High strain-rate assessment of additively manufactured mathematical lattice structures

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Introduction:

- AM lattice structures offer new design opportunities in multiple industries, due the possibility of manufacturing periodic lattice structures with a high degree of accuracy
- Possible applications for the geometries tested in this study include medical implants and aerospace parts

Triply periodic minimal surface geometries:

- Schoen Gyroid, Schwarz Diamond and Schwarz Primitive geometries were tested in this study
- All 3 geometries are self-supporting, meaning that they may be favoured for additive manufacturing due to reduced requirement for build supports
- They all contain continuous channels, and for this reason they have been suggested as possible candidates for heat exchanger designs
- Equation for Primitive isosurface gives shell of geometry shown below, where u = unit cell size

$$\cos\left(2\pi\frac{x}{u}\right) + \cos\left(2\pi\frac{y}{u}\right) + \cos\left(2\pi\frac{z}{u}\right) = 0$$

Primitive isosurface equation

Gyroid, Diamond and Primitive structures manufactured by SLM and tested in compression

- Increase in unit cell size with fixed relative density corresponds to decreased peak strength under quasi-static compression [1]
- SLM allows a high degree of control over final geometry, including varying wall thickness, unit cell size and SLM material to provide a range of structural properties – these variables can be manipulated to provide SLM parts with properties specifically matched to application

Commercially sensitive

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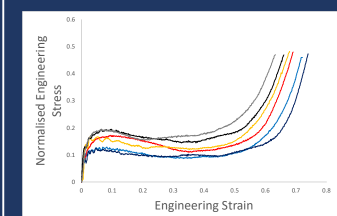
Experiments and Modelling:

- TPMS and bulk material specimens were manufactured by selective laser melting of Ti6Al4V and AlSi10Mg
- High strain rate compression experiments were performed using SHPB apparatus at IEL, Begbroke Science Park to characterise the response of the geometries to dynamic compression
- Quasi-static experiments performed to provide comparison to dynamic tests
- Bulk material tested in quasi-static and high strain rate compression to provide benchmark values for comparison of geometries and calibrated material models for finite element analysis (FEA)
- FEA compared predicted behaviour of TPMS geometries to measured behaviour under high strain rate compression

High strain rate experiments:



AlSi10Mg Diamond structures with thin (Blue), medium (Red) and thick (Black) wall thicknesses

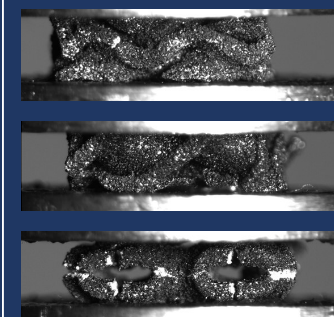
- All geometries demonstrated a degree of stretch dominated behaviour, characterised by peak engineering stress followed by minimum engineering stress prior to densification
- Shape of engineering stress – engineering strain curves is important as this will affect attractiveness of geometries for energy absorbing and structural applications

References:

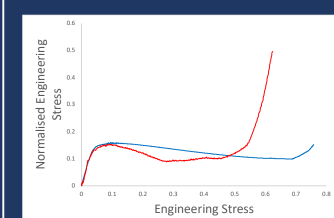
1. C. Yan, L. Hao, A. Hussein, D. Raymont, Evaluations of cellular lattice structures manufactured using selective laser melting, International Journal of Machine Tools and Manufacture, Volume 62, 2012, Pages 32-38

Comparison of Deformation Modes under Quasi-Static Compression:

- Images show Gyroid (top), Diamond (middle) and Primitive (bottom) geometries after initial peak stress in quasi-static compression experiments
- Significant localised deformation and failure is visible in Primitive geometry compared to other two geometries
- Ti6Al4V Primitive specimen shows significant local deformation on circular cross-section, leading to catastrophic failure of the specimen under quasi-static compression – the distribution of stress in the structure is corroborated by FEA analysis



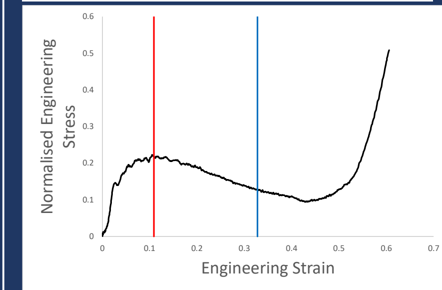
Comparison of FEA and Experimental Results:



FEA (Blue) and Experimental Results (Red) of Compression of AlSi10Mg Primitive Structures

- Comparison shows good agreement on initial peak stress, suggesting FEA can be used to predict strength of structures with high degree of accuracy

Comparison of Deformation Modes and Engineering Stress – Strain Curve under Dynamic Compression:



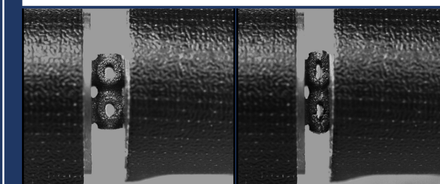
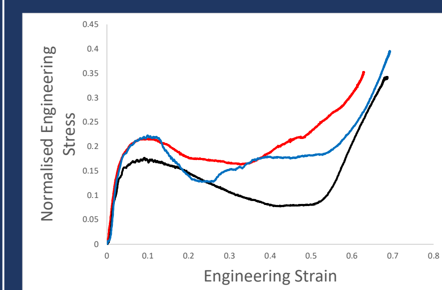


Image 1 Image 2

- Image 1 shows AlSi10Mg Primitive specimen in dynamic compression experiment, at time corresponding to red line on the engineering stress – engineering strain curve – Image 2 shows the corresponding image for the blue line
- No significant local deformation visible at peak stress (Image 1), specimen appears to deform in uniform manner with circular cross-sections still visible
- Image 2 shows local failure in circular cross-section, suggesting that the deformation mode of the Primitive structure is similar across range of strain rates tested - this behaviour is consistent across two materials tested

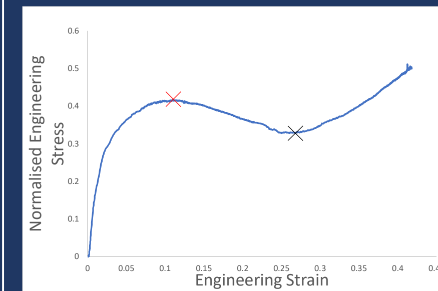
Comparison of Engineering Stress – Engineering Strain Curves under Dynamic Compression:



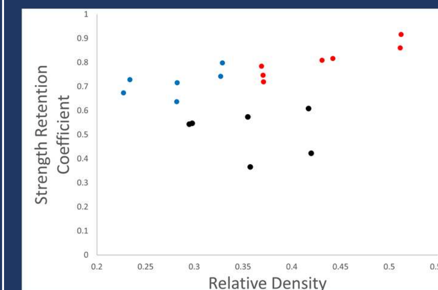
Comparison of Dynamic Compression Experiment Results of Ti6Al4V Gyroid (Red), Diamond (Blue) and Primitive (Black) Structures with similar relative densities

- Gyroid showed the lowest drop-off in engineering stress after initial peak stress, with Diamond structures showing an oscillatory stress response

Comparison of Strength Retention Coefficient Values for AlSi10Mg TPMS Structures:



$$SRC = \frac{\textit{Minimum Stress (Black Cross)}}{\textit{Peak Stress (Red Cross)}}$$



Measured SRC for Gyroid (Red), Diamond (Blue) and Primitive (Black) structures tested in dynamic compression

- SRC is useful to evaluate degree of stretch dominated behaviour exhibited by structures, a key component of design for energy absorbing applications
- Gyroid and Diamond geometries exhibited similar performance by this metric, with the Primitive geometry demonstrating a greater loss of strength after initial yield
- More testing must be done over a greater range of relative densities to enable further comparison

Conclusion:

- The response of 3 types of additively manufactured, triply periodic minimal surface geometries were tested under dynamic and quasi-static compression, and results were compared to finite element analysis
- The Primitive and Diamond geometries were shown to exhibit some strain rate hardening effects, while no significant strain rate hardening was observed for Gyroid structures
- The deformation modes were compared, with the Primitive structure showing a large degree of localized deformation
- The Gyroid and Diamond geometries showed lower degrees of oscillatory engineering stress-strain behaviour after the initial peak stress, suggesting these structures may be preferable for energy absorbing applications
- More work must be performed to enable comparison of dynamic compression behaviour of TPMS structures over a range of relative densities