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Simulation-based approach on relative intensity effect in multi material X-Ray computed tomography evaluation

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Abstract

Evaluation of multi material parts by means of X-ray computed tomography (XCT) remains as a challenge in terms of dimensional measurements. Several factors (differences in material density, gap between parts, etc.) may affect the characterisation of an assembly, creating the need of an adjustment in the XCT settings to reduce artifacts. A key parameter is the relative intensity (I/I_0) registered in the detector, which is an indicator of the attenuation of the X-rays. In this paper, a metrological study of the effects of the variation in the I/I_0 registered is presented. A simulation-based experiment is conducted with a metal-polymer test object, using the thickness of the outer part as a variable to modify this I/I_0 value. Results confirm a correlation between dimensional accuracy on polymeric features and higher I/I_0 values, as well as in the contrast-to-noise ratio (CNR); however, significant differences are found between scenarios with similar I/I_0 values but different metals, indicating that results could not be automatically extrapolated.

Keywords: X-ray computed tomography, Multi material, Simulation.

1. Introduction

The use of X-ray computed tomography (XCT) in metrology for the evaluation of industrial parts has increased recently due to its ability to non-destructively characterize both inner and outer geometries. It is able to measure macro and micro geometries, being an innovative technique for dimensional metrology [1].

However, as a new technology in industry, it still has several limitations. XCT is based on the X-ray penetration of the object, producing a grayscale histogram that varies depending on the beam intensity received by the detector. X-ray attenuation is directly related to the density of the material, so settings should be adjusted for each part [2]. In case of multi material parts, it could result in defects, such as noise and artifacts, consequently creating measurement errors. This becomes more evident if the difference in density between materials is elevated.

Here, an important indicator to consider is the relative intensity (I/I_0) between the beam emitted and received by the detector. This coefficient is directly related to the energy of the beam source [3], the penetration length and the attenuation coefficient of the material. Theoretically, the lower the relative intensity that reaches the detector, the poorer is the quality of the tomography and, hence, more defects will appear.

In this paper, a preliminary study of the effects of I/I_0 variation in a multi material test object is presented. An ad hoc artefact is designed, including a polymeric low-density measurand and outer metallic hollow cylinders made by aluminium (Al) and steel (St) with different thicknesses to create a range of I/I_0 values. XCT simulations have been performed, evaluating dimensional characteristics and contrast-to-noise ratio of the tomographies.

2. Design and methodology

2.1. Attenuation curve

First step has been to calculate the attenuation curve for the materials selected for the experiment, Al and St (Figure 1). Attenuation can be described by Beer-Lambert law [3] in Eq.1:

$$I(x) = I_0 \cdot e^{-\mu x} \quad (1)$$

Where I = intensity received by the detector, I_0 = intensity emitted and μ = linear attenuation coefficient of the material.

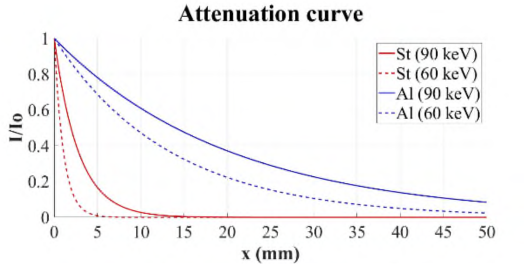

Figure 1. Attenuation curve for X-ray beams of different energies.

Curve is different depending on the average energy (E_{av}) obtained from the characteristic energy spectrum of the tube. Spectrums have been obtained using software SPEKTR 3.0 [4].

2.2. Test object

To conduct the experiment, an ad hoc test object has been designed. It consists in an outer metallic hollow cylinder and an inner polymeric part, with 4 polymeric cylinders (nominal diameters of Ø12 mm, distances between cylinders of 12 mm) for dimensional evaluation. Rest of dimensions of relevant features are shown in Figure 2.

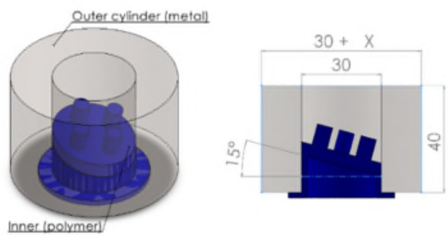

Figure 2. General assembly (left), relevant dimensions (right)

Outer diameter of the metallic cylinder is modified for each scenario, considering its thickness as the variable to calculate

I/I_0 (Figure 1). The target has been to obtain values of $I/I_0 \approx 0.50 - 0.08$. Ranges used in the experiment are shown in Table 1.

Table 1. Penetration length and relative intensity for each material.

Material	X [mm]	I/I_0
Aluminium	10 - 40	0.472 - 0.093
Steel	2 - 8	0.471 - 0.081

2.3. Simulations and evaluation

XCT simulations have been performed by software aRTist 2.12 (BAM, Germany). One simulation has been done for each scenario, including the case with no metal. Settings have been optimized for each scenario, aiming for the most uniform configuration in terms of voltage and physical filter. Post processing has been done by software VG Studio Max 3.4.2, extracting contrast-to-noise ratio (CNR) by gray value difference between material and background [5] and a dimensional evaluation of the cylinders. CNR is relevant as an indicator of the quality of the image: better contrast in tomographies of the same part is correlated with lower noise. Regions of interest (ROI) have been created for each material for proper CNR study.

3. Results

3.1. CNR comparison

In Figure 3, the relationship between CNR and I/I_0 for each scenario (Al-St) and each ROI (metal/polymer) is shown.

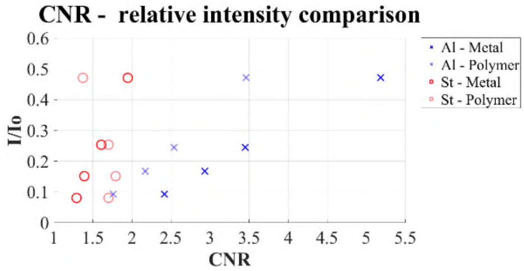

Figure 3. CNR comparison for each scenario and each ROI.

Although in general CNR increases for cases with higher relative intensity, it is shown that trend is not always followed and values do not agree for Al and St scenarios with same I/I_0. An XCT slice from scenarios with similar I/I_0 is shown in Figure 4 and their gray values histogram is shown in Figure 5.

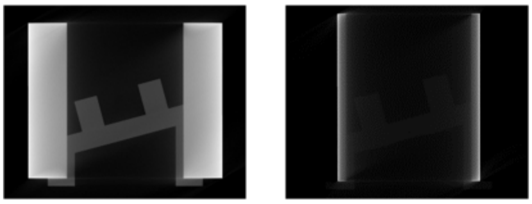

Figure 4. XCT 2D slices. Al 20 mm (left), St 4 mm (right).

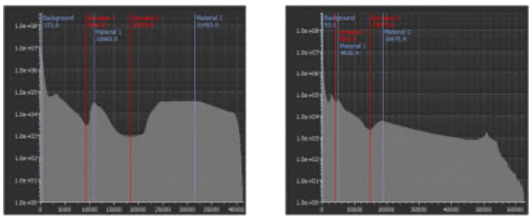

Figure 5. Gray values histograms. Al 20 mm (left), St 2 mm (right).

3.2. Dimensional measurements

Diameters, form error and distances between elements have been extracted from the cylinders. Absolute form error of the cylinders for each scenario is shown in Figure 6.

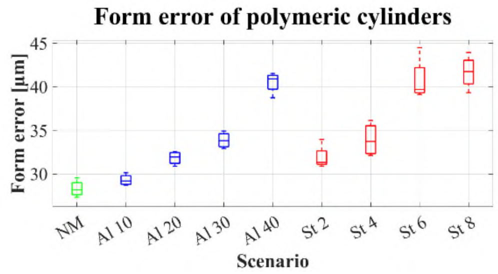

Figure 6. Absolute form error of polymeric cylinders for each scenario.

A trend is followed for both Al and St scenarios, obtaining higher form errors in scenarios with lower I/I_0 values; however, Al results are more stable (less standard deviation) and closer to no metal (NM) scenario. In Table 2, diameter and distances mean deviations from NM values are shown.

Table 2. Mean deviation in same-material scenarios from NoMetal XCT.

Material	Diameters [µm]	Distances [µm]
Aluminium	3.25	0.19
Steel	-3.81	-9.69

Significant differences have been found between Al and St scenarios. Noise present in St tomographies difficult a proper characterization of the cylinders, modifying the points extracted and consequently the diameter and the central axis. This becomes more evident in the higher deviation in distances.

4. Conclusions and future work

A simulation-based analysis of the effect caused by variations of relative intensity in metal-polymers assemblies is presented. Experiments show that results obtained in different metals could not be extrapolated. Trends are followed in most cases, as CNR values and dimensional measurements improve as I/I_0 increases; however, higher deviations are shown in steel scenarios, where also CNR values are significantly lower than Al scenarios with same I/I_0, suggesting that this parameter cannot be considered alone as an indicator. As results are only extracted from virtual simulations, future work should focus on obtaining experimental results from real XCT measurements to validate the simulations and corroborate the hypothesis here presented.

Acknowledgements

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