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Experimental investigations on the accuracy of X-ray computed tomography for porosity measurements of additive manufactured parts

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Abstract
Recent advances in Additive Manufacturing (AM) have shown a great potential in production of intricate structures due to its almost unlimited design freedom even for internal features. However, inherent imperfections such as internal porosity arise from the AM process. As these internal defects cannot be completely removed, knowing the information about the defects shape, size and distribution becomes crucial. Recently, X-ray computed tomography (CT) has emerged as an advanced tool for internal defects measurement; however, the errors of CT porosity measurements have not yet been thoroughly quantified. In this work, in a first step, CT porosity analysis conducted on Ti6Al4V specimens produced by AM is compared to results by Archimedes method, microscopic analysis and multisensor CMM. In a second step, a newly developed reference object is used for evaluating errors of CT porosity measurements.

Keywords: X-ray computed tomography, Additive Manufacturing, porosity, internal defects, reference object.

1. Introduction

At the state-of-the-art, AM technologies can produce parts with almost unlimited design freedom. Some of these technologies, such as Selective Laser Melting (SLM) [1], are capable of producing metal parts. Although SLM is capable of producing nearly full dense parts, internal porosity due to entrapped gas bubbles, oxides and unmolten particles [2-3] can never be completely eliminated, often leading to reduced mechanical properties of materials [4]. For this reason, knowing the information about the defects shape, size and distribution along the entire part becomes crucial.

Over the last years, quality control by CT scanning has emerged as an innovative possibility for AM parts, due to its unique capability of performing non-destructive porosity analysis and dimensional measurements of inner as well as outer features [5-6].

Previous works have dealt with the comparison of CT with other well-established inspection techniques such as Archimedes method and microscopic analysis [7-8]. However, reference porosity measurements were not available in these works, although they are necessary for measurement errors assessment [9].

In the present work, besides comparing the results obtained by the above mentioned inspection techniques, a multisensor CMM was used to obtain reliable reference values for dimensions of pores visible in cross-sections. Furthermore, a new reference object with artificial hemispherical defects was designed and manufactured in order to quantify typical errors of CT porosity measurements.

2. Material and methods

CT measurements reported in this work were performed using a metrological CT system (Nikon X-Tek MCT225) equipped with a 225 kV micro-focus X-ray source, 2000×2000 flat panel detector (16 bit) and temperature controlled cabinet. The maximum permissible error (MPE) for length measurements is MPE = 9 + L/50 µm (L is the length in mm). The acquired datasets were processed using VGStudio MAX 2.2.6 software.

2.1. Comparison of porosity evaluation methods

The comparison has involved experiments on Ti6Al4V specimens produced by SLM with different process parameters and, consequently, different porosity content. The relative CT porosity (complementary to relative density) was compared with density obtained by the Archimedes method. In addition, a new procedure was developed for comparing results by microscopic analysis of cross-sections with CT results: specimens were CT scanned before and after the cutting procedure, in order to (i) identify in the CT volume the exact cross-section analysed for the comparison and (ii) to compare CT results obtained before and after cutting the samples. To obtain reliable reference values, the areas of specific pores lying on the cut-section were measured by a multisensor CMM equipped with image processing sensor (Werth Video-Check-IP 400; MPE = 1.8+L/250 µm, with L in mm).

2.2. Errors evaluation in CT porosity measurements

Errors in CT porosity measurements were evaluated using a newly developed reference object with artificial defects (Figure 1) [10]. The object is made of aluminium and contains hemispherical features with diameters ranging from 100 µm to 500 µm resembling real internal voids/porosity. Its dismountable configuration allows external dimensional calibration of the artificial defects. The reference measurements of pores' diameters, depths, areas and volumes were acquired by means of: (i) a 3D optical profiler (Sensofar PLU Neox) used in confocal mode, (ii) the multisensor CMM presented in the previous section, and (iii) the CT system used at high magnification.

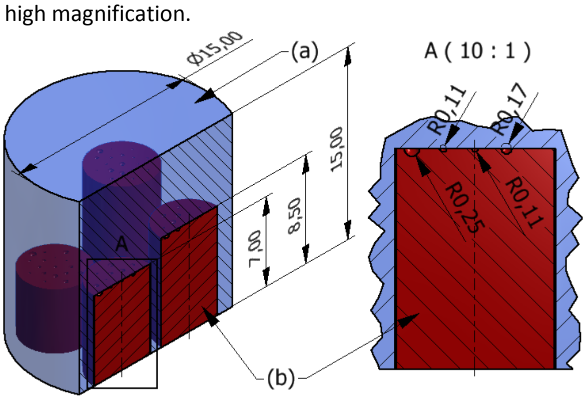

Figure 1. Dimensions (in mm) of the newly designed reference object. (a) Cylindrical body, (b) dismountable pin including 18 hemispherical calottes with diameter ranging from 100 to 500 µm.

3. Results

A systematic error was observed between CT porosity measurements and results by the Archimedes method: relative densities determined by the Archimedes method were systematically 0.2 – 0.4 % lower than the corresponding CT values. Causes of this difference can be attributed both to Archimedes method and to CT. On one hand, Archimedes' relative density determination is based on the nominal material density, which however is not reliable for non-homogeneous parts. On the other hand, CT results are influenced by image artefacts due to the interaction between X-rays and material, by the achieved resolution in the CT reconstruction (e.g. pores with size lower than the spatial resolution cannot be detected) and by the thresholding procedure.

The results by microscopic analysis of cross-sections were found to be very close to the CMM results, however CT always measured smaller areas (Figure 2). Besides the aforementioned CT main influences, micrographs are affected by light and focus settings, stitching operations, thresholding and binarization. The systematically lower area measured by CT post-cut with respect to CT pre-cut reveals other two possible causes: (i) deformations due to cutting/polishing operations and (ii) presence of entrapped unmolten powder residue that may fall out during the cutting.

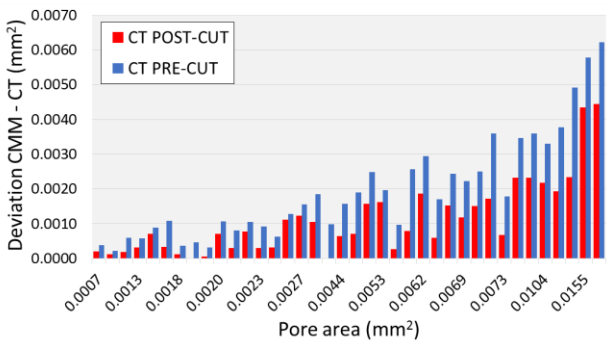

Figure 2. Example of deviations between pore areas measured by multisensor CMM and CT (pre and post cut) on Ti6Al4V specimens.

Experimental investigations using the newly developed reference object (Figure 1) proved that for optimal CT parameters settings, the errors can be below 5 µm in case of diameter, below 3 µm for depth and below 3 % for volume measurements. However, the errors in case of smaller defects (smaller than 0.200 mm in diameter) are higher, as shown in Figure 3.

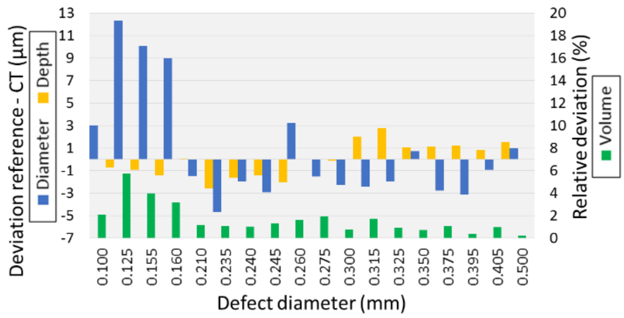

Figure 3. Example of CT porosity measurement errors evaluation using the newly designed reference object. Deviations of diameter and depth measurements from reference values are expressed in µm, while relative deviations of volume measurements are in %.

4. Conclusions

Experimental results have shown systematic errors between different porosity measurement methods. CT calculated densities were found systematically higher by 0.2 – 0.4 % than results by the Archimedes method. Furthermore, CT always measured pore areas smaller than optical measurement of cross-sections. These differences can be attributed to several reasons as discussed in the results section. Deviations were observed between CT measurements obtained before and after cutting the specimens. Two causes of these deviations were identified: (i) unmolten powder residues and (ii) deformations due to cutting/polishing operations. The investigation using the new reference object for errors evaluation of CT porosity measurements has shown that for larger pores it is possible to evaluate internal porosity with measurement errors below 5 µm for diameter, below 3 µm for depth and below 3 % for volume measurements.

Acknowledgements

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