Improving CT quality control of a micro injection molded part by multisensor data fusion

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Abstract

Acquiring holistic and accurate 3D measurements for industrial parts is highly demanded in the fields of quality control, process optimization and product development. The increasing complexity in the design and miniaturization make the task of holistic 3D data acquisition difficult. For the last few years, industrial computed tomography (CT) has emerged as a promising coordinate measuring technology, which enables integrated quality control of complex workpieces combining dimensional metrology and material defects analysis. In this study, the potential of CT is utilized for quality assessment of a micro molded part; in addition, data from confocal microscopy is used for enhancement of the CT result by data fusion.

Keywords: industrial computed tomography, multisensor data fusion, micro injection molding, shrinkage and warpage.

1 Introduction

Micro injection molding today is one of the key technologies for micro manufacturing due to its mass production capabilities and relatively low production cost. There exist a number of challenges for micro injection molding technology which need to be considered for the improvement of the process. Dimensional quality control is of prime importance as it helps in overall process optimization. Nowadays, a number of dimensional measuring technologies and instruments are available, but it is difficult to meet to all the metrological needs with a single sensor/measuring instrument \cite{1}. A classification with respect to structural dimensions and complexity was introduced by Bariani \cite{2}, which was modified by Hansen et al. \cite{3}; see Fig. 1. The structural complexity termed as 2D, 2½D and 3D are defined as features with aspect ratios $<1$, aspect ratios $\geq1$ and with undercuts/cavities/freeforms respectively \cite{3}. As the structural dimension is lowered and the complexity is increased there is a lack of instrument/technology which can provide a measuring solution singlehandedly. Multisensor data fusion could be a step towards filling the void to some extent.

In recent years, x-ray computed tomography (CT) has been proposed as a successful non-destructive technique for dimensional metrology. Nevertheless, measurement traceability is still challenging and there exist several influencing factors contributing to the measurement uncertainty, which are difficult to quantify \cite{4}. When it comes to measurements of micro features, the resolution
becomes significantly a limiting factor for typical industrial CT systems with micro- or nanofocus tubes. Using data from other sensors in addition to CT data can provide holistic geometrical measurement information, even for complex objects, thus complementing the CT data set. For example, Bartscher et al. [5, 6] used multisensor data fusion for measuring a cast cylinder segment. The outer and inner geometries were measured with fringe projection system and 2D-CT system respectively. Both the data sets were fused together and the results were compared with tactile measurements; the reported deviations were less than ±0.38 mm (of the order of voxel size of CT measurement).

2 Case study

In micro injection molding, the part quality depends on a number of factors, which need to be optimized usually with the help of simulations/experiments. Part quality assessment through dimensional measurements plays an important role in achieving the desired process optimization. Shrinkage and warpage (deviation from the desired geometry) are two major issues affecting the part quality; however, uniform shrinkage can easily be compensated, but non-uniform shrinkage results into warpage. There can be one (leading than others) or more causes for part warpage, such as material characteristics, part and mold design, mold and melt temperature and packing pressure. Parts with larger ratio between area and thickness are more prone to experience warpage [7]. From the point of view of shrinkage and warpage of the part, the holistic geometrical 3D measurement is of great importance.

![Fig. 2: Nominal part geometry (a) and micro channel dimensions (b).](image)

In this study, a part obtained from micro injection molding process is used as shown in Fig. 2 (a). The part has a micro channel of the height of 20 µm and width of 30 µm (Fig. 2 (b)). It is manufactured with two different materials: Cyclic Olefin Copolymers (COC) and Polycarbonate (PC). Therefore, it is relevant to see which material produces better replication quality. Within the scope of this work mainly X-ray CT is used for directional shrinkage measurements and geometry deviations. The resolution achieved for the CT data is not sufficiently high for the micro channel assessment. To overcome this limitation, confocal microscopy is used for acquiring high resolution/high density data for the micro channel region. As a next step, the data from both the instruments are combined together for enhancement and to provide all the required information in a single dataset.

3 X-ray CT scanning

A Nikon MCT 225 x-ray computed tomography system was used for scanning the micro molded part. The aspect ratio of the part and the micro details make the CT scanning a challenging task. The placement of part for CT scanning is shown in Fig. 3.

![Fig. 3: Placement of the parts for CT scanning COC (a) and PC (b).](image)
In order to optimize the CT measurement results, several preliminary scans were performed varying the parameters: mainly the voltage, current and exposure time. The set of optimal scanning parameters is provided in Table 1. The magnification achieved for the complete part scan was 15x; in addition a partial scan (only the micro channel) was made at a magnification of 20x.

### Table 1: CT scanning parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage, kV</td>
<td>90</td>
</tr>
<tr>
<td>Current, µA</td>
<td>56</td>
</tr>
<tr>
<td>Exposure time, s</td>
<td>4</td>
</tr>
<tr>
<td>Number of Projections</td>
<td>2000</td>
</tr>
<tr>
<td>Magnification</td>
<td>15x (full scan)</td>
</tr>
<tr>
<td></td>
<td>20x (partial scan)</td>
</tr>
<tr>
<td>Voxel size, µm</td>
<td>~14 (15x)</td>
</tr>
<tr>
<td></td>
<td>~10 (20x)</td>
</tr>
<tr>
<td>Repetitions</td>
<td>3</td>
</tr>
</tbody>
</table>

#### 3.1 Scan quality and shrinkage measurement

The obtained CT data was reconstructed and post-processed (i.e. surface determination and measurements etc.) using the VG StudioMax software package. While the overall scan quality is good, the quality at the micro channel region is affected by the noise and the limited resolution, as visible in Fig. 4 (a). The arrows show the areas of the CT data at the micro channel region that are more affected these limitations. For better resolution, the magnification can be increased but it introduces negative effects, e.g. blurring depending on the x-ray spot size [4]. A higher resolution scan was acquired at a magnification of 20x which is also used for the data fusion procedure, see section 5. As explained in Fig. 4 (b), the shrinkage was measured on the volumetric data in X, Y and Z directions around the center and the measured values are $D_x$, $D_y$ and $D_z$ respectively. The measurement was performed on all 3 repetition scans and the mean values of $D_x$, $D_y$ and $D_z$ are reported in Table 2.

![Fig. 4: Noise level at micro channel region (a) and dimensions measured for shrinkage evaluation (b).](image)

#### Table 2: Shrinkage measurement results.

<table>
<thead>
<tr>
<th>Nominal, mm</th>
<th>COC</th>
<th>Measured (mean), mm</th>
<th>Deviation, %</th>
<th>PC</th>
<th>Measured (mean), mm</th>
<th>Deviation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_x$</td>
<td>20.1</td>
<td>19.928</td>
<td>0.86</td>
<td>19.883</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>$D_y$</td>
<td>20.1</td>
<td>19.953</td>
<td>0.73</td>
<td>19.928</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>$D_z$</td>
<td>2.0</td>
<td>1.940</td>
<td>2.99</td>
<td>1.929</td>
<td>3.53</td>
<td></td>
</tr>
</tbody>
</table>

From the results in Table 2, it is evident that the shrinkage is not uniform in all the directions. The differential shrinkage results into the warpage of part, which is shown in the next section with the help of nominal-actual comparison. Additionally, it can also be concluded that the part with PC witnesses more shrinkage compared to the COC. The CT results are advantageous for the macro quality assessment of the part but the resolution and noise limit the reliability of the CT data for micro measurements of this particular case. There arises a need of other measuring instrument/technology for the micro channel quality assessment; therefore, confocal microscopy was used for this purpose, section 4.
3.2 Warpage/geometry deviation

Simulation

In injection molding process simulation is widely used for the warpage/shrinkage prediction; it could also be useful in strategizing the critical areas thus the measurement approach. Autodesk® Simulation Moldflow® was the numerical code used in the current work. The part geometry along with the feeding system was uploaded and meshed with multiple densities for reducing computation time. For example, the micro channel region required finer meshing than the rest of the part. The simulation was performed for only COC part. The warpage results of the simulation is in the form of deflection considering all the effects e.g. the shape of part, packing pressure and cooling, shown in Fig. 5. The Fig. 5 (a) shows the deflection in x, y and z components altogether and Fig. 5 (b) shows in z component alone. The section in yellow/red shows the highest warpage defect corresponding to the high deflection. The scale factor used here is 10 for better visualization. The part shows clear tendency to shrink towards the injection plane, which helps in deciding the alignment for the nominal-actual comparison.

![Simulation Results](image_url)

From CT data

The part deviation from the nominal geometry was analysed with the help of CT volumetric data. The nominal-actual comparison was performed for both COC and PC, which is presented in Fig. 6. Clearly, the part with PC shows larger deviations from the nominal than that of COC.

![CT Comparison](image_url)

Fig. 5: Representative deflections for warpage considering all effects in x, y and z components (a) and in z component (b). For better visualization, a scale factor of 10 is used here.

Fig. 6: Nominal-actual comparison performed on CT data.
It should be noted that the comparison has been performed with respect to the injection plane (dotted black line) as the part shows tendency to shrink towards that direction which is clearly visible from the simulation results in Fig. 5.

4 Confocal microscopy results

In order to measure the micro channel with sufficient resolution, another non-contact measuring technique is needed, such as confocal microscopy, which is a 3D microscopy imaging technique that utilizes an aperture at the confocal plane of the objective [8]. In this work, a Sensofar PLu neox 3D optical profiler was used for micro channel measurements. The objective chosen for this purpose was 20x, with a field of view of 636 x 477 µm, and 0.31 µm optical resolution. In order to have a larger area scan, extended topography measurement was performed, by stitching a number of single small areas (636 x 477 µm for the chosen objective) to cover the desired measuring area with a specified overlap (default overlap is 10%). The results obtained are presented in Fig. 7. The drawbacks of this procedure for extended topography measurement are the long scanning time, stitching errors and the limited z-range; for instance, one extended topographic measurement was over 4 hours long. Due to these drawbacks, measurement of the entire surface of the part (20 x 20 mm) is not feasible by extended topography using confocal microscopy only (in particular, stitching errors on such large areas would increase to values that are not acceptable for accurate evaluation of overall part geometry). Hence, fusion with CT data is beneficial for overall part measurement (see section 5).

![Fig. 7: Surface data obtained from 3D optical profiler.](image)

It can be seen from the Fig. 7, that the local channel height varies significantly over the entire range. The linear profiles at two locations 1 and 2 are extracted and shown in Fig. 8. Important to note that the height varies roughly within a range of 10 to 20 µm, which makes CT data quite unreliable for measuring the micro channel features, as the CT resolution is also of the same order.

![Fig. 8: Linear profiles drawn from the profiler data at location 1 (a) and 2 (b) as specified in Fig. 7.](image)

5 Data fusion

The term data fusion is quite broad in itself and used in different fields, more information can be found in [9, 10]. The purpose of using data fusion here is to combine the individual information (point clouds) and merge them together in a single dataset including both the complete geometry scanned by CT and the high resolution data for the micro channel area scanned by confocal microscopy. A data fusion procedure was implemented using the software package GOM Inspect V8 for this purpose. In this procedure, the two datasets are placed on a common coordinate system and aligned together using the CAD. The overlapping area in the low resolution full scan is replaced with the high resolution partial data; the output is a single dataset with better resolution at micro channel region. Data was merged/fused in two ways:
- F1: Low resolution CT scan (CT15x) + high resolution CT scan (CT20x);
- F2: Low resolution CT scan (CT15x) + high resolution profiler scan (Pro).

Fig. 9: CAD comparison obtained for CT15x (a), CT15x + CT20x (b) and CT15x + Pro (c).

This analysis was performed only for the COC part. The CT data was extracted in the form of point clouds. As the profiler output is only from the top surface, hence the top surface data from CT volumetric dataset was considered. The crucial step is the registration procedure, which limits the accuracy of the overall data fusion. The authors are currently working on the improvement of the procedure, the results presented here are preliminary from simple registration method.

Fig. 10: Surface quality as resulted from the fused datasets CT15x (a), CT15x + CT20x (b) and CT15x + Pro (c).

The original CT dataset (CT15x) and the fused datasets, i.e. F1 and F2, are then compared with the CAD and the results are provided in Fig. 9 (a), (b) and (c) respectively. F1 does not show significant changes in the results as compared to the CT15x which is due to the fact the resolutions for both datasets were limited by CT constraints. F2 shows improvements at the micro channel region in the local height distribution compared to the CT15x.

The similar trends reported above are visible in the raw datasets. As shown in Fig. 10, the first merging result i.e. F1 does not show significant improvement in the surface quality at the micro channel region, which is due to the fact that the difference in the resolution/point density is not really considerable. The second set of fused data i.e. F2 shows significant improvement at micro channel region owing to the higher resolution of the profiler data.

6 Conclusion

The current work was about utilizing the potential of x-ray CT for quality assessment of micro molded part. To overcome the limitation (mainly resolution), data fusion was implemented by merging CT data with high resolution data obtained from confocal microscopy. The experimental investigation presented in this paper showed preliminary results obtained for a 20 x 20 mm micro injection molded part with a micro channel of the height of 20 µm and width of 30 µm. The quality of the results depends on both the individual datasets and also on the data fusion procedure. The data fusion method presented here will undergo improvements in near future.

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References


