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Experimental investigation on multi-material gap measurements by computed tomography using a dedicated reference standard

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Abstract
Geometrical measurement of multi-material assemblies can be a challenging task. This is particularly important considering that an assembly of parts that individually passed through quality control does not necessarily result in a defect-free product. More specifically, the geometrical verification of multi-material assemblies should be performed by a non-destructive method, as invasive techniques can cause distortion of parts, relaxing of materials and other unwanted effects. In this context, computed tomography (CT) emerges as a promising technology. However, there are still challenges in achieving full traceability of CT measurements. Moreover, measurements of parts with multi-material interfaces generate even more complex measurement scenarios. In this study, multi-material effects on CT measurements are addressed. More specifically, the measurands defined as a gap between two different materials are investigated, as this is the typical application in industry (e.g. verification of fitting tolerances). The errors of gap measurements are evaluated on a series of dedicated reference standards. Several critical aspects of multi-material measurements are addressed in this study and preliminary results of CT performance in multi-material gap measurements are presented.

Keywords: Computed tomography, multi-material measurements, gap measurements, assemblies, reference standards

1. Introduction

Measurements of multi-material parts or multi-material assemblies are common measurement tasks in today's industry [1]. With increasing complexity, decreasing size of the whole parts or single details and tighter tolerances, reliable dimensional control is of growing importance. However, even if individual parts of an assembly pass quality control (i.e. before assembly), the quality of the assembled product is not guaranteed due to the assembly process and other factors [2]. Therefore, measurements on the final assemblies should be performed as well in order to ensure defect-free products. Traditional tactile and optical measurement techniques are based on physical contact or visibility of the measured features, respectively. While the external surface of typical multi-material assemblies can be probed/scanned by traditional coordinate measuring systems (CMSs) without any invasive intervention, these measuring instruments cannot non-destructively measure the internal/non-accessible features.

Computed tomography (CT) is a promising technique for non-destructive testing that has emerged as an alternative to traditional tactile and optical CMSs [3]. The most relevant advantage over traditional CMSs is that by CT scanning a 3D volumetric model of the part is obtained including the complete information about external and internal structures. Although CT has been recognised as an instrument for dimensional metrology, there is still lack of international standardisation [4]. Furthermore, the current standardisation efforts are mainly oriented towards single-material measurements, and multi-material effects are side-lined. However, multi-material measurement scenarios bring new effects and influencing factors and are, therefore, addressed in this study. More specifically, the scenario where the measurand is a gap – usually filled with air – between two materials is discussed here.

Typically, the performance of CMSs is tested using a dedicated reference object [3]–[7]. Single-material effects on measurement results were addressed by various authors; e.g. *Bartscher et al.* [8] used hole plates and stepped cylinders, or *Kiekens et al.* [9] used so called "cactus step-gauge". However, these reference standards are not suitable for investigating the aspects of multi-material gap measurements.

In this study, a dedicated set of reference standards presented in [10] (Fig. 1) was used to test the performance of a CT system in measurements of gaps between different materials. Furthermore, a set of single-material samples was used as well to clearly isolate single- and multi-material effects. Crucial aspects that affect multi-material measurements, surface determination and volume segmentation for instance, are addressed.

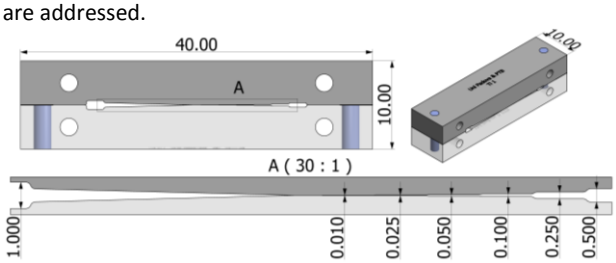

Figure 1. Design of the reference standard (dimensions given in mm)

A typical application of multi-material gap measurements is the verification of whether a gap is left between two parts of an assembly or not, and its size. It is therefore necessary to know, what are the limits of CT and what is the smallest measurable gap (i.e. the smallest gap where the two oposite surfaces defined by software are still not in contact) in a certain configuration. Thus, a preliminary study on the smallest measurable gap with respect to materials between which the measurements are performed is presented here.

2. Materials and methods

CT measurements presented in this work were obtained using a metrological CT system (Nikon X-Tek MCT225) and compared with reference values obtained by a high precision tactile micro-CMS (Zeiss F25). The CT data were evaluated in VGStudio MAX 3.0.

2.1. Reference standard

A series of single- and multi-material reference standards were used in this study. Design and general dimensions of one of the reference standards are shown in Fig. 1. These objects feature two types of gaps: (i) discrete steps and (ii) a continuous gap formed by two opposite tempered surfaces. While the steps provide robust gap reference values ranging from 10 µm (approximately half of voxel size [VS] given the current configuration), the tempered planes allow measurements of gaps down to zero. The reference standards were manufactured in three different materials: Titanium, Aluminium, and carbon-fibre reinforced silicon carbide (Cesic®).

2.2. Evaluation methods

The acquired data were evaluated using several surface determination methods in order to thoroughly investigate the multi-material effect on the measurement results. Furthermore, for each sample, the smallest measurable gap was evaluated to gain preliminary information about the limits of CT with respect to single- and multi-material gap measurements and given CT configuration.

The gaps were measured as a distance between two opposite points. The measurement points were constructed based on a patch-based procedure explained in [10].

3. Results

The results confirmed the hypothesis that the multi-material aspect introduces additional errors into CT dimensional measurements. This can be observed in Fig. 2 where the measurement errors are plotted against the gap size. The presented results were acquired on tilted planes (left part of the standard; see Fig. 1 for reference) as they provide a continuous gap which facilitates finer gap sampling as well as proper determination of the smallest measurable gap (see Tab. 1).

Table 1. Smallest measurable gap for different multi-material samples

Sample	Smallest measurable gap /µm	Measurement error /µm
Ti/Ti	25.9	-13.6
Al/Al	24.7	-17.0
Cesic®/Cesic®	23.7	-19.1
Cesic®/Al	25.5	-14.3
Ti/Al	**153.6**	9.5

It can be clearly seen from Fig. 2 that the measurement errors obtained on the multi-material sample with significant difference in absorption (i.e. Ti/Al) are higher than for all mono-material cases as well as for the multi-material assembly with low absorption difference (i.e. Cesic®/Al sample). Similarly, clear difference between single-material samples (including Cesic®/Al sample) and the Ti/Al sample can be observed in values presented in Tab. 1. The smallest measurable gap for the Ti/Al sample is roughly 6 times larger than for the single-material samples (including Cesic®/Al sample), which confirms that the multi-material measurements are more problematic.

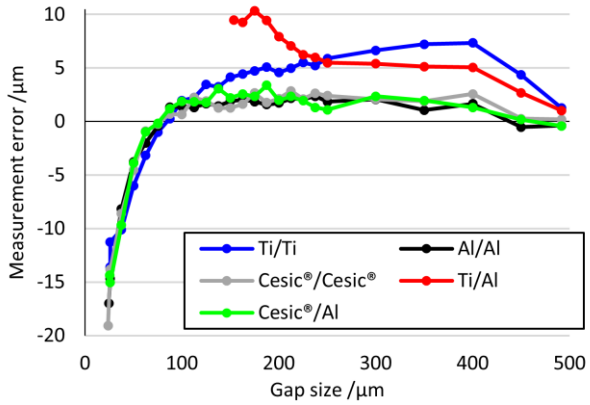

Figure 2. Measurement errors of gap measurements

4. Conclusions and outlook

The performance of CT in multi-material gap measurements was tested through a dedicated set of reference standards. The preliminary results confirmed that the multi-material aspect affects the magnitude of measurement errors as well as the size of the smallest measurable gap especially for the sample where two materials with strongly different attenuation coefficients were used. Future research will be aimed at investigating multi-material effects on gap measurements and at evaluating task specific measurement uncertainty.

Acknowledgements

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