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Uncertainty determination of X-ray computed tomography dimensional measurements of additively manufactured metal lattice structures

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Abstract
Metal additive manufacturing (AM) technologies can produce complex lattice structures with advantageous strength-to-weight properties, for which there is increasing interest by important industrial sectors such as aerospace, automotive and biomedical. However, the geometrical and dimensional quality of AM lattice structures needs to be assessed by adequate measurement techniques. Differently from conventional contact and optical coordinate metrology, X-ray computed tomography (CT) enables non-destructive measurements of both external and difficult-to-access features. To establish the metrological traceability of CT dimensional measurements needed to effectively improve the AM process, the task-specific measurement uncertainty must be determined. This paper investigates the possibility of using the "multiple measurements approach" for the uncertainty determination of CT dimensional measurements performed on Ti6Al4V lattice structures fabricated by laser powder bed fusion. The main advantage of this approach is that it is not limited by the unavailability of low-uncertainty calibration measurements, which is a common issue for very complex workpieces such as the lattice structures investigated in this work.

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

1. Introduction

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) technology that can be used to produce complex metallic components with unique and controlled lattice architectures and advantageous strength-to-weight properties, for which there is increasing interest by important industrial sectors as aerospace, automotive and biomedical [1]. However, the geometrical and dimensional quality of LPBF lattice structures – which is often too poor to meet the specification and to guarantee the desired structural properties [2] – need to be assessed by adequate measurement techniques.

X-ray computed tomography (CT) is an advanced three-dimensional (3D) measurement technique increasingly used for the quality control of AM products [3]. The main advantage with respect to conventional tactile and optical measurement techniques is related to the capability of metrological CT systems of performing non-destructive measurements of external as well as internal geometries and features [3]. The traceability establishment of CT dimensional measurements needed to effectively improve the AM process requires the determination of the task-specific measurement uncertainty [4]. However, the quantification of uncertainty of CT dimensional measurements is a very complex task due to several error sources difficult to be identified and quantified, and to the lack of internationally standardized procedures [5]. A commonly adopted method is the "substitution approach" (described in VDI/VDE 2630-2.1 [6]), which bases the uncertainty determination on the measurement of calibrated reference objects similar to the actual workpieces in terms of material, dimensions and geometry. However, AM lattice structures are characterized by non-accessible geometries and significant form errors and surface roughness; therefore, calibrating a task-specific reference object would be particularly difficult or even unfeasible for inaccessible features.

In order to overcome this limitation, the present work investigates an alternative route for the uncertainty determination of CT dimensional measurements performed on LPBF lattice structures: the extension of the "multiple measurements approach" [7] (see Section 3), which does not require the use of calibrated objects similar to the actual workpieces.

2. Specimens and CT instrumentation

Lattice structures with nominal strut size of 0.4 mm were manufactured by LPBF of Ti6Al4V alloy and measured using a metrological CT system (MCT225, Nikon Metrology, UK), setting the X-ray tube voltage at 180 kV, the current at 38 μA and the exposure time at 2000 ms. The achieved voxel size was equal to 9 μm. The measurements performed on the CT reconstructed volumes (Figure 1-left shows an example) were focused on the size of the actual features with cylindrical nominal geometry composing the lattice structure (see Figure 1-right) to be compared to the nominal size, as the discrepancies between as-built and as-designed geometries can be critical for mechanical and fatigue properties [2].

3. Multiple measurements approach

The multiple measurements approach, new for CT metrology, is an adaptation of the procedure that was previously proposed for determining the uncertainty of dimensional measurements conducted by tactile coordinate measurement machines (CMMs) [7] and is currently under refinement within the European project EUCoM (Evaluating Uncertainty in Coordinate Measurement; *http://eucom-empir.eu/*).

The approach is based on the idea to stimulate and randomize the systematic errors (e.g. CT system geometrical errors and typical CT image artefacts) by repeated measurements on the workpiece of interest, in different orientations of the workpiece itself within the measurement volume, so that errors can be reduced by averaging the obtained results and the uncertainty can be determined based on the variance of results. Figure 2 shows the five different orientations chosen to perform the repeated measurements selected in a way to randomise typical CT errors. Since repeated measurements alone do not account for all errors (e.g. scale errors), additional measurements are also performed using (simple) calibrated length and form standards to achieve traceability to the unit of length. Such calibrated standards are not required to be similar to the objects to be measured, as instead required when using the substitution approach. For example, in this work, the selected standard is composed by six 1-mm-spheres arranged on a carbon-fiber support, with calibrated diameters and center-to-center distances, to evaluate and correct for possible systematic errors, such as scale errors.

In order to provide a metrological validation of the multiple measurements approach and to compare it with the substitution approach [6], the reference sample described in [8] was used. It was designed and produced to achieve an acceptable comparability with respect to LPBF Ti6Al4V lattice structures as those investigated in this work. In particular, a dismountable configuration was chosen, where the main body was characterized by six pins with size of 0.4 mm (comparable to the nominal size of cylindrical features of the investigated lattice structures), and the counterpart serves to measure the pins as non-accessible internal features by CT when the two bodies are assembled. Reference measurements of pins diameters were conducted on the main body (with the counterpart not assembled) using a tactile CMM Prismo Vast 7 (Zeiss, Germany; maximum permissible error MPE = (2.2+L/300) µm, L = length in mm).

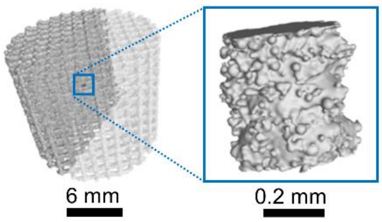

Figure 1. CT reconstructed volume of a Ti6Al4V LPBF lattice structure (left) and extraction of an internal element with cylindrical nominal geometry (right).

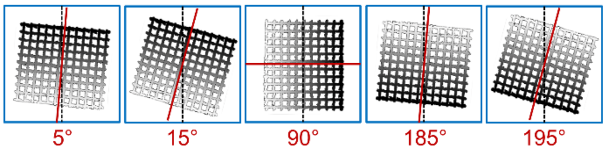

Figure 2. Representation of the five orientations of the lattice structure within the X-ray detector field of view (blue square), with angles of 5°, 15°, 90°, 185° and 195° between the detector vertical axis and the sample vertical axis.

4. Results

The uncertainty of CT measurements of the lattice struts size (nominally equal to 0.4 mm) was determined using both the multiple measurements approach and the substitution approach. The multiple measurements approach led to an expanded uncertainty (95% of confidence interval) of 4.0 µm, while with the substitution approach the expanded uncertainty was 3.8 µm.

In order to provide a metrological validation of the multiple measurements approach, it was also applied to the reference object as if it was the object under investigation. In this case, the expanded uncertainty was determined equal to 3.8 µm. The metrological compatibility between reference CMM measurements and CT measurements was demonstrated by computing the normalized error E_N [9], which was below 1 for all the measured pins.

5. Discussion and conclusions

The multiple measurements approach, new for CT metrology, was investigated in this work as an alternative route to determine the uncertainty of dimensional measurements performed on LPBF Ti6Al4V lattice structures. The metrological compatibility between calibration measurements and CT measurements performed using the multiple measurements approach was demonstrated by applying the approach to the calibrated object similar to the investigated lattice structures, treated as if it was the specimen under investigation.

In addition, the expanded uncertainty obtained with this approach was found to be very close to the uncertainty determined with the most common substitution approach. However, an important aspect to be considered is the fact that, according to [6], the substitution approach should take into account also the effect of surface texture and form errors, which are consistently different in the reference object's pins and in the lattice struts. In principle, this is a limit of the substitution approach, as the obtained expanded uncertainties could be significantly overestimated when including such effect.

Future investigations are planned to further improve the understanding of how the approach should be applied to ensure reliable uncertainty determination and correction of systematic errors, considering also other case studies. For example, investigations will be oriented to understand if the approach gives sufficient weight to the effect of surface texture and form errors and to address the difficulty related to the choice of multiple orientations, which are difficult to standardize because should vary depending on the object geometry and dimension.

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References

[1] du Plessis A., Yadroitsava I., Yadroitsev I. (2018). Ti6Al4V lightweight lattice structures manufactured by laser powder bed fusion for load-bearing applications. Optics & Laser Technology, 108:521-528.

[2] Dallago M. et al. (2019). On the effect of geometrical imperfections and defects on the fatigue strength of cellular lattice structures additively manufactured via Selective Laser Melting. International Journal of Fatigue, 124:348-360.

[3] Carmignato S., Zanini F., Baier M., Sbettega E. (2020). X-Ray Computed Tomography. In: Leach R., Carmignato S. (eds), Precision Metal Additive Manufacturing (pp. 313-346). CRC Press.

[4] Wilhelm R. G. et al. (2001). Task specific uncertainty in coordinate measurement, CIRP Annals, 50(2):553–563.

[5] Zanini F., Carmignato S. (2019) X-Ray Computed Tomography for Dimensional Metrology. In: Gao W. (ed.), Metrology. Precision Manufacturing. Springer, Singapore.

[6] VDI/VDE 2630-2.1:2015, Determination of the uncertainty of measurement and the test process suitability of coordinate measurement systems with CT sensors. VDI, Düsseldorf.

[7] Trapet E. et al. (2004). New advances in traceability of CMMs for almost the entire range of industrial dimensional metrology needs. CIRP Annals Man. Tech. 53/1:433-438.

[8] Zanini F, Sorgato M, Savio E, Carmignato S. Development of a reference object for the evaluation of CT measurement accuracy of additively manufactured metal lattice structures. euspen 2020.

[9] ISO/IEC 17043:2010, Conformity assessment — general requirements for proficiency testing, ISO, Geneva.