Design & Analysis Methods for Additively Manufactured Metal Lattices

JOINT INDUSTRY PROJECT OUTLINE

PROP302747

Summary

Metallic cellular materials and lattices offer unique combinations of thermal, mechanical and acoustic properties that are often unachievable with fully dense materials (Cabras and Brun, 2016). These material systems have been used in a range of industrial applications such as energy absorbers, lightweight structural components, heat exchangers, vibration control mechanisms and medical implants. Although there are many standard fabrication methods for cellular metals, Additive Manufacturing (AM) – and in particular, Selective Laser Melting (SLM) – is capable of producing complex shapes, topologies, and unit cells that could not otherwise be produced.

However, as-built AM lattices almost always deviate from their ideal geometry. AM lattices contain geometric imperfections that strongly influence their stiffness and strength. This is a result of strut thickness variations, build orientation effects, local oversizing or undersizing, and process-induced distortion.

Over the past few years, Design-for-AM, topology optimisation, and lattice design software have been rapidly advancing, resulting in a step-change in design freedom. However, design rules and analysis methods for assessing metal AM parts containing lattices have not developed at the same pace.

The objective of this project is to develop and validate robust design guidelines and analysis methods to assure the integrity of metal AM parts that incorporate lattices. This will involve a combined numerical modelling and experimental work programme, leveraging TWI's advanced AM capabilities and expertise.

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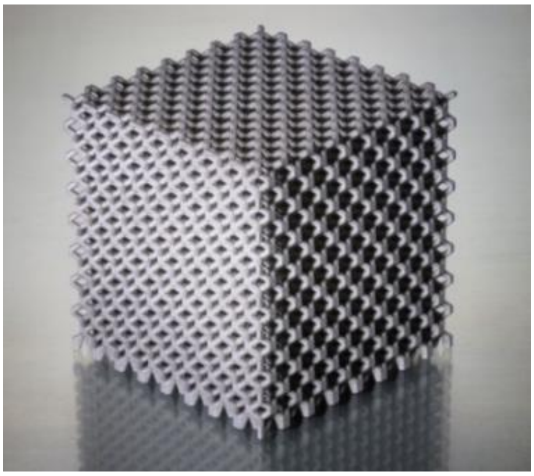
Project Concept

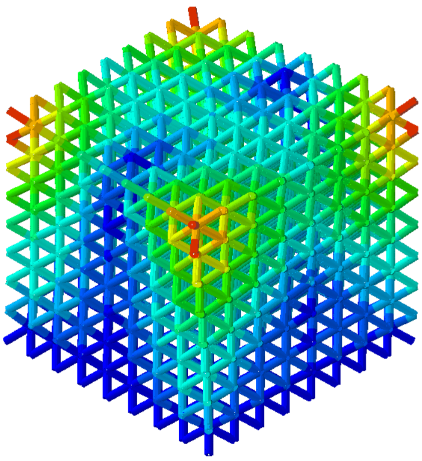
Metal lattices and cellular materials offer unique combinations of thermal, mechanical and acoustic properties that are often unachievable with fully dense materials (Cabras and Brun, 2016). These material systems have been exploited in a range of industrial applications such as energy absorbers, lightweight structural components, heat exchangers, vibration control mechanisms and medical implants. Although there are many standard fabrication methods for cellular metals, SLM is capable of producing complex shapes and topologies that could not otherwise be produced.

A metal AM lattice is typically comprised of a periodic array or spatial tiling of a unit cell. A typical unit cell contains an array of struts connecting the corners or faces of a geometric cell such as a body centred cubic (BCC) array (shown right). However, unit cells can be designed to exhibit unique features such as negative Poisson's ratios (auxetic materials); high surface area to volume ratios; and excellent energy absorption due to the combined effects of plasticity, self-contact, and compactification. Moreover, unit cells need not feature only lattices but can contain complex curved surfaces such as gyroidal unit cells.



BCC lattice built at TWI with stainless steel.

Rapidly evolving design-for-AM software packages like Materialise Magics™ and 3-Matic™, nTopology Element Pro™, Autodesk Within™, and Synopsys Simpleware™ enable the generation of volume-filling lattices. These periodic or stochastic lattices can directly conform to the complex geometry of the original part design and be graded from high to low density regions. However, whilst these design capabilities are powerful for filling low-stress regions of parts, reducing build time, and optimising a part for AM production, the assessment of the final component design incorporating the lattice is challenging.



FE model of a lattice array at TWI.

It has been shown extensively (London et al, 2016; Fahlbusch et al, 2016) that the performance of as-built AM lattices is inferior to analytical calculations or Finite Element (FE) simulations. This is because each as-built unit cell is slightly different from the ideal geometry. The net effect is a difference in stiffness and strength that means existing calculation methods can overestimate the performance of a part containing lattices. There is therefore a strong need to improve existing calculation and FEA workflows to ensure that the performance of a part is well-understood. This project concept details a multi-disciplinary approach for the development of new design rules and analysis methods to enable the confident application of parts containing lattices.

Objectives

- Build a large number of AM lattices using different SLM machines, unit cells and materials.
- Characterise and quantify the statistical deviations of the as-built lattices from their ideal representations using microfocus X-ray Computed Tomography scanning.
- Test the lattices under compression to failure.

- Develop and validate analytical modelling and simulation methods to account for the inherent geometric imperfections of AM lattices that lead to inferior performance.
- Combine the outcomes of the modelling and experimental test programmes to produce design guidelines and assessment approaches for the use of AM lattices in structural parts.
- Validate the design rules on representative demonstrator parts.
- Implement the modelling techniques in a software app to be delivered to sponsors.

Benefits

The proposed project will enable AM lattices to be used with confidence in load-bearing components by quantifying the expected variability in their behaviour. This will allow sponsors to make better use of state-of-the-art design-for-AM software for next-generation parts. The software app will allow sponsors to directly integrate the FE modelling approaches in-house, and the results of the test programme will help inform the statistically-representative number of tests that need to be undertaken to qualify the performance of parts integrating metal AM lattices. The combined outcomes of the project will be valuable in streamlining the qualification of new, optimised, lightweight metal AM parts that can enhance product differentiation for sponsors and minimise trial-and-error experimentation.

Approach

Overview

The accurate understanding of the performance of SLM lattices requires a statistical representation of their inherent imperfections. SLM processing enhances design freedom, but also leads to significant local deviations from the ideal geometry. Although any given unit cell in a lattice array may exhibit only small imperfections, the contribution of these features can lead to significant reductions in stiffness, strength, and ductility. Variability has been reported to be as high as 20% (Fahlbusch et al, 2016). To overcome this challenge, this project proposes to develop a validated modelling approach that statistically represents the geometric imperfections in lattices.

Design and manufacture of specimens

Multiple different unit cells will be selected for demonstrating and validating the modelling results. The sponsor group will have final approval of the selection of lattices. Cubic lattice arrays comprising a minimum of 10x10x10 (1,000) cells will be produced. For each lattice, multiple densities (e.g. strut diameters given a fixed unit cell size) will be considered.

Two different SLM machines based at TWI Yorkshire will be used for the project to ensure the robustness of the database of statistical deviations. Each combination of unit cell and lattice density will be built using different process parameters. Multiple materials (eg an Al-, Ti- and Ni-base alloy) will be used. The sponsor group will select the final materials as most suitable for their needs.

The overall experimental test programme will therefore involve different unit cells, unit cell densities, processing conditions, materials and repeats, resulting in several hundred samples being produced.

Characterisation and testing of samples

The SLM manufacturing activities will provide a large and robust set of samples for developing statistics of the inherent geometric imperfections. For each sample, X-ray computed tomography (XCT) scanning will be undertaken to quantify different geometric imperfections. These measurements will be used to provide probability distributions of non-ideal geometric features. Following characterisation, the parts will be tested under compression to failure to generate their effective stress-strain curves.

Analytical and numerical modelling

For relatively simple unit cells, analytical formulae exist for predicting the elastic and limit responses. These equations will be collected and implemented for a library of unit cells. This approach can be used by sponsors to provide a quick method for choosing the right unit cell for a new design.

FEA will then be used to analyse the tested lattices. Different approaches (eg solid elements and beam arrays) will be used. An automated procedure for incorporating statistical representations of imperfections will be implemented, and a Monte Carlo approach will be used to understand the behaviour of the as-built lattices. The modelling method will be validated against the test results.

The automated modelling approach will be developed as a software app that will be provided to Sponsors at the end of the project so that they can implement the simulation procedures in-house.

Validation on a representative part and production of design guidelines

Finally, the combined numerical modelling and test programmes will be used to generate design guidelines and modelling best practice for the use of lattices in parts. The design guidelines will consider what safety factors are needed for different unit cells so that parts can be confidently designed to perform as required. This will be validated on a representative part.

Deliverables

- A report on the design guidelines and simulation methods for SLM lattices in AM parts.
- A software app with a built-in library to (1) calculate the stiffness and strength of unit cells; and (2) model lattices incorporating statistical geometric imperfections in each unit cell.

Price and Duration

The overall estimated price for the work is £200,000 (excluding VAT), which requires £25,000 total from each of the 8 Sponsors. The duration of the project will be 15 months.

References

Cabras L and Brun M, 2016: 'A class of auxetic three-dimensional lattices', Journal of Mechanics and Physics of Solids, Vol 91, pp 56-72.

Fahlbusch NC, Grenestedt JI and Becker W, 2016: 'Effective failure behaviour of an analytical and a numerical model for closed-cell foams', International Journal of Solids and Structures, Vol 97-98, pp 417-430.

London T, De Bono D and Allison A, 2016: 'A statistical method for predicting the compressive strength of geometrically-imperfect metal microlattices produced by selective laser melting', 27th Advanced Aerospace Materials and Process (AeroMat) Conference, Bellevue, Washington, 23-25 May, 2016.

Further Information

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