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Development of a reference object for accuracy evaluation of CT measurements of additively manufactured metal lattice structures

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Abstract
Additive manufacturing (AM) technologies can be successfully used to produce metal parts with controlled and complex lattice structures. However, AM parts are intrinsically characterized by dimensional and geometrical errors, which need to be properly identified and quantified to improve the quality of AM processes and the properties of end products. In this work, X-ray computed tomography (CT) is applied to enable advanced non-destructive dimensional measurements. The CT measurement accuracy is evaluated using a reference object specifically designed and produced to be similar to AM lattice structures. The reference object can be used to implement the substitution approach as well as to validate alternative methods for uncertainty determination.

X-ray computed tomography, additive manufacturing, lattice structures, dimensional metrology, accuracy

1. Introduction

Lattice structures are components constituted by a three-dimensional geometrical arrangement of unit cells that can be successfully fabricated exploiting the layer-based approach of additive manufacturing (AM) technologies, even when other manufacturing techniques are not applicable due to complex geometry and high structural complexity [1]. Among the available AM processes, powder bed fusion using laser beam (PBF-LB) has proven to be suited to fabricate strong, lightweight and complex metallic lattice structures [2]. Thanks to the good achievable properties, lattice structures are showing a great potential, for example in aerospace and biomedical sectors [2]. However, PBF-LB products are typically characterised by geometrical and dimensional errors that might lead to mechanical properties degradation and product failure [3].

X-ray computed tomography (CT) is increasingly used to provide information-rich geometrical description of AM lattice structures thanks to the capability of performing non-destructive dimensional analyses of both outer and inner geometries, including cylindrical features of lattice structures that are not accessible by traditional measuring techniques [4]. In order to evaluate the accuracy of CT measurements of lattice structures, in this work, a reference object was designed, produced and calibrated using a design for metrology approach and ensuring comparability to AM lattice structures in terms of size, geometry and material characteristics.

2. Components and CT measurements

Specimens manufactured by PBF-LB of Ti6Al4V alloy characterized by specific lattice design were used as case study. The specimens were scanned using a metrological CT system (Nikon Metrology MCT225), achieving a voxel size equal to 9 µm. The measurements performed on the CT reconstructed volumes (Figure 1a shows one of these volumes as an example) were focused on dimensions of cylindrical features composing the lattice structure as they can be critical for mechanical and fatigue properties [5]. In particular, a number of these features were selected within different regions of the sample. The analysis and visualization software VGStudio MAX 3.2.3 (Volume Graphics GmbH) was then used to measure the diameter of each feature, according to a measurement strategy that in principle can be implemented using both CT and coordinate measuring machine (CMM) data.

3. Reference object

A well-known approach for the uncertainty assessment in CT dimensional metrology is the substitution method described in the guideline VDI/VDE 2630-2.1 [6]. It is based on the availability of calibrated objects that might be costly or not available in the case of lattice structures, especially due to difficulty of performing accurate calibration measurements on complex structures which, in most cases, are inaccessible by traditional measuring systems from the outside. For these reasons, new approaches not requiring the use of reference samples are currently under development by the authors [7]. However, the metrological validation of newly proposed methods has to be based on the comparison to reference measurements and already available methods such as the above-mentioned substitution approach. In order to apply the substitution method and provide a validation tool for new methods, a reference sample was designed and produced to achieve an acceptable comparability with respect to the investigated PBF-LB Ti6Al4V lattice structures in terms of material composition, size and geometry, as required by the guideline VDI/VDE 2630-2.1 [6]. The reference sample is an assembly of two bodies, both machined starting from a bulk Ti6Al4V bar, combining turning and ultra-precision milling operations. The main body (Figure 1b) is characterized by six pins with nominal diameter of 0.4 mm (comparable to the nominal diameter of cylindrical features of the investigated lattice structures) and different heights ranged between 0.8 and 2 mm. The pins are disposed along a spiral path, randomizing the relative distances between each couple of pins. The counterpart is assembled to the main body as shown in Figure 1c to (i) increase the maximum thickness to be

penetrated by the X-ray beam enabling the use of the same CT scanning parameters and (ii) measure the pins as non-accessible internal features by CT when the counterpart is assembled, and as accessible external features by CMM when the counterpart is removed. Reference measurements of pins diameters, heights and relative distances were conducted on the main body (with the counterpart not assembled) using a tactile CMM Zeiss Prismo Vast 7 (MPE = (2.2+*L*/300) µm, *L* = length in mm).

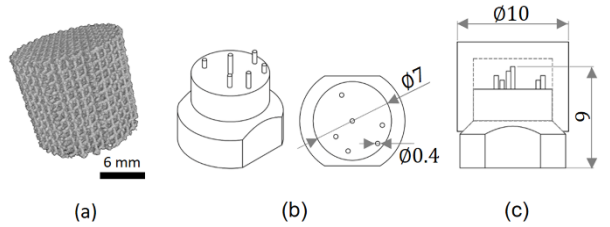

Figure 1. CT reconstructed volume of a Ti6Al4V PBF-LB lattice structure (a). Representation of the reference object: main body (b) and assembly with the counterpart (c).

4. Evaluation of CT measurement repeatability and errors

The reference object and the lattice structures under investigation were scanned multiple times to evaluate the CT measurement repeatability and to quantify and correct the systematic measurement errors, as recommended in the VDI/VDE 2630-2.1 [6]. Since the reference object pins are contained in a limited volume with respect to the cylindrical features composing the lattice structure, they were both scanned at different positions and orientations within the CT measurement volume to investigate the effect of variations of geometrical errors and errors due to CT typical image artefacts on the measurement repeatability. The standard deviations obtained from repeated CT scans of both reference object and lattice structures were compared in the case of single tested position and in the case of multiple positions. Figure 2 shows that the average standard deviation related to CT measurements of diameters increase of about 50 % for both reference object and lattice structure, when different sample positions are considered.

Although the similarity conditions between lattice structures and reference object (required to apply the substitution approach [6]) are well respected in terms of material composition, size and geometry, they are not respected for surface roughness and form errors that are consistently larger for the AM lattice structure cylindrical features than for the reference object pins. The influence of surface roughness and form errors on the measurement repeatability was hence investigated by comparing the standard deviation of repeated measurements of the reference object and of lattice structures. As shown in Figure 2, the surface roughness and form errors leaded to an increase of the average standard deviation (computed from repeated CT measurements of diameters) around 240 %, either when testing a single sample position or different positions. This clearly shows that the evaluation of measurement repeatability (that is a component of the measurement uncertainty) is influenced by the effect of surface roughness and form errors. The substitution approach requires to consider such effect as an additional contribution, as it is a known cause of deviation between reference CMM measurements and CT measurements [8]. On the contrary, alternative methods not based on the measurement of a reference object (similar to lattice structures) won't require to add such separate contribution.

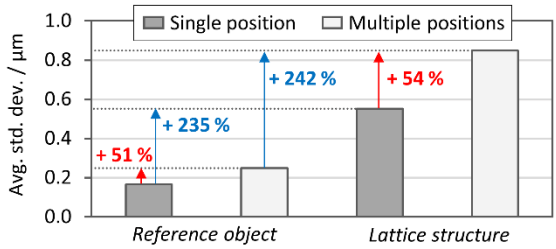

Figure 2. Average standard deviations computed from repeated CT measurements of diameters performed on both reference object and lattice structure, considering a single position as well as multiple positions.

5. Conclusions

In this work, a reference specimen – developed using a design for metrology approach and ensuring comparability to Ti6Al4V PBF-LB lattice structures – was used to evaluate the CT measurement repeatability and errors. The similarity between the reference object and lattice structures is well respected for size, geometry and material composition. However, the reference object pins – compared to lattice structures cylindrical features – are contained in a limited volume and are characterised by different surface roughness and form errors. For these reasons, the effect of varying the scanning position within the CT measurement volume of both reference sample and lattice structures and the effect of different surface roughness and form errors on the measurement repeatability were investigated experimentally. Results showed that the average standard deviation related to CT measurements of diameters increased of about 50 % when different sample positions were considered and of about 240 % due to the higher surface roughness and form errors of lattice structures with respect to the reference sample. The use of the reference object will be extended in future works to implement the substitution approach [6] for uncertainty determination of CT measurements and to investigate and validate other alternative methods.

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