Creating a Multi-Material Length Measurement Error Test for the Acceptance Testing of Dimensional Computed Tomography Systems

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Abstract
Non-destructive testing (e.g. defect detection, material characterization), reverse engineering, fibre orientation, and more recently coordinate metrology represent the broad range of today’s applications of industrial X-ray computed tomography (CT). However, the use of CT as a coordinate measurement system opens up new challenges to technology. This is especially true of dimensional inspections of multi-material assemblies which are characterized as promising, but very demanding applications of CT. The reliability of multi-material CT measurements is still an open issue due to the complexity of multi-material measurements and also because it is not covered in the current guidelines and standard drafts. Thus, this paper presents – as part of a multi-material acceptance test and to create trust in multi-material CT measurement – a new design and concept for multi-material length measurement error testing. It also discusses the test design and procedure based on the first experimental results. The paper attempts to perform a critical analysis of the new reference standard design – a multi-material hole cube – and tries to verify the concept in several steps.

Keywords: Acceptance testing, multi-material measurements, dimensional computed tomography (CT), standardization, length measurement error testing (E-test)

1 Introduction to acceptance testing and respective length measurement error tests

During the purchasing process of a new measurement device, the decision to buy is primarily based on the technical specifications. Important values of the measurement system’s specifications are the so-called maximum permissible errors (MPEs). The MPEs of a coordinate measuring system (CMS) are obtained by a series of test measurements under specific conditions. Those test measurements and procedures are called acceptance testing and reverification tests. The main difference between acceptance testing and verification testing is: the first test is to check whether the metrological performance of the new measurement system is performing according to the manufacturer’s specifications (e.g. MPE), and the second is to assure reliability during operation at regular time intervals or after an unusual event, e.g. a system collision. The acceptance testing results are normally also relevant for financial aspects as well as warranty claims. Therefore, CT users and manufacturers share a large interest in realistic, reliable, but also economic acceptance testing. From the metrological point of view, acceptance testing, indeed, creates trust in the CMS by helping to reach traceability to the metre (an SI unit) for the measurands under study, and by creating specification definitions, enabling decision-making for both CMS users and manufacturers [1].

In order to reach a compromise between the manufacturers’ interests (i.e. simple measurement tasks) and the users’ interests (i.e. complex measurement tasks), the acceptance tests are regulated by international standards and national guidelines. While the tactile CMS technologies and to some extent also optical CMSs have reached a satisfying level of reliability, a significant amount of effort has been devoted to bringing CT to the same level of trust. At the national level, the German guideline series VDI/VDE 2630 is focused on how to apply ISO 10360 in CT and it was the first set of guidelines which were published [2]. The most relevant standard for acceptance testing for CMS is the ISO 10360 series of standards; to date, only optical- and tactile-based CMSs have been publically available.

According to ISO 10360, the main principle of acceptance testing is to perform an overall test of the entire performance of the CMS. Therefore, the test should be performed as an integrated system (i.e. as a black box) and it should assess the system using the complete measurement chain. The acceptance test should also reflect the standard use of the system and cover all dominant error behaviour of the CMS under study. Real-life effects and, for example, the request for simple geometry reference standards should be taken into account in the test design. Besides this, the use of a real-life specimen in the scope of acceptance testing is limited due to the complexity and variety of such objects, making comparability between different CMSs more difficult.

Another important principle of acceptance testing is to assess the local and global performance of the error characteristics of a CMS. Local performance – showing the ability to precisely locate and measure the surface of a structure under test in a small spatial region – is assessed as a probing error test (P-test) by means of measuring the size and form of a (small) test sphere.
Global performance is assessed as a length measurement error test (E-test) by means of measuring (long) length reference standards. Examples of length reference standards used to assess the E-test are shown in Figure 1.

![Figure 1. Length reference standards potentially used to assess length measurement errors: (a) PTB hole plate (designed by PTB and NMIJ) [3], (b) PTB calotte cube, (c) multi-sphere standard (courtesy of Carl Zeiss) and (d) DTU step gauge [4]](image)

Length measurements can be evaluated as bi- and/or unidirectional measurements, see Figure 2. The difference between unidirectional and bidirectional measurements is the probing direction when using a tactile CMS. In other words, a bidirectional length is obtained when both arrows creating a length are pointing in opposite directions as shown by the direction of the arrows in Figure 2 (right). However, when both arrows creating a length are pointing in the same direction, this characterizes a unidirectional measurement. Unidirectional centre-to-centre distance is also possible, when the length is calculated by the centre of two fitted elements, circles for instance. However, the last type of measurement does not reveal the potential local error of the systems, e.g. the surface determination influence on CT measurements is not included in the centre-to-centre measurements, due to the massive data averaging and is also different from point-wise unidirectional measurements (cf. Figure 2). Thus, according to some of the existing ISO 10360 standards, bidirectional measurements are mandatory for acceptance testing and unidirectional measurements are optional. It is expected by some and there are some technical indications – but no guarantee – that a future ISO 10360 for CT will also favour this approach. Either uni- or bidirectional measurements may be evaluated using patches to create a representative point. This approach – which entered into ISO 10360 methodology with ISO 10360-8 for optical distances sensors [5] – enables more stable results when measuring lengths by reducing the influence of the sensor noise. Furthermore, the patch approach improves comparability between CMSs with different sensor technologies, mainly due to the high density of points obtained by CT and to the morphological filtering being present in tactile probing. On the other hand, the use of patches has intrinsic low pass filtering properties and can hide local effects of the system, which might be relevant for the CMS user. However, in the current international standard for optical distance sensors some unsolved issues exist, e.g. the patch geometry is described in a non-satisfactory way.

Since 2010, the ISO technical committee 213 working group 10 has been working on the development of a new ISO 10360 standard for CT as a CMS. However, no multi-material-related statements or studies have been covered in the developments of ISO for CT to date. Since CT has presented a great potential for measuring complex workpieces and multi-material workpieces or assemblies [6], this work presents a first novel proposal for creating a multi-material length measurement error test (E-test) following the principles of the well-established ISO 10360 series of standards.

![Figure 2. Global behaviour assessment as length measurement error acceptance testing](image)
2 Creating a multi-material length measurement error reference standard

This paper addresses the challenge of creating the first, complete multi-material acceptance test for dimensional CT – specifically in this paper – the multi-material length measurement error test (E-test). The multi-material probing error test (P-test) is addressed in a further contribution to iCT2017 [6]. An important statement is that the whole multi-material test is designed to complement – but not to substitute – the mono-material test! Thus, this paper presents a new multi-material reference standard design for the E-test and discusses the first results based on experimental CT data. The creation of the multi-material length measurement error test as well as the reference standard was mainly based on ISO 10360 principles and on the following list of requirements:

- Multi-material test complementary to the standard mono-material test
- Overall test of the entire performance of the (CT-based) CMS applying the whole measurement chain
- Assessment of the global (long-range) error behaviour of the (CT-based) CMS
- Ability to reveal potential multi-material effects and error influences
- Applicability to different (CT-based) CMSs
- Compromise in testing between worst case and best case scenarios
- Sufficient low test value uncertainty (low enough to allow multi-material related specification statements)
- Reference standard should allow flexibility of measurands (inter-material and simultaneously in-material measurands, uni- and bidirectional measurands, pointwise and patch-based measurands) (for a definition of in- and inter-material measurands cf. Figure 3)
- Size of the reference standard should allow mid-range magnification, i.e. magnification neither too high nor too low (assuming that multi-material related effects are generic in nature and thus the most appropriate measurement scenario can be selected)
- Reference standards should feature short and long lengths to be measured in seven different spatial directions (similar to other standards in the ISO 10360 series)
- Multi-material reference standards covering different absorption coefficient scenarios using adequate materials concerning X-ray attenuation coefficient
- Different penetration length per material along the standard (variation of material ratio)
- Mono-material scenarios should be included (as references)
- Analysis of relative effects and/or comparison with reference values should be possible
- Dimensional stable reference standards
- Good properties of reference standards concerning manufacturing and achievable precision of geometric elements
- Manufacturing costs should be limited (if possible) to allow industrial dissemination and use

Figure 3. Measurement scenarios: mono-material scenario (creation of the elements for the measurand based on mat. A and air, mat. A and air, no mat. B present); inter-material measurements in multi-material scenario (creation of the elements for the measurand based on mat. A and air, mat. B and air); in-material measurements in a multi-material scenario (creation of the elements for the measurand based on mat. A and air, mat. A and air, however, mat. B is part of the penetration length)

2.1 Multi-material hole cube standards

The new reference standard design, the multi-material hole cube (MM-HC), is presented in Figure 4. It has a size of 30 mm × 30 mm × 30 mm featuring 17 holes inside and 12 “V”-shaped grooves outside. The design consists of two symmetric parts made of different materials; the fixture of the two parts is guaranteed by fitting pins and a screw/nut system made of the polymer, polyether ether ketone (PEEK), due to its low X-ray absorption. The MM-HC also features a step-like “cut” shape enabling different multi-material ratios along the standards’ height, see Figure 4-c. Due to the hole-like structure, the MM-HC design also allows in- and inter-material measurands in a multi-material scenario as well as measurands in a mono-material scenario (depending on the orientation in the CT, mono-material measurements can be performed in a multi-material assembly too, e.g. in G1 and G12 in a horizontal setting, see Figure 4-c). The remaining grooves G2, G3, G4, G5 and G6 feature different material ratios, see Table 2. With the different material ratios along the body, real-life scenarios can be obtained, e.g.
G6 features 80% of material B and 20% of material A. Besides this, the V-shaped grooves are used for the registration/alignment of the standard in the data analysis phase only.

The positions of the holes are designed to have at least three independent lengths in seven main directions, featuring lengths from 1 mm to 35 mm. This is a first difference to the ISO 10360 standard where five independent lengths in seven main directions are frequently required in several parts of ISO 10360. However, material penetration as well as restrictions of the manufacturing process limit the design to having at least three independent lengths per direction. Once the multi-material test is designed to complement the mono-material test, the multi-material test focuses on the assessment of systematic effects, but is not intended to sample the error behaviour covered by the mono-material test, however, it is worth noting that also for the mono-material case, it is not clear if a request for five independent lengths in seven main directions will be part of a future ISO 10360 for mono-material CT measurement specification and testing.

In total, six complete MM-HC standards have to be created, three mono- and three multi-material specimens. For the production, one composite material – carbon fibre reinforced silicon carbide SiC (Cesic®) and two metal materials – aluminium (Al) and titanium (Ti6Al4V) were selected due to their large applicability in industry, adequate mechanical properties and an adequate X-ray attenuation coefficient, see Table 1. As stated in the list of requirements, the test was designed to provide a broader range of attenuation coefficients for 225 kV CT systems.

Although Cesic® is a ceramic material, it is possible to use high-precision electrical discharge machining-based methods to manufacture Cesic® due to its sufficient electrical conductivity. This property of Cesic® has shown significant advantages over other materials considered, as all materials in use for the multi-material design can be manufactured using the same manufacturing technology (i.e. similar manufacturing quality is obtained). There are two kinds of Cesic® available on the market: HB-Cesic® and Cesic-MF®. The main difference between the two kinds of Cesic®, as stated in the manufacturer's datasheets, is the starting material used for creating the ceramic material. The main concern while selecting the kind of Cesic® to be used was the non-homogeneity of the material being a carbon-fibre-reinforced silicon carbide. Some preliminary tests were carried out with the aid of an optical device (sensor based on focus variation principle) and CT using a higher resolution than required here. Both materials seem to be adequate for such a reference standard. Actually, HB-Cesic® was used in the MM-HCs. Besides this, for the magnification used, no significant effect of the non-homogeneity of Cesic® on the measurements is expected. On the other hand, Cesic® as a ceramic is a fragile material and it should be manufactured and handled carefully. Therefore, the MM-HCs were machined at PTB by erosion. Moreover, fitting pins and fixing screws/nuts were turned in PEEK material.

Reference measurements of the MM-HC are performed using a tactile CMS (a classical coordinate measuring system CMS). All 17 holes are measured at seven heights (height indicated by the groove position), Figure 4-b. For each groove height, seven circumferential lines at different heights (circumferential lines distance 25 µm) are measured inside the holes, Figure 4-c. In total, 0.5 million points are obtained from the tactile scanning measurements using a diamond probe. This measurement approach allows the flexibility of the measurands, i.e. it enables the use of single-point, multi-point and patch measurements, improving comparability between the CMSs. Distances using different measurands (e.g. unidirectional centre-to-centre, patch-based measurements) are calculated automatically using scripting-based analyses using the evaluation software GOM Inspect.

Due to its design, the MM-HC enables the investigation of potential multi-material effects on the length measurements. What is possible are 272 mono-material lengths in a multi-material scenario, 274 in-material and 238 inter-material measurements in a multi-material scenario. Additionally, 160 lengths using the unusual measurands where a single primitive (e.g. cylinder, circle) is created by two materials is still possible.

Figure 4. Multi-material hole cube (MM-HC) design: (a) isometric view of the MM-HC; (b) top view of the design highlighting the position of the holes; (c) central cut of the design highlighting the stepwise diagonal cut separating materials, “V”-shaped grooves and calibration strategy, CMM probe (in red) added here for visualization of relative dimensions only.
### 2.2 Experimental CT set-up

For this study, only Al/Cesic® and Al/Ti MM-HCs were considered. The remaining cubes for the complete test are in a later phase of the manufacturing process. For the CT scans, the MM-HCs were positioned horizontally in the rotary stage in the PTB’s Nikon MCT 225 system with a voxel size of approximately (32 µm)³, see Figure 5. In order to remove residual scaling errors, and thus improving the accuracy of the analyses, a multi-sphere scale correction (using the standard visible in Figure 1-c) was applied. The scale correction is based on the average between the multi-sphere CT scans before and after each MM-HC CT scan. The relative stability between the before and after scans was less than 0.8 µm over a length of 40 mm in both cases (Al/Ti and Al/Cesic®). The temperature in the CT cabin was recorded to be (20 ± 0.5) °C. Therefore, the thermal expansion influence of the materials has been neglected.

The CT scanning parameters using the Nikon Metrology X-Inspect 3.1.9 software, shown in Table 4, were selected for each MM-HC in such a way as to have similar contrast-to-noise ratios (CNR), defined according to [8]. The CNR ratio calculated per MM-HC and separated by material can be seen in Table 3.

![Figure 5. Experimental set-up of the MM-HC inside the PTB’s Nikon MCT 225 system: (a) aluminium and titanium assembly; (b) aluminium and Cesic® assembly; and (c) mounting set-up of the MM-HC in the CT system](image)

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Al/Ti</th>
<th>Al/Cesic®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>CNR</td>
<td>CNR</td>
</tr>
<tr>
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<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Ti</td>
<td>13</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 3. CNR of the MM-HCs
2.2 Evaluation

The evaluation of the multi-material influence on the E-test was based on the deviation from tactile CMS reference measurements. Mono-material as well as multi-material, in-material and inter-material measurements in the following scenarios were considered in this paper, see Figure 3. To ensure comparable analyses, the same alignment procedure as well as the same measurement strategy as those used in the reference measurements were also applied to the CT data. The reference measurement points were also obtained for the 17 holes at seven heights (i.e. grooves). Thus in total, also for the CT data, approximately 0.5 million points were stored for one MM-HC. The reference points (tactile CMM data) were fitted into CT data surface. The workflow of the analysis is described below:

1. Reference measurement of the MM-HC using a tactile CMS → Tactile CMS points
2. Calculation of reference lengths between tactile CMS points using different measurands (e.g. centre-to-centre, bidirectional patch-based lengths) → tactile CMS reference length results
3. CT scans and surface determination of the MM-HC (surface determination for multi-material cubes are performed in two steps: optimized for the high absorption material (HAM) and optimized for the low absorption material (LAM) → CT surface (in two volumes)
4. Load and fit the tactile CMS points into the CT surface(s) (CT data aligned) → CT points (two point clouds; one for HAM and one for LAM)
5. Length measurements of the CT points using different measurands (e.g. unidirectional centre-to-centre, bidirectional patch-based lengths) → CT results
6. Difference between CT results and tactile CMS reference results is the measurement error

Once the final (fine) alignment procedure has been performed through a measurement template, a first preliminary alignment is then required. The fine alignment procedure is performed as follows:

- Cylinder axis created from H9 (covering one material only) defines the primary datum (+z-axis), see Figure 4-b
- Secondary datum (-y-axis) is defined by the line created from the two circles in H3 and H15, see Figure 4-b (one material involved only)
- The origin of the coordinate system is defined by the projection of the symmetry line created from the grooves and the cylinder axis H9. The symmetry line is created from the symmetry element between the grooves G2, G3, G5 and G6, see Figure 4-c. The intersection line between the two groove planes creates the groove element

The following remark is of great importance: elements and features present only in one material are used for the alignment procedure of the MM-HC, as in the version of the data analysis software in use (VG Studio Max 2.2), a common and optimal surface determination for different materials in the same scene is not possible.

Uni- and bidirectional length measurements were both evaluated in this paper. Unidirectional measurements are evaluated as the distance defined by the two least-squares short cylinder centre points at a specific height. Bidirectional length measurements are evaluated as the distance defined by two representative points created through patch operators. The patch operator used in this analysis has a spherical shape with a radius of 500 µm (~16 times the voxel size of the experimental setup), see Figure 6-a. Thus, each length created involves the use of around 2 × 300 data points.

In total, 956 unidirectional centre-to-centre lengths and 378 bidirectional patch-based lengths at different heights (i.e. different material ratios) were calculated. The difference in the total number of lengths is due to the calculation time which, for the patch-based analysis, is much longer than centre-to-centre measurements. Thus, not all possible bidirectional lengths have been used in this analysis. For the unidirectional lengths, all possible distances between the holes are measured in the plane perpendicular to the hole axes. However, for the bidirectional measurements, at least six lengths (not independent) in seven

1. Nikon Metrology CT PRO 3D version 3.1.9 standard beam hardening correction based on a polynomial function of order 2 (preset 2) was carried out during the reconstruction of the projections.
2. Nikon Metrology CT PRO 3D version 3.1.9 standard software-based noise reduction was carried out during the reconstruction of the projections. The settings applied to all of the assemblies evaluated were: Filter type: Hanning, cut off frequency: 100% of maximum frequency, order: 1 and scaling: 1 were used (corresponding to preset 2 of software in use)
main directions of the MM-HC are measured, e.g. line of holes 1-16 in Figure 6-b and lengths created from H1-H4, H1-H10, H1-H16, H4-H10, H4-H16 and H10-H16 are measured. In order to provide a better view of the material influence depending on the material ratios, the average, the range and the standard deviation of length measurement errors per groove are also evaluated for both unidirectional centre-centre and bidirectional measurements.

Besides this, in order to evaluate the influence of material A on material B and vice versa, in-material measurements in mono- and multi-material scenarios are also separately evaluated. The results are then compared with the inter-material measurements which are separately assessed, too. For the in-material measurements, only lengths created of the same material elements in a multi-material scenario and in a mono-material scenario (i.e. G1 for Al and G12 for Ti) were considered. Inter-material measurements are characterized by the measurand (i.e. length) of elements created in different materials, with the interface with air.

Additionally, in order to evaluate the multi-material influence on the geometry, the diameter and the form deviation of the 17 holes at seven different material ratios are measured. However, at some specific positions, there are some holes which comprise two materials. This characterizes an unusual measurand and therefore they are excluded from these analyses.

![Figure 6. (a) Creation of the representative point based on the patch operator; (b) Seven main directions used for the bidirectional measurements](image)

### 3 First CT results

Computed tomography datasets obtained with different multi-material scenarios of the new MM-HC reference standards were performed. Material pairings of Al/Ti and Al/Cesic® were scanned in order to investigate the multi-material influence on the E-test acceptance testing. The Al/Ti assembly characterizes materials with rather different attenuation coefficients, on the other hand; Al/Cesic® characterizes materials with similar attenuation coefficients, cf. Table 1.

Centre-to-centre unidirectional as well as bidirectional length measurements (cf. Figure 3) in multi-material and mono-material scenarios were carried out in the new MM-HC reference standards. The results of the bidirectional patch-based measurements for the Al/Ti and Al/Cesic® assemblies are presented in Figure 7; and the centre-to-centre unidirectional measurement results are shown in Figure 8. Besides this, geometrical evaluations of the holes, for size and form deviation at different heights, were carried out additionally and are shown in Figure 9. Both bi- and unidirectional length measurements were carried out in seven different material ratio scenarios.

In general, a significant multi-material influence on the CT measurements was observed. For the bidirectional patch-based measurements, a total measurement error range of almost twice the voxel size (i.e. 57 µm) was obtained. Figure 7-a and 7-b presents the average, standard deviation and max/min values per groove (i.e. per height) for all bidirectional lengths measured in the Al/Ti and Al/Cesic® MM-HCs, respectively. Concerning the standard deviation and max/min range, the Al/Ti assembly presents significantly worse results than Al/Cesic®. A second observation is that for the Al/Ti MM-HC, the larger the groove number (G6 and G12) is, the larger the standard deviation and total range are, see Figure 7-a. The broader measurement error for the grooves G6 and G12 can be explained by the increasing amount of Ti at higher grooves. For the “easy” scenario, i.e. Al/Cesic®, the max/min range was observed to be smaller than one voxel size for the bidirectional measurements, see Figure 7-b. This is a first indication of the multi-material effect on the CT measurements.

Figure 7-c and 7-d present bidirectional inter-material measurements. For the Al/Cesic® assemblies, a total range of almost twice the voxel size for the Al/Ti MM-HC, and half the voxel size for the Al/Cesic® MM-HC were observed. Similar error behaviour as in the inter-material measurements was observed for the in-material and mono-material for bidirectional measurements, see Figure 7-e and 7-f. It is assumed that the similar error behaviour between in- and inter-material measurements is due to that fact that bidirectional measurements are prone to noise and the CT scans have a similar noise levels for both materials, e.g. Al and Ti have similar CNR in the Al/Ti scenario scan, cf. Table 3.
Figure 7. Errors of the multi-material bidirectional length measurements of the MM-HC reference standard in the seven main directions of the MM-HC at seven different material ratios, cf. Figure 4 and Table 2: (a) and (b) average, standard deviation and min/max values of the MM-HC lengths for Al/Ti and Al/Cesic® respectively; (c) and (d) inter-material measurements of the MM-HC lengths for Al/Ti and Al/Cesic® respectively; and (e) and (f) in-material as well as mono-material measurements of the MM-HC for Al/Ti and Al/Cesic®, respectively.
A total measurement error range of approximately half of the voxel size (i.e. 14 µm) for the unidirectional centre-to-centre measurements was obtained, and Figure 8-c, Figure 8-a and 8-b present the average, the standard deviation and the max/min values per groove (i.e. per height) for all unidirectional centre-to-centre lengths measured in the Al/Ti and Al/Cesic® MM-HCs, respectively. Noticeably, the Al/Ti assembly presents a significantly larger standard deviation and max/min range than Al/Cesic®. This is a second indication of the multi-material influence on the CT measurements, as early as in the centre-to-
centre measurements where averaging is present. For the “easy” multi-material scenario, i.e. Al/Cesic®, the max/min range is smaller than 14% of the voxel size, see Figure 8-b.

Figure 8-c and 8-d present unidirectional inter-material measurements. For the Al/Ti and Al/Cesic® assemblies, a total measurement error range of 43% of the voxel size and 10% of the voxel size were observed, respectively. For the in-material and mono-material measurements which can be observed in Figure 8-e and 8-f, the measurement error range was 21% of the voxel size for the Al/Ti scenario and 13% for the Al/Cesic® scenario.

Another observation is that for the unidirectional centre-to-centre measurements, the measurement error behaviour is dominated by the inter-material measurements.

Additionally, cylinder diameters and form deviations are also evaluated for all 17 holes at seven different heights (i.e. different material ratios). The cylinders’ diameter and the form deviation average values, the standard deviation and the max/min values per groove are plotted and presented in Figure 9. The results of the cylinder diameter obtained in the Al/Ti assembly and the Al/Cesic® assembly are presented in Figure 9-a and 9-b, respectively. A slight indication of the multi-material effect on the diameter measurements depending on the material ratio could be observed. A slight increase of the total range (max/min values) for the grooves G4, G5 and G6 could be observed for the Al/Ti scenario, where the amount of Ti becomes larger than the amount of Al, cf. Table 2. For the Al/Cesic® scan, no significant effect could be observed.

On the other hand, a clear indication of the multi-material effect on the form deviation measurements was observed. An upward trend of the average value, the larger standard deviation and the broader total range were observed depending on the groove number (material ratio) measured for the Al/Ti assembly. Furthermore, a total form deviation of about 53 µm was observed. For the Al/Cesic®, no significant multi-material effect was observed and a total form deviation of about 38 µm was also obtained.

4 Conclusion and discussion

This paper presents – as part of a multi-material acceptance test for dimensional CT – the new design and concept of the multi-material hole cube reference standard (MM-HC), for testing CT systems in the scope of acceptance testing and for multi-material length measurement error testing. The MM-HC reference standard designed and manufactured in this work has outer dimensions of 30 mm × 30 mm × 30 mm featuring 17 holes inside and 12 “V”-shaped grooves outside. The design consists of
two symmetric parts made of different materials; it also features a step-like “cut” shape enabling different multi-material ratios along the standards’ height. The holes are positioned in such a way to obtain seven main directions of length measurements. On the other hand, the grooves are positioned to locate and identify different material ratios in a multi-material measurement scenario.

Mono- and multi-material pairings made of aluminium, titanium and carbon-fibre reinforced silicon carbide (Cesic®) were selected for the MM-HC, featuring a broad range of attenuation coefficients.

For the CT measurements presented in this work, two multi-material assemblies of the MM-HC design were studied. Al/Ti and Al/Cesic® were scanned providing a broad range in the attenuation coefficient ratio. The CT measurement results were compared with the reference values obtained by a tactile CMS. The remaining assemblies – including the mono-material composite standard as references – are in a later phase of the manufacturing process.

Bi- and uni-directional lengths were measured in multi- and mono-material scenarios. Besides this, in-material measurements were performed in order to verify whether there is an influence caused by one material in another material.

In general, the results present a clear indication of the multi-material influence on the length measurements. This is especially true of the specific assembly with the larger difference concerning attenuation coefficient, i.e. Al/Ti.

For bidirectional length measurements in the Al/Ti assembly, a total measurement error range of about 1.8 times the voxel size was observed. Besides this, a slight increase of the standard deviation and the max/min range of length errors was observed for those material ratios containing more Ti than Al, i.e. grooves G5, G6 and G12. On the other hand, for the Al/Cesic® assembly having similar material attenuation coefficients, no significant influence on the multi-material effects could be observed and the measurement error range was approximately half of the voxel size. This is the behaviour the authors would also expect for the mono-material case and which will be checked when the respective standards are available.

Similar in-material and inter-material measurement error behaviour for the bidirectional measurements was observed for both the Al/Ti and Al/Cesic® cases. This is due to that fact that bidirectional measurements are prone to noise and the CT scans have similar noise levels for both materials, e.g. Al and Ti have similar CNRs in the Al/Ti scenario scan, cf. Table 3.

Besides this, the in- and mono-material measurements in Al are significantly influenced by a high absorption material (i.e. Ti). This becomes clear when comparing the Al error range for bidirectional measurements in the Al/Ti and Al/Cesic® scenarios. However, unidirectional measurements present a total measurement error range smaller than the bidirectional measurements (smaller than half of the voxel size for unidirectional measurements). For the Al/Ti assembly, a total measurement error range of nearly half of the voxel size was observed in the analyses. Besides this, a clear multi-material influence on the measurements could be seen by the increase of the measurement error range, and a standard deviation is observed for the grooves featuring more Ti than Al in a multi-material scenario, i.e. grooves G4, G5 and G6.

Another observation of the unidirectional measurements was that the measurement error behaviour is dominated by the inter-material measurements for the Al/Ti case. The in-material error behaviour was observed to be half of the inter-material measurements for the Al/Ti case. However, this multi-material influence on the measurements could not be seen in the Al/Cesic® scenario.

Diameter and form measurements were performed in the holes to check whether there is an influence on the geometry of the element under study. A slight indication of the multi-material effect could be seen in the diameter measurements of the Al/Ti scenario. However, for form deviation, a clearer indication of the multi-material effect can be observed. Larger form deviations as well as larger standard deviations and total error ranges could be observed for the material ratio containing more absorption material.

It is clear that for the Al/Ti scenario, significant larger measurement errors are observed in comparison with the Al/Cesic® scenario. This observation will be further investigated and confirmed in future work related to the multi-material testing with the complete set of reference standards.

It is also worth mentioning that further CT scans of the same MM-HCs were carried out using an independent CT system. The results obtained by this system – not included in this publication – appear to be consistent with the results presented in this paper and lead to the same overall observations.

Furthermore, based on preliminary experiments, the MM-HC showed great potential for testing and benchmarking multi-material-related data correction methods. This kind of application and the results of the MM-HC will be addressed in a further publication.

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References


