Development of test bodies for deployment in Industrial Computed Tomography

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Abstract

For calibration and performance assessment of industrial CT devices, reference objects can be used. This paper presents three unique test bodies comprising of distinctive geometric characteristics and traits resembling those that are often exhibited by real industrial components. The framework for the conception and development process of these objects is based on a systematic approach to ascertain the geometry, dimensions and suitable materials for the final test bodies. The specimens are designed to cover all common geometric tolerances in addition to dimensional measures. Moreover, the distinctive properties and features exhibited by each of the three designs, along with an allowance for a comprehensive geometric dimensioning and tolerancing (GD&T) analysis, challenge different aspects of the CT process. To ensure traceability, the test bodies are calibrated with high accuracy micro coordinate metrology. Therefore, a data evaluation strategy is discussed, which allows the comparison of data points from the tactile measurement to the extracted surface of the CT measurement.

Keywords: computed tomography; metrology; reference standards

1 Introduction

Although CT has been extensively used as an effective means to examine and inspect different specimens in the medical field and in industry, its application as a tool for dimensional metrology has only gathered pace in the last decade. Over this period, extensive effort has been invested in advancing CT as a viable method for carrying out reliable and accurate dimensional measurements, particularly through the development of numerous reference standards. A comprehensive overview of developed reference standards can for example be found in [1].

These reference standards are widely used to evaluate the properties of CT scanners under well-known conditions and usually comprise (ruby) spheres or ball bars in different setups (Figure 1a) and 1b)). The first reference objects took inspiration from metrological standards designed for conventional coordinate measuring machines (CMM). Alongside facilitating inter-method comparison, their similarity to commonly accepted CMM standards allow them to be used on different types of CMMs. They are, however, not always successful in verifying inaccuracies or calibrating CT scanners [1]. These reference objects can for example be used to evaluate and correct systematic errors, such as scale errors. Another example of a reference standard is the titanium sphere calotte cube (Figure 1c)), which was developed by [2] to assess length, size and form errors.

![Figure 1: a) CT ball plate [3] b) standard developed by Zeiss [4] c) calotte cube [2]](image)

Apart from the specimens displayed in Figure 1, certain workpiece-near reference objects have also been proposed by different institutions to better reflect the industrial use of CT.

Step-cylinders with a central (inner) bore, as proposed in VDI/VDE 2630-1.3 [5], support internal measurements and thus allow a differentiation to be made between edge detection offset errors (threshold errors) and scaling errors. The VDI/VDE guidelines define several accuracy characteristics regarding size, form and straightness for step-cylinders. Step-cylinders are useful for studies regarding the absorption behaviour of the respective material, which can be also used for beam hardening correction. [1]

A set of multi cross-section workpieces made from aluminium and titanium was developed by [7] (see Figure 2b)). These workpieces were designed to provoke beam hardening and scattering artefacts that influence the threshold determination.

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Other workpieces reflecting plane-parallel surfaces are shown in Figure 3. The so-called cactus step gauge is a prismatic aluminum part with through grooves that enable multiple distance measurements on parallel surfaces [8]. Common step gauges as shown in Figure 3b) are often used for performance verification of CT systems [9].

While displaying several features that can be found in industrial components, these reference standards are still far away from real workpieces. The standards presently deployed for this purpose do not reflect the complexity and intricacy of most industrial components, leaving insufficient scope for the thorough assessment of the geometry, form, orientation and location of individual part features, all of which have a significant impact on CT measurement results. As CT is of prime relevance in the industrial environment, it is important to establish its validity as a precise measuring technique by evaluating it not only with laboratory reference objects, but also with respect to geometries and features exhibited by real industrial components.

In the case of automotive die casting, a miniature modified aluminium cylinder head casting with dimensions of 12 cm x 9 cm x 6 cm was developed by [10], as shown in Figure 4. The object is dismountable in four parts, allowing access of tactile probes to the inner features of the assembled head, which otherwise would not have been accessible.

Despite the fact that CT is largely used in plastics industry, most of the previously developed test bodies are made from metal materials. With exception of the modified cylinder head, all show very simple geometries, not reflecting real dimensions and features of industrial parts. Thus, a set of test bodies was developed that cover all common geometric tolerances, while resembling real industrial components.

### 3 Test bodies

Three unique test bodies comprising of distinctive geometric characteristics and traits resembling those often displayed by real industrial components have been developed at the Institute of Production Science (wbk) at Karlsruhe Institute of Technology, Germany. The test objects have been named after the components that predominantly influenced their conception, and are as follows:

#### 3.1 ED housing

The first test body developed was termed ‘ED housing’. ED refers to electronic device, as the concept of this test body took inspiration primarily from the housing and casing of electronic devices such as credit card swipe machines, calculators, mobile phones, etc. This test body exhibits maximum outer frame dimensions of 44 mm x 43.5 mm x 17.5 mm. In its inner frame, eight
bores are located - four on each side of the plane of symmetry - with diameters ranging from 2 mm to 5 mm. Their location has been defined and tolerated with respect to three datum surfaces present on the test body. This through bore system resembles the calotte plate reference object and allows multiple length measurements to be made between the central axes of the different bores, as well as threshold independent point-to-point measurements to be carried out between the points arising due to the intersection of the central axis with the workpiece surface planes. Conversely, the through bores can also be fitted with calibrated ruby spheres (preferably as attachments on rods made of a low-density highly penetrable material) in order to accurately measure centre-to-centre distances of the spheres, which act as threshold independent reference dimensions for reducing voxel size errors through voxel size correction. Furthermore, the inner frame of the ED housing also contains three 1 mm wide steps running across the entire 43.5 mm length of the housing. With a step height of 1.5 mm and an inter-step distance of 2.5 mm, this step formation is comparable to common step gauges, which are often used as reference objects for the characterisation of CT system measurement errors (e.g., systematic errors), and similarly features bidirectional surface-to-surface lengths.

The ED housing geometry facilitates the evaluation of more than 50 distinctive geometric characteristics, including a minimum face-to-face length measurement of 0.8 mm, along with a minimum feature measurement of 1 mm (diameter). Depending on the part orientation, the maximum possible planar length to be penetrated in this test body equals 60 mm (inner frame diagonal). In addition, the ED housing test body also accommodates a number of different types of tolerances, including angularity, cylindricity and surface profile.

### 3.2 Stepped cap

The second presented test body, named ‘stepped cap’, was based largely on components such as radiator caps, fuel tank caps and different kinds of flange mountings. The outer surface of the design was adapted to the step cylinder reference object. The reason for modifying the exterior of this test body to resemble a step cylinder was that step cylinders are commonly used in CT as reference objects for optimising threshold values and for differentiating between inner and outer edge detection offset errors. Step cylinders also aid in examining the impact of error sources like beam hardening on internal dimensions. With maximum outer dimensions of 40 mm x 40 mm x 13 mm, the stepped cap comprises of both outer and inner geometric features.

The outer geometry consists of five cylindrical steps at a consecutive vertical increment of 2 mm. The diameters of these steps range from 30 mm (bottommost) to 22 mm (topmost). The bottommost step element represents a circular flange of thickness 2 mm containing four protruding rectangular-faced adapted clevis-type features located orthogonally from each other. Instead of having through bores on their side faces as regular clevises do, these features alternately display pairs of through bores and mounting legs. The dimensions of each of the mounting legs (four in total) are 2 mm x 1.8 mm x 3 mm, while the through bores are 1.5 mm in diameter. On the other hand, the inner geometry of the stepped cap features a 2 mm thick hollow cylinder (D = 14 mm, d = 12 mm) with a height of 6 mm. The innermost feature of the test body is a dual keyway keyed joint system with a bore diameter of 5 mm. Similar to the ED housing, the stepped cap test body also displays bilateral symmetry. Its geometric characteristics include a minimum face-to-face length measurement of 0.6 mm, along with a minimum feature measurement of 1 mm (diameter). It also encompasses the straightness, flatness and perpendicularity tolerances.

### 3.3 Wheel rim

The third and final test body has been designated ‘wheel rim’. It can be viewed as a modified miniature version of common automobile rims. From all the three presented test bodies, the wheel rim is the closest representation of an actual industrial component. It entails maximum outer dimensions of Ø 46 mm x 8 mm. The outer geometry can be described by means of four cylindrical elements, with the two outermost cylinders having diameters of 46 mm and 44 mm respectively, along with a height of 6 mm. Moving inwards, the next two cylindrical features exhibit diameters of 36 mm and 34 mm respectively with a height of 8 mm. Starting from the inside face of the 34 mm cylinder, four spokes taper towards the centre disk (Ø 14 mm). The side taper of the spokes, as viewed from the top, is at an angle of ~ 5.2°. The centre disk of the wheel rim has a thickness of 6 mm, with a 1 mm offset each from the top and bottom faces of the test body. It includes four Ø 1.5 mm through bores in a circular pattern at an angular spacing of 90°, as well as an inner bore with a diameter of 4 mm, whose centre is located 4.5 mm from the centres of each of the through bores. A notable difference between the wheel rim and the other two test bodies is the absence of any rectangular-faced features. Although it offers fewer measurable features than the two previously introduced test bodies, the wheel rim demonstrates the unique property of rotational symmetry around the centre axis. Rotationally symmetric objects are generally easier to measure, with the projection angle not exerting as much of an influence. This test body also enables the evaluation of, amongst others, the circularity, parallelism and concentricity tolerances.

Table 1 summarises the key elements of the three presented test bodies.
The framework for the conception and development process of these objects has been dictated by certain predefined boundary conditions, such as the technical properties of the CT system used and the eligible material spectrum. The emphasis was laid on polymers, whereas composites and reinforced materials were entirely excluded from the material selection process. Another crucial factor taken into consideration was the stability of the final test bodies. As they are to undergo regular experimentation and measurements over a length of time, it was imperative that the geometric, dimensional and material characteristics of the produced workpieces remained consistent throughout this duration. Additional constraints that contributed to the development process included the influence of the manufacturing technique (machining), existing CT reference standards, the reference measurement method used for the establishment of traceability (tactile CMM), as well as the specific material properties desired for the final test bodies (see Table 2).

Based on the stipulated material properties, the materials that were shortlisted as suitable candidates for the manufacturing of the test bodies were polymers in the priority order PPS > PEEK > ABS. However, due to scant market availability of PPS in unreinforced and semi-finished form, it was decided to manufacture the test bodies using PEEK. Additionally, the test bodies were also manufactured in aluminium due to its extensive and diverse application spectrum in industry.

<table>
<thead>
<tr>
<th>Test body</th>
<th>Tolerance type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED housing</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Stepped cap</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Wheel rim</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
</tbody>
</table>

Table 1: An overview of the three presented test bodies and their core characteristics.
### Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>PPS (Polyphenylene sulphide)</th>
<th>PEEK (Polyether ether ketone)</th>
<th>ABS (Acrylonitrile butadiene styrene)</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope of application in industry</td>
<td>Automotive</td>
<td>Medical technology</td>
<td>Automobile interiors</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Turbines</td>
<td>Pharmaceutical</td>
<td>Telecommunications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electronics</td>
<td>Semiconductors</td>
<td>Music instruments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Semiconductors</td>
<td>Micro-electronics</td>
<td>Domestic appliances</td>
<td></td>
</tr>
<tr>
<td>Machinability</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td></td>
</tr>
<tr>
<td>Moisture absorption at room temperature</td>
<td>Very low</td>
<td>Low</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Dimensional stability</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Surface roughness (Rz value in µm)</td>
<td>4.6 - 8.2</td>
<td>4.7 - 7.5</td>
<td>6.3 - 10</td>
<td></td>
</tr>
<tr>
<td>Constitutional resistance to X-rays</td>
<td>High</td>
<td>Very high</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.36</td>
<td>1.31</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Availability as semi-finished product</td>
<td>Unclear</td>
<td>Readily available</td>
<td>Easily available</td>
<td></td>
</tr>
<tr>
<td>Material cost per kg</td>
<td>Medium-High</td>
<td>High</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Material selection process for the test bodies in a nutshell (Material data see [11]).

### 4 Evaluation Strategy

To evaluate the accuracy of CT measurements, a reference measurement has to be performed with a CMM. An advantage of tactile measurements in comparison with other methods is that they are still the most accurate method, enabling measurement uncertainties below 1 µm.

The feature of interest is measured and evaluated both by CT and CMM. Usually a Gauss fit (or any other appropriate fit for the purpose) is done for the measured surface (CT) respectively point cloud (CMM).

A main drawback of this procedure is that only selected points of the feature are accessed by the point probe, but a complete surface of the object in the CT scan is available. A fit to geometric elements thus can lead to different results of CMM measurement and CT scan, especially if local surface deviations occur or local artefacts, such as noise, appear in the CT scan. In both cases, only a direct and local comparison between probed points and CT surface points can lead to a better estimation of the quality of the CT scan and visualize local inaccuracies.

Nowadays, a direct comparison of the determined surface is not possible. Hence, the surface geometry has to be exported. We thus suggest a conversion of the CT surface to a polygonal mesh, which can be handled by commercially available software. [12, 13] propose a method with stl conversion of local patches of the CT surface, which are situated around the same position as the CMM measured points. The disadvantage of this method is that it is highly complex and time-consuming. We thus suggest a simplified method where the adaptive threshold-determined CT surface of the part is completely converted to a triangulated surface mesh, such that no additional manual effort has to be undertaken. The simplified method consists of the following steps:

After reconstruction, an adaptive thresholding is used to determine the part’s surface. In our approach, this was done with VGStudio MAX. The surface is then converted to the above mentioned stl format and imported in another software, in this case Geomagic Control 2015. The registration of the data has to be carefully chosen. 3-2-1 registration has delivered the best results for our approach. If reference spheres are available, as in the ED housing, these can serve as a reliable reference structure between CMM and CT measurement. Otherwise, outer plane surfaces and cylinder axes can be used as well. Now, a pointwise comparison between CMM and CT measurement can be performed.

To evaluate the accuracy of the method’s first step, the stl conversion, which was reported by other researches to show large deviations to the initial surface [9, 14], a nominal-actual comparison of the surface with its stl converted counterpart was performed. A 95% threshold of the overall deviation was defined as the comparative value for all conversions (Figure 7).

First, the influence of the size of the used triangles on the 95%-accuracy of the conversion was measured. Figure 8 shows the results for the aluminium stepped cap. Not surprisingly, in the highest stl-resolution, the minimal 95%-threshold deviation was achieved with 1.4 µm. For less complex geometries, such as a ruby sphere, even deviations below 0.5 µm were measured.

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In addition, the accuracy of the conversion at non-regular geometries was checked. Figure 9 shows exemplarily a bore with diameter 1 mm, where a burr is left from machining. The deviation between the actual scanned surface and its conversion is the same as for the defined geometries of the part.

CT-induced artefacts are prone to higher deviations at stl conversion because of the unclear surface structure with noise. In Fig. 10 the wheel rim shows a small artefact after the CT scan. To distinguish between artefacts and real flaws of the parts, an optical inspection of the parts was performed under the microscope. Because of its noisy appearance, the artefact shows deviations up to 6 µm, which can lead to a local overestimation of the measurement deviation of the CT scan if compared to the CMM point cloud.
Figure 9: Comparison between microscopic picture of (Peek) wheel rim bore and its equivalent in surface. It can be seen that even with a small burr the stl surface matches well with the CT surface.

Figure 10: Influence of artefacts on the stl surface (Peek wheel rim)

5 Conclusion

Workpiece-near reference standards with traits resembling those that are often exhibited by real industrial components can help to analyze CT systems and their properties in a more realistic manner. The distinctive properties and features exhibited by each of the three developed test bodies, along with an allowance for a comprehensive geometric dimensioning and tolerancing (GD&T) analysis, challenges different aspects of the CT process. To ensure traceability, the test bodies are calibrated with high accuracy micro coordinate metrology and allow feature-based evaluation as well as a point-wise comparison after stl-conversion. Still, stl conversion goes along with a loss of accuracy at the determined surface. Highest deviations of the converted surface occur at sharp edges, such as introduced by artefacts. Even though stl conversion generally shows good results, it can lead to local overestimation of the measurement deviation between CT and CMM at the position of artefacts. If artefacts cannot be completely avoided in the scan, this should be considered in the interpretation of the data.

Acknowledgement

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References


