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Abstract
This paper concerns an investigation of the accuracy of Computed Tomography measurements using multi-material assemblies. In this study, assemblies involving similar densities for elementary parts were considered. The investigation includes dimensional and geometrical measurements of two 10 mm high cylindrical assemblies, where each item contained a male and a female part machined by turning. The male parts are made of polypropylene PP ($\rho = 0.950$ g/cm$^3$), while the two series of female parts are made of polyethylene PE ($\rho = 0.910$ g/cm$^3$), and polyoxymethylene POM ($\rho = 1.420$ g/cm$^3$), respectively. Traceability was ensured using a tactile CMM.

Keywords: Computed Tomography, multi-material assemblies, polymer materials

1. Introduction

The incessant reduction of product life cycles demands quicker response speeds and lower defect rates in industrial production. Computed Tomography (CT) is becoming an accepted inspection tool due to its ability to simultaneously measure external and internal features with uncertainties ranging from 6 to 53 µm with maximum values up to 158 µm [1]. From an industrial point of view, however, the major interest associated with CT is its capability to inspect assemblies in their assembled condition [2]. This represents a real breakthrough compared to traditional CMMs and other industrial quality control tools. This work investigates the use of CT for assemblies with similar densities and absorptions. Two assemblies composed of different polymers materials with different geometrical and dimensional features were measured to identify the scanning parameters necessary to generate sufficient contrast and maximize the width of the gray value histogram. Misdetermination of volume segmentation were analyzed and quantified. Finally, deviations of measurands with respect to CMM measurements were compared for assembled and non-assembled sections in single and multi-material contexts.

2. Items

Two 10-mm height cylindrical multi-material assemblies were used. Each item consists of two parts (male and female) as shown in Figure 1a. The male parts are made of polypropylene (PP). The female parts are made from polyoxymethylene (POM) and polyethylene (PE). Information about materials investigated is displayed in Table 1. An H7/h7 fit (clearance fit) was used to ensure good fit accuracy and easy disassembly. The items were manufactured at DTU via CNC turning from commercial stock. The configuration of the assembly used allows information to be collected in the area of interest on the male parts in both a non-assembled and an assembled state. Selected dimensional and geometrical characteristics are shown in Figure 1b.
Figure 1 Reconstructed volume showing the assembly configuration (a) and (b) selected measurands on the male parts.

Table 1 Material characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>ASSEMBLY 1</th>
<th>ASSEMBLY 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PP (male)</td>
<td>POM (female)</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>0.910</td>
<td>1.420</td>
</tr>
<tr>
<td>CTE</td>
<td>10⁻⁶ K⁻¹</td>
<td>155</td>
<td>110</td>
</tr>
</tbody>
</table>

3. Reference measurements on tactile CMM

Traceability of measurements was assured using a Zeiss OMC 850 tactile CMM. A 45mm-long stylus with a 2mm-sphere was selected. During the calibration, the mean temperature varied from 20.1 °C to 20.4 °C. 50 distributed points were recorded and fitted using the Minimum Circumscribed Element (MCE) [3]. The measurement uncertainties associated with the dimensional ($U_{D}^{cal}$) and geometrical ($U_{r}^{cal}$) measurements were quantified according to ISO 14253-2 [4]. Unless differently stated, a Type B evaluation of uncertainty was assumed according to equation 1.

$$U_{D}^{cal} = k \times \sqrt{u_{p}^{2} + u_{C}^{2} + u_{T}^{2}}$$

(1)

where $u_{p}$ is standard uncertainty due to traceability transfer, it is calculated as $u_{p} = \frac{u_{cal}}{2}$, where $u_{cal}$ is the expanded uncertainty stated in the calibration certificate; $u_{C}$ is the standard uncertainty of the measurement procedure treated using a type A evaluation, $u_{C} = \tilde{u}$; $u_{T}$ is the standard uncertainty related to a temperature deviation of 0.3°C, $u_{T} = \frac{\alpha \Delta T}{\sqrt{2}}$, where $\Delta T$ is the temperature deviation during calibration, $\alpha$ corresponds to CTE of the material and $L$ is the nominal diameter. A U-distribution ($b = \frac{1}{\sqrt{2}}$) is assumed. The same approach was adopted for the uncertainties of geometrical measurements as show in equation 2 except that the uncertainties related to the temperature deviation were neglected.

$$U_{r}^{cal} = k \times \sqrt{u_{p}^{2} + u_{C}^{2}}$$

(2)

To obtain a coverage factor ($k$) at 95 % confidence level, the effective degrees of freedom ($v_{eff}$) were counted from the Welch–Satterthwaite equation according to [5]. Expanded uncertainties were found to be 2.0 µm and 2.5 µm for diameters at +2 mm and +7 mm, respectively. Expanded uncertainties for the roundness were 2.2 µm and 2.9 µm respectively. A finite element analysis was performed to quantify the male shrinkage. It was found to be -4 µm. The amount of shrinkage was
used to correct the measurements related to the measurands at +7 mm.

4. Measurements via CT scanner

The two assemblies were scanned using a Nikon Metrology XT H 225 ST CT scanner. The selection of scanning parameters was carried out with the aim of achieving the histogram of the grey value as wide as possible, but at the same of paying attention to prevent an enlargement of the focus spot size. The process resulted in the choice of scanning parameters shown in Table 2. To scale down image artifacts related to X-ray paths through the object, a tilted configuration was chosen. The undesired brightness variation in the background was limited using shading correction (128 projections and 4 reference images). Voxel size correction was carried out using the CT ball plate. The CT ball plate was scanned before each assembly with the same scanning parameters and shading correction. The correct voxel size was found to be 0.9987. A hardware-based correction (BHC) was performed during the reconstruction to enhance the image quality. A 2nd order correction was selected per assembly. The coefficients are listed in Table 3.

<table>
<thead>
<tr>
<th>Table 2 Scanning parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>X-ray tube voltage</td>
</tr>
<tr>
<td>X-ray tube current</td>
</tr>
<tr>
<td>Uncorrected voxel size</td>
</tr>
<tr>
<td>Magnification factor</td>
</tr>
<tr>
<td>No. of projections</td>
</tr>
<tr>
<td>No. of image for projection</td>
</tr>
<tr>
<td>Pixel size</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3 Coefficients of BHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>$x^2$</td>
</tr>
<tr>
<td>$x$</td>
</tr>
<tr>
<td>Scale</td>
</tr>
</tbody>
</table>

4.1 Surface determination

Surface determination on the male parts was made using inspection software VG Studio Max 2.2. First Global threshold method was used, and Local threshold method together with region of interest (ROI) to refine the surface. For the assembly 1, the determination of the surface was done without any problems due to the sharp distinction between POM-part and PE-part and background in the histogram (Figure 2a). A complete separation of the female and male part was achieved, but a residual ring of the female part was present on the male surface (Figure 3). The ring was always present, even after performing the surface determination several times. It is believed that the residual ring is due to the overlap of gray values between the tail of the distribution of the POM-part and the bell of the PE-part. Nevertheless, a sharp distinction between materials is present within the gray value histogram.
Figure 2 Histograms of gray value distributions of the reconstructed volume of the assembly 1 (a) and assembly 2 (b). Three peaks are visible in the item 1. For item 2, only two peaks are present.

Figure 3 (a) A 2D view of assembly with a misidentification of the male surface outlined in red (b).

In contrast, a complete segmentation of the male part was not possible for assembly 2, because it was not easy to make a distinction between PP-part and PE-part in the histogram (Figure 2b). To improve the detectability of assembly 2, a series of attempts were made using different combinations of higher current levels and X-ray pre-filtering (Cu filters with thickness from 0.1 to 0.5 mm), but these were unsuccessful. It seems that due to the persistent lack of contrast, the detectability of assemblies where $\Delta p = \left| \frac{\rho_{\text{male}} - \rho_{\text{female}}}{\rho_{\text{male}}} \right|$ is below 6% cannot be managed in an industrial CT. A new investigation will be arranged to define the minimum $\Delta p$ that results in a sufficient contrast. In the following, the investigation was only focused on the male part of assembly 1.

5. Results and discussion

The deviations with respect to reference values are shown in figure 4. By normalizing with respect to the correct voxel size, the deviations belonging to the non-assembled section (at $+2$ mm) lie in the range 35-36% and 25-32% per diameter and its roundness, respectively. Results recorded are in good agreement with the studies carried out upon accuracy of CT measurements encompassing mono-material specimens [1,6]. A different situation is registered at $+7$ mm (the assembled section), where deviations vary in the range from 6% to 7% and from 94% to 95% for diameter and its roundness, respectively. Looking at the roundness results, the larger deviations could be explained in terms of a change in the female and male shapes during the assembly, but also an increase of image noise, resulting from the surface determination. The increase of noise was observed using the distribution of the fitted points. The limited deviations of diameter measurements are due to the ring of the female material, surrounding the male volume. An attempt to measure the ring was carried out with the aim of removing the effect of the ring thickness from evaluations carried out at $+7$ mm. The thickness of the ring was measured as the difference of two
cylinders fitted on the inner and outer surface of the ring itself. Each cylinder was obtained by a
collection of 1000 points equally distributed. 4 replications of ring-thickness measurements were
performed. The standard deviation of the thickness measurements of the ring, $\sigma_{ring}$, was indirectly
found by squaring the standard deviations of inner, $\sigma_i$, and outer, $\sigma_o$, cylinder measurements
according to the equation 3. The ring was found to be $15 \pm 0.8 \, \mu m$.

$$\sigma_{ring} = \sqrt{\sigma_i^2 + \sigma_o^2}$$  \hspace{1cm} (3)

Figure 4 (a) Results of diameter measurements and (b) roundness measurements at z +2 mm (non-assembled area) and
at z +7 mm (assembled area).

Figure 6 illustrates the diameter deviations after removing the ring. The deviations are in the range
of -14 $\mu m$ and -8 $\mu m$ for the two diameters at +2 mm and +7 mm, respectively. The diameter
evaluations at +7 mm present a 33%-bigger standard deviation than the evaluations at +2 mm due to
the variability of the ring thickness the measurements. Additionally, in both cases an
underestimation of measurands is noted that could be associated with the high magnifications used.
In fact, the same trend of results was recorded in the investigation about voxel size correction and
its prediction [7]. It can be concluded that the scanning parameters and the selected geometrical
features selected in this study limited the difference in CT performance in mono- or multi-material
investigations. The scanning parameters, particularly the selection of X-ray voltage, produced a
well-defined histogram of gray values with very limited tails, representing a key element to achieve
a high quality of segmentation. The selection of axial-symmetric features (diameters) made the
feature evaluation more robust to the noise and inaccuracies associated with the segmentation of
multi-material assemblies, because generally speaking the fitting algorithms can limit surface
outliers by averaging the information over a symmetrical surface. It is reasonable to expect wider
differences if bidirectional measurements (e.g. the distance between two planes) are investigated
due to the lack of symmetry during the fitting of points.
6. Conclusions

The results of an investigation involving CT of two multi-material assemblies have been presented. Three main results have been recorded. The first one is related to lack of detectability of assemblies with similar densities. Such preliminary results shall be investigated further in order to achieve a wider statement upon the detectability in industrial CT. The second one is related to the possible misidentifications of surface when assemblies are post-processed. A quantification of such effect was attempted. The third one states that increasing the number of materials does not influence the CT performance, if an efficient surface segmentation is performed and robust geometrical features are selected.

7. Acknowledgment

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References