) and 25% infill b).

general recommendation is to keep the surface temperature of the polymeric injection moulds below their glass transition temperature.

Fig. 13 a) shows four thermal imaging camera images of the mould at characteristic time points. The limited thermal conductivity of the resin

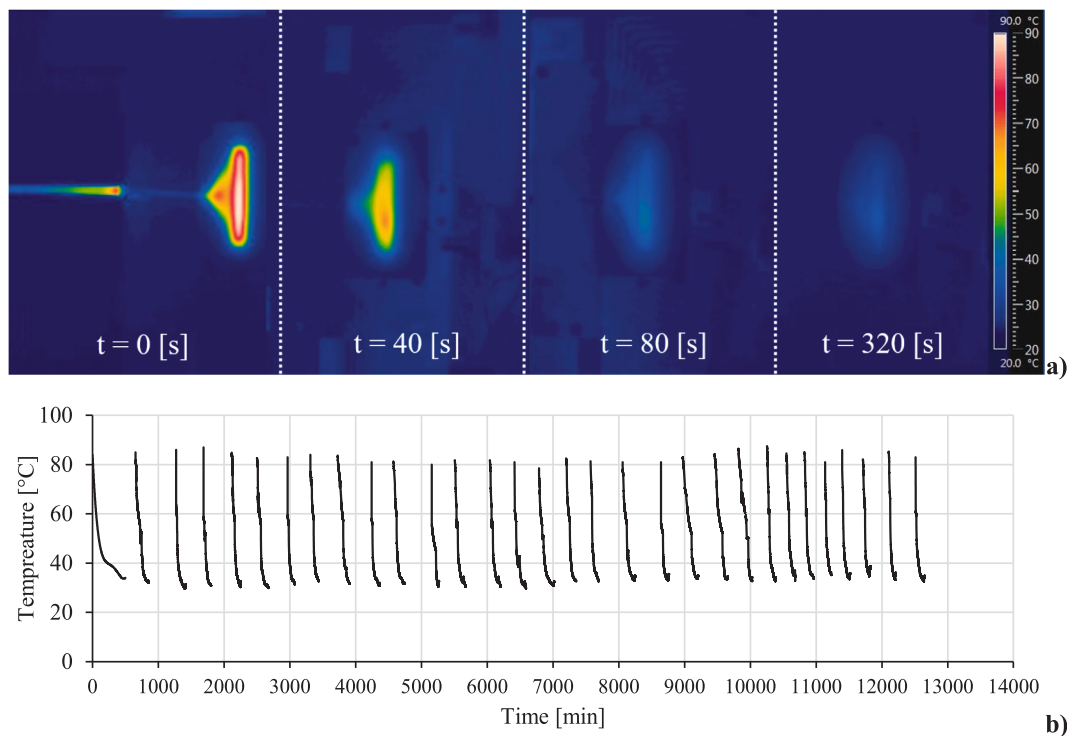


Fig. 13. Surface temperature of the injection mould insert during overmoulding on the rib reinforcement insert a). Cavity surface temperature of the injection mould insert during production b).

resulted in a strongly localised heated zone around the cavity surface. Heat dissipation is relatively slow, therefore a long idle time (200 s) is required between the cycles to prevent overheating and the early failure of the insert. The Clear resin has a relatively high T_g , and sufficient strength, stiffness and resistance to shock loads (Table 1). Fig. 13 b) shows the surface temperature of the cavity of the mould insert as a function of time. Maximal surface temperature is measured at mould opening and it varies in the 79–86 °C range, which is below the T_g of the material with a proper safety margin. We applied compressed air cooling in the idle times between the cycles to enhance the cooling of the mould insert. Idle time was set to allow the mould insert to cool to the 30–35 °C range, which is suitable to prevent the early failure of the insert. The inclusion of the different reinforcement insert geometries did not have a significant effect on the surface temperature of the mould insert.

The fill pattern was measured with the high-speed camera (Fig. 14 a) for the rib insert, b) for the grid insert with 35% infill and c) the gyroid insert with 35% infill). The tendency with 35% infill is similar to the fill patterns of the inserts with 25% infill. The lowest fill time during the

overmoulding tests was reached with the rib insert because of its relatively simple geometry. The fill times were 1.1 s for the rib insert, 1.7 s for the grid insert with 35% infill and 2.1 s for the gyroid insert with 35% infill. As the complexity of the reinforcement inserts grew, so did cavity fill time, which is in accordance with preliminary expectations. The shape of the flow front also became very complex in the case of the grid 35% and the gyroid 35% inserts as the melt front was split and recombined several times. It has to be considered during the design of the reinforcement inserts that the splits in the melt front act as weak spots because air traps and weld lines are formed there.

Therefore, the insert design has to be a well-informed compromise between the beneficial reinforcing effect of the insert and the weakening effect of the air traps and weld lines in the matrix material that form during the cavity filling. To support the design process, preliminary Autodesk Moldflow simulations were performed to identify potential air-trap and weld-line locations and to estimate insert deformation using Core Shift analysis. Fig. 15 presents the predicted deformation of the gyroid insert with 35% infill, which showed good qualitative agreement

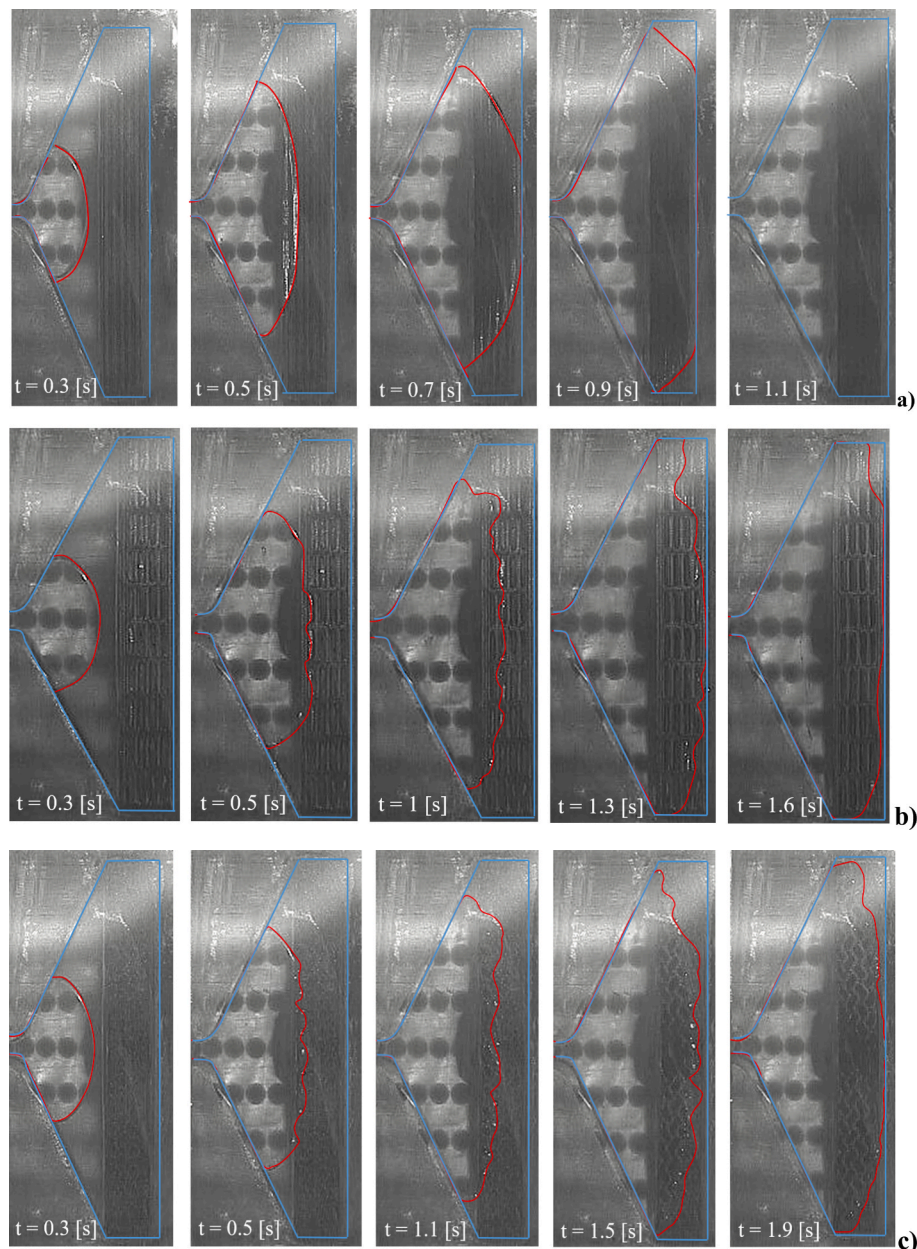


Fig. 14. The measured fill pattern during overmoulding on the rib insert a), the grid insert with 35% infill b) and the gyroid insert with 35% infill c).

with the insert deformation observed by high-speed imaging during cavity filling (Fig. 14 c)). A systematic simulation-driven optimisation of the insert geometries will be the subject of future work.

3.3. Scalability of the FFF printing-overmoulding hybrid process

Injection moulding is generally a large-volume technology, while FFF is a low-volume, prototyping method. The proposed hybrid overmoulding process, which applies photopolymer moulds, is applicable in the small series and customised production of injection-moulded parts (around one hundred parts), which is highly beneficial during the product development process. If the injection mould is manufactured with conventional machining from aluminium, then the cycle numbers can be extended into the several thousand range. In the present study, the injection moulding cycle time was 267 s (including the delay time between the cycles) mainly because of the cooling requirement of the photopolymer injection mould. The cycle time of injection moulding with an aluminium mould is a fraction of that because of the outstanding thermal performance of aluminium.

The printing times of the different reinforcement inserts in continuous production are summarised in Table 4. The printing times are completely comparable to the long injection moulding cycle time, which can be reached with the polymeric injection mould. Another advantage of the printing process is that it is scalable much faster and easier than injection moulding because of the low price, technical simplicity, easier maintenance and low energy consumption of FFF printers, compared to conventional injection moulding machines. Because of this, several FFF printers can serve a single injection moulding machine simultaneously. Insert placement into injection moulds is already a well-elaborated and automated production step. This way, the proposed hybrid overmoulding process can be extended into the middle volume production range (even by metallic moulds). The presented insert overmoulding production strategy has clear practical relevance when producing functional prototypes, customised parts in low and middle volumes and high-added-value technical components where load-bearing capacity is essential.

3.4. Mechanical and thermomechanical characterisation of the hybrid structures

3.4.1. Three-point bending

Fig. 16 a) shows the test arrangement and Fig. 16 b) shows the

Table 4

The printing time of the different reinforcement structures.

Insert geometry	Printing time of a single insert [s]
Rib	312
Grid 25%	354
Grid 35%	431
Gyroid 25%	334
Gyroid 35%	437

measured average flexural stress–strain curves with the standard deviations. Table 5 contains the flexural modulus and flexural stress at conventional deflection (according to ISO 178). The highest flexural modulus was reached with the grid 25% insert, while the highest flexural stress at conventional deflection was achieved with the rib insert. The rib insert was placed on the tensile side of the specimen during the bending test. Both geometries are effective reinforcements for bending because the rib insert reinforces the most loaded, outer layer of the specimens and the grid insert also has material in the outer layer of the structure. The increase in flexural modulus is 74% in the case of the grid 25% insert and 63% in the case of the rib insert, compared to the neat PP specimen. The stress at conventional deflection grew by 46% in the case of the rib insert and 38% in the case of the grid 25% insert. The grid insert is a closed-cell reinforcement structure which is suitable for quasi-static bending load. The gyroid inserts also increased the strength and stiffness of the part compared to neat PP but the reinforcing effect is limited (14% in stiffness for the gyroid 25% insert and 2% for the gyroid 35% insert). This behaviour can be attributed to the open-cell architecture of the gyroid structures, which provides favourable energy absorption capability but lower resistance against quasi-static loads [32,33]. Another important result of the bending test is that increasing the infill density of the cellular structures does not increase strength and stiffness; it may even have an opposite effect. It is because the denser cellular structure results in more difficult cavity filling and an increased number of weld lines and air traps during injection moulding. Therefore, the infill density of the reinforcement structures has to be optimised by considering both reinforcing efficiency and the resulting manufacturability of the hybrid structures.

The overmoulded specimens (after the three-point bending tests) are presented in Fig. 17 for the five different insert geometries. Overmoulding was successful because the injected polypropylene completely filled the cellular structures. The presented specimens were cut 10 mm

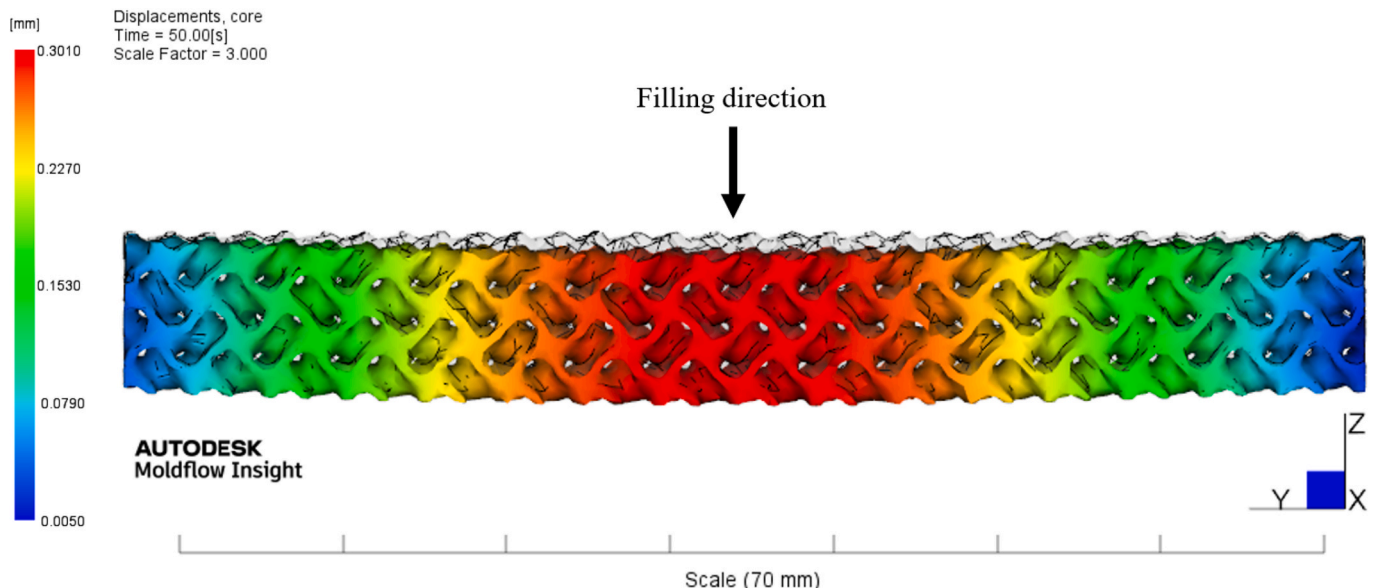


Fig. 15. The deformed shape of the gyroid 35% insert after overmoulding. The deformation scale factor is ($\times 3$).

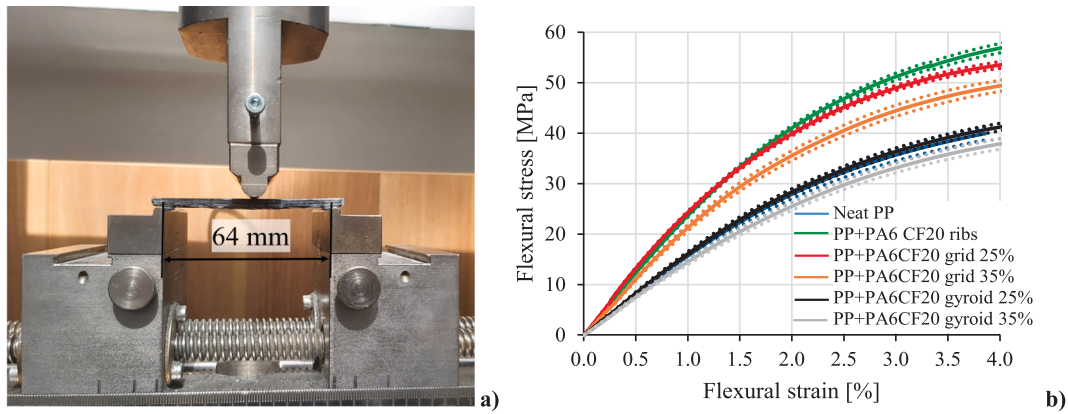


Fig. 16. The measurement arrangement a). The flexural stress–flexural strain curves of the different specimens b). The averages of the curves are shown by the continuous lines, while the standard deviations are indicated by dotted lines.

Table 5

The flexural modulus and flexural stress in the case of conventional deflection for the different specimens.

Specimen name	Flexural modulus [MPa]	Flexural stress during conventional deflection (at 3.5%)
Neat PP	1472 ± 130	37.3 ± 2.2
PP + PA6.6 CF20 ribs	2405 ± 50	54.6 ± 1.5
PP + PA6.6 CF20 grid 25%	2563 ± 79	51.7 ± 1.1
PP + PA6.6 CF20 grid 35%	2183 ± 193	47.7 ± 2.1
PP + PA6.6 CF20 gyroid 25%	1681 ± 135	39.6 ± 1.3
PP + PA6.6 CF20 gyroid 35%	1500 ± 108	36.4 ± 1.9

from the end to better show their internal structure.

3.4.2. Charpy impact test

Table 6 shows the results of the impact tests. The impact strength of the specimens with a grid or gyroid structure were considerably less. The decrease in impact strength was the lowest in the case of the gyroid 25% insert, which proves that the open-cell gyroid structure is more suitable for impact loading than the closed-cell grid structure. On the other hand, the rib insert increased impact strength by an additional 107%, which is a very significant improvement considering that polypropylene and polyamide 6.6 are chemically incompatible polymers. The conclusion from the impact test is that the proper choice of reinforcement insert geometry is essential because it hugely influences impact strength either

Table 6

The Charpy impact strength results of the various specimens.

Specimen name	Charpy impact strength [kJ/m ²]
Neat PP	24.4 ± 4.8
PP + PA6.6 CF20 rib	50.5 ± 9.4
PP + PA6.6 CF20 grid 25%	11.3 ± 1.7
PP + PA6.6 CF20 grid 35%	12.3 ± 0.5
PP + PA6.6 CF20 gyroid 25%	18.3 ± 3.5
PP + PA6.6 CF20 gyroid 35%	12.9 ± 2.1

positively or negatively.

Fig. 18 shows the broken Charpy impact test specimens. Fracture occurred in the midplane of the specimens where the shock load acted on the inserts. Fracture surfaces were relatively straight for all inserts except the grid 25% insert. In the case of the grid 25% insert, the fracture surface is mainly determined by the cellular reinforcement structure. The grid structure with 25% infill has a higher cell size compared to the 35% infill structure. This causes the relatively complex fracture surface.

3.4.3. Dynamic mechanical analysis

The thermomechanical performance of the different specimens was characterised by dynamic mechanical analysis. Fig. 19 a) shows the storage modulus and b) shows the loss factor as a function of temperature. The storage modulus characterises temperature-dependent stiffness, while the loss factor highlights any potential phase changes of the material. Table 7 contains the storage moduli of the different specimens at different temperatures. The two specimens reinforced with the grid inserts performed best among the analysed specimens. The specimen

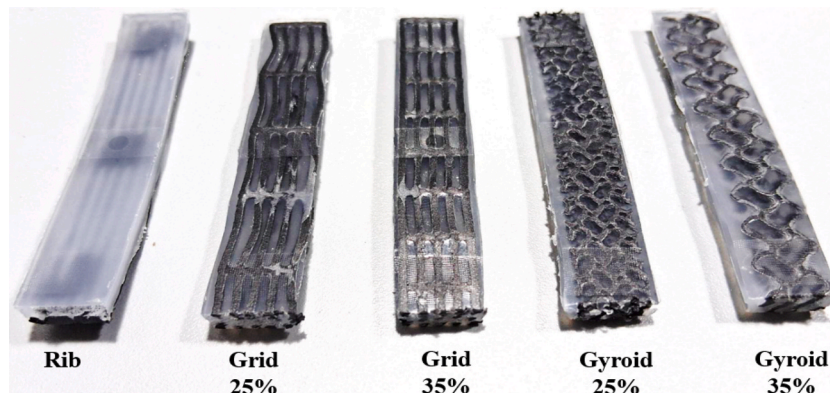


Fig. 17. The overmoulded hybrid structures after the three-point bending tests.

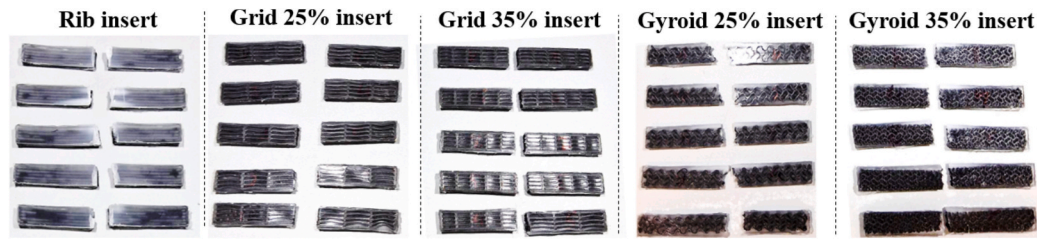


Fig. 18. The broken Charpy impact test specimens.

with the grid 25% insert showed the highest modulus in the entire analysed temperature region. At room temperature, the storage modulus of the specimen with the grid 25% insert was 28% higher and its modulus was higher in the entire analysed temperature range. At elevated temperatures (125 °C and 150 °C), the difference in modulus grew to 42% and 86%, respectively, which is a significant improvement. The loss factor curves indicate no significant state change in the specimens in the analysed temperature range, which is in accordance with our expectations because the analysed temperature range is above the T_g of the PP matrix material but below its melting point. The DMA tests prove that an appropriate part reinforcement geometry significantly improves the thermomechanical performance of hybrid structures, which has clear practical relevance.

3.4.4. Statistical significance analysis

One-way ANOVA test was performed on the flexural modulus, the flexural stress at conventional deflection and the Charpy impact test data. The main parameters of the one-way ANOVA test are presented in Table 8. The F value for 5 degrees of freedom between the groups and 24 degrees of freedom within the groups exceeded the $F_{critical}$ in all cases, indicating that the analyses were significant. The p values were less than 0.001, which fall below the critical level of 0.05. This indicates that the means of the six groups show statistically significant differences.

Tukey's honestly significant difference (HSD) test was also performed to check if there are statistically significant differences between the mean mechanical properties of the neat PP and the different hybrid structures. HSD was calculated according to Eq. (2).

$$HSD = q \cdot \sqrt{\frac{MS_w}{n}} \quad (2)$$

where: q is the value from the studentized range table, MS_w is the mean squares within the groups, and n is the number of measurements. Table 9 shows the results of the HSD post-hoc test when comparing the mean flexural modulus, the mean flexural stress at conventional deflection and the mean Charpy impact strength of the neat PP specimens to the respective means of various reinforced structures. The HSD test proved that the rib insert and the two grid inserts (with 25% and 35% infill)

Table 7

Storage moduli of the analysed specimens at different temperatures.

Specimen type	Storage modulus at various temperatures [MPa]					
	25 °C	50 °C	75 °C	100 °C	125 °C	150 °C
Neat PP	1263	895	536	346	216	104
PP + PA6.6 CF20 rib	1279	749	461	349	261	155
PP + PA6.6 CF20 grid 25%	1613	926	554	413	308	193
PP + PA6.6 CF20 grid 35%	1494	870	523	388	285	176
PP + PA6.6 CF20 gyroid 25%	1118	729	430	292	193	101
PP + PA6.6 CF20 gyroid 35%	1204	758	452	313	214	119

Table 8

Results of the one-way ANOVA test.

Tested quantity	F [-]	$F_{critical}$ [-]	p [-]
Flexural modulus	49.08	2.62	<0.001
Flexural stress at conventional deflection	67.62	2.62	<0.001
Charpy impact strength	35.01	2.62	<0.001

improved all three analysed mechanical properties statistically significantly. The gyroid inserts did not cause statistically significant differences in the analysed mechanical properties except for the Charpy impact strength of the structure with 35% infill.

3.4.5. Optical microscopy

We used optical microscopy to analyse the fracture surfaces of the Charpy impact test specimens (Fig. 20). The higher toughness of the structure with the rib insert is visible on the fracture surface because the area of the ductile crack propagation zone is relatively high compared to the brittle fracture zone. The overmoulded PP showed good conformity around the printed reinforcement structure, as there were no interfacial voids. The grid reinforcement inserts exhibited smaller ductile crack propagation zones and considerably larger brittle fracture regions. The

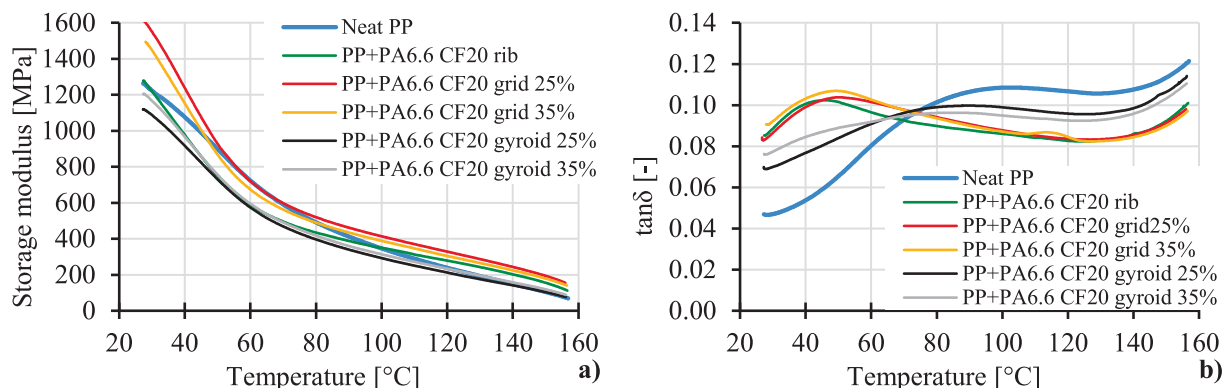


Fig. 19. The storage modulus a) and the loss factor b) of the specimens with different reinforcement geometries.

Table 9

Results of the HSD post-hoc test.

Comparison	Flexural modulus (HSD = 298 [MPa])		Flexural stress at conventional deflection (HSD = 4.15 [MPa])		Charpy impact strength (HSD = 9.15 [kJ/m ²])	
	Absolute difference of means [MPa]	Significant difference	Absolute difference of means [MPa]	Significant difference	Absolute difference of means [kJ/m ²]	Significant difference
PP – PP + rib	933	Yes	17.28	Yes	26.07	Yes
PP – PP + grid 25%	1091	Yes	14.35	Yes	13.17	Yes
PP – PP + grid 35%	711	Yes	10.34	Yes	12.18	Yes
PP – PP + gyroid 25%	208	No	2.30	No	6.16	No
PP – PP + gyroid 35%	28.5	No	0.88	No	11.59	Yes

crack propagation zone is located around the outer contour of the specimens while the brittle fracture zone closely correlate with the volume of the reinforcement structure. This sharp contrast can be attributed to the limited interfacial adhesion of the PA 6.6 CF20 reinforcement and the overmoulded PP [37]. The fracture surface of the gyroid 25% and 35% inserts also show large brittle fracture zones and even air traps, which are caused by the complex cavity filling of the gyroid forms. One larger air trap can be observed in the 25% infill gyroid specimen and several smaller air traps can be observed in the 35% infill specimen. These voids act as local stress concentrators and reduce the strength of these hybrid structures.

3.4.6. Dimensional accuracy of the mould insert after the injection moulding series

The dimensions of the injection mould insert were measured by 3D scanning after the injection moulding series, and the results are presented in Fig. 21. The deformations were mainly localised on the cavity surface because that is the area where the cyclic pressure and heat load act on the mould insert. This cyclic load causes tool wear and cavity surface deterioration. Cavity surface deformations ranged from + 0.43 mm to − 0.22 mm, indicating that the specimens could be injection moulded with adequate dimensional accuracy. The fan gate area did not

show significant residual deformations, which proves the adequacy of the gate design. The clamping surface of the injection mould insert showed slight residual deformations, especially around the shorter edges of the cavity. Maximal deformations were + 0.21 mm and + 0.19 mm. The 3D scanning results show that the insert survived the injection moulding series, but localised residual deformations remained in the cavity.

4. Conclusions

This article presents the novel concept of injection overmoulding on additively manufactured, fibre-reinforced thermoplastic cellular reinforcement inserts. The injection mould inserts were produced by stereolithography. The different reinforcing and cellular structures were printed by fused filament fabrication from carbon fibre-reinforced polyamide 6.6 (ribs, grids with 25% and 35% infill density, and gyroids with the same densities). These inserts were overmoulded with polypropylene because of its excellent flowability and low required melt temperature. Operational strain measurements of the polymeric mould insert showed that the printed reinforcement inserts increased the operational deformation of the injection mould insert and higher infill density resulted in higher deformation. Thermal imaging camera

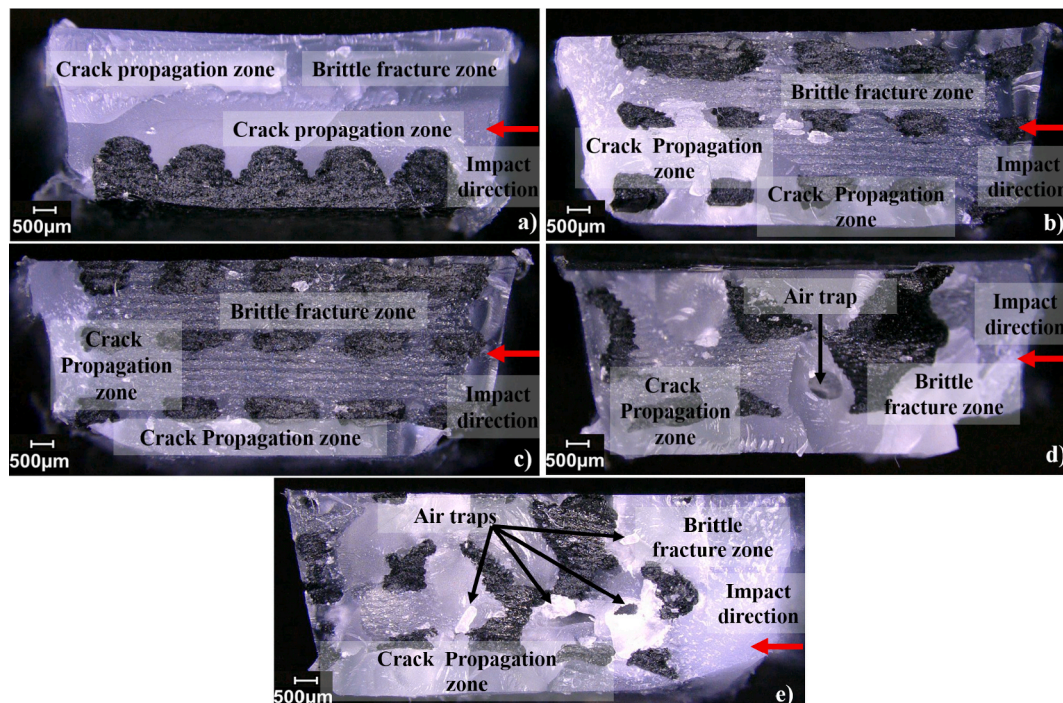


Fig. 20. Optical microscopic images of the different specimens. Rib insert a), grid 25% insert b), grid 35% insert c), gyroid 25% insert d), gyroid 35% insert e).

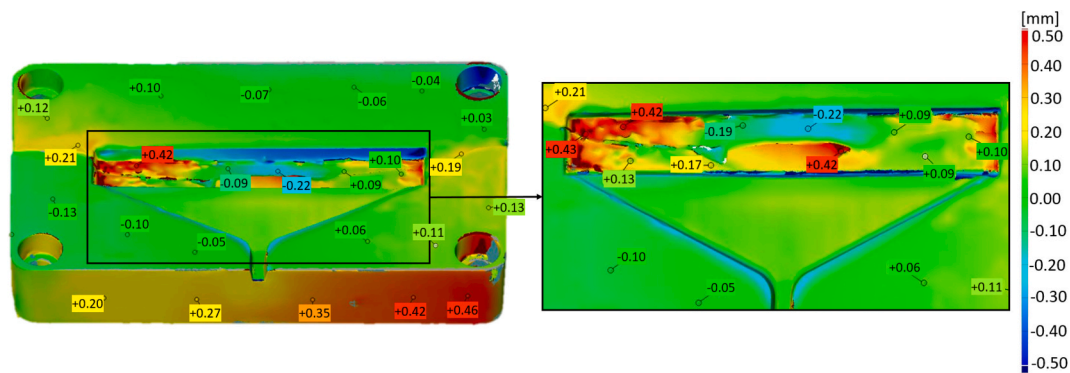


Fig. 21. The dimensional accuracy of the injection mould insert after use.

measurements showed that the reinforcement inserts did not have an effect on the thermal state of the polymeric mould. High-speed camera measurements highlighted that more complex insert geometries with higher infill ratios result in slower cavity filling, and increase the number of air traps and weak spots. After a thorough investigation of the overmoulding process, the produced hybrid structures were mechanically characterised. The performance of the inserts under quasi-static load were characterised by three-point bending tests. The grid 25% insert performed the best; it produced a 74% increase in flexural modulus and a 38% increase in stress at conventional strain, compared to neat PP specimens. The other grid insert and the rib insert also showed considerably increased modulus and strength but the gyroid inserts exhibited nearly identical results to neat PP. We also performed Charpy impact testing to evaluate the behaviour of the hybrid structures under dynamic loading. The rib insert showed the best impact strength (a 107% increase compared to neat PP). The other insert geometries showed worse performance, which is most likely explained by the incompatibility of the PP matrix and the PA 6.6 CF20 reinforcement. The gyroid inserts still outperformed the grid inserts under dynamic loading. The thermomechanical performance of the different hybrid structures was analysed by dynamic mechanical analysis. The grid structures and the rib structure substantially increased the stiffness of the structures at 25 °C. The storage modulus of the grid 25% hybrid structure was 28% higher than that of neat PP. The increase in stiffness remained even at higher temperatures (up to 150 °C), where the difference grew to 86%. DMA proved that these hybrid cellular structures extend the applicability of the parts even to high temperatures, where the unreinforced injection moulded structures are no longer applicable. The results of this article can provide a deep insight into the processability, and the static and dynamic mechanical and thermomechanical performance of injection moulded hybrid components, reinforced with additively manufactured cellular structures. The presented approach provides new opportunities for the localised reinforcement of injection moulded components in lightweight engineering applications. Future studies will focus on the optimisation of the reinforcement geometries, the interfacial adhesion between the matrix and the reinforcement structures, and the additive manufacturing of lightweight cellular reinforcement structures with enhanced energy absorption capability.

CRedit authorship contribution statement

Szabolcs Krizsma: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **András Suplicz:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Márton Tomin:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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