Cairo University

EVALUATION OF ADDITIVELY MANUFACTURED METALLIC MICRO-LATTICE FOR ENERGY ABSORPTION APPLICATIONS UNDER QUASI-STATIC AND DYNAMIC LOADINGS

By

Mahmoud Magdy Ahmed Moustafa Osman

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Design and Production Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under the Supervision of

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Title of Thesis:

Evaluation of Additively Manufactured Metallic Micro-lattice for Energy Absorption Applications under Static and Dynamic Loadings

Key Words:
Additive manufacturing; Selective Laser Melting; Finite element analysis; Energy absorption

Summary:

Truss lattice materials are man-made open porous cellular solids with periodic truss microstructures. Recent developments in additive manufacturing (AM) have enabled the fabrication of metallic lattice structures with dimensions close to micrometer scale. Among different lattice geometries, the octet truss lattice configuration is investigated in this study, as it provides nearly isotropic elastic properties and high specific strength. An extensive finite element (FE) parametric study was conducted on the design variables of the octet truss lattice aiming at increasing the specific energy absorption (SEA) and the energy absorption efficiency (EAE). Microlattice samples made from stainless steel 316L were manufactured using selective laser melting (SLM) based on the best design conditions obtained through the FE simulations. Quasi-static compression experiments were carried out on the fabricated samples which confirmed the results anticipated by FE simulations. In addition, the dynamic compressive behavior of the microlattice samples was reported from Split Hopkinson Pressure Bar (SHPB) testing technique at strain rate of the order 10^3/s. Additional experimental studies were performed to elaborate the effect of heat treatment and acrylic filling of the microlattice spaces on the microlattice large deformation behavior statically and dynamically.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

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Nomenclature

Symbols

A	area
a	unit cell edge length
C	elastic wave speed
D	diameter
E	Young's Modulus
k	coefficient in Eqs. 4.3, and 4.4
L	length; thickness
m_a	mass measurement in air
m_m	mass measurement in methanol
R	radius
R_i	inner radius
R_o	outer radius
t	time
V_{st}	striker velocity
σ	stress
σ_{cr}	critical stress
σ_{crush}	crush stress
σ_p	plateau stress
σ_{tr}	transmitted stress
σ_y	yield stress
σ_{yl}	lattice yield strength
ε	strain
ε_D	densification strain
ρ_a	density measurement in air
ρ_b	base material density
ρ_l	lattice density
ρ_m	density measurement in methanol
$\bar{\rho}$	relative density

Acronyms

AM	additive manufacturing
BCC	body-centered cubic
CAD	computer aided design
DIF	dynamic increase factor
EAE	energy absorption efficiency
EBM	electron beam melting
EDM	electric discharge machine
FCC	face-centered cubic
FE	finite element
FOPS	falling object protective structures
KE	kinetic energy

P.P.	perfect plastic
ROPS	roll-over protective structures
RSEA	relative specific energy absorption
SE	strain energy
SEA	specific energy absorption
SEM	scanning electron microscope
SHPB	Split Hopkinson Pressure Bar
SLM	selective laser melting

Abstract

Truss lattice materials are man-made open porous cellular solids with periodic truss microstructures. These materials are excellent candidates for lightweight and energy absorbing applications such as automotive parts and personal protective equipment, due to their high specific strength properties. Recent developments in additive manufacturing (AM) have enabled the fabrication of metallic lattice structures with dimensions close to micrometer scale. Among different lattice geometries, the octet truss lattice configuration is investigated in this study, as it provides nearly isotropic elastic properties and high specific strength. Finite element (FE) parametric studies were conducted considering some design variables of the octet truss lattice aiming at increasing the specific energy absorption (SEA) and the energy absorption efficiency (EAE), i.e. a constant plateau stress between the initial yield and densification strain. The design variables considered in the present work were the relative density, hollow strut inner to outer radii ratios, and cell aspect ratio. Based on FE simulations, the octet truss lattice with relative density of 0.2 was found to offer the best combination of high SEA and EAE. Microlattice samples made from stainless steel 316L were manufactured by selective laser melting (SLM) based on the best design conditions obtained through FE simulations. The quality of the fabricated microlattice samples were investigated through hydrostatic weighing, optical microscopy, scanning electron microscopy and polarized light microscope imaging. Quasi-static compression experiments were carried out on the fabricated samples which confirmed the results anticipated by FE simulations. In addition, the dynamic compressive behavior of the microlattice samples was obtained using the Split Hopkinson Pressure Bar (SHPB) testing technique at strain rates in the order of 10^3/s. Dynamic tests revealed an increase in the plateau stress of the lattice with a dynamic increase factor (DIF) of 1.27, which is attributed to the material strain rate sensitivity. Additional experimental studies were performed to explain the effect of heat treatment and acrylic filling of the microlattice spaces on the microlattice large deformation behavior, both quasi-statically and dynamically. Filling the microlattice with acrylic resin featured a substantial increase in the microlattice specific strength with a considerable deformation capacity which could be beneficial for load bearing structures when material toughness is desirable. However, both SEA and EAE dropped for the composite lattice due to the low achievable densification strain in the presence of acrylic filling material.

Keywords:

Microlattice Metamaterials, Hybrid, Additive manufacturing, Selective Laser Melting (SLM), Finite element analysis, Energy absorption, Split Hopkinson bar testing