euspen’s 17th International Conference &
Exhibition, Hannover, DE, May 2017
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# Replication quality assessment and uncertainty evaluation of a polymer precision injection moulded component

Federico Baruffi[1], Matteo Calaon[1], Guido Tosello[1], Hans N. Hansen[1], Manfred Prantl[2], Nathan Miller[3]

[1]Technical University of Denmark, Department of Mechanical Engineering, Kgs. Lyngby, Denmark
[2]Alicona Imaging GmbH, Raaba, Austria
[3]Flann Microwave Limited, Cornwall, United Kingdom

febaru@mek.dtu.dk

## Abstract

Precision injection moulding holds a central role in manufacturing as only replication process currently capable of accurately producing complex shaped polymer parts integrating micrometric features on a mass scale production. In this scenario, a study on the replication quality of a polymer injection moulded precision component for telecommunication applications is presented. The effects of the process parameters on the component dimensional variation have been investigated using a statistical approach. Replication fidelity of produced parts has been assessed using a focus variation microscope with sub-micrometric resolution. Measurement uncertainty has then been evaluated, according to the GUM considering contributions from different process settings combinations and mould geometries. The analysis showed that the injection moulding manufacturing process and the utilized measurement chain are indeed capable of providing the high precision needed for the production. The calculated uncertainties are compatible with the imposed part requirements.

Precision injection moulding, Uncertainty budget, optical micro metrology, polymer replication

## 1. Introduction

When the conventional polymer injection moulding process is downscaled in order to meet the demanding requirements of precision engineering components, new challenges arise both in terms of process and product control [1]. In fact, the process window becomes tighter and the scale of the dimensional features makes the produced parts more difficult to measure and thus to assess [2]. In this context, the current paper investigates the replication quality of the precision injection moulding process applied to a component for telecommunication applications [3]. In particular, the deviation of functional linear dimensions between parts and mould has been chosen as replication quality indicator. Measurements were performed using a state-of-the-art 3D focus variation optical microscope. A DOE involving the main injection moulding parameters has been carried out in order to quantify the process parameters effects on the measured output. Finally, an uncertainty evaluation procedure based on GUM [4] considering both the contributions related to the moulding process and the mould geometries has then been applied to assess process capabilities within the tolerance limits enabling product functionalities.

## 2. Experimental setup

The injection moulding machine used was an Engel EVC 80/50 having a screw diameter of 22 mm. The moulded polymer was a liquid crystal polymer (LCP) VECTRA® E820i. In order to achieve a stable process characterized by complete filling of the cavity and absence of visual defect on the parts, preliminary experiments were run allowing to identify a suitable process window. Within this window, the effects of four process parameters (see Table 1) were studied. In particular, a full factorial design resulting in $2^4$ process settings combinations was performed. Three repetitions were carried out and thus a total number of 48 moulding experiments were run.

**Table 1** Experimental moulding process parameters.

| Process parameter | Low level | High level |
|---|---|---|
| Melt temperature [°C], $T_{melt}$ | 330 | 340 |
| Mould temperature [°C], $T_{mould}$ | 90 | 110 |
| Holding pressure [bar], $p_{hold}$ | 175 | 275 |
| Injection flow rate [cm$^3$/s], $v_{inj}$ | 22.5 | 47.5 |

Four different geometrical features were measured for both the mould and each of the produced polymer parts. These features are indicated in Figure 1 along with a scheme of the U-shaped moulded component. $Y_L$ and $Y_R$ are oriented in parallel to the polymer flow direction, while $X_L$ and $X_R$ are orthogonal to it. The design tolerances are set to ± 11 µm for all the indicated dimensions.

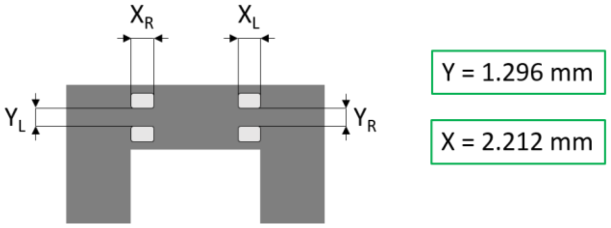

**Figure 1.** Polymer component scheme and measured dimensions. The part nominal dimensions are shown.

Since the aim of the paper is to evaluate the quality replication and its uncertainty, the deviation $\Delta = D_{polymer}-D_{mould}$ between polymer and mould measurements was considered as numerical output of the analysis.

## 3. Measurement strategy and uncertainty evaluation

Measurements of both moulded parts and mould were performed using a state-of-the-art focus variation optical microscope with sub-micrometric resolution. A stitching operation, combined with the programmed movement of the objective lens, guaranteed a fully automatic measuring routine. Three measurement repetitions were carried out for each measurand shown in Figure 1.

The collected data were then analysed in order to evaluate the measurement uncertainty. The uncertainty of the deviation is equal to:

$$U_{\Delta}=\sqrt{U_{polymer}^{2}+U_{mould}^{2}} \tag{1}$$

where $U_{polymer}$ is the expanded uncertainty of the polymer part and $U_{mould}$ is the one related to the mould.

### *3.1. Uncertainty of polymer measurements*

Firstly, the data were cleaned of the outliers by applying the Chauvenet's exclusion criterion. Successively, the most influencing process parameters were identified using the ANOVA. Finally, a regression model was built considering the chosen parameters as predictors and Δ as response. This regression model was then employed as model equation for calculating $U_{polymer}$ using the law of propagation of uncertainty as described in the GUM [4]. In particular, uncertainty contributions related to the regression coefficients, to the process parameters and to the measurement reproducibility (standard deviation of the model residuals) were included in the calculations. The coverage factor was identified in order to achieve a 95 % confidence level on the expanded uncertainty. The main advantage of this approach is that the sources of uncertainty related to the manufacturing process are properly weighed on the parameters effect by means of the model equation and not just summed as in most uncertainty evaluation methods.

### *3.2. Uncertainty of mould measurements*

The uncertainty related to the mould measurement $U_{mould}$ was estimated by means of a repeatability value based on the standard deviation of 20 repeated measurements.

## 4. Results

For all the four measurands, the ANOVA allowed to conclude that the most influencing process parameters were the mould temperature $T_{mould}$ and the holding pressure $p_{hold}$. This is clearly shown in Figure 2, where the main effect plots of the deviation on $Y_L$ are reported as example.

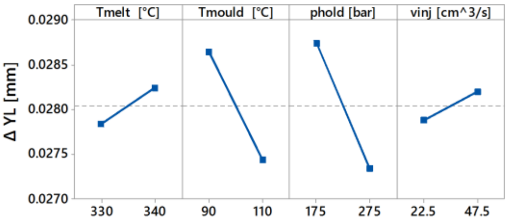

**Figure 2.** Main effect plot of *Δ* related to the measurand *$Y_L$*.

It is important to notice that the average deviation is positive for the Y quantities (0.028 mm for $Y_L$ and 0.014 mm for $Y_R$), while it is negative for the X ones (-0.008 mm for $X_L$ and -0.004 mm for $X_R$). Therefore, the polymer part tends to expand along the injection direction while it shrinks along the orthogonal to it.

Following the method presented in section 3.1, a first order regression model was fitted on these two variables. Thus, the model equation utilized for $U_{polymer}$ calculations was:

$$\Delta=c+a\cdot T_{mould}+b\cdot p_{hold}+\epsilon \tag{2}$$

where $c$, $a$ and $b$ are the regression coefficients and $\epsilon$ represents the model residual. Figure 3 shows, as example, the experimental distribution of the Δ values calculate on $Y_L$ and the fitted regression plane.

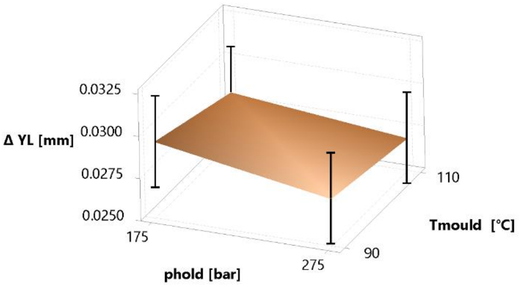

**Figure 3.** Experimental distribution of Δ related to $Y_L$ and fitted regression plane (orange). The uncertainty intervals are indicated.

After having applied the procedure, $U_{polymer}$ resulted equal to 0.003 mm for all the four measurands and in all the process conditions. On the other hand, $U_{mould}$ was estimated as equal to 0.001 mm, resulting in an expanded uncertainty on the deviation $U_{\Delta}$ equal to 0.0032 mm for all the cases. The ratio of this uncertainty on the design tolerances equals 29 %. Considering the extremely high precision requirements, it is possible to conclude that the utilized injection moulding process, combined with the optical 3D instrument, is capable of producing parts compatible with the design specifications.

## 5. Conclusion

An investigation on the replication quality of a precision injection moulded polymer process was carried out. The deviation between produced geometries measured on the polymer part and their corresponding master geometries measured on the mould was considered as output. The expanded uncertainty of the measured deviation was calculated using an adapted procedure, based on the GUM, which included the process variability by means of a regression model on the relevant process parameters. Results show high repeatability of the outputs, independently from the selected process settings. Finally, the calculated uncertainties resulted compatible with the tight tolerance requirements, demonstrating that the manufacturing technology, combined with the focus variation microscope, are capable of satisfying the precision and the accuracy required by the product design specifications.

## Acknowledgements

This research work was undertaken in the context of MICROMAN project. MICROMAN is a European Training Network supported by Horizon 2020, the EU Framework Programme for Research and Innovation (Project ID: 674801).

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