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Metallic Microlattice Structures

Manufacture, Materials and Application

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Preface

The book has five main themes, namely:

1. Enhancement of specific selected structural applications using additive manufacturing lattice structures, e.g. sandwich beams, sandwich panels and energy absorption devices (static and impact), for use in lightweight structures.
2. Integrated discussion of manufacture, materials and application is followed. In the developing additive manufacturing technology, a development in one area will influence other areas, and so an integrated approach is needed.
3. The structural behaviours and applications discussed here have been studied for many years for conventional structures manufactured using traditional processes, and some of this relevant literature is discussed before introducing additive manufacture.
4. A specific set of structural cases and additively manufactured lattice structures are discussed here, but these are part of the larger fields of Architectured (Architected) Cellular Materials, and part of the larger field of Industrial Processes (including standardisation and certification).
5. Finally, an overall aim of the book is to give the researcher an introduction to some of the fundamental ideas underlying the increasingly sophisticated computer based realisation tools. These include manufacturing parameters, materials optimisation, topology optimisation and multi-function aspects.

The book is written from the perspective of the structural engineer. The book is aimed at researchers and technical practitioners, who need a focussed state of the art introduction to a specific area of additively manufactured metallic lightweight structures. In this way, the current 'design space', using state of the art technology, can be related to the fast developing technologies, and to other available additive manufacturing approaches. The approach taken here is experimental and application orientated.

The author's main research activity over the years has been in structural impact, e.g. foreign object impact and impact energy absorption. Back in 2003, the manufacturing group at the University of Liverpool was studying selective laser melting microlattice structures for bio-implants and micro-heat exchangers. These structures were identified as having potential application for use in lightweight structures. The manufacturing group at Liverpool initially worked with SLM machines from the manufacturing company MCP (2000–2006), then MTT (2006–2010) and finally Renishaw (2010–date). The selective laser melting technology has evolved from a few research laboratories in 2003 to global research activity today, with industrial products.

The discussion here, due to the author's experience, is on the first generation selective laser melting machines (MCP/MTT). First generation selective laser melting machines are discussed in the open literature, whereas, as the field becomes more industrially focused, less detail on selective laser melting machine developments is given in the open literature. Electron beam melting is discussed to compare and contrast with selective laser melting. Electron beam melting and selective laser melting are mature additive manufacturing process, and there are a number of other metal additive manufacturing processes, with more being developed all the time. Photopolymer wave guides, woven wire and binder jetting are processes that will also be discussed. Hence, the enabling additive manufacturing technology is constantly developing.

Given the fact that selective laser melting and electron beam melting are now relatively mature industrial processes, then detailed synthesis and study of realised structures can be made. The book focuses on lattice structures (including surface based lattices), as these are a well defined cellular structure that can be realised using selective laser melting, electron beam melting, photopolymer wave guides, woven wire and binder jetting. Discussion is also restricted to a few conventional materials (stainless steel, titanium alloy and aluminium alloy) and lattice topologies (Body Centred Cubic, BCCZ, Octet Truss) that are most appropriate to the selected structural applications, viz. sandwich beams and panels, and energy absorbers. Currently available additive manufacturing technology is applied to the selected structural applications, and enhancements in performances are quantified. The aim is to fully exploit additive manufacturing technologies (manufacture, materials and simulation) to enhance structural performance. The book does not push the boundaries of developing materials science for additive manufacture, but stays with conventional metallic structural materials. Currently, additive manufacture for non-metals has the greater potential for innovative development and multi functionality. However, the main potential for developing innovative metallic additive manufactured materials is at small (nano) scale.

A note on terminology. The focus of this book is on *microlattice* structures, and these are taken to have a feature size of 100–2000 μm and a cell size of 1–5 mm. Microlattices are contrasted with *nano-lattices*, the latter having feature size less than 100 nm and a cell size less than 10 μm. However, it should be noted that electroplated microlattices have wall thicknesses less than one micron. *Macro-lattices* are taken to have a feature size greater than 1 mm and a cell size greater than 5 mm, and they tend to be manufactured using conventional forming processes. These informal definitions reflect the different manufacturing processes (and to a lesser extent, materials) for each scale.

A detailed overview of the book is given in Chap. 1, and conventional lattice structural theories are given in Chap. 2. Chapter 3 discusses selected additive manufacturing processes (SLM, EBM, BJ), Chap. 4 discusses parent material and lattice characterisation, Chap. 5 discusses lattice analysis and synthesis theories, and Chap. 6 introduces photopolymer wave guides and woven wire lattice solutions. The book culminates in Chap. 7, where specific structural applications are discussed and improvements in structural performance are quantified. Finally, Chap. 8 gives conclusions and highlights future prospects, including eight suggested research themes.

The focus of the book is on overall themes and ideas, and so selected references are discussed briefly and the reader is encouraged to follow items of interest in the original papers. The book is in the form of a 'Tour d'Horizon'. The book cites over 200 journal papers, over half of which have been published within the last 4 years covering manufacturing, materials and structural applications.

Thanks are due to co-workers, Prof. Norman Jones, Wesley Cantwell and Chris Sutcliffe. Thanks are also due to graduate students and research assistants: Drs. Simon McKown, Sozon Tsopanos, Eva Shen, Recep Gümrük, Matt Smith and Rafidah Hasan. The authors' research in this field was mainly sponsored by EPSRC and EU FP6 Celpact.

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Contents

Notation

A	Constant in Johnson Cook Model or Absorptivity
AlSi10/12Mg	Aluminium alloy for Additive Manufacture
AM	Additive manufacture
B	Constant in Johnson Cook model
b	Number of struts in Maxwell analysis or sandwich beam width
BCC	Body centred cubic lattice topology
BCC, Z	BCC with Z strut lattice topology
BJ	Binder jetting process
C	Constant in Johnson Cook model
CT	Computed tomography scan
D	Cowper Symonds constant or Thermal diffusivity
d	Microstrut diameter
D_i	Constraint in material for rupture
DMLS	Direct Metal Laser Sintering
E	Elastic Modulus
E^*_{BCC}	Stiffness of BCC lattice block
EBM	Electron beam melting
E_p	Laser energy in SLM process
F2 BCC	Face centred body centred cubic lattice topology
F2 CC	Face centred cubic lattice topology
FCCZ	Face centred with Z strut lattice topology
H	Specific enthalpy in SLM process
HIP	Hot iso-static processing heat treatment
j	Number of joints in Maxwell analysis
JC	Johnson Cook constitutive model
l	Gauge length or cell length
L	Length of strut
LP	Laser Power in SLM process
LR	Lloyds Register
LX	Laser exposure time in SLM process

m	State of mechanism in Maxwell analysis
M	Maxwell criterion
MIM	Metal Injection Moulding
OT	Octet truss lattice topology
PBF	Powder bed fusion process
P_f	Failure load
PPWG	Photopolymer wave guide
q	Cowper Symonds constant
s	State of self stress in Maxwell model
SLM	Selective laser melting
STL	Stereolithography file format
SMS	Size matching and scale method for optimisation
SS316L	Stainless steel 316L
t	Sandwich skin thickness
T*	Homologous temperature in Johnson Cook model
TB	Textbook values
Ti 64	Titanium alloy Ti—6Al-4V
TPMS	Triply periodic minimal surfaces
TWI	The Welding Institute
u	Laser speed in SLM process
UV	Ultra violet light
V_{CR}	Critical impact velocity
V_i	Impact velocity
WW	Woven wire
$\acute{\varepsilon}$	Strain rate
$\acute{\varepsilon}_0$	Reference strain rate
ε_D	Densification strain
ε_f	Rupture strain
η	Stress triaxiality
ρ	Material density
$\sigma^*_{pl,BCC}$	Plastic collapse strength of BCC block
σ_0	Static block crush stress
$\sigma_{0.2}$	0.2% proof stress
σ_c	Core compression strength
σ_{CR}^{qs}	Quasi-static collapse strength
σ_d	Material dynamic yield stress
σ_s	Material static yield stress or sandwich skin tensile stress
σ_{UTS}	Ultimate tensile strength
ϕ	Laser spot diameter in SLM process