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A study on replication and quality correlation of on-part and on-runner polymer injection molded micro features

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Abstract

Injection molding is increasingly gaining place in manufacturing of polymer components as is can ensure a cost efficient production with short cycle times. To ensure the quality of the produced parts and the stability of the process it is essential to perform frequent metrological inspections. In contrast to injection molding's short cycle time, a metrological quality control can require a significant amount of time. The late detection of the problem can result to high losses and scrap rate. This paper presents an alternative approach to process monitoring and part quality control with fast off/in-line metrology of physical part quality indicators ("Product Fingerprint"). The proposed approach is based on the concept of metrology applied to dedicated micro features, positioned on the runners, similar or equal to those in the part in order to access the quality of the produced plastic parts. A designed experiment was employed to map the experimental space and quantify the pillars replication depending on position and processing parameter combinations. The pillars were assessed and the main effects of the processing parameters, were calculated to reveal that the effects of process parameter change were similar in all measurement positions. Results showed that the product fingerprints have a correlation to the quality of on-part micro features. The concept can support the creation of a fast part quality monitoring system that has the potential to decrease the use of off-line time-consuming detailed metrology for part approval.

Keywords: Precision injection moulding, Quality Control, Process monitoring.

1. Introduction

Injection molding is increasingly gaining place in manufacturing of more products as is can ensure a cost efficient production with short cycle times. It is used for many applications such as in the automotive components communication, electrical appliances, toys and medical devices. In the medical sector, many of the applications have functional features of micro dimensions with tight tolerances. To ensure the quality of the produced parts and the stability of the process it is essential to perform frequent metrological inspection of parts. However, in contrast to injection molding's short cycle time, a metrological investigation can require a significant amount of time. In case of parts rejection and out of tolerance production process, the late detection of the problem can result to high losses and scrap rate. This paper presents an alternative approach to process monitoring and part quality control with fast off/in-line metrology of physical on part features (part quality indicatorsP.Q.I.) or as lately have been introduced as "Product Fingerprint". The approach under consideration includes the use of dedicated micro features positioned on the runner of the moulding that are equal or similar in size and shape to the features on the part. The correlation of the features replication on the runner to the ones in the part is going to be explored. Current research has shown examples were nano-features placed on different areas of a component provide the necessary indicators for fast part quality assessment [1]. In addition, multiple studies were conducted from researchers and industry, utilize in-mold sensors to regulate and monitor the process with promising results [2], [3][4][5], even though with increased tooling costs. However, none of the conducted studies so far presented examples of out of cavity micro features used to assess the quality of the injection-molded part.

2. Experimental Set up

2.1. Molding tool Geometry

In order to access the quality of on-part micro features, in correlation with on-runner/ off-part micro features, new tool inserts to produce a biochip were manufactured. The biochip has the form of a 20x20x2 mm tablet with on-part conical micro- pillars features with 600 μm nominal height, a Ø250 μm base diameter and a Ø200 μm top diameter as seen in figure 2. The mould inserts were adapted to accommodate pillar micro-features on the runner equal to those on the part, as it can be seen in the lower half of figure 1.

Figure 1. Geometry and measurement positions

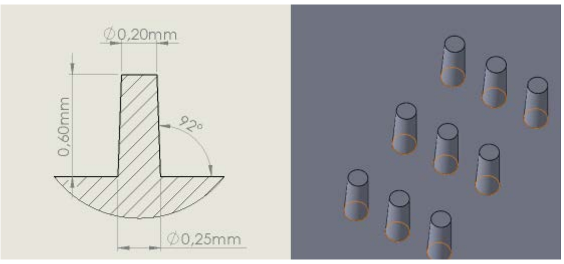

Figure 2. Pillar Shape and Dimension

To assess the quality of pillar replication both on the part and the runner (nominal diameter 5mm), four measurement positions were selected for measurements, both on injection molded components and mold. The positions are presented in Figure 1 and are Position "PP1" close to the gate of the part, Position "PP6" in the middle of the part, Position "PP11" at the end of the parts and Position "RP2" in the middle on the runner.

2.2. Experimental Conditions

From available research[6] and previous experiments it is known that the most significant parameters that affect part quality in Injection Moulding are: Tmelt [°C], Tmould [°C], Injection Speed [mm/s] and Packing Pressure [bar] . Thus, a $\mathbf{2^4 \cdot 3}$ Full Factorial randomized design was chosen to investigate the experimental space. The standard experimental runs with the chosen parameters are presented in Table 1. The process parameters were selected taking into consideration the material in used, which is a commercial grade ABS (ABS Terluran GP-35). The material has a relatively large processing window and the full range of the experimental parameters was used in order to map the effect on the pillar quality based on all the processing space.

Table 1. Experimental Parameters

Run	Tmelt [°C]	Tmould [°C]	Inj.Speed [mm/s]	Pack.Pressure [bar]
1	220	40	100	440
2	260	40	100	440
3	220	60	100	440
4	260	60	100	440
5	220	40	140	440
6	260	40	140	440
7	220	60	140	440
8	260	60	140	440
9	220	40	100	540
10	260	40	100	540
11	220	60	100	540
12	260	60	100	540
13	220	40	140	540
14	260	40	140	540
15	220	60	140	540
16	260	60	140	540

The experiment was conducted within one day, for all experimental runs. It was performed on an electric Arburg 370A injection-moulding machine, with a clamping unit of maximum 60 tons of clamping force and a screw diameter of Ø18mm, and was well matched for the modified mould geometry.

For every run, the initial 20 parts were molded in order to achieve stability in the process and were consequently disposed. The next 10 parts were then collected. However, due to time limitations only three parts were consequently investigated for the assessment of micro pillar replication quality on the parts and runner.

2.3. Measurement Procedure and Equipment

The replication quality assessment for every experimental run was based on three parts per run. The pillars in every position of all parts were then scanned with the use of an "Alicona Infinite Focus" focus variation microscope. The middle pillars in positions PP6 and RP2 were measured five times in order to ensure the repeatability of the measurement (standard deviation in the range 0.1-0.2 μm). The files were then processed with SPIP 6.4.1 software to extract the height of the pillar in each scan.

The procedure involved the use of functions that corrected the 1st order tilt in the scan as well as to set the zero background for all data-point. Four profiles that intersected the centre of the pillar were consequently extracted, to be averaged and calculate the pillar height as shown in Figure 2. The same procedure was applied to scans from both mold and parts.

By subtracting the height of the mold feature from the height of the part feature, the height deviation response variable that is used for the replication assessment was calculated.

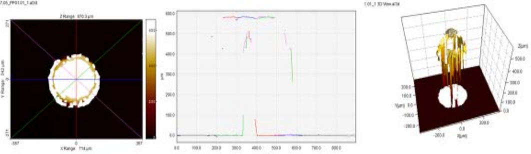

Figure 3. Pillar height measurement

3. Results & Discussion

After the completion of the measurements, the data were sorted and prepared for the analysis. The dataset was consequently cleaned from the most profound outliers. The purpose of the current research was to map the experimental space, assess the process parameter effects on the replication of the pillars and verify that on- and off-part micro features are similarly affected by any parameter combination.

The standardized values (Z-scores) of the (equation 1) height deviation values, of every position are then plotted against each other to facilitate a comparison among the measurement positions.

$$Zscore = \frac{x-\mu}{\sigma} \qquad (1)$$

Where: x: Observation 'x', μ: Mean value of all observations and σ: Standard deviation of all observations

Figure 4 provides a comparison of all runs and positions. It can be seen that the runs with low level of Tmelt (Run 3,7 and 9) are less replicated. Moreover, the height deviation for all three-measurement positions on the part follow the same trend, whereas position RP2 follows the same trend partially. It is important to note that there is significant pressure difference between position RP2 and positions PP1, PP6 and PP11, as the latter are located on the part and there is a large pressure drop at the gate. Furthermore, the shape and size of the geometry at the specified positions is different; as such, the area of runner around the position RP2 is thicker than the part and thus solidifies later, allowing more differences to appear in comparison to the part. Thus, the larger amount of “spikes” at position RP2 can be explained.

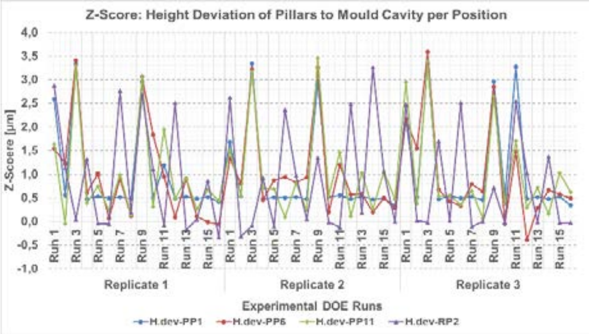

Figure 4. Z-Score of Height deviation (H.dev) for all runs and positions

3.1. Analysis of Main Effects

The original data can already provide a significant amount of information, as for the most experimental runs, the curves follow the same trend.

However, at the runs representing the limit of the experimental space the same behaviour does not apply. Thus, it is important to further process the data. The dataset is processed in order to calculate the main effects and the interaction effects of the parameters, by making use of equation 2 as it is known from the theory of Design of Experiments [7].

$$Effect = \frac{2 * Contrast}{n * 2^k} \qquad (2)$$

Where: Contrast: The summary of responses for all experimental runs with the summary of each response to be dictated by the Yates method [7], n: number of Replicates and k: Number of Factors.

Figure 5 illustrates the main effects of the process Tmelt and Injection Speed parameters are the ones that have the largest effect, (height deviation decrease) when their value is switched from low to high level for the observations associated to the on-part positions (PP1, PP6, PP11). Moreover, the increase of Tmould and Packing Pressure parameters has a positive effect on the response for position PP1 and PP6, with the largest effect to apply to PP6. In comparison, a high Tmould increases the H.dev., though only a small amount and packing pressure has no effect.

On the other hand, the micro pillars of position RP2 on the runner follows a different behaviour. The papameter of Injection Speed is again the one that has the largest effect on the response, followed by the Tmould and Packing Pressure parameter. It is interesting to notice that a high level of Tmelt increases the response by a small amount. This occurs due to the relationship of the material’s solidification time, the Tmelt and the geometry at the position. The geometry has relatively large thickness at position “RP2” and when coupled with a high melt temperature can increase the time required for the solidification. Thus, a larger shrinkage of the melt in the pillars to the main body of the runner is possible.

3.2. *Comparison of effects to Position.*

It is possible to acquire information for the significance of main effects and interaction via a probability plot of the standardized effects. Table 2 includes the significant effects sorted within the order of significance.

It is shown that effects AC, C & A are the largest for the observations in positions PP1, PP6 and PP11. Instead, the effect ABC is the largest and most significant for position RP2. However, three factor interactions and above

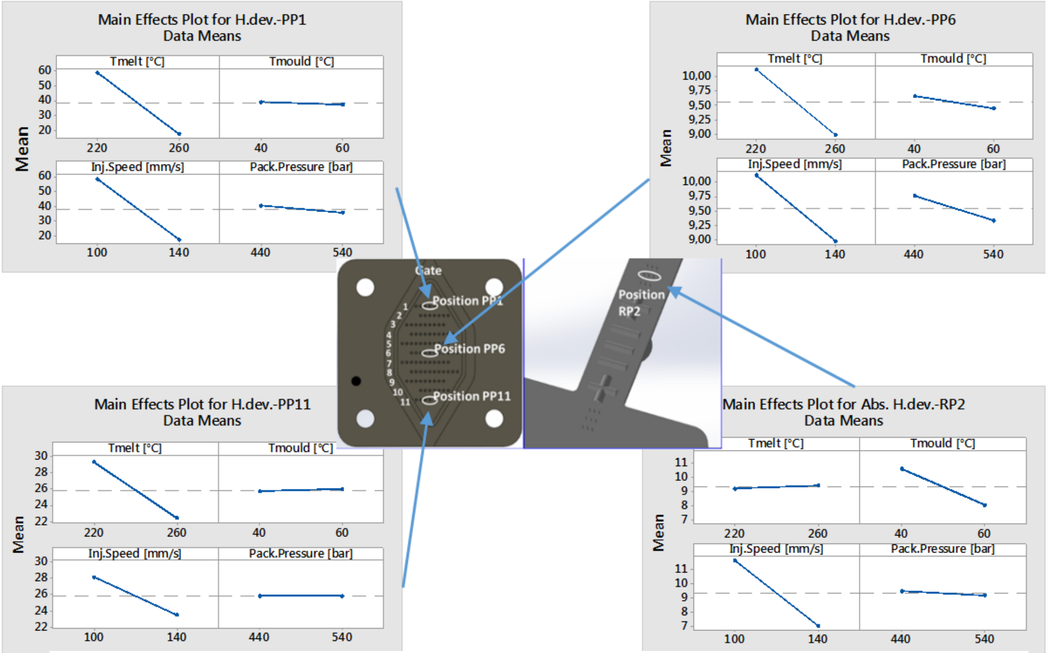

Figure 5. Main Effects of the process parameters per measurement position

are proven to be insignificant for manufacturing processes [8] and are not taken into consideration.

Independently of the indication for the most significant effect, it is necessary to plot effects and their standardized values (Z-Scores) to assess if the effect from position RP2 follows the same or similar trend to the effects based on responses for the on-part positions. Thus, it is possible to identify if the pillar features on the runner (RP2) can be used as “product fingerprint”.

Table 2.Significant effects per position

	H.dev-PP1	H.dev-PP6	H.dev-PP11	H.dev-RP2
Effects	AC	AC	AC	ABC
	A	A	A	
	C	C	C	

Where:
A: Tmelt,
B: Tmould,
C: Injection Speed and
D: Packing Pressure

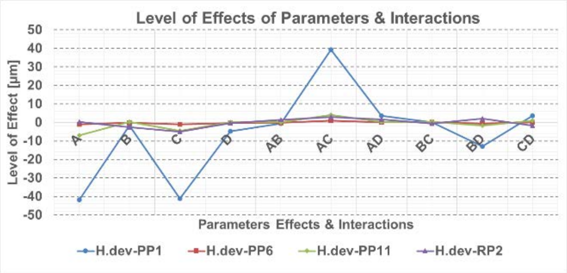

Figure 6. *Main & Interaction effects of parameter in measurement position*

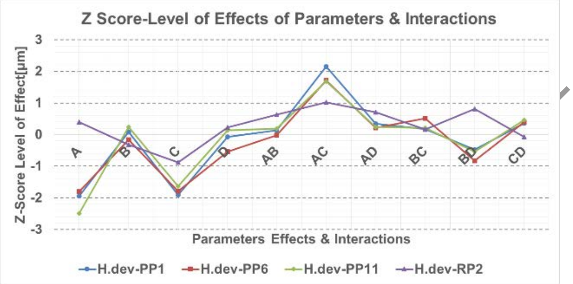

Figure 7. Standardizes values of Main & Interaction effects of parameters in measurement position

Figures 6 and 7 illustrate the levels and standardized values of all main and interaction effects, respectively. From Figure 6 it is shown that main and interaction effects for all four positions do follow a similar trend. The relatively large difference in magnitude for each position though, is making the trend less visible. However, on the standardized dataset as presented in Figure 7 the effects follow a similar trend for the main and 2-way interactions. This indicates that a change in parameter combination does have similar effects to micro features both on-part and on-runner. Similar to figure 5, in figure 7 it can be noticed that the trend deviates for the factor Tmelt (A) for the pillars on the runner of the part (RP2). As discussed earlier, this behaviour originated to the different thickness of the runner, in comparison to the part. As such, the previous statement does not apply for the factor “Tmelt”, in the presented application. Considering all the above, it is possible to utilize on-runner micro features for feature quality assurance, by thus shorten the time, and decrease the effort required for a metrological investigation.

4. Conclusions

The current paper presents an investigation on a new concept, for product quality assurance on injection-moulded parts. The concept makes use of off-part micro features, to correlate the quality of on-part micro features to external micro features on the runners, in order to aid the metrological investigations to assure part quality by fast offline /online metrology. A DOE methodology was utilized to investigate the experimental space and calculate the effects of parameter level change. It was shown that the standardized effects for all measurement position follow similar trends for the main and 2-way interactions except for the main effects of “Tmelt”. Thus, the off-part micro-features on the runner present similar behaviour to on-part micro features in the experimental space and could be used to assess part quality based on off-part/on-runner micro features. However, a deeper investigation is required to quantify the relation and assess the uncertainties involved in the process.

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