POLYMER CAVITY MADE BY FREEFORMER® 3D PRINTER: AN INFLUENCE ON INJECTION MOULDED PARTS

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Injection moulding is a major technology in mass production of high quality plastic and composite parts. On the other hand, additive technology is suitable for prototyping, but produced parts do not reach as high mechanical properties as injection moulded parts do. Main advantage of additive technologies is production without expensive injection moulds. Polymer injection mould cavity inserts made by an additive technology use advantages of both mentioned technologies. Moreover, Arburg Freeformer® system presumes high quality parts made of common plastic granules.
On the contrary, polymers are thermal insulators, therefore different cooling conditions cause differences in morphology.
Removable injection mould cavity inserts from ABS and PA 10 were made using Freeformer system. The main goal was to study crystallization, morphology and thermo-mechanical properties of PP (Polypropylen) parts produced by injecting to polymer mould.

KEYWORDS

injection moulding, prototyping, additive manufacturing, Arburg Freeformer®, polymer inserts

1 INTRODUCTION

Injection moulding technology is mostly used for mass production. More than one part is often made in one operation. Typical products are high quality plastic parts of various shapes. High dimensional accuracy and short cycle time is given by precise moulds (hundredths of millimetres) usually made of steel (high temperature conductivity). High quality moulds are expensive, therefore, great emphasis is placed on product development process. [Stoeckert 1998] [Kazmer 2007]
Demand for faster product development in injection moulding increases popularity of rapid prototyping (RP) technologies. RP is used for direct mould fabrication the same as for product patterns making. Use of RP technologies in product development process can reduce delivery of final tool by 50 % or even more. [Levy 2003]

Injection moulding

Injection moulding machine is used for injection process. Machine consists of two main units, clamping and injection unit. Clamping unit manage mould opening and closing, injection unit processes polymer melt which is injected into the mould through nozzle. Process control unit and hydraulic, electric or combined power supply are also essential components. Injection moulding manufacturing is a cyclic process that consists of plastification (polymer melt preparation) followed by filling process (the molten plastic is injected into the mould). Product quality is influenced by filling process parameters: mould temperature, filling pressure, molten polymer temperature and also holding pressure, which is used for shrinkage elimination, and cooling conditions. One or more products are ejected after cooling which is usually the longest part of cycle time because of low thermal conductivity of polymers. [Stoeckert 1998] Very low thermal conductivity (typically 0.1-1 $Wm^{-1}K^{-1}$) is caused by poorly crystalline structure. Heat is transmitted by phonons and conduction electrons in solids but phonons cannot diffuse easily in polymer semi crystalline structure. [Henry 2013]

Additive Manufacturing (AM) – Arburg Freeformer®

Beginning of mass production is the most demanding phase. It is time consuming and also expensive. Prototyping is often required, even patterns of prototype tools are needed in order to verify product dimensions and mechanical properties the same as tool design. Cost-effective prototypes can be made quickly by AM. Directly fabricated parts are generated by 3D CAD systems without any complex process planning.
How does it work, AM is a 3D object making layering process. Material is consequently added in each layer as a thin cross section of a 3D object. It means that accuracy of AM made parts is based on accuracy of a particular AM technology and on invested time given by the amount of layers. Higher AM machine accuracy and smaller cross sections mean longer production time but higher shape similarity to real product. Used materials make major differences in AM technologies the same as a way how the layers are created and bonded to each other. [Gibson 2015]
Additive Manufacturing using Standard Granulate is possible thanks to Arburg Plastic Freeformer®. Principle of freeforming is in fact based on injection moulding. Plastic granulate is melted in cylinder unit. Homogenized plastic melt is transported in front of a three zone screw to the nozzle tip and variable pressure is applied. Additive manufacturing process is realized by a discharge unit. Plastic droplets are generated using nozzle closure at variable frequency. Deposited droplets build up 3D objects layer by layer onto a movable part carrier in a build chamber. Arburg freeforming process is shown in fig.1. [Neff 2014]

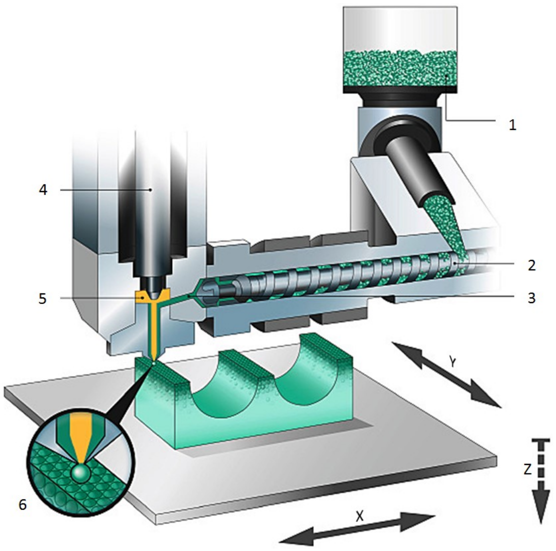

Figure 1. Arburg plastic freeforming process:
1-Conventional granulate
2-Material preparation with screw (comparable to injection moulding)
3-Material reservoir between screw and nozzle tip is under pressure
4-Piezo actuator performs pulsed nozzle closure
5-Nozzle closure
6-Discharge of individual droplets from the nozzle tip
[ARBURG GmbH 2017a]

Every Freeformer® machine consists of two discharge units that can be used for various materials. Material combination possibilities are:

- Two same materials of different colours
- Building material + supporting material
- Two different building materials (two component AM), p. e. combination of hard and soft material or core and contour combination

One basic ruler exists for any material being used. The more densely the droplets are positioned in relation to one another, i.e., the more tightly the parts are "packed", the higher the mechanical properties. [Arburg GmbH 2017a]

Compact design and needs of Freeformer® allows even office use. On the other hand, build chamber size does not allow a huge part production. Despite this, compact final products can be made is small series.

Basic technical data:

Maximal material (injection) pressure: 75 MPa
Build chamber temperature: 50-120°C
Processing temperature: max 350°C
Part size (one nozzle use): 189 x 134 x 230 mm
Part size (two nozzle use): 154 x 134 x 230 mm
Nozzle diameter: 0.15-0.3 mm (basic version: 0.2 mm)
Wall thickness: min. 0.6-1 mm (basically 0.8 mm for ABS)
Absolute part precision: ±0.15 mm (x,y axis; for ABS)
[Arburg GmbH 2017b]

Freeforming can be used not only for prototyping but also for final product manufacturing. Even small-volume batches can be produced in any industrial sector at a high quality. On the contrary, injection moulding is a major technology in mass-production of high quality plastic and composite parts. Because of different production conditions, parts made by injection moulding reach higher accuracy dimensions the same as better mechanical properties. Using advantages of both technologies, injection moulding and additive manufacturing, is possible at the same time. Polymer injection mould cavity inserts made by an additive technology could be useful during product development process ahead of time consuming and expensive steel mould machining. Despite these advantages, polymer's thermal conductivity is hundred times lower than that of steel. Therefore, cooling conditions are different and can cause differences in morphology that can cause also differences in final product visual and mechanical properties.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 *Test part design*

Simple block was chosen as a very simple specimen that can be easily tested.
Block dimensions: 120 x 10 x 4 mm
Cross section was designed according to the methodology of injection moulding part design using demoulding angels of 2°.

2.2 *Freeformer® made cavity inserts design and fabrication*

First of all, universal mould frame for removable cavity inserts was needed. Small plate with cooling and assembling elements was designed in order to use parts of existing specimen making mould. Tool steel 1.2312 (40CrMnMoS8-6) was used. Dimensions predetermined one or two cavity mould. Because of block dimensions, two cavity solution was chosen. Basic cold runner was used in combination with film gate. Film gate cross section dimensions were 10x4 mm in order not to cause any forces that could damage plastic inserts.

Basic dimensions of cavity inserts are shown in fig. 2. Orange is polymer insert screwed (shoulder screw) to steel plate (green) that includes drilled cooling channels. Blue steel shims position insert in a right place.

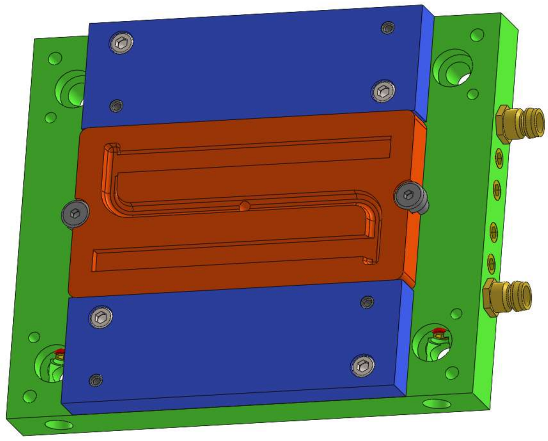

Figure 2. Universal mould frame with cavity insert

Cavity inserts of 15 mm thickness were made by Arburg Freeformer® using original plastic granulates – PA 10 (Grilamid® XE 4010) and ABS (Terluran® GP35) without any post processing. ABS was chosen as a basic widely used material in additive manufacturing technology. PA 10 is a representative of a polymer with higher mechanical and thermal properties. Basic mechanical and thermal properties can be seen in tab. 1 and 2. Both materials are directly supported by Arburg GmbH®.

Table 1. Mechanical and thermal properties of PA 10 (Grilamid® XE 4010) [Prospector 2018]

Mechanical Properties	**Test Method**	**Metric value**
Nominal Strain at Break, 23 °C	ISO 527-2	>50 %
Tensile Modulus	ISO 527-2	1 700 MPa
Hardness, Ball Indentation	ISO 2039-1	110 MPa
Thermal Properties	**Test Method**	**Metric value**
Glass transition temperature (10°C/min)	ISO 11357-1/-2	118°C
Coefficient of Linear Thermal Expansion	ISO 11359-1/-2	$100\ 10^{-6}K^{-1}$
Melt temperature		220-260 °C

Table 2. Mechanical and Thermal properties of ABS (Terluran® GP35) [Ineos Styrolution 2016]

Rheological properties	**Test Method**	**Metric value**
Melt Volume Rate 220 °C/10 kg	ISO 1133-1	$34\ cm^3/10$ min
Mechanical Properties	**Test Method**	**Metric value**
Nominal Strain at Break, 23 °C	ISO 527	12 %
Tensile Modulus	ISO 527	2 300 MPa
Hardness, Ball Indentation	ISO 2039-1	99 MPa
Thermal Properties	**Test Method**	**Metric value**
Vicat Softening Temperature VST/B/50 (50N, 50 °C/h)	ISO 306	95°C
Coefficient of Linear Thermal Expansion	ISO 11359	$80 – 110\ 10^{-6}K^{-1}$
Thermal conductivity	DIN 52612-1	$0.17\ Wm^{-1}K^{-1}$
Melt temperature		220-260 °C

Cavity inserts were placed on a moving mould side. Fixed part of mould was a steel plate which allows us to compare different heat transfer from opposite sides of injected specimen.

2.3 *Injected material*

One of basic injection moulding materials was used - PP (Mosten® MT 230). Typical applications of this PP are transparent thin-walled products for households. The most important properties were selected in tab. 3 including recommended processing conditions.

Table 3. Basic properties of injected PP (Mosten® MT 230) [Unipetrol 2018]

Rheological properties	**Test Method**	**Metric value**
Melt Mass Flow Rate (230 °C/2,16 kg)	ISO 1133-1	30 g/10 min
Moulding Shrinkage Parallel	ISO 294-3,4	2.03 %
Moulding Shrinkage Normal		2.45 %
Thermal Properties	**Test Method**	**Metric value**
Melting Temperature (DSC)	ISO 11357-1, 3	168-172 °C
Recommended processing conditions		**Metric value**
Melt temperature		200-280 °C
Mould temperature		20-60 °C

2.4 *Injection moulding into Freeformer® made cavity inserts*

Hydraulic injection moulding machine was chosen: Arburg 270S 400-100 (maximal clamping force: 400 kN, screw diameter: 25 mm, L/D ratio: 20).

Injection moulding parameters:

Melt temperature: 230°C

Clamping force: 400 kN

Maximal injection pressure: 32.5 MPa

Switch to holding pressure: 0.6 s

Cooling time inside mould: 60 s

Mould temperature (steel plates): 40 °C

2.5 *Injection moulding into steel mould*

Experimental cavity plate made of corrosive resistant steel (1.2316, hardness 50-60 HRC, mechanically polished cavity according to rules given for making injection moulded specimens) was used for product properties comparison.

Injection moulding parameters into steel cavity mould were similar to parameters used for injection moulding into additive technology made cavity inserts. Also cooling time was the same length but ejected products had different temperatures. Parts injected into polymer cavity inserts were ejected at higher temperature because of very low thermal conductivity of polymers.

2.6 *Experimental methods*

2.6.1 Measurement, microscope

Caliper was used to measure cavities and injected products in order to compare production from steel and plastic mould. Microscope was used to check surface of PA and ABS inserts (stereo microscope Olympus SZ61) and to observe differences in morphology caused by different cooling conditions (digital microscope Olympus DSX510).

2.6.2 Differential scanning calorimetry (DSC)

Differential scanning calorimetry, thermo-analytical technique was used to compare morphology of injected samples based on heat flow measurements. Comparison of relevant energy used for linear heating of the examined sample and reference is used to polymer type recognition and morphology evaluation.

The difference in morphology between injection moulded products into steel mould and Freeformer made cavity was observed using DSC device DSC1/700. An empty aluminium crucible was used as the reference sample. Test samples (10 ± 0.3 mg) were heated linearly (linear heating rate: $10\ ^{\circ}C \cdot min^{-1}$) in flowing atmospheres of nitrogen (flow rate $50\ ml \cdot min^{-1}$).

Crystallinity degree was determined from the difference of melting enthalpy, see equation (1). 207 $J \cdot g^{-1}$ was used as a theoretical enthlapy of fusion fully crystalline sample (value of isotactic PP is accurate enough in this case).

$$\chi_{CA} = \frac{\Delta H_m}{\Delta H_{m,100}} \cdot 100\ [\%] \qquad (1)$$

X_{ca} [%] - degree of crystallinity

ΔH_m [$J \cdot g^{-1}$] - enthlapy of fusion

$\Delta H_{m,100}$ [$J \cdot g^{-1}$] - theoretical enthlapy of fusion fully crystalline sample

2.6.3 Charpy Notched Impact Strength

Impact strength is tested by measuring energy absorbed by a standard specimen when being stroke. PP impact strength was tested using V-notched specimen because of high impact strength of this polymer. This test was chosen because of various notch toughness of specimen of various morphology and crystallinity caused by different cooling conditions.

Resil Ceast 5.5 device with Charpy hammer was used to measure absorbed energy using the standard Charpy V-notch specimen (notch type: 'A') according to ISO 179-1, see equation (2).

$$a_{CA} = \frac{KV_2}{h_N \cdot w} \cdot 10^3 \left[kJ \cdot m^{-2}\right] \qquad (2)$$

a_{CA} [$kJ \cdot m^{-2}$] - notch toughness; V-notch type 'A'

KV_2 [J] - absorbed energy

h_N [mm] - height of specimen without notch

w [mm] - width of specimen

3 RESULTS

ABS and PA 10 inserts were used for injection moulding but ABS insert was destroyed during second injection cycle. Because of ABS crash, another ABS insert was made but injecting finished in the same way as it is shown in fig. 3. First layer which was in contact with PP melt was broken and PP demolished part of the insert. Cohesion of ABS layer was insufficient for 230°C PP melt injection. For that reason, only samples injected into PA inserts were evaluated.

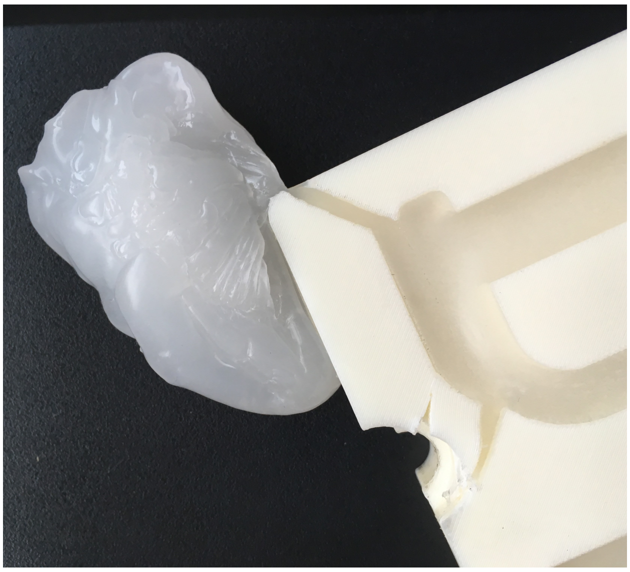

Figure 3. Damage of ABS insert during injection moulding

Surface of PA insert made by Freeformer® is compared to insert made by FDM technology in fig. 4. Freeformer® made insert indicates droplet chain determined by jetting technology.

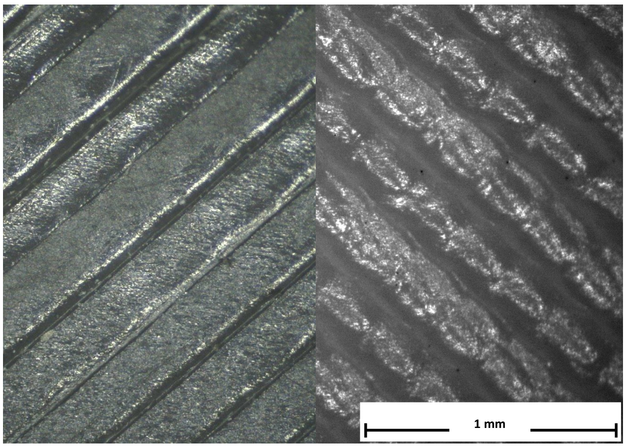

Figure 4. Comparison of FDM (on the left) and Freeformer made (on the right) insert surface

3.1 Measurement

Dimension differences of specimens injected into PA insert and steel mould were compared. Cavity depth, sample thickness and sink marks were measured. Dimension data are shown in tab. 4.

Table 4. Dimensions comparison: cavity depth, part thickness and sink marks

	Cavity depth [mm]	Part thickness (maximal) [mm]	Sink marks (maximal) [mm]
PA insert	4.17-4.22	4.28-4.32	0.42-0.85
Steel mould	4.19-4.21	4.20-4.21	0.08-0.12

Specimens injected into PA insert are thicker than the depth of cavity is. It means that cavity was deformed by melt pressure during injection. Enormous sink marks were caused by too slow cooling. Another reason is rough surface caused by layering freeforming technology that retains air film that cannot escape from the cavity during injection.

Visual properties are based on processing technology. Additive manufacturing layering technique causes rough surface which is well copied to injected parts. See fig. 5.

Figure 5. Specimen injected into PA cavity insert

3.2 Differential scanning calorimetry (DSC)

DSC was made in order to compare crystallinity of opposite sides of specimen made by injection into PA insert with a steel plate at a fixed side of injection moulding machine. Thickness of the surface layer used for DSC was 60 µm and was taken from the middle part of specimen.

Differences in morphology can be seen in first heating cycle which is shown in fig. 6. Differences in heat flow prove different morphology (crystallinity) of opposite sides of specimen caused by different cooling conditions. Average heat flow at PA insert side was 98.35 $J \cdot g^{-1}$ while that at steel side was only 90.63 $J \cdot g^{-1}$. It means that crystallinity at PA side is higher, 47.51%, against 43.78% at steel side. (Used melting enthalpy was 207 $J \cdot g^{-1}$.

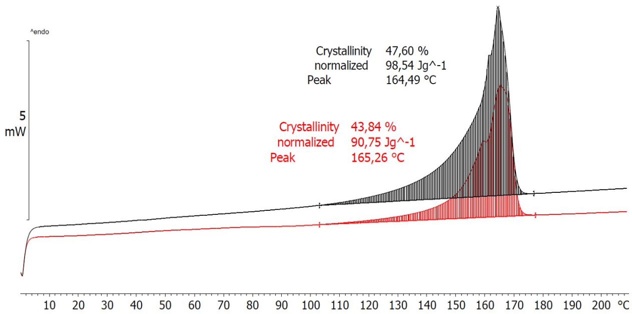

Figure 6. DSC results: black - PA side, red - steel side

3.3 Charpy pendulum V-notched test

Charpy pendulum V-notched test compares notch toughness of specimens injected into PA insert and specimens injected into full steel mould.

Average notch toughness of specimen injected into Freeformer® made cavity inserts is 3.1±0.5 $kJ \cdot m^{-2}$ and notch toughness of specimen injected into full steel mould is 3.2±0.3 $kJ \cdot m^{-2}$. Because of no difference in notch toughness, only thin surface layer must have been influenced by PA surface. Thickness of this layer was observed using digital microscope.

3.4 Surface layer microscopy

Cross section of specimen injected into PA insert was observed by Olympus DSX510. Fig. 7 shows that only about 80 µm surface layer is at the steel side of injected specimen. And there was not observed any surface layer at the PA side of specimen.

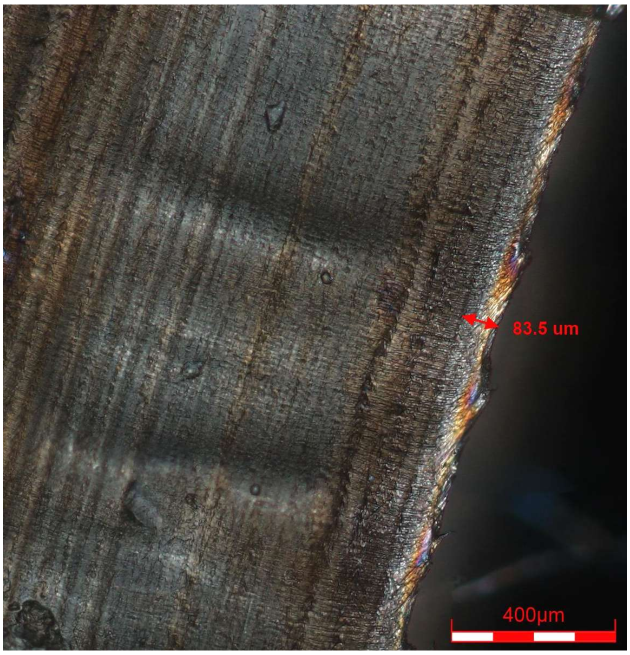

Figure 7. Steel mould side surface layer thickness

4 CONCLUSION AND FUTURE WORK

ABS is not suitable material for PP injecting because of low disposable temperature (about 100°C). PP melt temperature was much higher (230°C). On the other hand, PA 10 does not show any damage.

Huge sink marks on specimen injected into Freeformer® made cavity insert were caused by very slow cooling that caused thermal insulator PA used for insert making. Thermal conductivity of PA is 100 times lower than that of steel. Rough surface caused by layering freeforming technology retains air film that cannot escape from the cavity during injection and causes wide shallow holes or lines on the surface. Surface structure of cavity insert in flow melt direction could help. Another reason of surface defects was insufficient specimen thickness (typical wall thickness of injection moulded products is 1-2 mm). Therefore, most mechanical test methods are based on 4 mm specimens (according to ISO standards).

Arburg Freeformer® made cavity inserts prove quality of freeforming technology. This technology is suitable for making mould prototypes thanks to high material variability given by the use of common plastic granules. Nozzle temperature can be set up to 400°C which presumes hi-tech plastic use. On the other hand, it is hard and time consuming to find processing parameters for newly used materials. Therefore, this additive manufacturing technology is developing in product development process the same as in final product manufacturing.

The impact of various cooling systems should be investigated, cooling channels inside additive manufactured insert can be compared to external cooling systems in adjacent steel plates in order to lower cooling problems. Better cooling conditions would make freeforming cavity insert production prototyping technology even closer to final products made by injection moulding.

ACKNOWLEDGEMENT

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