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Metrology of additively manufactured lattice structures by X-ray tomography

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Abstract: Additive manufacturing allows complexity of manufactured metal structures. Lattice structures hold the most promise for high complexity, tailorable and ultra-lightweight structures. In medical applications, these structures find application especially in bone implants – allowing matching of local elastic modulus of implant to that of bone while also allowing osseointegration. With this new complexity comes new manufacturing quality control and metrology challenges. Traditional metrology tools cannot access the entire structure and the only reliable method to inspect the inner details of these structures non-destructively is by X-ray tomography.

I. Introduction

Metal additive manufacturing (AM) allows the production of high quality end-use parts such as medical implants in biomedical titanium alloys. This has become one of the largest commercial applications of additive manufacturing to date, with continued interest in its further development [1]. By using biomimetic design principles [2], cellular or lattice structure design can be used as a part of the implant to match the effective elastic modulus of the implant to that of the bone alongside it, minimizing stress shielding while simultaneously allowing osseointegration [3]. Lattice structures manufactured by laser or electron beam powder bed fusion for use in bone implants have been well described in a number of reviews, for example as in [4].

The primary design parameter is the lattice density, which dictates the effective elastic modulus of the lattice. With a given density in mind, there are many design options for lattices varying from strut-based to minimal surface designs [5] and even topology optimized designs [6]. These designs might vary in their performance for the application of bone implants due to differences in pore sizes, macroporosity connectivity, and the details of their manufacturing success. In general, metal AM has many potential manufacturing errors necessitating stringent quality control and qualification of processes [7–9]. The same challenges extend to lattice structures, and become especially important when these structures are on the level required for bone growth, with fine feature sizes.

X-ray tomography (also known as microCT) is used already widely for inspection of additively manufactured parts and implants, as routine quality control tool [10–12]. In addition to checking for porosity and cracks, it can be used for dimensional metrology – similar to a coordinate measurement machine [13]. Its use for this purpose requires dimensional calibration prior to the microCT scan of the object, which is standard procedure in commercial metrology CT systems. The same principles apply to non-metrology CT systems, and despite the lack of dimensional calibration, the data can still be used to evaluate the quality of the produced parts. This paper provides an overview of the capabilities for accurate measurement of medical implants and lattice structures with examples of commercially produced implants.

II. Results and discussion

This section outlines the useful forms of measurement of lattice structures from X-ray tomography data.

II.I. X-ray tomography sub-voxel precision

Various manufacturing imperfections can cause differences between the actual manufactured lattice and the design, including scan strategy, dross formation on downskin surfaces, warping, stair-step effect, and more. In Fig. 1 is shown a simple lattice with dross formation on horizontal struts in a close up view. With high scan quality, sub-voxel precision can be achieved as shown by the white line. This refers to CT voxel size which is seen by close inspection of the image as small squares.

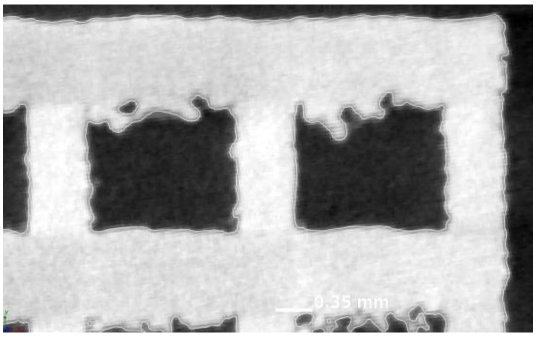

Figure 1: Close-up view of simple cube-design lattice structure showing in white the sub-voxel surface determination. Horizontal struts have dross formation on down-skin surfaces.

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II.II. Analysis types

Typical analyses might include comparison of the actual part to its nominal design, local wall thickness measurement, evaluation of macro-porosity, or the measurement of micro-porosity (inside struts). In addition to these options, basic checking for flaws such as broken struts, cracks, trapped powder, specific pore types, etc. cannot be automated and it is good practice to report this in cross sectional slice images.

II.III. Implant examples

The analysis accuracy depends on voxel size, which depends on part size. Therefore, larger implants with lattice structures cannot be inspected at the same detailed level as for coupon samples. Nevertheless, inspection to ensure the implant is free of major flaws is useful as shown for a good implant with lattice region in Fig. 2. It is seen how the strut thickness is constant across the (non-planar) region and extends ~1.5 mm from the surface (as expected, changes in local thickness would have a different color). In Fig. 3 is shown another example where the local height of the struts match well with the designed spherical geometry.

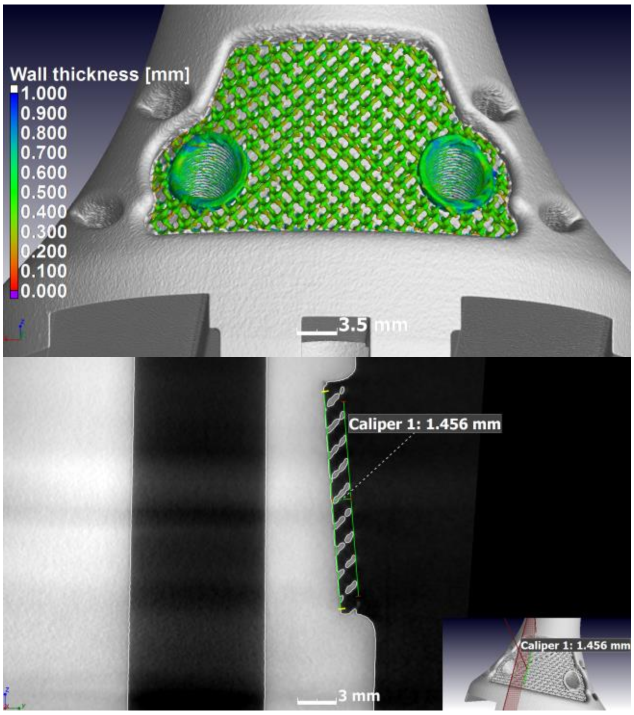

Figure 2: Example of an implant with lattice incorporated in one region only, up to a depth of ~1.5 mm, with struts of 0.5 mm thickness.

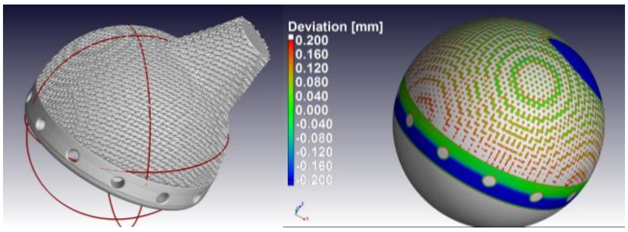

Figure 3: Example of sphere fitted to latticed implant, with local variation of actual lattice elements highlighted in color.

III. Conclusions

Metrology and quality control of additively manufactured lattice structures by X-ray tomography is critically important yet is currently not implemented widely, mainly due to lack of knowledge of the capabilities. Further use of these capabilities will enhance the performance and wider application of additively manufactured lattice structures.

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AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest.

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