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Published in:
Proceedings of the 11th International Conference on Multi-Material Micro Manufacture (4M2016) : co-organised with 10th International Workshop on Microfactories (IWMF2016)

Link to article, DOI:
10.3850/978-981-11-0749-8 743

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Process Optimization for Injection Moulding of Passive Microwave Components

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Abstract

The demand for micro components has increased during the last decade following the overall trend towards miniaturization. Injection moulding is the favoured technique for the mass manufacturing of micro components or larger parts with micro-structured areas due to its ability to cost effectively replicate very complex shapes, precise tolerances and in high numbers. In order to secure Europe's leading role in the sector of micro-fabrication the capabilities of injection moulding need to be further developed.
In this research a product for telecommunication, a diplexer unit, has been manufactured utilizing the injection moulding process. A design of experiment study has been carried out, varying process parameters such as injection speed, holding pressure, mould- and barrel temperature. The replicated parts are characterized by measuring geometric features and the part weight. Using an evaluation algorithm for modelling, the influence of different moulding parameters on the final part quality was assessed. Firstly a process model and secondly a quality model has been calculated. The results shows that part quality can be controlled by monitoring characteristic numbers.

Keywords: Injection moulding, process optimization, accuracy, metallization, optical metrology

1. Introduction

Injection moulding (IM) of polymer materials is widely used throughout a wide variety of industries. The main advantages are the low costs for large production numbers, the near-net-shape replication and the high repetition quality if the process is controlled correctly. In order to control the process and thereby ensure high quality parts, the whole moulding cycle has to be fully understood for each product. For the filling of very small and delicate parts or geometrical details high pressures and injection speeds are needed, which in combination with temperature changes leads to locking of residual stresses, orientation and other part properties that can have influence on the final polymer part [1]. Especially the filling stage has been in the focus of many researchers in the past years [2,3]. The findings show that typically the main factors affecting the process are melt temperature [4], mould temperature [5], injection speed [4,6] and injection pressure, leading to a better overall performance and longer flow length. For thin parts, the holding pressure seems to be the most influential factor [7], especially when dealing with warpage issues.

HINMICO, a European collaborative project aims to improve high volume production of multimaterial parts via injection moulding by investigating the interaction of different materials and suitable back-end processes. The concept is to integrate different processes in order to accelerate the production of multicomponent devices, avoid cost-intensive assembly steps. In parallel, a reduction of supply chain space and manufacturing cost will be achieved. The main goals of the project can be summarized as follows:

- Fast and precise µ-replication-assembly processes with new tooling concepts for 3D multi-material micro-components
- Establishment of high-throughput process chains for multi-material functional devices
- Global process chains with increased reliability
- High added value µ-devices with advanced functionalities

Within the project five demonstrator parts are manufactured, each one representing a specific challenge in the fabrication of functional micro-parts from transport, health, audio and information technology:

- A functionalized packaging for a micro-actuator
- An implantable medical metal screw with a µ-structured coating made of biodegradable polymer
- A mechanically improved polymer dental bracket
- A complex multi-material sensing actuator
- A passive microwave component (diplexer)

A crucial prerequisite for a successful implementation of injection moulding for highly precise parts is the application of optimized process parameters and the investigation of relations between different critical parameters and their repeatability on the manufacturing process. The work presented here will be focussing on the optimization of the aforementioned diplexer unit, describing the experimental approach from the replication step, data

Proceedings of the 4M/IWMF2016 Conference
Edited by Guido Tosello, Hans Nørgaard Hansen, Kornel Ehmann and Stefan Dimov

ISBN: 978-981-11-0749-8 :: doi:10.3850/978-981-11-0749-8_743

processing to evaluating the manufacturing step and identifying the most influential moulding parameters.

2. Experimental

The replication trials for the microwave diplexer were carried out at the facilities of IPC (Innovation Plastics Composites) with an Engel 50 ton injection moulding machine (EVC 50/80) with a screw diameter of 22 mm. The moulding parameters were measured with a process monitoring system from S.I.S.E. SAS (Oyonnax, France) throughout the whole process.

In order to examine the impact of the moulding parameters a design of experiments (DOE) method was used to acquire data in controlled way and thereby obtaining information on the behaviour of the IM-process and the significant factors influencing the moulding step. In case of the diplexer a 4-parameters 5 levels design was chosen and the number of trials was reduced by applying a reduced factorial design of experiments approach. The resulting combinations of process parameters are shown in Table **1**. 5 experiments were carried out for each parameter set after stabilizing the process resulting in a total of 414 runs. The four parameters chosen for variation were barrel temperature (T_B), injection speed (v_I) and mould temperature (T_M). For an evaluation of the packing phase the holding pressure (P_H) was also varied. Prior research indicated that the pressure in the cavity can be correlated with the pressure measured at the injection screw [8] and the data measured directly can therefore be used to give time-resolved pressure data instead of adding an additional sensor in the moulding tool.

Table 1: 4-parameters 5-level fractional design of experiments

Run	T_B	T_M	P_H	v_I
1	325	100	225	35
2	335	100	125	35
3	335	100	325	35
4	335	100	225	10
5	335	100	225	60
6	335	120	225	35
7	335	80	225	35
8	345	100	225	35
9	330	90	175	22,5
10	330	90	175	47,5
11	330	90	225	22,5
12	330	90	225	47,5
13	330	110	175	22,5
14	330	110	175	47,5
15	330	110	225	22,5
16	330	110	225	47,5
17	340	110	175	22,5
18	340	110	175	47,5
19	340	110	225	22,5
20	340	110	225	47,5
21	340	90	175	22,5
22	340	90	175	47,5
23	340	90	225	22,5
24	340	90	225	47,5
25	335	100	225	35

Due to preliminary trials all parameters could be set within an already small range avoiding risk of damaging the material or incomplete filling of the cavity. A LCP material (LCP Vectra E820i Pd, Celanese) was chosen with regard to later steps in assembly and post processing. The barrel temperature was kept in the recommended window for that material.

The replicated diplexer parts were measured at ALICONA using a Infinite Focus G5 system equipped with a 5x lens which features a resolution of 3.52 µm in lateral direction and 0.41 µm in z-direction. The stated repeatability of the measurements is depending on the measured feature. For example, a height step of 1 mm can be measured with an accuracy of 0.5 µm ± 0.1 µm. Although the diplexer design is slightly asymmetrical, different structures along the flow path of the injected material were chosen for measurement, giving the opportunity to evaluate the actual filling behaviour. The channel-shaped geometries are placed at the beginning and end of the flow path, parallel and perpendicular to the melt direction and on the left and right side of the actual structuring (see Figure **1**). On each geometrical feature the width of the channel was measured three times on three specimen of each parameter and an average value was calculated and used for later analysis for each specimen in order to minimize the impact of the measurement insecurity.

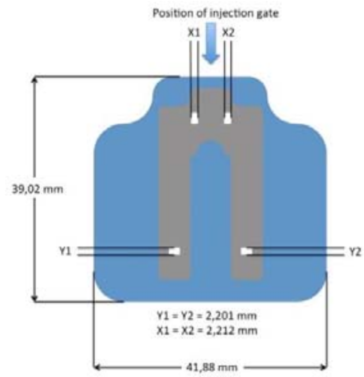

Figure 1: Schematic sketch of diplexer unit and measurement points

In addition, the mass of each manufactured piece was measured using a high precision laboratory scale. The dimensions and the mass were later used as quality marks for the optimization process with higher mass values and smaller dimensions representing a better part quality, since smaller channels mean a smaller shrinkage.

Following the replication and measurement steps, the data sets were processed for the investigation of the parameter influences on the dimensional part quality. A sketch of the overall approach for the data analysis used is depicted in Figure **2**.

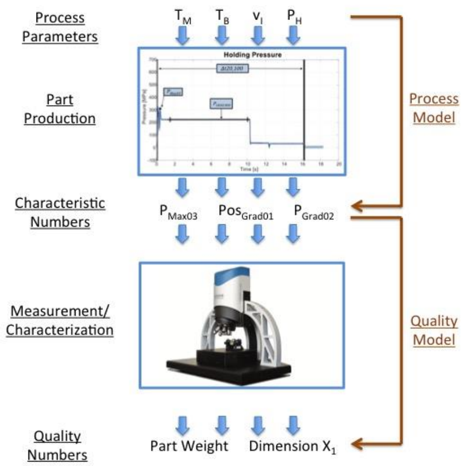

Figure 2: Descriptive model of analytical approach

Due to the large amount of condition monitoring data that can be recorded it is often necessary to reduce it by employing pre-processing techniques. In this way, it is easier to construct the profiles for further analysis. In case of this study, Matlab ® was used to calculate some process characteristic numbers to describe the conditions during the moulding process. As an example, the method for determining the characteristic values is explained for the pressure curve (Figure **3**).

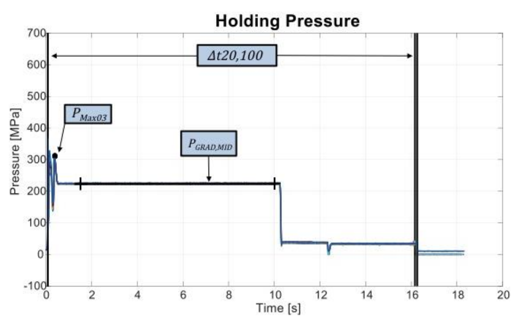

Figure 3: Characteristic numbers evaluated for parameter holding pressure (P_H)

As it can be seen from Figure **3** the measured value of pressure is not strictly constant in its course. Instead, when narrowly analysed, it's seen that it contains very small variations in the order of 10^{-5} bar (1 Pa). In order to the gradient value do not be impacted by these and provide a more faithful model, mean values were calculated, within a range of ±0.05s around the chosen start and end points of the gradient. Hence, the gradient value $P_{GRAD,MID}$ can be calculated by Eq.1

$$P_{GRAD,MID} = \frac{Pressure\ [\,MPa\,]}{Time\ [\,s\,]}$$

$$= \frac{M2 - M1}{t_2 - t_1} \qquad (1)$$

M1 = $mean(P(t_1 - 0.05)\ ,\ P(t_1 + 0.05))$
M2 = $mean(P(t_2 - 0.05)\ ,\ P(t_2 + 0.05))$

where t_2 is the time for the end point of the gradient, t_1 the time for the start point of the gradient, and P the pressure.

A close to zero $P_{GRAD,MID}$ represents a high capacity of the injection machine to maintain the preset holding pressure over the time. That is important to ensure that the expected pressure has been in fact maintained the same along the whole process and will provide therefore the same expected results.

The characteristic number P_{Max03} represents the last peak value of the pressure curve before the holding pressure reaches a constant value (varying slightly as described by the characteristic number $P_{GRAD,MID}$).

The characteristic number $\Delta t_{20,100}$ represents the cycle time from a pressure level of 100MPa on the beginning of the cycle, where the pressure is constantly rising until its first peak (P_{Max01}), to a pressure level of 20MPa on the end of the cycle, where the pressure is constantly dropping until it reaches the zero and ends the process, being therefore able to sum up how much time the effectual process takes and precisely estimate production time for mass production.

These characteristic values were then correlated with the quality numbers (= measurements and weight) to analyse the impact and establish a quality model. In the next iteration the quality numbers were correlated with the original process parameters to generate the process model. Finally, the main effects of the parameter sets of the DoE could be correlated to the quality marks and the influence and significance of each moulding parameter could be investigated. Figure **4** exemplarily shows the main effect plot for part weight vs. the process parameters.

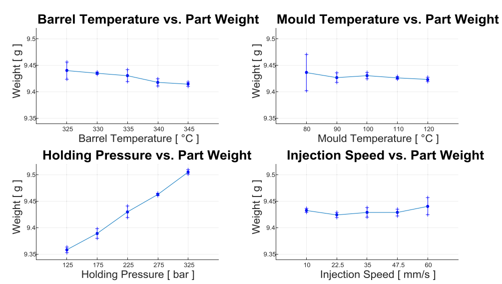

Figure 4: Main effect plots for injection parameters vs. part weight

3. Results

From the analysis of the main effects and regression analysis, following behaviours could be observed:

- Barrel temperature had a small but consistent influence on the part weight (Figure 4), leading to lower weights as it increases, while holding pressure can be strongly correlated to the part weight, being the most important parameter and having an impact of factor 5.8 higher than barrel temperature. The lower weights can be explained by the higher temperature gradient between barrel and mould, which leads to a higher shrinkage and therefore lighter parts. A higher holding pressure can lead to a better filling of the mould, since a higher amount of polymer material can be packed in the cavity during the cooling process to counteract the shrinking of the material.

- For the measurement results $X1$ and $X2$, higher values of injection speed led to better-filled parts, represented by the lower values of dimension.

- For the measurement results $Y1$ and $Y2$ by the way, only extreme low injection speed values led to very high dimensions, showing that a minimum value of injection speed needs to be avoided for these, in order to do not impact the desired size and maximize the accuracy.

- Parameter combinations with high injection speeds led to higher values of both gradients from the transitory period - P_{Grad01} and P_{Grad02}, with a much higher impact on the first – allowing therefore a faster material entry in the filling phase of the process.

- No process parameter had a constant influence on the characteristic number $\Delta t_{20,100}$. However, it is important to mention that extreme parameter sets led to considerably higher values of it. Additional fabrication time i.e. costs might be considered when dealing with such higher/lower parameter sets.

- On the curve of the screw position over the time, the characteristic number POS_{Grad01}, which represents its position during the holding pressure phase of the curve, was strongly correlated to the holding pressure, leading to higher absolute values of POS_{Grad01} as the pressure increases. The higher the pressure applied by the screw is, the greater is its capacity to compact the material in the cavity, compensating the material shrinkage and therefore a greater POS_{Grad01} value.

- In conclusion, P_{Max03} has been shown as a good and the only predictor for the part weight (Figure 5). Being also tightly correlated to the holding pressure enables to establish a relation between Quality Number - Characteristic Number - Process Parameter, creating a control linkage between the characteristic number and good or bad parts and thereby opening to possible in-line quality control system.

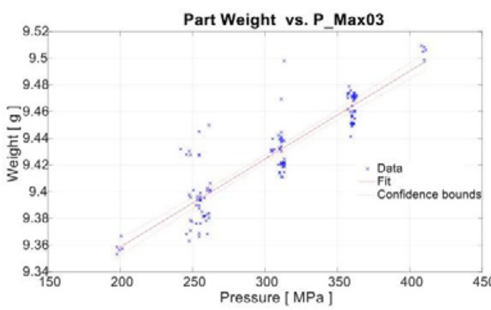

Figure 5: Regression analysis for part weight vs. P_Max03

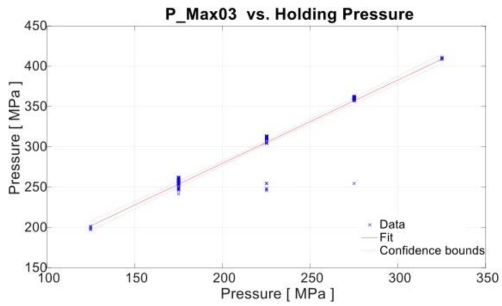

Figure 6: Regression analysis for holding pressure vs. P_Max03

It is also important that the inclusion of other variables on the model does not disturb this relation. Figure 7 and Figure 8 show that the correlation between quality number and characteristic number, and between characteristic number and process parameters is still valid in this case and does not disturb the results even for all variables together, making this a good prediction and quality control model.

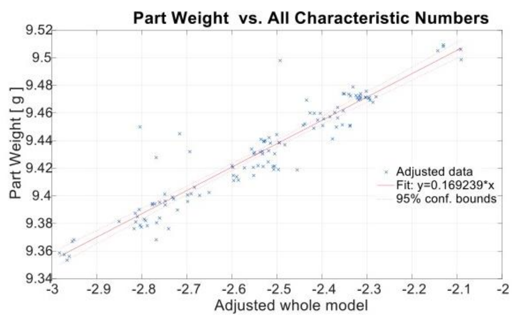

Figure 7: Regression analysis for part weight vs. all characteristic numbers

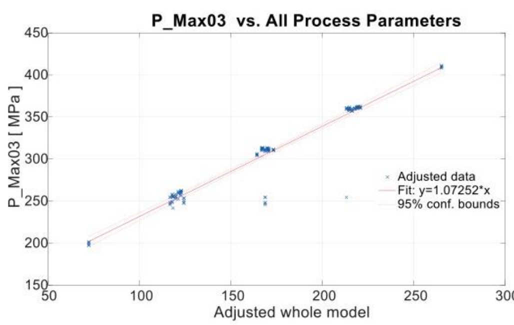

Figure 8: Regression analysis for P_Max03 vs. all process parameters

4. Conclusions

The experiments carried out within the HINMICO project and with the diplexer demonstrator showed the importance of a sophisticated process analysis for the optimization of the injection moulding process. Based on an already narrow process window a well thought-through design of experiments can be used to identify the process parameters with the most significant influence with even a low amount of moulding trials. By establishing good quality process and quality models the direct description of the process and adaption of production parameters is possible during the actual running process without having to rely on a cost- and time intensive quality inspection step.

Acknowledgements

The authors would like to thank the European Community for funding the HINMICO project within the European Community's Seventh Framework Programme (FP7-2013- NMP-ICT-FOF) under grant agreement n° 609110

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