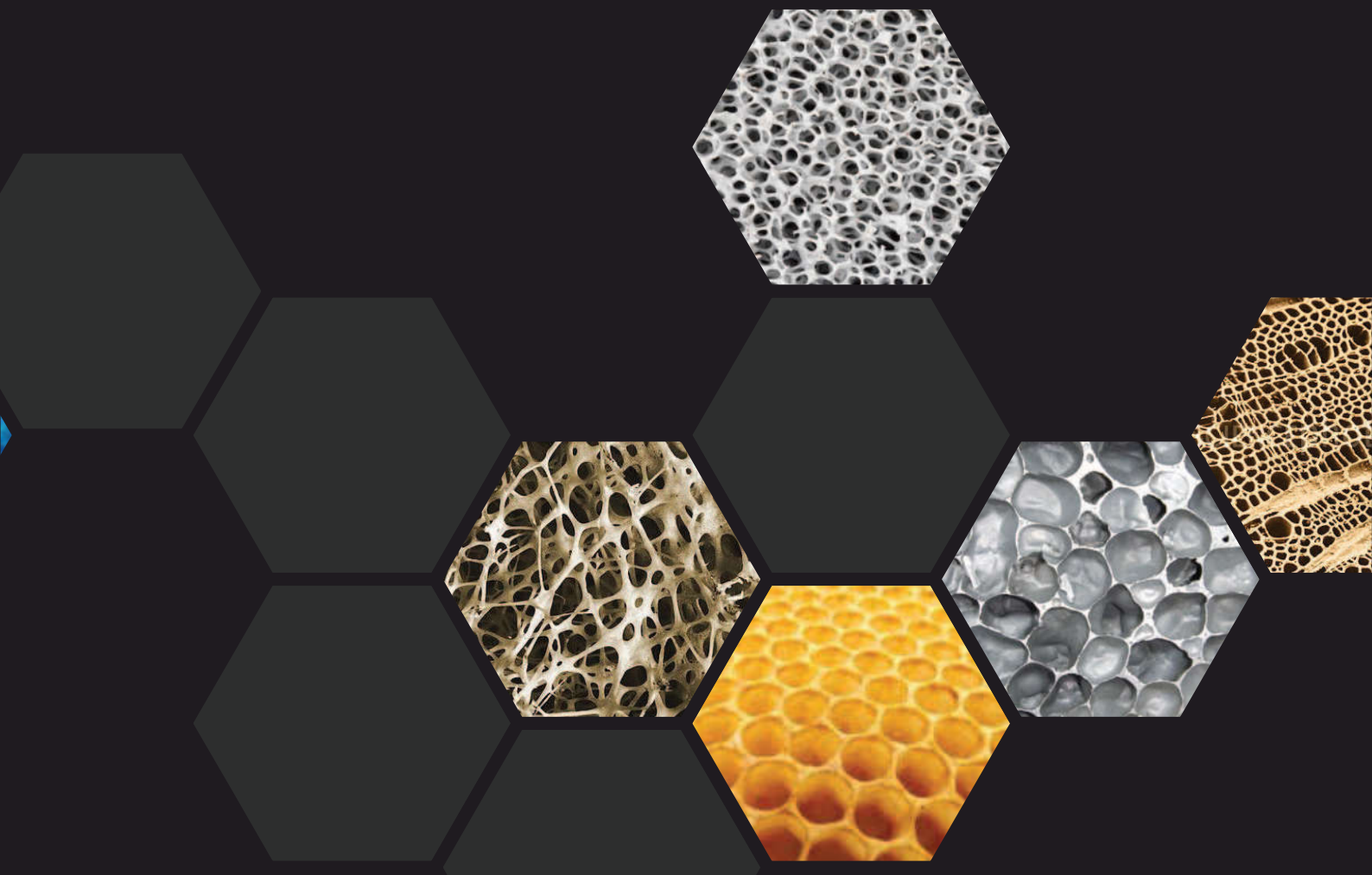
# Cellular Materials: Structural Behaviour, Modelling and Characterisation

Edited by
Isabel Duarte, Nuno Peixinho
António Andrade-Campos, Robertt Valente



# Cellular Materials: Structural Behaviour, Modelling and Characterisation

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**António Andrade-Campos, Robertt Valente**

**Proceedings of the Conferences on Cellular Materials: MatCel'2017 & DynMatCel'2017"**

**Aveiro (Portugal)**
**September 25th – 27th, 2017**

**Organised by**
**University of Aveiro (Aveiro, Portugal)**
**University of Minho (Guimarães, Portugal)**

**Supported by**
**Portuguese Society of Materials (SPM)**
**DYMAT Association**
**GRIDS Research Group**

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| | |
|---|---|
| MatCel'2017 | Second Edition of the National Conference on Cellular Materials |
| DynMatCel'2017 | International Conference of Dynamic Behaviour of Cellular Materials |

This book contains abstracts of the papers presented at the conferences on Cellular Materials, held at the Department of Mechanical Engineering, University of Aveiro, Aveiro, Portugal, from September 25$^{th}$ to 27$^{th}$, 2017. These conferences were organised by the University of Aveiro and the University of Minho, both sponsored by the Portuguese Society of Materials (SPM), DYMAT Association and GRIDS.


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# CONTENTS

# PREFACE

Cellular materials (both natural and artificial) are regarded as one of the most promising classes of multifunctional lightweight materials for industrial applications in a wide variety of sectors (e.g. biomedical, transportation, construction). This is due to the combination of interesting properties exhibitted by these materials, which enable their use to perform multiple functions, either alone or incorporated into a single engineering component. Furthermore, these materials can be easily tailored to obtain the desired properties for a given application, by controlling the arrangement of the cellular structure (e.g. open-cells, closed-cells, pore shapes, pore diameters) and the base solid material (e.g. metal, ceramic and polymer). Their use considerably contributes to an immediate and significant weight reduction and material savings while having other advantages, such as excellent performance in vibration damping and sound attenuation, energy absorption and heat insulation. Examples of these multifunctional cellular materials range from natural materials (e.g. wood, cork, trabecular bone, coral and sponge) to artificial ones based on metal, polymer, ceramic (closed-cell and open-cell foams, hollow-sphere foams, syntactic foams, periodic and optimized truss structures and honeycombs). The latter ones can be produced by a wide range of processing methods, from conventional (e.g. Powder Metallurgy) to modern technologies (additive manufacturing, such as 3D Printing).

Cellular materials have become a hot research topic in the last decades. For this reason, several workshops, symposiums and conferences have paid special attention to this topic. Eufoam, Metfoam and Cellmat series are the most important international conferences in this thematic. In 2015, the first edition of the national conference dedicated to cellular materials (MatCel'2015*) was organised at the University of Aveiro, in Portugal, with the support of the Society of Portuguese Materials (SPM). This conference was held at the Department of Mechanical Engineering on September 7-8, 2015, having provided a forum for discussion, exchange of research ideas and experiences in this field, covering experimental, numerical and theoretical investigations among active Portuguese researchers and renown international experts in these thematic fields. After its first successful edition, a second edition was organised from September 25$^{th}$ to 27$^{th}$, 2017.

After its first edition in Aveiro with about 30 participants, most of them from Portugal, listening and discussing 25 research works, this second edition, MatCel'2017, also in Aveiro (Portugal) and from September 25 to 27, 2017, has attracted about 40 participants from different countries with almost 50 papers. MatCel'2017 was jointly organised with the international Conference on Dynamic Behaviour

of Cellular Materials (DynMatCel'2017), by the University of Aveiro and the University of Minho, and with the support of the Portuguese Society of Materials (SPM), DYMAT Association and GRIDS research group (UA). This event was organised and structured in three days with scientific sessions including both presented papers and posters, as well as five plenary lectures given by renowned international experts. This event has now assumed itself a biennial conference, aiming to be a regular and priviledged forum for the exchange and discussion between scientists, academia and industry, inspiring future collaborations and bringing up new ideas within this field.

This book contains the abstracts of the fifty contributions presented in this event by all the participants from all parts of the world, including those from the renowed invited speakers. The book is intended to serve as a reference for researchers, engineers and graduated students working on lightweight multifunctional materials (cellular materials), giving an overview of the current state-of-the-art in this field, covering experimental, numerical and theoretical investigations.

The editors would like to acknowledge the invited speakers Prof. John Banhart (TU Berlin and Helmholtz-Centre Berlin, Berlin, Germany), Prof. Lovre Krstulović-Opara (University of Split, Croatia), Prof. Maria Emília Rosa (Instituto Superior Técnico, University of Lisbon, Portugal), Prof. Matej Vesenjak (University of Maribor, Slovenia) and Prof. Renato Natal Jorge (Faculty of Engineering of University of Porto, Portugal), for their willingness in supporting this innovative event in Portugal.

The Editors of the present publication are also grateful to the reviews and support from the Scientific Committee, who helped to ensure the scientific quality of the presented papers. A special word of acknowledgment goes to the Authors, that actively contributed to the content of this book.

Aveiro, 25th September 2017

Isabel Duarte
Nuno Pexinho
António Andrade-Campos
Robertt Valente

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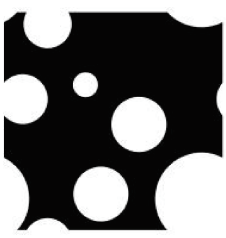
[*] I. Duarte, R. Valente, A. Andrade-Campos (Guest Editors). Special issue on Cellular Materials. Ciência & Tecnologia dos Materiais. Vol. 28. Issue 1. Janeiro/Junho 2016. ISSN 0870-8312.
[*] I. Duarte,R. Valente, A. Andrade-Campos. Proceedings of the first national conference of cellular materials. September 7-8, 2015. ISBN 978-972-99784-3-2 (print version); 978-972-99784-4-9.

# ORGANISING & SCIENTIFIC COMMITTEES



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João Dias-de-Oliveira (jalex@ua.pt, University of Aveiro, Aveiro

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## Conference Secretariat

Tânia Barbosa
Department of Mechanical Engineering
University of Aveiro
Campus Universitário de Santiago
3810-193 Aveiro
Portugal

Tel: +351.234.370830
e-mail: tania.barbosa@ua.pt

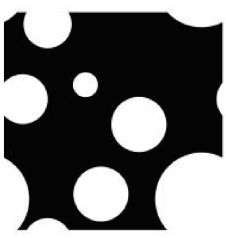
Webpage: http://matcel2017.web.ua.pt/
e-mail: dem-matcel2017@ua.pt

## General Information

### Language

The official language of the meeting is English.

# INVITED SPEAKERS



***John Banhart*** studied Physics at the University of Munich and obtained a degree in Physical Chemistry from the same university in 1989. He joined the Fraunhofer Institute in Bremen in 1991 and worked in the field of cellular materials. In 2002 he became a professor of Materials Science at the TU Berlin and head of a research department at the Hahn-Meitner Institute (now Helmholtz-Centre Berlin). His current focus of research lies on lightweight and cellular materials and on imaging with X-rays and neutrons. Throughout his scientific career, he registered 11 patents, published more than 312 articles in SCI journals, 152 conference proceedings and book contributions, 54 miscellaneous publications, and 16 editorships for books and journal issues. He has scientific papers in ISI international journals with over 6556 citations. Moreover, he is the founder and main organizer of the MetFoam series conference (International Conference on Porous Metals and Metallic foams), started in 1999 (at IFAM, Bremen) and taking place every two years.
More details: http://www.helmholtz-berlin.de/media/media/spezial/people/banhart/html/index.html

***Lovre Krstulović-Opara*** is a Professor of the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture at University of Split, Croatia. He received his Dipl.Ing. degree in Mechanical Engineering at the University of Zagreb in 1994, got the teaching assistant position and obtained his M.Sc. degree in 1997. After this he joined the research group of Prof. Peter Wriggers, first at TU Darmstadt, and then at University of Hannover where in 2000 he received his Dr.-Ing. degree. In 2001 he moved to University of Split, and in 2015 he was elected to Full professor with permanent position. His research interests include numerical methods in contact mechanics, experimental mechanics, non-destructive testing and infrared thermography. He is certified expert in several NDT methods. Currently he is the president of the Croatian Society of Mechanics.

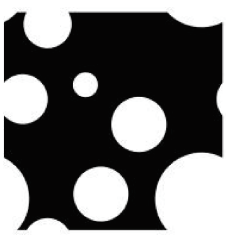
More details: http://marjan.fesb.hr/~opara/index.html

***Maria Emília Rosa*** is an Associate Professor in the Department of Mechanical Engineering at Instituto Superior Técnico. She received his B.Sc. degree in Metallurgical Engineering at the Technical University of Lisbon in 1980 and obtained her PhD degree in Materials Engineering at the same university in 1990. She was a member of the Portuguese research group, headed by Prof M. Amaral Fortes, that, in 1985, initiated the work on cellular materials. In 1989, she received, with Prof M. Amaral Fortes, the Gulbenkian Science and Technology Award for their work on cork. Her main research interests focus on structure and mechanical properties of cellular materials, in general, and of cork, in particular. She has participated in several research projects and published more than one hundred papers in journals and conference proceedings.
More details: https://fenix.tecnico.ulisboa.pt/homepage/ist11941

***Matej Vesenjak*** is an Associate Professor of the Faculty of Mechanical Engineering at University of Maribor, Slovenia. He received his B.Sc. degree in Mechanical Engineering at the University of Maribor in 2001 and obtained his Ph.D. degree at the same university in 2006. From 2012 he is a visiting professor at the Kumamoto University, Japan and was also a visiting professor at the Okinawa National College of Technology, Japan. His research interests focus on porous and cellular materials, mechanical and geometrical characterization of advanced materials, computational mechanics, crashworthiness and fluid-structure interaction. He has been awarded with numerous scholarships and fellowships and has gained professional experience at several universities and institutions all over the world. His bibliography contains more than 450 entries.
More details: http://lace.uni-mb.si/vesenjak/en/cv.html

***Renato Natal Jorge*** is graduated in Mechanical Engineering from the University of Porto (UP – www.up.pt), Portugal, since 1987. In 1991, he obtained the Master degree in Structural Mechanics, also at University of Porto. In 1999, he obtained the PhD degree in Mechanical Engineering from the same University. He was a member (2011-2014) of the executive board of the Institute of Mechanical Engineering from the Faculty of Engineering of University of Porto. Between 2007 and 2011, he is the Scientific Coordinator of the Design and Experimental Validation Research Unit of IDMEC. Furthermore, also since 2008, he has been Associate Professor of the Department of Mechanical Engineering (DEMec) of the Faculty of Engineering of University of Porto and he is Deputy Director of DEMec. His main research areas include Computational Mechanics, Biomedical Engineering, Biomechanics and Mechanobiology. He has been supervisor and co-supervisor of several Master and PhD Thesis. He is co-author of more than 160 papers in international journals and he has collaborated in more than 450 papers in international conferences. His h-index is 30 (Scopus). He is co-editor of 12 international books and guest-editor of several special issues of international journals. He has been involved in several projects, both as researcher and as scientific coordinator. Additionally, he has been serving as a reviewer of several international journals, such as the Journal of Biomechanics, Annals of Biomedical Engineering, International Journal for Numerical Methods in Engineering, Computer Methods in Applied Mechanics and Engineering, Finite Elements in Analysis and Design, International Journal of Urogynaecology, Computer Methods in Biomechanics and Biomedical Engineering.

# SCIENTIFIC PROGRAMME



## Programme overview

| | Day 1 (25th September) | Day 2 (26th September) | Day 3 (27th September) |
|---|---|---|---|
| 8:00-9:00 | Registration | | |
| 9:00-9:15 | Welcome and Opening | Registration | Registration |
| 9:15–10:00 | Plenary lecture (1) | Plenary lecture (3) | Plenary lecture (5) |
| 10:00–10:30 | Coffee-break* | Coffee-break | Coffee-break |
| 10:30-10:50 | Regular oral presentations | Regular oral presentations | Regular oral presentations |
| 10:50-11:10 | | | |
| 11:10-11:30 | | | |
| 11:30-11:50 | | | |
| 11:50-12:10 | | | |
| 12:10-12:30 | | | Closing |
| 12:30-14:00 | Lunch | Lunch | |
| 14:00-14:45 | Plenary lecture (2) | Plenary lecture (4) | |
| 14:45-15:05 | Regular oral presentations | Regular oral presentations | |
| 15:05-15:25 | | | |
| 15:25-15:50 | Coffee-break* | Coffee-break | |
| 15:50-16:10 | Regular oral presentations | Regular oral presentations | |
| 16:10-16:30 | | | |
| 16:30-16:50 | | | |
| 16:50-17:10 | | | |
| 17:10-17:30 | | Social programme | |
| | | | |
| 20:00 | | Dinner Conference | |

***Poster Session**

## Scientific programme

| **Day 1** | **25th September 2017 (morning)** |
|---|---|
| **8:00-9:00** | **Registration** |
| **9:00-9:15** | **Welcome and Opening session** |
| **9:15–10:00** | **Plenary lecture**<br>*In-situ* X-ray tomoscopy: Insights into the evolution of liquid Aluminium alloy foams<br>**John Banhart**, Technical University of Berlin, Helmholtz-Centre, Germany |
| **10:00–10:30** | **Coffee-break (Poster Session )** |
| **10:30-10:50** | Metal foams in research and development –new approaches in industrial aluminium foam production<br>**T. Hipke**, Fraunhofer-Institute for Machine Tools and Forming Technology, Germany<br>**René Vogel**, Fraunhofer-Institute for Machine Tools and Forming Technology, Germany<br>**J. Hohlfeld,** Fraunhofer-Institute for Machine Tools and Forming Technology, Germany<br>**F. Schuller,** Havel Metal Foam GmbH, Germany |
| **10:50-11:10** | Use of polymers for the production of metal matrix composite porous structures<br>**Lisa Biasetto**, University of Padova, Italy<br>**H. Elsayed,** University of Padova, Italy, National Research Centre, Egypt |
| **11:10-11:30** | Remote Laser cutting of open cell foams: Processes for the factory of the future<br>**Robert Baumann**, Technical University (TUD) of Dresden, Germany<br>**P. Herwig**, Fraunhofer Institute for Material and Beam Technology (IWS), Germany<br>**A. Wetzig**, Fraunhofer Institute for Material and Beam Technology (IWS), Germany<br>**E. Beyer**, Technical University (TUD) of Dresden, Germany |
| **11:30-11:50** | Development of SLM cellular structures for injection molds manufacturing<br>**D. Oliveira,** Polytechnic Institute of Leiria, Portugal<br>**C. Santos,** Polytechnic Institute of Leiria, Portugal<br>**Artur Mateus,** Polytechnic Institute of Leiria, Portugal<br>**C. Malça,** Polytechnic Institute of Coimbra, Portugal |
| **11:50-12:10** | Processing of open-pore silicon foams using graphite composite as space holder<br>**Johann Heimann**, Pforzheim University of Applied Sciences, Germany<br>**A.M. Matz,** Pforzheim University of Applied Sciences, Germany<br>**B.S. Mocker,** Pforzheim University of Applied Sciences, Germany<br>**N. Jost,** Pforzheim University of Applied Sciences, Germany |
| **12:10-12:30** | Functional bio-based polyurethane foams from industrial residues<br>**Nuno Gama,** University of Aveiro, Portugal<br>**R. Silva,** Sapec-Química SA, Portugal<br>**A. Ferreira,** Escola Superior de Tecnologia e Gestão de Águeda, Portugal<br>**A. Barros-Timmons,** University of Aveiro, Portugal |
| **12:30-14:00** | **Lunch** |

| **Day 2** | **26th September 2017 (morning)** |
|---|---|
| **8:00-9:00** | |
| **9:00-9:15** | **Registration** |
| **9:15–10:00** | **Plenary lecture**<br>Mechanical behavior of cellular metals<br>**Matej Vesenjak**, University of Maribor, Slovenia |
| **10:00–10:30** | **Coffee-break** |
| **10:30-10:50** | Visualizing Strain in dynamically loaded cellular materials<br>**Lovre Krstulović-Opara**, University of Split, Croatia<br>**M. Vesenjak**, University of Maribor, Slovenia<br>**I. Duarte**, University of Aveiro, Portugal |
| **10:50-11:10** | Control of the compressive properties of metallic foams through the fractal distribution of the porosity<br>**Ismeli Afonso**, Universidad Nacional Autónoma de México, México<br>**J.C. Carranza**, Universidad Nacional Autónoma de México, México<br>**L. Pérez**, Universidad Técnica Federico Santa María, Chile<br>**I.A. Figueroa**, Universidad Nacional Autónoma de México, México |
| **11:10-11:30** | The role of randomness in the elastic properties of soft mechanical metamaterials<br>**Mohammadi Mirzaali**, Politecnico di Milano, Italy<br>**R. Hedayati,** Delft University of Technology, The Netherlands<br>**P. Vena**, Politecnico di Milano, Italy<br>**L. Vergani**, Politecnico di Milano, Italy<br>**M. Strano**, Politecnico di Milano, Italy<br>**A. Zadpoor**, Delft University of Technology, The Netherlands |
| **11:30-11:50** | Experımental and numerıcal impact testing an aluminium corrugate layered structure<br>**M. Güden**, Izmir Institute of Technology, Turkey<br>**Mustafa Sarıkaya**, Izmir Institute of Technology, Turkey<br>**A. Taşdemirci**, Izmir Institute of Technology, Turkey |
| **11:50-12:10** | Mechanical properties of high-density TRIP-steel honeycomb structures with varying cell profile under different load conditions<br>**Christine Baumgart**, Technische Universität Bergakademie Freiberg, Germany<br>**L. Krüger**, Technische Universität Bergakademie Freiberg, Germany |
| **12:10-12:30** | Multiaxial experimental tests on a polypropylene foam<br>**A. Donnard**, Arts et Metiers ParisTech, France<br>**S. Guérard**, Arts et Metiers ParisTech, France<br>**Laurent Maheo**, CREC, St-Cyr Military Academy, University of South Brittany, France<br>**P. Viot**, Arts et Metiers ParisTech, France |
| **12:30-14:00** | **Lunch** |

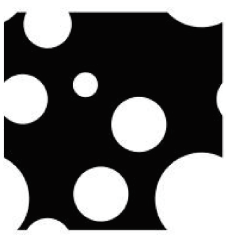
| **Day 2** | **26th September 2017 (afternoon)** |
|---|---|
| **14:00-14:45** | **Plenary lecture**<br>On the forming of sandwich shells with closed-cell foam cores<br>**Renato Natal Jorge**, Faculty of Engineering of the University of Porto, Porto |
| **14:45-15:05** | Multi-scale analysis of composite materials using the natural neighbour radial point interpolation method<br>**Daniel Rodrigues**, Institute of Science and Innovation in Mechanical and Industrial Engineering, INEGI, Portugal<br>**J. Belinha**, Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Faculty of Engineering, University of Porto, Portugal<br>**L.M.J.S. Dinis**, Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Portugal<br>**R.M. Natal Jorge**, Faculty of Engineering, University of Porto, Portugal |
| **15:05-15:25** | Multiscale simulation of temperature and stress state for high temperature gradient for 3D periodic composites<br>**Gleb Gorynin**, Surgut State University, Russia<br>A. Vlasko, Surgut State University, Russia |
| **15:25-15:50** | **Coffee-break** |
| **15:50-16:10** | Modelling and effective properties prediction of metal foams<br>**José Aquino**, University of Aveiro, Portugal<br>**I. Duarte**, University of Aveiro, Portugal<br>**J. Dias-de-Oliveira**, University of Aveiro, Portugal |
| **16:10-16:30** | Defining the anisotropic constitutive tensor of trabecular bone using the fabric tensor concept<br>**Marco Marques**, Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Portugal<br>**J. Belinha**, Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Faculty of Engineering, University of Porto, Portugal<br>**A.F. Oliveira**. Abel Salazar Institute of Biomedical Sciences, Portugal<br>**R. M. Natal Jorge**, Faculty of Engineering, University of Porto, Portugal |
| **16:30-16:50** | Dynamic mechanical behaviour of cellular materials under compressive load<br>**Gerald Portemont**, Onera-The French Aerospace Lab, France<br>**B. Langrand**, Onera-The French Aerospace Lab, France<br>**V. Marcadon**, Onera-The French Aerospace Lab, France<br>**C. Davoine**, Onera-The French Aerospace Lab, France<br>**S. Kruch**, Onera-The French Aerospace Lab, France |
| **16:50-17:10** | Application of virtual cellular material concept for the simulations of dynamic loading processes<br>**Ryszard Pecherski**, Institute of Fundamental Technological Research, Poland<br>Z. Nowak, Institute of Fundamental Technological Research, Polish Academy of Sciences, Poland |
| **17:10-17:15** | **Information** |
| **17:15-20:00** | **Social Programme** |
| **20:00** | **Dinner Conference** |

| **Day 3** | **27th September 2017 (morning)** |
|---|---|
| **8:00-9:00** | |
| **9:00-9:15** | **Registration** |
| **9:15–10:00** | **Plenary lecture**<br>Infrared thermography as the tool for tracing plastification of cellular materials and composite structures<br>**Lovre Krstulović-Opara**, University of Split, Croatia |
| **10:00–10:30** | **Coffee-break** |
| **10:30-10:50** | Crush behaviour of auxetic cellular structures<br>**M. Vesenjak**, University of Maribor, Slovenia<br>**N. Novak**, University of Maribor, Slovenia<br>**Zoran Ren**, University of Maribor, Slovenia |
| **10:50-11:10** | Significance of cell number in the bulk elastic properties of auxetic reentrant lattices<br>**Vitor Carneiro**, University of Minho, Portugal<br>**J. Meireles**, University of Minho, Portugal<br>**N. Peixinho**, University of Minho, Portugal |
| **11:10-11:30** | Effective thermal conductivity of open cell foams for gas-solid reactors<br>**Marie-Line Zanota**, Université de Lyon, France<br>**Jonathan Gerardin**, Université de Lyon, France<br>**Isabelle Pitault**, Université de Lyon, France<br>**Régis Philippe**, Université de Lyon, France |
| **11:30-11:50** | Direct monte Carlo simulation of radiation heat transfer in semi-transparent cellular foams/ comparison with homogenized methods<br>**Salvatore Cunsolo**, LaMCoS, INSA-Lyon, France<br>**R. Coquard**, EC2-MODELISATION, France<br>**D. Baillis**, LaMCoS, INSA-Lyon, France<br>**N. Bianco**, Università degli Studi Federico II Napoli, Italy |
| **11:50-12:10** | Bi-material vehicle hood for impact absorption during pedestrians accidents<br>**Sergio Santos**, Polytechnic Institute of Leiria, Portugal<br>**D. Bastos**, Polytechnic Institute of Leiria, Portugal<br>**P. Freitas**, Polytechnic Institute of Leiria, Portugal<br>**H. Amorim**, Polytechnic Institute of Leiria, Portugal |
| **12:10-12:30** | **Closing** |

## List of posters

| | **25th September 2017 (10:00–10:30; 15:25-15:50)** |
|---|---|
| **Poster** | |
| **#1** | 3D printed Ti6Al4v porous structures by robocasting technology<br>**Lisa Biasetto**, University of Padova, Italy<br>**H. Elsayed**, University of Padova, Italy & National Research Centre, Egypt |
| **#2** | Radiant porous burners produced from an alternative ceramic raw material<br>**N.P. Stochero**, Federal University of Santa Catarina (UFSC), Brazil<br>**E.G. Moraes**, Federal University of Santa Catarina (UFSC), Brazil<br>**António P. Novaes de Oliveira**, Federal University of Santa Catarina (UFSC), Brazil |
| **#3** | Ceramic foams produced from ceramic shell waste and expandable styrofoam (eps) as pore former: processing and characterization<br>**L. Sangiacomo**, University of Moderna and Reggio Emilia (UniMore), Italy<br>**E.G. Moraes**, Federal University of Santa Catarina (UFSC), Brazil<br>**S. Arcaro, Federal** University of Santa Catarina (UFSC), Brazil<br>**N.P. Stochero**, Federal University of Santa Catarina (UFSC), Brazil<br>**C. Siligardi1**, University of Moderna and Reggio Emilia (UniMore), Italy<br>**António P. Novaes de Oliveira**, Federal University of Santa Catarina (UFSC), Brazil |
| **#4** | Vitrocrystalline foams from expandable styrofoam (EPS) as pore former: processing and characterization<br>**M. Bigi**, University of Moderna and Reggio Emilia (UniMore), Italy<br>**E.G. Moraes**, Federal University of Santa Catarina (UFSC), Brazil<br>**N.P. Stochero**, Federal University of Santa Catarina (UFSC), Brazil<br>**S. Arcaro**, Federal University of Santa Catarina (UFSC), Brazil<br>**C. Siligardi**, University of Moderna and Reggio Emilia (UniMore), Italy<br>**António P. Novaes de Oliveira**, Federal University of Santa Catarina (UFSC), Brazil |
| **#5** | Additive manufacturing of 3D porous alkali-free bioactive glass scaffolds by robocasting<br>**A.D. Marzi**, University of Padua, Italy<br>**A.S. Neto**, University of Aveiro, Portugal<br>**H.R. Fernandes**, University of Aveiro, Portugal<br>**P. Colombo**, University of Padua, Italy<br>**José M.F. Ferreira**, University of Aveiro, Portugal |
| **#6** | Porous chitosan-polyethyleneglycol composite membranes for antibacterial and controlled drug delivery applications<br>**I. Pereira**, University of Aveiro, Portugal<br>**A. S. Neto**, University of Aveiro, Portugal<br>**A. S. Duarte**, University of Aveiro, Portugal<br>**José M.F. Ferreira**, University of Aveiro, Portugal |
| **#7** | Process development of process for manufacturing of cellular structures with controlled geometry and properties<br>**Nuno Peixinho**, University of Minho, Portugal<br>**P. Pinto**, University of Minho, Portugal<br>**F.S. Silva**, University of Minho, Portugal<br>**D. Soares**, University of Minho, Portugal |

# INVITED ABSTRACTS



# IN-SITU X-RAY TOMOSCOPY: INSIGHTS INTO THE EVOLUTION OF LIQUID ALUMINIUM ALLOY FOAMS

F. García-Moreno[1,2], T. Neu[1,2], P.H. Kamm[1,2], K. Heim[1,2], C.M. Schlepütz[3], R. Mokso[4], J. Banhart[1,2,*]
[1]*Applied Materials, Helmholtz-Centre, Berlin, 14109, Germany*
[2]*Materials Science and Technology, Technische Universität, Berlin, 10623, Germany*
[3]*Swiss Light Source, Paul Scherrer Institut, Villigen, Switzerland*
[4]*Max IV Laboratory, University Lund, Sweden*
*Emails: garcia-moreno@helmholtz-berlin.de, tillmann.neu@helmholtz-berlin.de, paul.kamm@helmholtz-berlin.de, john.banhart@tu-berlin.de*

**Keywords:** Aluminium foam; X-ray tomography

## Abstract

Fast synchrotron X-ray radioscopy has been used to study time-resolved phenomena in liquid metal foams on a sub-second timescale [1]. Over the past years, the temporal resolution of synchrotron imaging has undergone continuous improvement. We present a newly developed in-situ 'tomoscopy' technique, which we define as a method that allows one to monitor time-dependent processes in a continuous way in three spatial dimensions, hence also known as 4D tomography [2]. We apply the method to evolving metal foams and resolve the entire foaming process in real time: from the solid precursor, over bubble nucleation and growth to the fully expanded liquid foam and eventually to the solidified sample. The whole process is analysed quantitatively at a rate of up to 20 tomographies/s (tps) during several minutes. Even more detailed analyses at higher temporal resolutions up to 50 tps are possible for a reduced period of time. We calculate the gas bubble nucleation rate and volume distributions for different alloys. Several nucleation stages can be identified and correlated with different gas sources. Moreover, a correlation between bubble location and certain powder particles is found. We observe diffusive intermixing between alloying components in pressed powder precursors during heating such as diffusion of copper into aluminium or aluminium into AlMg50 particles, and the formation of a liquid eutectic in their neighbourhood. We follow bubble growth and shape evolution in early stages: It leads from round bubbles to elongated features and sometimes long cracks. This behaviour is explained by the different alloy compositions and precursor compaction methods.

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*corresponding author: john.banhart@tu-berlin.de (J. Banhart)

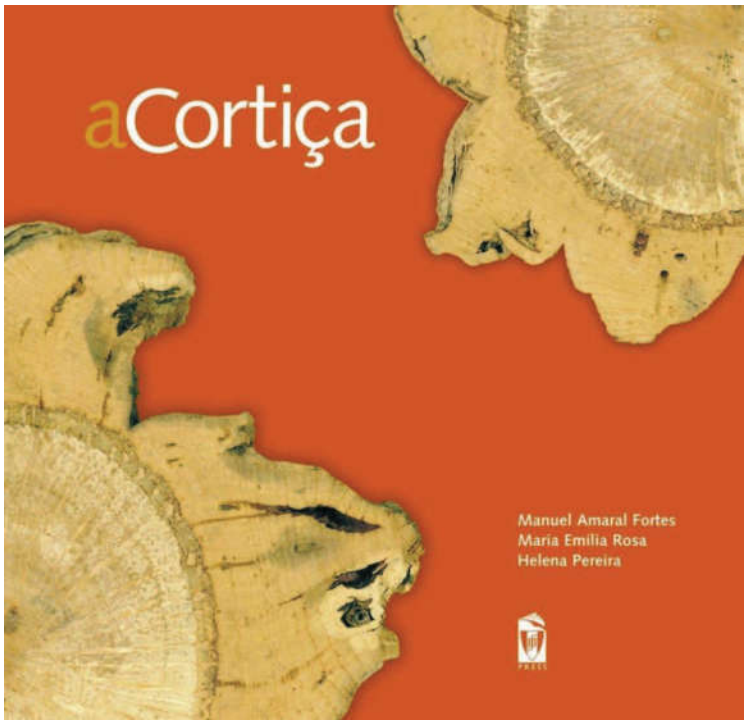
# CORK: A NATURAL CELLULAR MATERIAL

M. Emília Rosa
*Department of Mechanical Engineering, Instituto Superior Técnico, University of Lisbon*
*IDMEC – Mechanical Engineering Institute*
*Av Rovisco Pais, 1049-001 Lisboa, Portugal*
*Email: emilia.rosa@tecnico.ulisboa.pt*

**Keywords:** Cork; Cellular materials

**Abstract**

Cork is the bark of the cork oak tree (Quercus suber L.) that grows in the countries surrounding the Mediterranean ocean. Structure and its relation to the main properties and applications of cork will be analyzed and discussed.

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*corresponding author: emilia.rosa@tecnico.ulisboa.pt (M. Emília Rosa)

# MECHANICAL BEHAVIOR OF CELLULAR METALS

M. Vesenjak*, Z. Ren
*Faculty of Mechanical Engineering, University of Maribor, Maribor, SI-2000, Slovenia*
*Emails: matej.vesenjak@um.si, zoran.ren@um.si*

**Keywords:** Cellular metals; Geometrical characterization; Experimental testing; Computational modelling; Finite Element Method (FEM); Mechanical properties

**Abstract**

As the cellular metals [1] are directly applicable in contemporary industry it is necessary to better understand their mechanical response. Therefore, the knowledge about their morphology, topology and mechanical properties is of crucial importance. They can be explained by geometrical analysis, experimental testing and computational simulations.

Herein a short overview of geometrical characterization, experimental testing and computational modelling within the finite element method of various cellular metal types is given. The geometrical characterisation is based on the analysis of micro computed tomography scans and proper recognition of their internal cellular structure, taking into account the statistical distribution of morphological and topological properties. The results of conducted geometrical analysis provided means to develop methodology for proper 2D and 3D geometrical modelling of irregular cellular materials and consequent formation of computational models. These were used to study the mechanical behaviour of various cellular metals (e.g. open- and closed-cell foam [2], metallic hollow sphere structure, advance pore morphology foam [3], sintered metallic fibre structure [4], auxetic structure [5], uni-directional structure [6]) by means of quasi-static and dynamic nonlinear computational simulations. The numerical models were validated by quasi-static and dynamic mechanical experimental tests supported by infrared thermography.

New computational models and carefully characterized properties of cellular materials allow for parametric computational simulations, with the aim to define the most suitable design parameters (e.g. functional graded porosity) of parts made of cellular materials for a given application.

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*corresponding author: matej.vesenjak@um.si (M. Vesenjak)

# ON THE FORMING OF SANDWICH SHELLS WITH CLOSED-CELL FOAM CORES

R.M. Natal Jorge*, M. Parente
*INEGI, LAETA, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal*
*Emails: rnatal@fe.up.pt, mparente@fe.up.pt*

**Keywords:** Sandwich shells; Aluminum metal foams; Delamination; Cohesion

## Abstract

In this talk some issues related with the formability sandwich shells will be analysed, namely, structures composed by two aluminum sheets (skins) and separated by a core of aluminum metal. When compared with solid material, structural elements based on foams permit to introduce relative density as a design material variable, allowing potential advantages in both structural and non-structural design. As structural advantages it is possible to identify the following: weight minimization; stiffness maximization; energy dissipation increment; mechanical damping increment; controllable vibration absorption frequencies; and thermally dissimilar material potential compatibilization. The non-structural advantages are related with the thermal conductivity decrease; the acoustic performance improvement; the possibility to provide air/fluid transport within the foam material; and the electromagnetic and radiation shielding.
The finite element method is used to numerically simulate a three-points bending test and a bench bending test [1-2]. The bending tests are used to evaluate the type of yielding of this material, by the measure of the values of force and displacement at a middle span. Considering a structure composed by two different materials, each one present a different mechanical behavior separately. Since they work together, the use of adhesives is one way to build such kind of structures. From the numerical point of view, this type of construction presents some important particularities [3].

ABAQUS software was used to simulate the forming process of sandwich shells with closed-cell foam cores and the obtained numerical results present good agreement with the experimental results.

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*corresponding author: rnatal@fe.up.pt (R.M. Natal Jorge)

# INFRARED THERMOGRAPHY AS THE TOOL FOR TRACING PLASTIFICATION OF CELLULAR MATERIALS AND COMPOSITE STRUCTURES

L. Krstulović-Opara
*Faculty of El. Eng., Mech. Eng. and Naval Arch., University of Split, Split, HR21000, Croatia*
*Email: Lovre.Krstulovic-Opara@fesb.hr*

**Keywords:** Infrared thermography; Cellular materials; Metal foams; Composite structures; Cellular filler

**Abstract**

Infrared thermography is used to follow plastification processes in materials during dynamic loading. The method is based on the fact that irreversible yielding and rupture generates significant heat energy. Middle wave infrared cameras, based on photonic detectors cooled on cryogenic temperatures, enable capturing of heat radiance during dynamic loading processes with frame frequency up to several hundred Hz. Cellular materials, including open and closed-cell foams, Advantageous Porous Material spheres [1], and other forms of porous structures have very complex collapse mechanism that significantly influences material response and energy absorption characteristics. As energy absorption characteristics can only be evaluated under dynamic loading conditions, it makes infrared thermography proper method when acquiring and evaluating irreversible processes in specimens [2]. Tubular structural segments significantly increase their performances when cellular filler is introduced within hollow structures, resulting in higher load carrying capacity, higher energy absorption and reduced sensitivity to buckling [3,4]. To properly evaluate such complex structures, infrared thermography enables gathering information that significantly improves understanding of materials beside knowledge obtained by standard force-displacement diagrams. It is shown [5] that infrared thermography is a full field method capable of showing images equivalent to effective strain distribution obtained by Digital Image Correlation technique, what makes it valuable and applicable to experimental mechanics of cellular materials and composite structures involving cellular materials.

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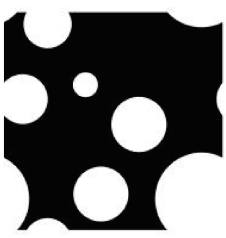
*corresponding author: Lovre.Krstulovic-Opara@fesb.hr (L. Krstulović-Opara)

# REGULAR ORAL ABSTRACTS



# METAL FOAMS IN RESEARCH AND DEVELOPMENT – NEW APPROACHES IN INDUSTRIAL ALUMINUM FOAM PRODUCTION

T. Hipke[1,*], R. Vogel[1], J. Hohlfeld[1], F. Schuller[2]
[1]*Lightweight Construction, Fraunhofer-Institute for Machine Tools and Forming Technology, Chemnitz, Germany*
[2]*Havel Metal Foam GmbH, Brandenburg a. d. Havel, Germany*
*Emails: thomas.hipke@iwu.fraunhofer.de, rene.vogel@iwu.fraunhofer.de, joerg.hohlfeld@iwu.fraumhofer.de, f.schuller@havel-mf.de*

**Keywords:** Aluminum foam; Sandwich structure; Lightweight design

## Abstract

In the last years metal foams were used in different applications like core material in light weight constructions, crash absorbers or damping elements in machine tools [1]. Sandwiches with aluminum foam core have been established as lightweight construction material. These semi-finished products are used particularly in the fields of engineering, construction, shipbuilding and commercial vehicle design [2]. The core operates as a shear resistant element and keeps the cover layers at a constant distance ensuring the functionality of the sandwich. Because of the high strength and stiffness commonly steel cover sheets are used for the sandwich manufacturing. In the manufacturing process the two cover sheets are placed and fixed in a foaming mold. A foamable precursor based upon aluminum and a foaming agent is inserted between these cover sheets. This is followed by a heat treatment at the melting range of the aluminum base alloy. During the foaming process a metallurgical bonding is created resulting in a rigid sandwich called SAS (steel – aluminum foam – steel) [3]. For the manufacturing process of aluminum foam sandwiches with aluminum cover sheets another production route was standard the last years. The foamable material is placed in between two aluminum sheets. Afterwards the loose bond is rolled to a single composite with metallurgical bonding. During the foaming process the heat transfer into the rolled composite especially the core precursor is very good. By choosing alloys having different melting ranges it is possible to expand the core layer without melting the cover sheets. For this technological process the term AFS® (Aluminum Foam Sandwich) has been established [4]. Beside the final foaming process the most important step for the production of these foamable composite is the rolling. The process is complex and expensive. Therefor alternative production methods needed to be considered as well.

A new and cheaper achievement is the manufacturing of aluminum foam sandwiches with aluminum cover sheets by using the already mentioned SAS-method. In this case the use of aluminum cover sheets it is rather more difficult, because core and cover sheets are made of nearly the same material. Furthermore there is no metallurgical bonding between the sheets and the core before the foaming process. Therefore it is necessary to achieve a stable heat is transferred through the cover sheets into the placed precursor material. The already successfully tested approach of the SAS production was revisited. By the construction of new foaming devices and a well-regulated heat transfer it was possible to manufacture small and large scale sandwiches with aluminum cover sheets according to the SAS process. First serial parts were produced in early 2017.

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*corresponding author: thomas.hipke@iwu.fraunhofer.de (T. Hipke)

# USE OF POLYMERS FOR THE PRODUCTION OF METAL MATRIX COMPOSITE POROUS STRUCTURES

L. Biasetto[1,*], H. Elsayed[2,3]
[1]*Department of Management and Engineering, University of Padova, Vicenza, I-36100, Italy*
[2]*Department of Industrial Engineering, University of Padova, Padova, I-35131, Italy*
[3] *Ceramics Department, National Research Centre, Cairo,* 12622*, Egypt*
*Emails:* lisa.biasetto@unipd.it, hamada.elsayed@unipd.it

**Keywords:** Ti6Al4V; Al12Si; Foams; Polymer-derived Ceramics

**Abstract**

Polymers and metals are usually combined together in powder metallurgy manufacturing processes: polymers have the double role of binding the metallic powders and controlling the rheology of pastes for injection moulded or extruded parts. After shaping, polymers are removed by mean of a de-binding step.
In this work, polymers are proposed both as reacting phase as well as foaming agent to produce porous metal matrix composite.

Silicon-based preceramic polymers are a specific class of polymers that, after pyrolysis at high temperature, give ceramic materials of composition that depends on the polymer itself, on pyrolysis atmosphere and temperature. Typical compositions are SiC, SiOC, SiBC, SiCN etc.

Silicones, in form of two liquid components with a ceramic yield of 50 wt.%, were mixed with gas atomized Al12Si or Ti6Al4V metallic powders: the gas release during crosslinking was used to foam the powders. The crosslinked polymer was used to give a stable porous structure. A thermal treatment was run with the double aim of decomposing the polymer and sintering the metallic powders. Carbides and silicides were the main reaction products between the silicon residues after pyrolysis and the metallic powders.

Al12Si metal matrix foams were produced, possessing open porosity ranging from 30 to 60 vol.% and compression yield up to 27 MPa.

Ti6Al4V foams were obtained following the same processing route with pores size ranging from 270 μmto 400 μm and compression yield strength up to 37 MPa for a total porosity of 47 vol.%.
The proposed process is fast and easy, representing a successful candidate for upscaling the process at the industrial level for the production of metallic foams at a reduced price and competitive structural and functional properties.

[*]corresponding author: lisa.biasetto@unipd.it (L. Biasetto)

# REMOTE LASER CUTTING OF OPEN CELL FOAMS– PROCESSES FOR THE FACTORY OF THE FUTURE

R. Baumann[1,2,*], P. Herwig[2], A. Wetzig[2], E. Beyer[1,2]
[1]*Faculty of Mechanical Engineering, Institute of Manufacturing Technology, Technical University (TUD), Dresden, 01277, Germany*
[2]*Fraunhofer Institute for Material and Beam Technology (IWS), Dresden, 01277, Germany*
*Emails: Robert.Baumann@iws.fraunhofer.de, Patrick.Herwig@iws.fraunhofer.de, Andreas.Wetzig@iws.Fraunhofer.de, Ralf-Eckhard.Beyer@iws.fraunhofer.de*

**Keywords:** Laser; Remote; Cutting; Open cell foam; Aluminum

## Abstract

It is well known that the global climate change is the largest challenge for the society of the 21th century. For managing the resulting consequences, innovative materials become more and more important for energy efficient applications [1]. Open cell metal foam contributes promising solutions to the light weight design, battery applications and renewable energy harvesting [2]. Still, challenges are present concerning the cutting into a defined shape. The remote laser cutting offers a solution for decreasing the production costs as well as the needed component accuracy. Our investigations consider that this technique has a high potential concerning cutting speed of open cell aluminium foam, which was increased more than 600 % compared to state of the art laser separation. Furthermore, different material thicknesses up to 20 mm were investigated. Additionally, the limit of the possible contour wall width was decreased to less than 1 pore size. This paper offers insight into the viability of remote laser cutting in overcoming the challenges dealing with mechanical milling or grinding. Investigating the process concerning thermal stress input as well as particle attachments will be the next steps in the future.

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[*]corresponding author: Robert.Baumann@iws.fraunhofer.de (R. Baumann)

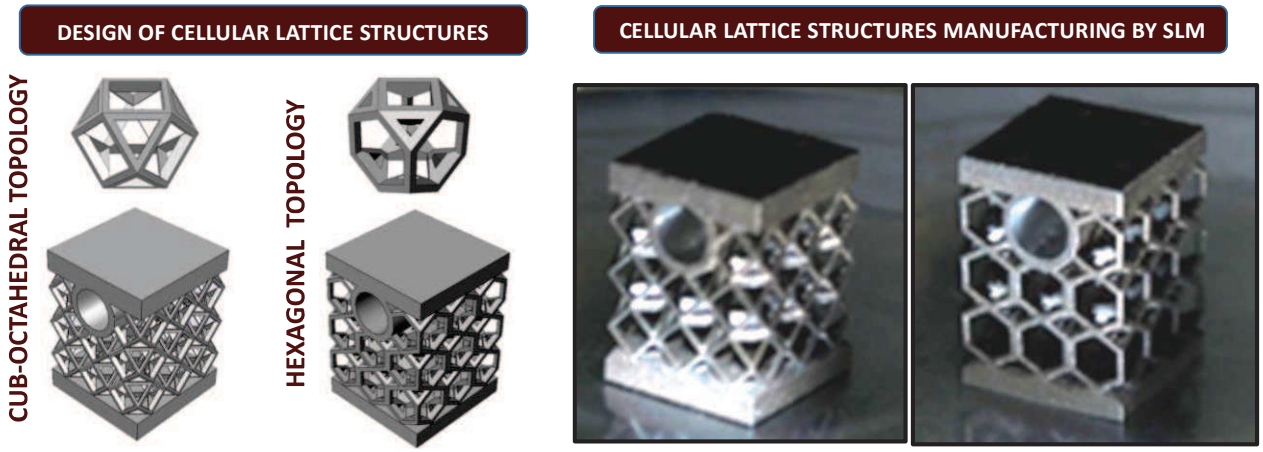
# DEVELOPMENT OF SLM CELLULAR STRUCTURES FOR INJECTION MOLDS MANUFACTURING

D. Oliveira[1*], C. Santos[1], A. Mateus[1], C. Malça[1,2]
[1]*Centre for Rapid and Sustainable Product Development, Polytechnic Institute of Leiria, Rua de Portugal, Marinha Grande, 2430-028, Portugal*
[2]*Department of Mechanical Engineering, Polytechnic Institute of Coimbra, Rua Pedro Nunes, Coimbra, 3030-199, Portugal*
*Emails: david.santos.oliveira@ipleiria.pt, cyril.santos@ipleiria.pt, artur.mateus@ipleiria.pt, candida@isec.pt*

**Keywords:** Cellular structures; SLM; Injection molding; Finite elements; Mechanical and thermal behaviors

## Abstract

Using Selective Laser Melting (SLM) is possible to manufacture moulds with cellular internal structures with different porosity degree. Furthermore, internal geometry design can be optimized as a function of the desired structural and thermal stress solicitations. In this work two types of cellular internal structures - hexagonal and cub-octahedral - were developed and manufactured using the SLM process. These topologies were generated with the purpose of creating a high degree of internal porosity and getting satisfactory results in terms of thermal and mechanical behaviour when compared with similar dimensional bulk structures. The mechanical and thermal behaviours of each cellular topology were evaluated numerically and experimentally through compression and thermal tests. From numeric and experimental results it can be concluded that hexagonal cellular internal topology provides a higher mechanical strength when compared to the cub-octahedral cellular structure while the thermal analysis shows that cub-octahedral topology is more efficient for heat dissipation. Both cellular topologies have demonstrated, however, to be appropriate for use in injection mould structures. In addition, the use of these cellular topologies provides light weight structuring with an approximate 58% weight reduction, which represents a considerable saving of material total cost to manufacturing of an injection mould.




*corresponding author: david.santos.oliveira@ipleiria.pt (D. Oliveira)

# PROCESSING OF OPEN-PORE SILICON FOAMS USING GRAPHITE COMPOSITE AS SPACE HOLDER

J. Heimann*, A.M. Matz, B.S. Mocker, N. Jost
*Institute for Materials and Material Technologies, Pforzheim University of Applied Sciences, Pforzheim, D-75175, Germany*
*Emails:* Johann.Heimann@hs-pforzheim.de

**Keywords:** Open-pore; Space holder; Silicon; Foam; Infiltration

**Abstract**

Open-pore metal foams are a relatively young class of material. The combination of base metal and open cellular structure makes a wide range of applications in energy absorption, heat exchangers and lightweight constructions.

In this study, a new space holder graphite composite (GC) is used for the fabrication of silicon foams with regular spheroidal cells. Conventional space holders as NaCl are not suitable for casting Si foams due to the differences in melting points of silicon and common space holders. The GC as space holder has many advantages such as low cost, good dissolution by oxidation, high melting point and it is free of toxicity. This space holder is chemically stable in contact with liquid and solid silicon, so it is suited for a melt metallurgical processing route. For manufacturing Si foams, in the first instance, a graphite casting mold is filled up with the space holder and subsequently the void between the spheroidal GC structures was infiltrated by pure molten silicon. The removal of the space holder by oxidation creates a filigree cellular open-pore structure. The reason is the point contact between the graphite composites during the infiltration. Hence, the silicon struts are dens and have a triangle cross section combined with a high surface area. The cell diameter is almost equivalent to the GC diameter. The process was set to reduce complexity and cost of silicon foams by using this space holder. The study was completed by a characterization of the micro- and mesostructure of the open-pore silicon foam. The structure is analysed with optical - and scanning electron microscopy (SEM) equipped with energy-dispersive spectroscopy (EDS).

*corresponding author: Johann.Heimann@hs-pforzheim.de (J. Heihmann)

# FUNCTIONAL BIO-BASED POLYURETHANE FOAMS FROM INDUSTRIAL RESIDUES

N. Gama[1,*], R. Silva[2], A. Ferreira[1,3], A. Barros-Timmons[1]
[1]*CICECO and Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal*
[2]*Sapec-Química SA, Z. I. Ovar – Lote 18, 3880 Ovar, Portugal*
[3]*Escola Superior de Tecnologia e Gestão de Águeda, 3750-127 Águeda, Portugal*
*Emails: nuno.gama@ua.pt, rsilva@saspecquimica.pt, Artur.ferreira@ua.pt, anabarros@ua.pt*

**Keywords:** Bio-based polyurethanes; Polyurethane foams; Renewable polyols; Crude glycerol

## Abstract

In view of the dependence of the polyurethane foams (PUFs) industry on fossil resources, there is a need to systematize efforts to find alternatives from renewable resources. Also due to the uncertainty about the cost of petroleum in the future, as well as the need to move towards a more eco-friendly materials, many efforts have been focused on replacing petroleum-based polyols by polyols derived from renewable resources. [1] In fact, in recent years many non-petroleum resources have been used in the polyurethane (PU) production, such as vegetable oils, biomass resources or industrial by-products. The use of industrial by-products, namely crude glycerol (CG) has also been used as polyol to produce rigid PUFs. [2] CG is an economic by-product of the biodiesel production and its chemical composition is variable, the effect of CG composition on PUFs was studied and formulations optimized using the design of experiments (DOE) tool. Next, formulations were developed aiming at materials for enhanced thermal comfort and energy efficiency, improved flammability properties and better acoustic insulation: in the latter case CG was combined with another eco-friendly polyol derived from spent coffee grounds.

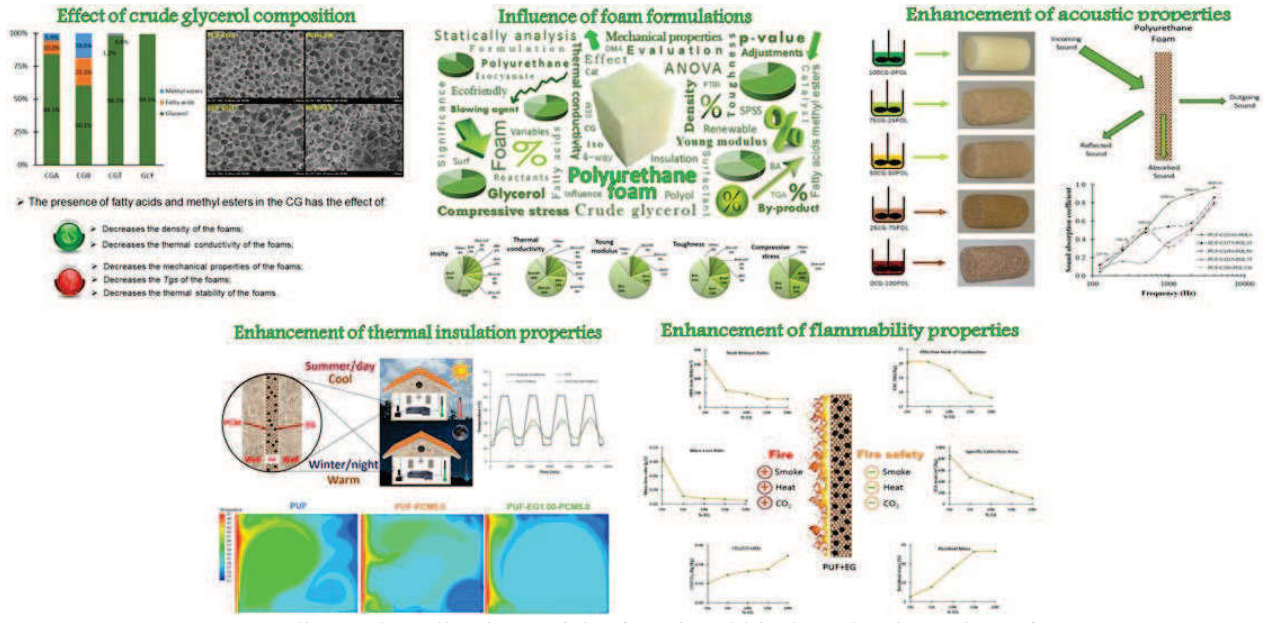



**Fig. 1.** Studies and applications of the functional bio-based polyurethane foams.

The present work summarizes our contributions to the sustainability of PUFs industry by using industrial by-products as polyols in the production of PUFs.

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*corresponding author: nuno.gama@ua.pt (N. Gama)

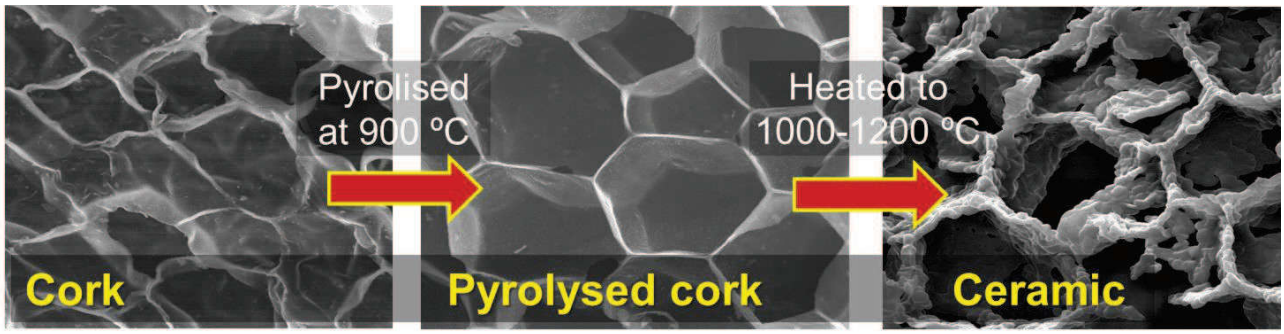
# LOW WEIGHT, HIGHLY POROUS, BIOMIMETIC 3-DOM ECOCERAMICS USING CORK AS A NATURAL SUSTAINABLE TEMPLATE

R.C. Pullar*, R.M. Novais
*Department of Materials and Ceramic Engineering / CICECO – Aveiro Institute of Materials, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*
*Emails: rpullar@ua.pt ; ruimnovais@ua.pt*

**Keywords:** Cork; Biomimetic; Ecoceramics; 3-DOM; Porous

## Abstract

Cork is a very lightweight wood, which consists of a matrix of hexagonal cells of ~20 micron in diameter, forming a 3-dimensionally ordered macroporous (3-DOM) structure, with up to 200 million cells per $cm^3$. Cork is a fully sustainable / renewable resource, as the bark is harvested every 8-13 years, without harming the tree, which continues to live on as a carbon sink for a productive lifetime of at least 200 years. Portugal is the world's largest cork producer, accounting for about 50% of annual global cork production. Ecoceramics (environmentally conscious ceramics) are a new class of biomimetic / biomorphic material that can be manufactured from renewable resources, such as wood from sustainable sources or wood wastes. The idea is to manufacture ceramics with the microstructure of wood. To this end, the wood is pyrolysed to convert it into carbon, which is very porous but maintains the microstructure / morphology. It is possible to infiltrate this carbon matrix with a ceramic precursor, and then heat it to around 1000 ºC in air to burn out the carbon and form the ceramic. The end ceramic product also has the microstructure of the wood template. We have done this for the first time using cork. The cork is pyrolysed to form carbon templates, which maintain the microstructure of cork, but become nanoporous. These are infiltrated with a range of precursor sols/solutions, made from simple and economic green aqueous chemistry methods, and then heated in air to remove the carbon, leaving a ceramic with the natural structure of cork (an ecoceramic). We have made a range of such materials, since reporting the first ever cork-based ecoceramics [1], magnetic hexagonal ferrite ecoceramics, which were lightweight "magnetic ceramic foams" with excellent magnetic properties. These materials were also on the cover of the January 2017 issue of *Materials Today* [2]. We are currently investigating a wide range of ceria, titania and zirconia based ecoceramics, and will report out latest results.

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*corresponding author: rpullar@ua.pt (R.C. Pullar)

# OPEN-CELL AND GLASS-CERAMIC FILLED CELLULAR ZIRCONIA STRUCTURES FOR BIOMEDICAL APPLICATIONS

B. Henriques[1,2*], J. Mesquita-Guimarães[2], J.C.M. Souza[1] , M.C. Fredel[1], F.S. Silva[2]
[1]*Ceramic and Composite Materials Research Group (CERMAT), Federal University of Santa Catarina (UFSC), Campus Trindade, Florianópolis/SC, Brazil*
[2]*CMEMS-UMinho, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal*
*Emails: brunohenriques@dem.uminho.pt, mesquitaguimaraesjoana@gmail.com, julio.c.m.souza@ufsc.br, m.fredel@ufsc.br, fsamuel@dem.uminho.pt*

**Keywords:** Zirconia; Open-cell structures; CNC machining; Replica method; Scaffolds

**Abstract**

The mechanical behaviour of cellular structures is governed by their internal architecture. Cellular bioinert ceramics, such as zirconia, are being considered in bone reconstruction and other dental and orthopaedic applications. The aim of this work was to determine the mechanical properties of CAD-CAM obtained zirconia cellular structures with controlled geometry. Three types zirconia cellular structures were produced. Hollow structures as well as glass-ceramic filled structures were accessed in terms of their elastic and inelastic properties. Scanning Electron Microscopy and X-Ray Diffraction techniques have been used in the characterization of the cellular structures. Experimental data has been compared with FEM data.

[*]corresponding author: brunohenriques@dem.uminho.pt (B. Henriques)

# WEAR AND AGEING BEHAVIOUR OF POROUS ZIRCONIA LAYERS

T.A. Dantas[1,*], S. Roedel[2], J. Mesquita-Guimarães[1], B. Henriques[1,2], M.C. Fredel[2], F.S. Silva[1]
[1]*Center for MicroElectroMechanical Systems (CMEMS), University of Minho (UMinho), 4800-058 Guimarães, Portugal*
[2]*Ceramic and Composite Materials Research Group (CERMAT), Federal University of Santa Catarina (UFSC), 88040-900 Florianópolis, SC, Brazil*
*Emails: telmalvesdantas@gmail.com, stephanie.roedel@gmail.com, mesquitaguimaraes@dem.uminho.pt, brunohenriques@dem.uminho.pt, m.fredel@ufsc.br, Fsamuel@dem.uminho.pt*

**Keywords:** Porous Zirconia; Gradient Porosity; Wear behaviour; Low Thermal Degradation

**Abstract**

Highly porous ceramics have shown a wide variety of potential applications due to unique properties such as low density, high permeability, high specific area, low thermal conductivity, high thermal shock resistance and chemical resistance to harsh conditions [1]. The gradient transition of properties, structures and/or compositions are designed to withstand different demands (mechanical, chemical, etc.) distributed along a section, and can be drawn to be at continuous or discrete format. Continuous transitions exhibit better properties although the processes are expensive and complex; while discrete transition can be produced by deposition of successive layers that gradually changes its porosity, forming a structure with transition bands [2,3].

The objective of this work was to produce porous surfaces (with three different powder sizes – Z40, Z70, Z100- and one with a gradient layer - GRAD) over a dense zirconia substrate and access their tribological behaviour against an alumina ball. Moreover, it was done an analysis of the low thermal degradation of the samples. The microstructure of surfaces before testing and the morphological characterization of the worn surfaces were assessed by SEM. Tribological tests were performed under 10 N of normal load with a constant stroke length of 4 mm. The hydrothermal treatment was performed at 134 °C in water steam at 2 bar and X-ray diffraction data (after 0h, 2h, 6h, 12h and 18h of ageing) were collected from 27° to 32° 2θ, with a step size of 0.04° and counting time of 1 s/step.

No significant differences were found for friction coefficient of the different groups, being the highest COF registered for graded layers (0.60 ± 0.02) and the lowest for both Z40 and Z100 specimens (0.55 ± 0.02). The same trend was found for the wear rate values, meaning that the highest values were obtained for the GRAD specimen.

Diffraction data revealed that the content of monoclinic phase increases with ageing time, and after 18h of hydrothermal medium, the average value of monoclinic content was approximately 49 %, for all the tested materials.

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*corresponding author: telmalvesdantas@gmail.com (T.A. Dantas)

# HYDROTHERMAL SYNTHESIS OF BIPHASIC CALCIUM PHOSPHATE SCAFFOLDS FROM CUTTLEBONE

A.S. Neto*, J.M.F. Ferreira
[1]*Department of Materials and Ceramic Engineering, CICECO, University of Aveiro, Aveiro, 3810-193, Portugal*
*Emails: sofia.neto@ua.pt, jmf@ua.pt*

**Keywords:** Cuttlefish bone; Scaffolds; Hydrothermal transformation; Bioactivity

## Abstract

Bone has a high regenerative capacity, however large bone defects like tumour resection hinder proper regeneration. Autografting, the main currently used strategy, is associated with donor site morbidity [1]. Bone tissue engineering is being explored as a promising alternative, involving the use of scaffolds that act as a temporary support material for bone growth. Calcium phosphate (CaP) materials have been used for bone repair due to their chemical similarity to the mineral component of bone. In addition, they are non-toxic, biocompatible, not recognized as foreign materials in the body and exhibit a bioactive behaviour [2]. Advanced techniques, such as rapid prototyping, have been used to produce synthetic scaffolds, in which porosity, microstructure, degradation rate and mechanics can be tailored made. Nevertheless, there are some limitations associated with this scaffolds, namely the high manufacturing costs. To overcome these drawbacks, natural materials have been showed to be a promising alternative for bone tissue engineering [3]. For instance, cuttlefish bone (CB) is an inexpensive, worldwide available and morphological complex natural material. Its lamellar matrix is highly porous and mainly composed of aragonite (CaCO3) [4]. In addition, it has been reported that the pore size and interconnectivity of this natural architecture is beneficial for bone ingrowth and vascularization [5,6]. In this study, CaP biomaterials were successfully produced via hydrothermal transformation of aragonite from CB at 185°C using an aqueous solution of (NH4)2HPO4 and urea as an additive. Posteriorly, the obtained samples were sintered. The exact amount of aragonite was assessed by thermal analysis (DTA/TG). The crystalline phases present in the raw CB and the derived CaP scaffolds were identified by X-ray diffraction (XRD). Further, the preservation of the initial structure of CB was confirmed by scanning electron microscopy (SEM). Bioactivity in vitro capability of the scaffolds was tested by immersion of the CaP biomaterials in simulated body fluid (SBF) at 37°C. The obtained results confirm the suitability of CB derived scaffolds as bone grafts.

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*corresponding author: sofia.neto@ua.pt (A.S. Neto)

# PRODUCTION OF ZICORNIA STRUCTURES FOR DENTAL IMPLANTS

P. Vieira, A. Marques*, F.S. Silva, O. Carvalho
*Center for Micro-Electro Mechanical Systems (CMEMS)*
*University of Minho, Campus de Azurém*
*4800-058 Guimarães – Portugal*
*Emails: paula.vieira95@hotmail.com, anacristinamarques13@hotmail.com, fsamuel@dem.uminho.pt oscar.carvalho@dem.uminho.pt*

**Keywords:** Cellular structures; Implants; Young's modulus; Zirconia; Milling

**Abstract**

In this work was produced and evaluated the young modulus of zirconia structures for medical implants. Many studies have been showed that elastic properties of the implant materials have an important role in load transfer to the bone. Some studies have been showed that the implants should have a young modulus similar to the bone in order to avoid the bone loss. It was considered that the manufacturing process for obtained the structures should be machining process because is the commercial available way of producing zirconia structures. The studied was developed in two main steps. The first step was the FEM simulations of possible structures. The parameter evaluated in this studied was wall thickness in structures obtained by milling using the driling operation. The second step was the production of the structures my milling. The machined structures were then sintered.. It was performed the mechanical evaluation of the young modulus of the structures.

*corresponding author: anacristinamarques13@hotmail.com (A. Marques)

# ASPHALTENES' PRECIPITATION AS A MECHANISM TO OBTAIN A HYDROPHOBIC SURFACE IN ALUMINUM FOAMS

L. Álvarez[1,*], J. Ramírez[2], P. Fernández-Morales[3]
[1]Facultad de Minas, Universidad Nacional de Colombia, Medellín, Colombia
[2]Facultad de Minas, Universidad Nacional de Colombia, Medellín, Colombia
[3]Facultad de Ingeniería Industrial, Universidad Pontificia Bolivariana, Medellín, Colombia
Emails: lcalvarezg@unal.edu.co, jframirp@unal.edu.co, patricia.fernandez@upb.edu.co

**Keywords:** Aluminum foam; Asphaltenes; Surface free energy; Polarity

## Abstract

In general, it can be stated that the degree of interaction at the solid-liquid interface is dominated by the surface free energy of the solid. For metallic materials, the surface characteristics have a direct influence over the corrosion rates and the material / fluid compatibility [1]. The reduction of surface free energy in solids can be due to surface polishing, the use of coatings and paints, the application of electrostatic insulating films, among others, these procedures have restrictions associated with the dimensions of the area to be treated, variations in the thickness of the material and the effective durability of the treatment [2]. Such conditions have led to the research and development of techniques that expand the ranges of application of surface alterations and which in turn minimize costs. Asphaltenes are high molecular weight hydrocarbons present in solution in crude oil and are retained during processing, becoming part of the refinery process residues. In its structure are substitutions of carbon atoms by heteroatoms such as oxygen, sulphur and heavy metals, in which the differential electronegativity determines the existence of dispersed polar bonds within the molecule [3]. Polarity focus are adhered to the surface of the neutral solids by weak atomic interactions thereby forming a film, while exposing their available neutral terminals to interact with the medium. The aim of this work is to know the influence of the concentration of refinery residue (2, 4 and 6%) in a toluene solution over the development of a hydrophobic film on aluminium plates [4]. Using as a principle of measurement the variation of aluminium / water contact angle pre and post treatment [5]. This, in order to verify its viable for further implementation in aluminium foams, in which the available surface area for the solid / liquid interaction is bigger than a simple aluminium plate [6]. The development of surfaces with affinity preferentially apolar in cellular materials, allows to improve the relative permeability of the medium to substances such as oils or fats, to generate flow conditions that favor the application of these materials in filtration processes [7].

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*corresponding author: sofia.neto@ua.pt (A.S. Neto)

# VISUALIZING STRAIN IN DYNAMICALLY LOADED CELLULAR MATERIALS

L. Krstulović-Opara[1,*], M. Vesenjak[2], I. Duarte[3]
[1]*Faculty of El. Eng., Mech. Eng. and Naval Arch., University of Split, Split, HR21000, Croatia*
[2]*Faculty of Mechanical Engineering, University of Maribor, Maribor, SI2000, Slovenia*
[3]*Department of Mechanical Engineering, TEMA, University of Aveiro, Aveiro, 3810–193, Portugal*
*Emails: Lovre.Krstulovic-Opara@fesb.hr, matej.vesenjak@um.si, isabel.duarte@ua.pt*

**Keywords:** Infrared thermography; Dynamic loading; Equivalent plastic strain

## Abstract

Energy absorption characteristics of cellular materials are highly dependent on the lattice deformation and the local densification that governs the propagation of yielding front within the material. An acquisition method appropriate to follow the yielding mechanism is the Digital Image Correlation (DIC), which often is limited with the CCD camera frame rate uncapable of acquiring dynamic occurrences in material. In our research [1], we have shown that the Infrared (IR) Thermography based on the fast cooled middle wave camera is providing images equivalent to effective strain obtained by the DIC. When comparing to DIC, the IR Thermography is capable of acquiring images at higher loading rates due to the fact that the method is based on acquiring the heat radiation, instead of the light reflection (DIC). The IR acquisition is applicable for open- and closed-cell cellular structures (metal foams with and without the skin) and composite structures with tubular structural elements filled with cellular material (foamed *in-* or *ex-situ*). Sequences of thermal images provide information where yielding or crack occurs, how densification propagates, and finally how whole section densifies. When evaluating the yielding front propagation: i) a sequence of images in form of a movie is analysed or ii) the gradient method [3] is applied to find the front propagation from a single thermogram.

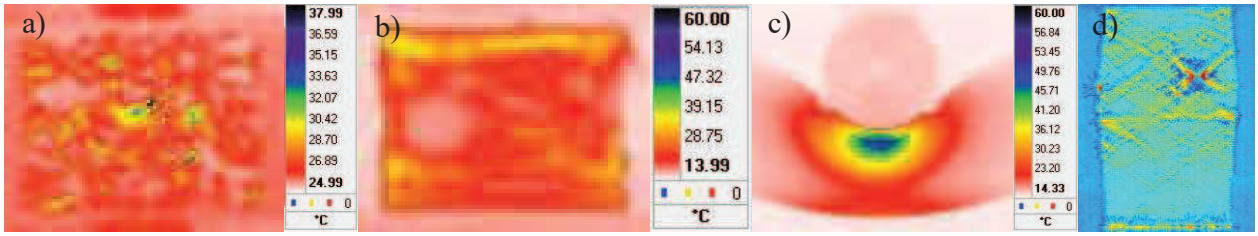


**Fig. 1.** Examples of: a) open-cell foam, b) closed-cell foam with integral skin, c) composite tube filled with foam, d) gradient field showing propagation of closed-cell foam with integral skin.

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[*]corresponding author: Lovre.Krstulovic-Opara@fesb.hr (L. Krstulović-Opara)

# CONTROL OF THE COMPRESSIVE PROPERTIES OF METALLIC FOAMS THROUGH THE FRACTAL DISTRIBUTION OF THE POROSITY

I. Alfonso[1,*], J.C. Carranza[1], L. Pérez[2], I.A. Figueroa[3]
[1]*Instituto de Investigaciones en Materiales, Unidad Morelia, Universidad Nacional Autónoma de México, Campus Morelia UNAM. Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de la Huerta. Morelia, Michoacán, México. C.P. 58190.*
[2]*Department of Mechanical Engineering, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile*
[3]*Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México. Circuito Exterior SN. Ciudad Universitaria. Del. Coyoacán. Ciudad de México. México. C.P. 04510.*
*Emails: ialfonso@unam.mx, carlos_jneta@hotmail.com, luis.perez@usm.cl, iafigueroa@unam.mx*

**Keywords:** Metallic foam; Fractal; Compression; Model; FEA

**Abstract**

This work studies, experimentally and simulated, the effect of the fractal distribution of the porosity on the compressive behaviour of aluminium foams, obtained by infiltration using NaCl as space holder phase. In order to modify the porosity, and then the compressive behaviour of the foams, models of the expected porosity were proposed according to the distribution of the NaCl particles. Three fractal distributions were selected, considering ratios small-to-big pores of 1:1, 2:1 and 4:1. The Young´s moduli of the models were estimated using Finite Element Analysis (FEA), and compared to the experimental results for Al-6Si-3Cu alloy foams obtained by infiltration, using distributions of the space holder particles that replicated the expected characteristics of the proposed porosities. Results demonstrated the fractal behaviour of the porosity, remaining the characteristics pre-established for the space holders. Porosities close to 65 % were obtained, being cell wall thickness ($w_t$) the characteristic most affected after modifying space holders: ratios of 1:1, 2:1 and 4:1 originated $w_t$ of 2.0, 1.63 and 1.24, respectively. The decrease of $w_t$ led to significant reductions in the compressive behaviour of the foams, showing that this behaviour can be controlled through the particles distribution. Besides, FEA estimations were in excellent agreement with the experimental results, demonstrating the efficacy of the proposed models for predicting the compressive behaviour of metallic foams.

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[*]corresponding author: ialfonso@unam.mx (I. Alfonso)

# THE ROLE OF RANDOMNESS IN THE ELASTIC PROPERTIES OF SOFT MECHANICAL METAMATERIALS

M.J. Mirzaali[1,2,*], R. Hedayati[2], P. Vena[3], L. Vergani[1], M. Strano[1], A. Zadpoor[2]
[1]*Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy*
[2]*Department of Biomechanical Engineering, Delft University of Technology (TU Delft), Mekelweg 2, 2628 CD, Delft, The Netherlands*
[3]*Department of Chemistry, Materials and Chemical Engineering Guilio Natta, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133, Milan, Italy*
*Emails: mirzaalimazandarani.mohammad@polimi.it*

**Keywords:** Metamaterials; Cellular structures; Functionally graded auxetic (FGA) materials; Elastic properties; Randomness

## Abstract

The elastic properties of mechanical metamaterials [1–4] are direct functions of their topological designs. Rational design approaches based on computational models could therefore be used to devise topological designs that result in the desired properties. It is particularly important to independently tailor the elastic modulus and Poisson's ratio of metamaterials. Here, we present patterned randomness as a strategy for independent tailoring of both properties. Soft mechanical metamaterials incorporating various types of patterned randomness were fabricated using an indirect additive manufacturing technique and mechanically tested. Computational models were also developed to predict the topology-property relationship in a wide range of proposed topologies. The results of the study show that patterned randomness allows for independent tailoring of the elastic properties and covering a broad area of the elastic modulus-Poisson's ratio plane. The uniform and homogenous topologies constitute the boundaries of the covered area, while topological designs with patterned randomness fill the enclosed area.

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[*]corresponding author: mirzaalimazandarani.mohammad@polimi.it; mirzaali.mohammad@gmail.com (M.J. Mirzaali)

# EXPERIMENTAL AND NUMERICAL IMPACT TESTING AN ALUMINUM CORRUGATE LAYERED STRUCTURE

M. Güden[1,*], M. Sarıkaya[2], A. Taşdemirci[3]
[1]*Dynamic Testing and Modeling Laboratory and Department of Mechanical Engineering*
*Izmir Institute of Technology, Izmir, 3430 Turkey*
*Emails: mustafaguden@iyte.edu.tr, mkemal_90@hotmail.com, alpertasdemirci@iyte.edu.tr*

**Keywords:** Aluminum; Corrugated; Direct impact; Modelling; Densification strain

## Abstract

A 1050 H14 Al zig-zig trapezoidal corrugated, multi-layered, light-weight structure (326 kg $m^{-3}$), comprised of 15 brazed trapezoidal zig-zig fin layers (Fig. 1a) with the height, width, length and thickness of 3.2, 1.6, 2.5 and 0.170 mm (Fig. 1b) were compression tested at quasi-static (0.0048 m $s^{-1}$) and dynamic velocities (~200 m $s^{-1}$). Two groups of dynamic tests were conducted: (i) the striker-rod and (ii) direct impact. In the former, the sample was placed in front of an incident bar of a Split Hopkinson Pressure Bar (SHPB) and impacted by a striker rod. In the later, the sample was directly fired to the incident bar end. The striker-rod tests were performed to determine the effect of inertia and the direct impact tests shock wave propagation. Both tests were performed in a strain-gaged SHPB set-up [1, 2] using the cylindrical test samples 19.4 mm in diameter and 48 mm in length (Fig. 1c). The test sample deformation was recorded using a high speed camera. Inconel alloy SHPB set-up had the same diameter with the sample and the velocity of the striker-rod and the test sample was measured just before the impact. The crushing of the corrugated structure in both group impact tests as wells as in quasi-static compression test, was simulated in LS-DYNA. The numerical models were implemented both for perfect and few imperfect models in order to identify the fidelity of the models at different velocity regimes. The simulation and experimental stress-time histories were further compared with those predicted by the rigid perfectly plastic locking (r-p-p-l) model [1]. The planar-impact end-crushing of corrugated layers, shock formation, started experimentally and numerically at about 60 m $s^{-1}$.This was also confirmed by the camera records of the striker-rod and direct impact tests. It was found that the inertial stresses increased experimentally and numerically linearly with velocity. The measured shock wave enhancement was partly attributed to this effect. Imperfect models were shown well-predicted the stress-time histories of the tested samples until about the critical velocities for shock deformation, while the perfect model showed better predictions above the critical velocities. The r-p-p-l model modified by the stress enhancement due to inertia showed better prediction of the crushing stress at higher velocities.

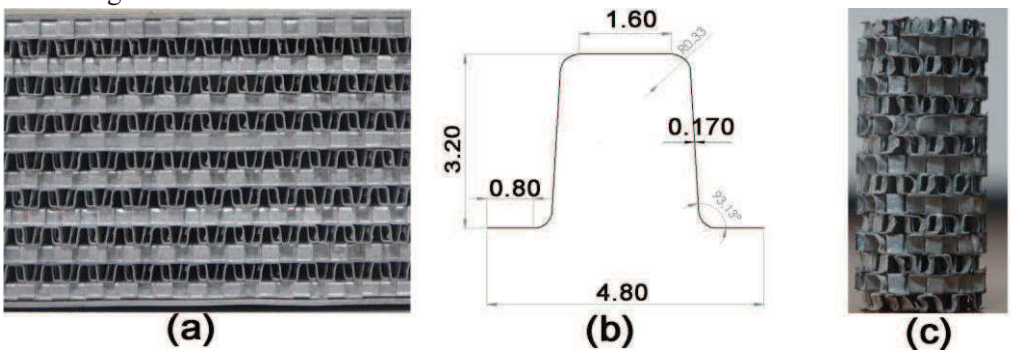


**Fig. 1.** (a) zig-zig trapezoidal corrugated multi-layered structure, (b) unit fin and (c) test sample.

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*corresponding author: mustafaguden@iyte.edu.tr (M. Güden)

# MECHANICAL PROPERTIES OF HIGH-DENSITY TRIP-STEEL HONEYCOMB STRUCTURES WITH VARYING CELL PROFILE UNDER DIFFERENT LOAD CONDITIONS

C. Baumgart*, L. Krüger
[1] Institute of Materials Engineering, Technische Universität Bergakademie Freiberg, Freiberg, 09599, Germany
Emails: christine.baumgart@iwt.tu-freiberg.de, krueger@ww.tu-freiberg.de

**Keywords:** honeycomb, cell design, out-of-plane/in-plane compressive properties, SEA capability

## Abstract

The intention of applying cellular materials as energy absorbing elements in fields of transportation industry requests a detailed evaluation of material performance under several load conditions especially in case of anisotropic structure properties. Recent studies [1, 2] have shown that the out-of-plane compressive behavior of high-density steel honeycomb structures with square celled profile is characterized by a linear-elastic region, followed by a distinct pre-buckling stage before buckling and structural collapse initiates at high strength levels. However, by comparing the outstanding out-of-plane specific energy absorption (SEA) capability with the potential under in-plane conditions, a significant decrease of SEA capacity has to be recorded due to the structural failure under asymmetrical shear deformation at early deformation stages. In order to investigate the influence of cell design on the honeycomb deformation behavior which is directly connected with the attainable SEA capability, FEM-based numerical analysis were conducted. The results revealed that an enhancement of absorbable energy especially in in-plane direction can be generated by replacing square cells with an ordered sequence of hexagons and triangles, the so called kagome geometry. In this study, the results of the analysis are verified by conducting quasi-static compression tests in out-of-plane and in-plane direction on honeycombs with both square and kagome cell profile which were manufactured via powder metallurgical processing. The adjustment of different strain levels contributes to a better traceability of deformation behavior as well as microstructure evolution of the cell wall material, which is composed of metastable austenitic steel showing the TRansformation Induced Plasticity (TRIP)-effect. Finally, the obtained results are comparative discussed with regard to deformation mechanism, strength level, collapse strength/strain and achieved SEA capability in dependence of the load condition.

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*corresponding author: christine.baumgart@iwt.tu-freiberg.de (C. Baumgart)

# MULTIAXIAL EXPERIMENTAL TESTS ON A POLYPROPYLENE FOAM

A. Donnard[1], S. Guérard[1], L. Maheo[2,3,*], P. Viot[1]
[1]*i2M, Arts et Metiers ParisTech, Talence, F-33405, France*
[2]*CREC, St-Cyr Military Academy, Guer, F-56381, France*
[3]*iRDL, University of South Brittany, Lorient, F-56321, France*
*Emails: adrien.donnard@ensam.eu, sandra.guerard@ensam.eu, laurent.maheo@univ-ubs.fr, philippe.viot@esam.eu*

**Keywords:** Cellular materials; Multiaxial experiments; Hyperelastic behavior; Failure

## Abstract

Cellular materials are ofently used in protective applications for their dissipative energy functions in crash or impact conditions. For soft impacts, polymeric foams are therefore good candidates to protect goods or persons [1,2]. The design of protections like boxes or helmets nearly always needs a Finite Element Analysis and the questions of the modelling of foam material behavior must come up. The first question is related to the scale of study. Foams can be described by their porosities at a micro-scale or a meso-scale level like in [3,4] or by an homogeneous volume to represent the behavior at a macro-scale level like numerical models presented in [5]. This present study framework is focused on this second option, which is more adapted in the case of FEA for large structures. Numerous numerical models use an uniaxial compressive test to characterize the foam, but during an impact, other loading conditions can overcome like shear, biaxial tension. Like several authors studied foams under multiaxial conditions [6-9], it seems interesting to us to perform multiaxial experiments and investigate the mechanical behavior of foams. Thanks to an hexapod device which allows 6 degrees-of-freedom motions, combined shear-compression tests can be obtained [10]. Several loading path are studied until failure: simple shear, compression following by shear, compression and shear simultaneously, and tension. To compare these different experimental tests among themselves, results are displayed using a classical separation of volume and shape changes. Results show that the shape change behavior is dependant of the pressure, *i.e.* the first invariant of the Cauchy stress tensor. In the same way, the volume change behavior is dependant of the distorsion intensity, *i.e.* the second invariant of the deviatoric Cauchy Stress tensor. The volume change and the shape change can not therefore be defined as independent behaviors and a coupling behavior between both contributions must be considered. Further discussion about these results gives some food for thoughts for the development of hyperelastic modelling of foams. Finally, the failure of foam specimens for different loading paths is discussed and failure criteria are proposed.

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[*]corresponding author: laurent.maheo@univ-ubs.fr (L. Maheo)

# MULTI-SCALE ANALYSIS OF COMPOSITE MATERIALS USING THE NATURAL NEIGHBOUR RADIAL POINT INTERPOLATION METHOD

D.E.S. Rodrigues[1,2], J. Belinha[1,2,*], L.M.J.S. Dinis[1,2], R.M. Natal Jorge[1,2]
[1]*Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Porto, Portugal,*
[2] *Department of Mechanical Engineering, Faculty of Engineering of the University of Porto, Porto, Portugal*
*Emails: drodrigues@inegi.up.pt , jbelinha@fe.up.pt , ldinis@fe.up.pt , rnatal@fe.up.pt*

**Keywords:** Meshless methods; Representative volume element (RVE); Computational homogenization; Multi-scale technique

**Abstract**

The analysis of the structural behaviour of heterogeneous materials is a topic of systematic research in the engineering field. Some of those heterogeneous materials have a macro-scale behaviour that cannot be predicted without considering the complex processes that occur in lower dimensional scales. Therefore, multi-scale approaches are often proposed in the literature in order to better predict the homogeneous mechanical properties of these materials. This work makes use of a multi-scale numerical transition technique, suitable for simulating heterogeneous materials, and combines it with a recently developed meshless method – the Natural Neighbour Radial Point Interpolation Method (NNRPIM) [1] – as numerical tool. Meshless methods only require an unstructured nodal distribution in order to discretize the problem domain. In the case of the NNRPIM, the numerical integration of the integro-differential equation from the Galerkin weak form is performed using a node-depending background mesh created from the Voronoï diagram. The nodal connectivity is then enforced by the overlap of influence-cells defined in each integration point.
In this work, using a plane strain formulation, a representative volume element (RVE) is modelled and periodic boundary conditions are imposed on it. A computational homogenization is implemented and the effective elastic properties of a composite material are determined. In the end, the solutions obtained using the NNRPIM are compared with the ones provided in literature.

**Acknowledges**

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[*]corresponding author: drodrigues@inegi.up.pt (D.E.S. Rodrigues)

# MULTISCALE SIMULATION OF TEMPERATURE AND STRESS STATE FOR HIGH TEMPERATURE GRADIENT FOR 3D PERIODIC COMPOSITES

G.L. Gorynin*, A. Vlasko
*Department of Building Technologies and Constructions, Surgut State University, Surgut, 628406, Russia*
*Emails: ggorynin@list.ru*

**Keywords:** Cell; Functions; Thermal; Stress; Strength

**Abstract**

Using high-energy parts of machines and cladding technologies high temperature gradients always occur. Composite materials with very complex internal structure very often are used in cladding and parts of machine. By regular order, temperatures cause high values of thermal stress. This work is devoted to calculation of temperature field and thermal stress and studies conditions of thermal strength of constructions. The body is consisted from 3D periodic composite. Composite is made of binder and inclusions of arbitrary shape. Cell functions method is utilized for calculations of temperature and stress fields. Cell functions method is special case for method of asymptotic splitting, it was created by Gorynin G.L. and Nemirovskii Yu.V. [1-3]. The method is based on using two types of spatial value scales and on asymptotic splitting of spatial problem of heat conduction theory and spatial thermal elasticity theory. Cell functions are analog of displacements and stresses within a periodic cell. They are found from solving of cell boundary-value problem. Received calculations show that in 3d periodic bodies there are thermal stress fields with intricate structure when tensile stresses is changed compressive stresses within the limits of a periodic material cell. Some of materials, for example concrete, gets extremely negative effect from tensile stress. Therefore, it is very difficult to predict its thermal break down without multiscale analysis. Such method of investigation for thermal stress can be used for such materials as 3D Periodic Materials, Porous Materials, Metallic Hollow Sphere Structures and other.

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*corresponding author: ggorynin@list.ru (G.L. Gorynin)

# MODELLING AND EFFECTIVE PROPERTIES PREDICTION OF METAL FOAMS

J. Aquino*, I. Duarte, J. Dias-de-Oliveira
[1]*Department of Mechanical Engineering, University of Aveiro, Portugal*
*Emails: jmra@ua.pt, isabel.duarte@ua.pt, jalex@ua.pt*

**Keywords:** Metal foams; Homogenization; Representative unit-cells; Kelvin Structure; Weaire-Phelan Structure

## Abstract

The continuous growth in the applications and usage of metal foams, from material for chemistry industry to structural components, implies a detailed understanding of the mechanical properties and behaviour in order to enlarge their application range. Therefore it is necessary to perform a proper characterization of its effective properties. However, due to their irregularities and micro-defects predicting the properties of these inhomogeneous materials is of great difficulty [1]. The aim of this work is to describe the mechanical behaviour of these foams in an elastic regime. For this purpose, numerical methods and analytical models, provided by previous works, were used. Based on space-filling polyhedra [2], Kelvin cells and Weaire-Phelan structures were model to represent both open and closed-cell representative unit-cells. These unit-cells were then subjected to different numerical simulation approaches: (i) considering a symmetry boundary conditions with a prescribed force, (ii) symmetry boundary conditions with an imposed displacement and (iii) periodic boundary conditions for the Asymptotic Expansion Homogenization (AEH) method. The analytical, numerical and experimental results were then compared. Additionally, given the detail of information that AEH provides, it was possible to perform an orientation dependence of the young modulus study for the selected geometries, in which the orthotropic behaviour of the unit-cells was confirmed. The results indicate that the approaches that use symmetry boundary conditions compares well with the analytical models. In opposition, the AEH predictions overestimate de Young's Modulus. Furthermore, on contrary to the closed-cells, the open-cell numerical methods and analytical models are within the experimental results range [3].

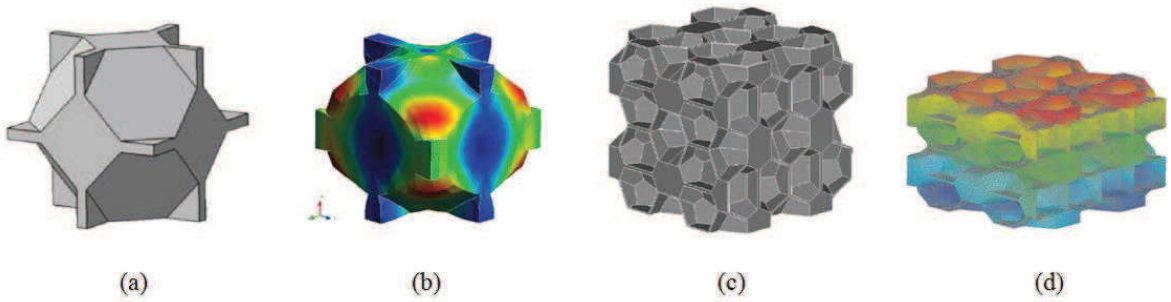


**Fig. 1.** Space-filling polyhedra subjected to the homogenization methods (a) Kelvin unit-cell (b) Characteristic displacement of the Kelvin Unit-Cell subjected to AEH (c) Weaire-Phelan periodic microstructure (d) Weaire-Phelan periodic microstructure deformed state by applying symmetry boundary conditions with a uni-axial disturbance.

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*corresponding author: jmra@ua.pt (J. Aquino)

# DEFINING THE ANISOTROPIC CONSTITUTIVE TENSOR OF TRABECULAR BONE USING THE FABRIC TENSOR CONCEPT

M. Marques[1], J. Belinha[1,2,*], A.F. Oliveira[3], R.M. Natal Jorge[1,2]
[1]*Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Porto, Portugal,*
[2]*Department of Mechanical Engineering, Faculty of Engineering of the University of Porto, Porto, Portugal*
[3]*CBAS - Institute of Biomedical Sciences Abel Salazar, Porto Portugal*
*Emails: mcmarques@inegi.up.pt, jbelinha@fe.up.pt,* afonsecaoliveira1@gmail.com*, rnatal@fe.up.pt*

**Keywords:** Anisotropy; Microscale; Fabric tensor; Trabecular bone; Meshless

## Abstract

A fabric tensor is a symmetric second rank tensor that characterizes the arrangement of a multiphase material. Fabric tensors can be obtained using mechanical based methods to morphologic-based methods. Morphologic-based methods use the interface between phases of the material to estimate the fabric tensors. Most of the proposed fabric tensors obtained using morphologic-based methods are usually computed, first, by an orientation distribution function (ODF) that is estimated from an orientation-dependent feature of interest, and at last the fabric tensor is approximated by the ODF, see Cowin, 1985 [1]. A relationship between the fourth rank elasticity tensor $\boldsymbol{C}_{ijkl}$, and the fabric tensor $\boldsymbol{A}$ was developed by Cowin, [1]. Later, the Mean Intercept Length tensor ($MIL$), a morphologic-based method, was developed by Whitehouse [2] and used to estimate the fabric tensors. It is computed by defining a family of parallel lines to a specified direction $v$. The number of intersections, $C(v)$, between lines and the interface between both phases is counted. $MIL$ is computed as a reason between the summation of the length of traced lines, $h$, with the number of intersections, $C(v)$: $MIL(v) = \mathrm{h}/C(v)$. For bone trabeculae, researchers found that an ellipse could be fitted to the MIL data, and with this, in 2D MIL, a tensor, $\boldsymbol{A}$, could be computed as the $2 \times 2$ matrix that represents the fitted ellipse [3]. From this ellipse several parameters can be obtained using the MIL fabric tensor, such as major and minor axis and major axis rotation. Using a material law proposed by Belinha et al, 2012 [4] and the ellipse parameters, it is possible to determine the material mechanical proprieties. In this work, the MIL technique is applied to obtain directly from the Micro-CT images the constitutive tensor of a trabecular patch. Then, the patch is analyzed using a linear elasto-static meshless and FEM analysis.

## Acknowledges

The authors truly acknowledge the funding provided by Ministério da Ciência, Tecnologia e Ensino Superior – Fundação para a Ciência e a Tecnologia (Portugal), under grants: SFRH/BPD/111020/2015, SFRH/BD/110047/2015, and by project funding UID/EMS/50022/2013 (funding provided by the inter-institutional projects from LAETA). Additionally, the authors gratefully acknowledge the funding of Project NORTE-01-0145-FEDER-000022 – SciTech – Science and Technology for Competitive and Sustainable Industries, co-financed by Programa Operacional Regional do Norte (NORTE2020), through Fundo Europeu de Desenvolvimento Regional (FEDER).

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*corresponding author: jbelinha@fe.up.pt (J. Belinha)

# DYNAMIC MECHANICAL BEHAVIOUR OF CELLULAR MATERIALS UNDER COMPRESSIVE LOAD

G. Portemont*, B. Langrand, V. Marcadon, C. Davoine, S. Kruch
*Department Materials and Structures, Onera-The French Aerospace Lab, France*
*Email: gerald.portemont@onera.fr*

**Keywords:** Cellular material; Dynamic behavior; Compression loading; Finite Element Analysis

**Abstract**

Cellular materials are very promising as lightweight aeronautical frames thanks to their higher specific mechanical properties such as impact resistance. For that purpose, brazed cellular sandwich structures made of tube stackings have been considered as model architectures. The present works aims at studying experimentally the dynamic mechanical behavior of two different tube stackings regarding lateral compressive loads. The compression tests were also simulated with the finite-element method. A specific device has been developed especially for high loading rate tests using a hydraulic jack (Fig. 1). The influence of the load rate on the compressive behaviour has been studied for each configuration for displacement rates from 5mm/min to 10m/s. The stacking influence (square or hexagonal) was analyzed for each load rate.

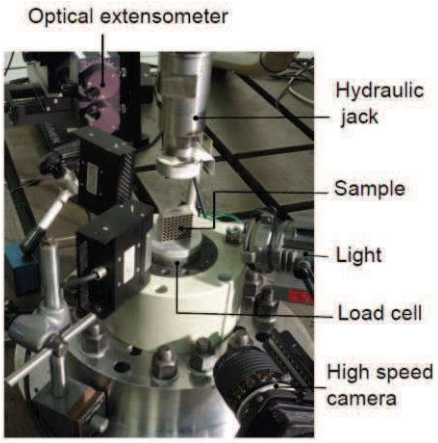


**Fig. 1.** Experimental device

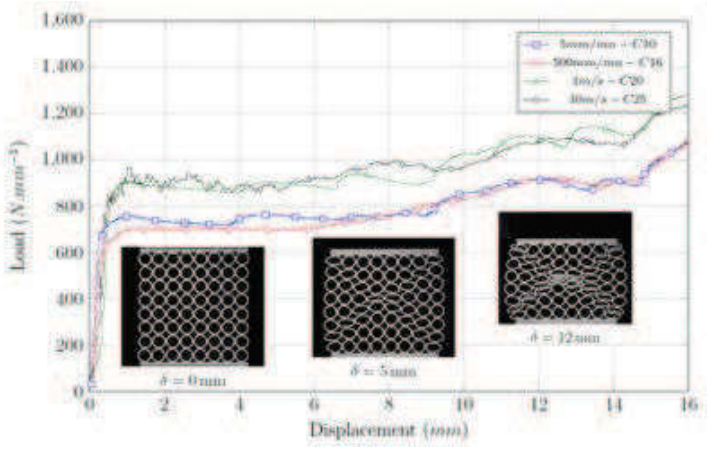


**Fig. 2.** Load vs Displacement for the square stacking in dynamic up to 10 m.s$^{-1}$

The analysis was based on the load versus displacement diagrams and also on the deformation process observed with the high-speed camera. The digital images correlation (DIC) technique was set up on the side of the sample in order to measure the displacements of the tubes during the test. The experimental results showed an evolution of the deformation as a function of the applied displacement rate for the square staking tubes (Figure 2). In contrast, for the hexagonal stacking no significant evolution of the overall behaviour was observed as a function of the displacement rate. The experiments were modeled with the fast transient dynamic code Europlexus. Results from the numerical model were compared with experiments to validate the numerical analysis. The numerical model was also used to better analyze the influence of the displacement rate on the deformation process of the different stackings (structural inertia and/or material strain rate).

*corresponding author: gerald.portemont@onera.fr (G. Portemont)

# APPLICATION OF VIRTUAL CELLULAR MATERIAL CONCEPT FOR THE SIMULATIONS OF DYNAMIC LOADING PROCESSES

R.B. Pecherski*, Z. Nowak
*Department of Theory of Continuous Media and Nanostructures, Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Pawinskiego 5B, 02-106 Warsaw, Poland*
*Emails: rpecher@ippt.pan.pl, znowak@ippt.pan.pl*

**Keywords:** Cellular material; Virtual material; Metallic open-cell foams; Dynamic loading; Crushing force

## Abstract

The subject of the study is the models based on digital microstructure, in particular open-cell metallic materials with the skeleton of convex or re-entrant cells. Recently, the auxetic materials have attracted increasing attention in the context of modern materials applications. The dynamic properties of such materials are less known. Impact compressions of the two kind of cellular materials under high-velocity are numerically analysed, [1]. To simulate the deformation processes the finite element program ABAQUS is used. The computer tomography makes the basis for the formulation of computational model and finite element discretization of the skeleton of virtual cellular material, [1]. For numerical simulations the constitutive elasto-viscoplasticity equations are applied that describe the dynamic behaviour of OFHC Cu, [2]. The numerical predictions of compression kinematics of the skeleton and crushing force for velocity 50 and 300 m/s are discussed. The results of computations are completed with the analysis of shock wave propagation according to the theory presented in [3], cf the related discussion in [4] and [5].

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*corresponding author: rpecher@ippt.pan.pl (R.B. Pecherski)

# CRUSH BEHAVIOUR OF AUXETIC CELLULAR STRUCTURES

M. Vesenjak*, N. Novak, Z. Ren
*Faculty of Mechanical Engineering, University of Maribor, Maribor, Slovenia*
*Emails: matej.vesenjak@um.si, n.novak@um.si, zoran.ren@um.si*

**Keywords:** Cellular structures; Auxetic; Numerical simulations; Dynamic crushing; Optimization

## Abstract

Auxetic cellular structures are modern materials which have some unique and superior mechanical properties. As a consequence of their internal structure deformation, they exhibit a negative Poisson's ratio, i.e. they get wider when stretched and thinner when compressed. The effect of negative Poisson's ratio can be useful for many different applications to enhance stiffness, fracture toughness, energy absorption and damping [1]. These properties can be further tailored by using variable cell geometry and density distribution, which can be achieved with functionally graded porosity of auxetic cellular structure. The structures with functionally graded geometry have many advantages in case of the dynamic loading (e.g. impact), where the response of the structure can be tailored for specific applications. This can be achieved using the optimization algorithms for optimization of different geometry parameters of auxetic structure's numerical models.

Auxetic cellular structures produced by additive manufacturing technologies can be fabricated with more complex geometries, which allows engineers to tailor mechanical properties for an expected type of loading. Auxetic structures analysed in this work were fabricated using selective electron-beam melting (SEBM) from Ti-6Al-4V powder at Institute of Materials Science and Technology (WTM), University of Erlangen-Nurnberg, Germany [2]. Quasi-static compressive testing up to densification of some selected auxetic structures in two perpendicular directions was performed to determine complete deformation behaviour of these structures. Furthermore, the high strain rate experimental testing of selected auxetic cellular structures was performed to determine also the deformation behaviour at higher strain rates.

Furthermore, representative discrete computational models built with the beam finite elements were developed and validated by experimental data. Homogenised computational models were also developed, validated and used to explore their response at different loading conditions and material distribution (including porosity variation) in an auxetic structure at reduced computational cost. The values of the critical strain rate determined by analytical expressions [3] and visual observation of deformation procedure in experiments were also compared. Validated discrete computational models were used for further optimization of auxetic structure geometry to obtain user defined response during dynamic compression loading by applying functionally graded porosity. The optimised geometries of new auxetic lattice structures with functionally graded porosity and user-defined response for the particular loading conditions were developed by changing structure's geometry and strut's thickness based on parametrical numerical analysis in Ls-Opt. The method is based on optimization task where the responses of the computational model and the target function are compared using the curve-mapping technique. The difference in response is minimalised with the shape optimization of the functionally graded auxetic structure.

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*corresponding author: matej.vesenjak@um.si (M. Vesenjak)

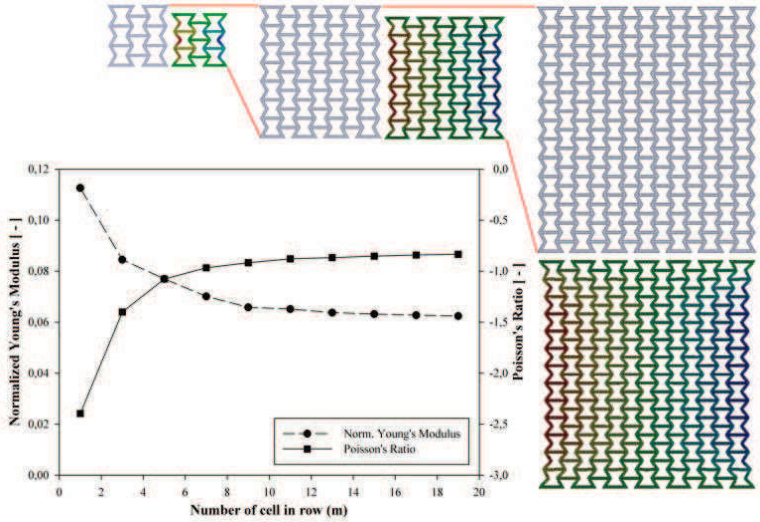
# SIGNIFICANCE OF CELL NUMBER IN THE BULK ELASTIC PROPERTIES OF AUXETIC REENTRANT LATTICES

V.H. Carneiro*, J. Meireles, N. Peixinho
*MEtRiCS - Centro de Engenharia Mecânica e Sustentabilidade de Recursos*
*University of Minho – Campus de Azurem, Guimarães, 4800-058, Portugal*
*Email: id5544@alunos.uminho.pt, meireles@dem.uminho.pt, peixinho@dem.uminho.pt*

**Keywords:** Auxetic; Reentrant; Lattices; Poisson's Ratio; Elastic

## Abstract

Auxetics are a characterized by possessing a negative Poisson's ratio and, thus, are able to expand/contract in tension/compression. This behaviour does not contradict the thermodynamic limits on isotropic solid bodies imposed by the classical theory of elasticity that states the values of Poisson's ratio are confined between -1 and 0.5 [1]. Given this counterintuitive deformation behaviour, this materials are expected to possess high relative shear and fracture resistance, elevated relative hardness and superior vibration damping [2]. Due to the apparent lack of isotropic auxetics in natural states, many researchers have devoted their efforts to the design and manufacture of artificial structures that mimic such behaviour, such as chiral, rotating geometry and re-entrant models [3]. Concerning the last, it is based on classic honeycomb structure which have their outwardly protruding ribs changed to inward configuration. Commonly, these are employed in lattice based designs and have already been thoroughly studied in terms of mechanical properties, deformation behaviour and design for manufacturing [4]. However, given that most of the referred lattices are assembled in a matrix shape (mxn) configuration and that the amount of cells have a direct influence in the overall structural behaviour, there seems to be an absence of a concise study that determines the minimum number of cells for the structure to present properties as a bulk. Recurring to Finite Element Analysis, this study is devoted to the determination of the minimum number of re-entrant cells that must be assembled to obtain an overall auxetic structure with bulk elastic behaviour, namely in terms of its apparent Young's modulus and Poisson's ratio.

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*corresponding author: id5544@alunos.uminho.pt (V.H. Carneiro)

# EFFECTIVE THERMAL CONDUCTIVITY OF OPEN CELL FOAMS FOR GAS-SOLID REACTORS

M.-L. Zanota[1,*], J. Gerardin[1], I. Pitault[2], R. Philippe[1]
[1] *LGPC, UMR 5285 CNRS-CPE, Université de Lyon, 43 bd du 11 Novembre 1918 69100 Villeurbanne*
[2]*LAGEP,UMR 5007, CNRS-UCBL , Université de Lyon, 43 bd du 11 Novembre 1918 69100 Villeurbanne.*
*Emails: mlz@lgpc.cpe.fr*

**Keywords:** Structured reactor; Metallic and ceramic foam; Thermal conductivity; Pressure drop; X-ray tomography

**Abstract**

Gas-solid catalytic reactors wherein the catalyst is washcoated on a solid foam structure are of interest to scientific and industrial communities as an alternative to conventionnal packed beds, mainly due to improvement in pressure drop, thermal control and radial mixing. The understanding of their performances remains limited. Macroscopic models of pseudo-effective medium linked to a few geometric properties are used but are not enough accurate for a fine performance prediction. Moreover, the geometry is only described in a global or simplified manner. Associated with materials of variable quality and regularity, this contributes to associate high uncertainties to the use of those structures.

In this work, a fine characterisation and robust description of foam (topological and geometrical) combined to measurements of effective thermal conductivity are performed. About twelve foams were studied (various suppliers, materials and cell densities). Image processing was carried out on tomography data to determine foam topological and geometrical properties. Foams were caracterised in terms of porosity, cell dimension and orientation, strut form and thickness. Statistical studies on samples cut in a same big sample of foam were made for six differents foams. Results were compared with effective conductivities measured on a home made device working on the principe of guarded hot plate. Pressure drop and thermal measurement with forced convection, were also performed throught stacked foam.

Results firstly allow the quantification of non-homogeneity and anisotropy of the objects. Differences in the order of 20 % on the effective conductivity measurement were observed with samples cut in a same initial slab of foam. For one sample, anisotropy caused an increase of effective conductivity of about 10% when the heat flux direction was changed. The stacking of foams had also an affect on heat and mass transfer, so in a way to develop a reliable model it could be important to take into account their different parameters.

[*]corresponding author: mlz@lgpc.cpe.fr (M.-L. Zanota)

# DIRECT MONTE CARLO SIMULATION OF RADIATION HEAT TRANSFER IN SEMI-TRANSPARENT CELLULAR FOAMS/ COMPARISON WITH HOMOGENIZED METHODS

S. Cunsolo[1,*], R. Coquard[2], D. Baillis[1], N. Bianco[3]
[1]LaMCoS, INSA-Lyon, UMR CNRS 5259, 18-20 Rue des Sciences, F-69621 Villeurbanne, France
[2]EC2-MODELISATION, 66 Boulevard Niels Bohr, F-69603 Villeurbanne, France
[3]Dipartimento di Ingegneria industriale, Università degli Studi Federico II, P.le Tecchio 80, 80125, Napoli, Italy
Emails: Salvatore.cunsolo@insa-lyon.fr, remi.coquard@ec2-modelisation.fr, Dominique.baillis@insa-lyon.fr, Nicola.bianco@unina.it

**Keywords:** Cellular foams; Monte Carlo; Homogenous Phase Approach; Numerical methods

## Abstract

It has been long known that radiation can be an important contribution to total heat transfer in both open and closed cell foams, in both insulation and heat exchange applications [1, 2]. The current state of the art approach consists in using Monte Carlo methods at the micro-scale to characterize the behaviour of the medium at the macro-scale. The most currently used approach at the macro-scale is the Homogeneous Phase Approach (HPA), which substitutes the complex morphology of the medium with a single, continuous material characterized in terms of extinction coefficient, scattering albedo and scattering phase function, which are directly obtained from the Monte Carlo micro-scale simulation [3-5]. However, this approach turns out to be not fully satisfactory in foams constituted of semi-transparent solid phase, especially at porosities under 95%. In the present work, we present a method to directly simulate propagation of radiation in a cavity of any shape, filled with a heterogeneous medium, using as input a Representative Volume Element (RVE) of the medium. Such a method is expected to provide high accuracy and to be useful as reference to validate simpler models. The new approach is tested on a set of 4 digitally-generated closed cell and open cell structures, which have been already validated by comparison with real tomographied samples in previous works [4, 5]. The testing encompasses simulation in different configurations: propagation of radiation in a plane layer, propagation of radiation in a 3D cube and heat exchange in a plane layer. Different values of the refraction index and absorption coefficient of the solid phase are considered. The comparison of results with traditional HPA approach evidences the limits of the latter: depending on morphological, physical and geometrical properties, the errors introduced by the HPA can be as high as 20%.

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*corresponding author: Salvatore.cunsolo@insa-lyon.fr (S. Cunsolo)

# BI-MATERIAL VEHICLE HOOD FOR IMPACT ABSORPTION DURING PEDESTRIANS ACCIDENTS

S. Santos*, D. Bastos, P. Freitas, H. Amorim
Escola Superior de Tecnologia e Gestão (ESTG), Instituto Politécnico de Leiria, Leiria, Portugal
*Emails: ssantos@ipleiria.pt, 2162030@my.ipleiria.pt; 2162035@my.ipleiria.pt, Henrique.amorim@ipleiria.pt*

**Keywords:** Automotive safety; Impact absorption; Lightweight; Cellular materials

## Abstract

The present work aims to increase the automotive safety regarding vehicle accidents with pedestrians. This study approach the capacity of reducing the impact force suffered by pedestrian when impacts to car hood, using a structural based material with an impact absorbing foam. A vehicle hood using expanded insulation corkboard was experimental and numerically tested. The cellular layers of cork are compose by a gas with similar composition of air that occupies around 90% of volume. The cells while being compressed showing a behaviour like a material with a low coefficient of Poisson, that allows them to bend in way that makes the lateral deformation practically non-existent, while also displaying a geometry recuperation akin to an air spring [1]. Through numerical simulation performed on LS-Dyna™, and experimental data from compression tests, benefits can be found by adding the cork micro-agglomerated under the bonnet in an automotive application (Fig. 1), by reducing the possible injury to the head which is the most vulnerable part of the human body in car accident. An optimum cork thickness (Fig. 2) was identify that produces maximum reduction of HIC value, considering a vehicle speed of 30 km/h.

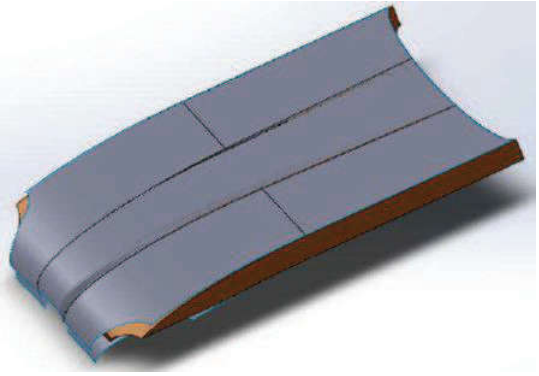

**Fig. 1.** CAD model of bimaterial hood in study [2].

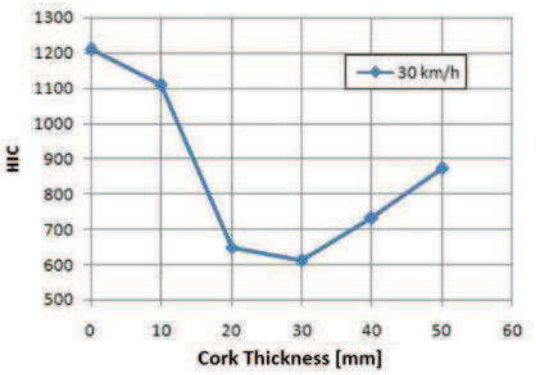


**Fig. 2.** HIC variation with cork thickness [2].

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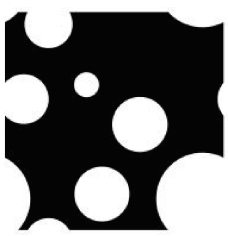
*corresponding author: ssantos@ipleiria.pt (S. Santos)

# POSTER ABSTRACTS



# 3D PRINTED Ti6Al4V POROUS STRUCTURES BY ROBOCASTING TECHNOLOGY

L. Biasetto[1,*], H. Elsayed[2,3]
[1]*Department of Management and Engineering, University of Padova, Vicenza, I-36100, Italy*
[2]*Department of Industrial Engineering, University of Padova, Padova, I-35131, Italy*
[3] *Ceramics Department, National Research Centre, Cairo,* 12622*, Egypt*
*Emails: lisa.biasetto@unipd.it ; hamada.elsayed@unipd.it*

**Keywords:** Direct ink writing; Pseudo plasticity; Ink; Paste; Titanium

**Abstract**

Ti6Al4V components, for biomedical and aerospace sectors, are receiving a great interest especially after the advent of additive manufacturing technologies. The most used techniques are Selective Laser Sintering (SLS) or Electron Beam Melting (EBM): a laser or an electron beam (of known power and beam size) are used to sinter the metallic powders in complex geometries. Pores or holes are often present, due to uncomplete sintering or design constraints. The main advantage of these 3D printing technologies is their flexibility that allows for the production of complex geometries without the need of moulds. Consequently, production costs are deeply reduced especially when only small batches are needed. The disadvantage is related to the high cost of printing units.

In this work, we developed a different approach that consists on the use of a low cost robocasting printer to print Ti6Al4V inks. A proper ink formulation was realized by controlling the rheological properties of the paste with a proper use of a polymers mixture into a water dispersion. After, printing and drying, the components were heat treated under high vacuum.

Highly porous scaffolds (up to 65% total porosity) were produced and different geometries were printed. The influence of the porosity on the morphology and compressive strength of the scaffolds was investigated.

[*]corresponding author: lisa.biasetto@unipd.it (L. Biasetto)

# RADIANT POROUS BURNERS PRODUCED FROM AN ALTERNATIVE CERAMIC RAW MATERIAL

N.P. Stochero, E.G. Moraes, A.P. Novaes de Oliveira*
*Graduate Program in Materials Science and Engineering (PGMAT), Laboratory of Glass-Ceramic Materials (VITROCER)*
*Federal University of Santa Catarina (UFSC), Florianópolis (SC), PO Box 476, Brazil*
*Emails:* naianestochero@hotmail.com, lisguzi@gmail.com, antonio.pedro@ufsc.br

**Keywords:** *Ceramic shell wastes; Cellular ceramic; Direct Foaming; Gelcasting; Radiant porous burners*

## Abstract

Cellular ceramics from an alternative source of raw material (ceramic shell) generated in the process of precision casting by lost-wax were produced by direct foaming and protein gelcasting. This waste material has very interesting and suitable characteristics and properties for the manufacturing of cellular materials in applications involving high temperatures (> 1400 °C) such as in radiant porous burners [1, 2]. Thus, ceramic suspensions containing between 35 and 42 vol% of solids (ceramic shell powder $d_{50}$ <2 μm) were prepared. Ceramic shell foams were obtained by varying the rotation speed from 500 to 2000 rpm followed by a gelation process (at 80 °C for 2 h) and a firing step at 1550 °C (2 °C / min, 2 h). The obtained ceramic foams were then characterized from the point of view of their physical, chemical, thermal and mechanical properties. X-ray computer tomography (XCT) images were used to characterize the microstructure of the fired ceramic shell foams. The values obtained for porosity and pore size distribution were then compared with the standard method of analysis of 2D images by optical (OM) and scanning electron microscopy (SEM). Subsequently, the porous structures were subjected to bench test by applying different thermal cycles, i.e. in the 1250–1500°C temperature range for holding times between 10 min and 6 h, respectively to evaluate the loss of resistance in operation. The results showed that it is possible to obtain cellular materials, consisting predominantly of mullite and zirconite, with porosities of up to 78%, pore size between 100 μm and 900 μm, compressive strength varying from 3 to 20 MPa and thermal conductivity varying from 0.06 and 0.09 W / mK. The radiant porous burners tested resisted the thermal cycles and the imposed temperatures, proving thus that they can be used in real conditions.

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*corresponding author: antonio.pedro@ufsc.br (A.P. Novaes de Oliveira)

# CERAMIC FOAMS PRODUCED FROM CERAMIC SHELL WASTE AND EXPANDABLE STYROFOAM (EPS) AS PORE FORMER: PROCESSING AND CHARACTERIZATION

L. Sangiacomo[1], E.G. Moraes[2], S. Arcaro[2], N.P. Stochero[2], C. Siligardi[1], A.P. Novaes de Oliveira[2,*]
[1]*Department of Engineering "Enzo Ferrari", University of Moderna and Reggio Emilia (UniMore), Modena (MO), Italy*
[2]*Graduate Program in Materials Science and Engineering (PGMAT), Laboratory of Glass-Ceramic Materials (VITROCER), Federal University of Santa Catarina (UFSC), Florianópolis (SC), PO Box 476, Brazil*
*Emails:* lorenzo.sangiacomo33@gmail.com, lisguzi@gmail.com

**Keywords:** Ceramic foams; Ceramic shell waste; Styrofoam (EPS); Pore forming agent; Thermal insulation

## Abstract

Ceramic foams were produced using ceramic shell (mullite source), an industrial solid waste from the lost-wax casting process, and expandable styrofoams, EPS ($d_{50}$ < 500 μm) as foaming agent, envisaging thermal and acoustic insulation applications. Physical and chemical properties of the selected and prepared raw materials (wastes) were characterized. The influence of the amount and morphology of the EPS as well as of the sintering temperature of ceramic shell foams on the microstructure, thermal conductivity, acoustic absorption and compressive strength were evaluated. Batches containing well mixed ceramic shell powder ($d_{50}$ < 2 μm), EPS beads (10 – 70 vol%) and BonderPlus ($Na_2SiO_3$ solution) were obtained and uniaxially pressed at 20 MPa. The obtained powder compacts were dried in air for 24 h and then fired in two steps: firstly at 900 °C, 1 °C/min for 1 h; and afterward at 1200 °C, 10 °C/min for 1 h. The experimental results showed that homogeneous microstructures of elongated and interconnected pores with sizes between 100 and 900 μm can be obtained. Ceramic shell foams with porosities up to 77% and thermal conductivity of 0.061 W/mK, for foams containing 70 vol% of pore former were produced. The microstructural characteristics of the produced ceramic shell foams associated with the measured properties are suitable for applications that require thermal and acoustic insulation [1].

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*corresponding author: antonio.pedro@ufsc.br (A.P. Novaes de Oliveira)

# VITROCRYSTALLINE FOAMS FROM EXPANDABLE STYROFOAM (EPS) AS PORE FORMER: PROCESSING AND CHARACTERIZATION

M. Bigi[1], E.G. Moraes[2], N.P. Stochero[2], S. Arcaro[2], C. Siligardi[1], A.P. Novaes de Oliveira[2,*]
[1]*Department of Engineering "Enzo Ferrari", University of Moderna and Reggio Emilia (UniMore), Modena (MO), Italy*
[2]*Graduate Program in Materials Science and Engineering (PGMAT), Laboratory of Glass-Ceramic Materials (VITROCER), Federal University of Santa Catarina (UFSC), Florianópolis (SC), PO Box 476, Brazil*
*Emails:* matteo.bigi89@gmail.com, lisguzi@gmail.com

**Keywords:** Vitrocrystalline foams; Bottle glass; Styrofoam (EPS); Pore forming agent; Thermal insulation

## Abstract

In this work, discarded soda-lime glasses (from glass bottles) and expandable styrofoams, EPS ($d_{50}$ < 500 μm) were successfully converted into vitrocrystalline foams for thermal insulation applications. Physical and chemical properties of the selected and prepared raw materials (wastes) were characterized. Batches containing well mixed glass powder ($d_{50}$ < 4 μm), EPS beads (10 – 40 vol%) and BonderPlus ($Na_2SiO_3$ solution) were prepared so that powder compacts uniaxially pressed at 20 MPa were obtained. The powder compacts were dried at room temperature for 24 h and then fired at 850 °C, 10 °C/min for 30 min. Vitrocrystalline foams with interconnected cells sizes between 150 and 850 μm, homogeneously distributed in a crack free matrix were produced and characterized from the point of view of their typical physical, chemical, morphological and mechanical properties. The results showed that it is possible to obtain vitrocrystalline foams (main phase consists of cristobalite), with porosity up to 90% and compressive strength of 2.5 ± 0.4 MPa and thermal conductibility of 0.06 W/mK, for foams containing 40 vol% of pore former. The magnitude of the measured properties of the produced vitrocrystalline foams are adequate for a number of applications requiring low thermal conductivity [1].

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*corresponding author: antonio.pedro@ufsc.br (A.P. Novaes de Oliveira)

# ADDITIVE MANUFACTURING OF 3D POROUS ALKALI-FREE BIOACTIVE GLASS SCAFFOLDS BY ROBOCASTING

A.D. Marzi[1,2], A.S. Neto[1], H.R. Fernandes[1], P. Colombo[2], J.M.F. Ferreira[1,*]
[1]*Department of Materials and Ceramics Engineering, CICECO, University of Aveiro, Aveiro, 3810-193, Portugal*
[2]*Department of Industrial Engineering, University of Padua, Padua, 35131, Italy*
*Emails: anna.demarzi@studenti.unipd.it, sofia.neto@ua.pt, h.r.fernandes@ua.pt, paolo.colombo@unipd.it, jmf@ua.pt*

**Keywords:** Tissue Engineering; Bioactive glass; Robocasting; Scaffolds

## Abstract

Tissue Engineering is a multidisciplinary field of study embracing techniques, methods and knowledge from several commentary areas such as biology, medicine and engineering. The aim is to produce artificial devices able to act as temporary substitutes of damaged tissues: the structure realized must serve as supports for cell attachment and proliferation as well as the production of extracellular matrix, ideally until the same device degrades. The great issues related to this approach are therefore implementing a suitable scaffold material produced with an adequate technique in order to satisfy the above mentioned requirements [1,2].

In this work, an alkali-free bioactive glass composition in the binary system of Diopside-Tricalcium Phosphate was selected based on its promising properties for tissue engineering and bone regeneration [3]. The Robocasting technique was adopted for manufacturing 3D porous scaffolds with adequate structures and porosities according to a CAD model [4]. The work included different steps such as: (i) preparation and characterization of glass powders with different particle size distributions to enhance the packing ability; (ii) preparation of concentrated suspensions and investigate the dependence of their rheological properties on solid loading and the content of CMC selected as the single processing additive; (iii) production of the scaffold with different porosity; (iv) characterization of the printed structures before and after sintering process.

The results obtained demonstrated that a 1:1 mixture of glass powders having mean particle diameters of 1 μm and 4–5 μm enables preparing suitable suspensions by playing with the contents of CMC and solid loading. The printed scaffolds present well-defined geometry and good shape retention. Therefore, the work carried out could be considered as a very promising starting point for further studies aiming at obtaining further improvements

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*corresponding author: jmf@ua.pt (J.M.F. Ferreira)

# POROUS CHITOSAN-POLYETHYLENEGLYCOL COMPOSITE MEMBRANES FOR ANTIBACTERIAL AND CONTROLLED DRUG DELIVERY APPLICATIONS

I. Pereira[1], A.S. Neto[1], A.S. Duarte[2], J.M.F. Ferreira[1,*]
[1]*Department of Materials and Ceramics Engineering, CICECO - Aveiro Institute of Materials, Aveiro 3810-193, Portugal*
[2]*Department of Biology & CESAM, University of Aveiro, Aveiro 3810-193, Portugal*
*Emails:sofia.neto@ua.pt, jmf@ua.pt*

**Keywords:** Chitosan-Polyethyleneglycol composites; Calcium phosphate; Metal oxides; Nanopowder; SEM; Biocompatibility

## Abstract

Some common human pathologies such as dental caries and periodontitis, inflammation in wounds, among others, are caused by the formation of bacterial biofilms. Their incidence is also significant with respect to medical devices such as catheters, stents, orthopedic implants, contact lenses, and implantable electronic devices [1]. Thus, the objective of this study is the development of bioactive porous composite membranes based on chitosan and polyethylene glycol [2] loaded with nano- and micro-particles of calcium phosphate (CaP), zinc oxide (ZnO) and copper oxide (CuO) (Fig. 1) with bactericidal activity. The main purpose of CaP particles is to provide membranes with the ability to induce the regeneration of damaged tissues [3]. On the other hand, the main function of the metallic powders is to offer excellent antibacterial properties to the membranes [4][5]. The obtained membranes were characterized for porosity, microstructure, mechanical tensile strength, biocompatibility, antibacterial activity and controlled release of drugs.

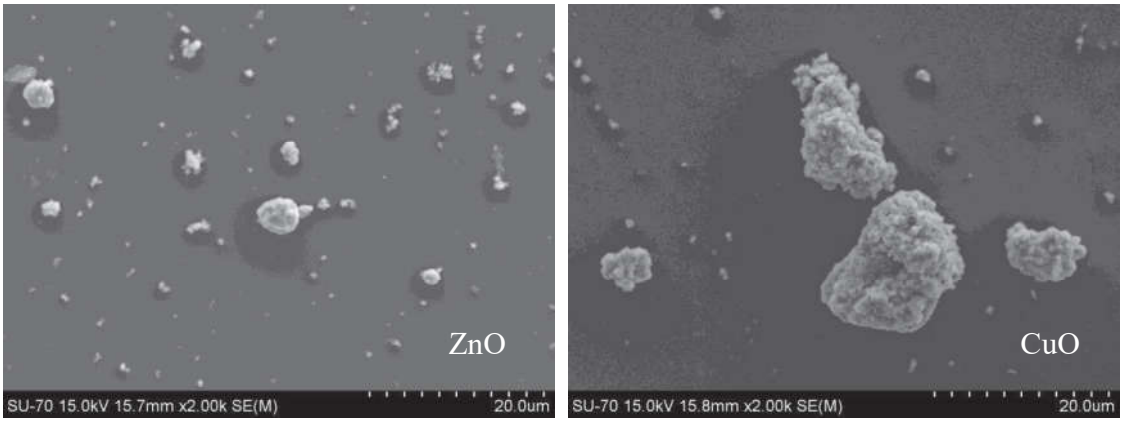


**Fig. 1.** ZnO and CuO particles to be incorporated in the membranes.

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*corresponding author: jmf@ua.pt (J.M.F. Ferreira)

# PROCESS DEVELOPMENT OF PROCESS FOR MANUFACTURING OF CELLULAR STRUCTURES WITH CONTROLLED GEOMETRY AND PROPERTIES

N. Peixinho*, P. Pinto, F.S. Silva, D. Soares
*Department of Mechanical Engineering, Universidade do Minho, 4800-058 Guimarães, Portugal*
*Emails: peixinho@dem.uminho.pt,paulopinto@dem.uminho.pt, fsamuel@dem.uminho.pt, dsoares@dem.uminho.pt*

**Keywords:** Cellular structures; Mechanical properties; Aluminum

## Abstract

This study presents experimental results on the behaviour of aluminium alloy metal structures and foams manufactured by lost-wax casting and using 3D printed components for internal structure definition. Results for tensile tests, metallurgical properties, surface quality and geometry tolerances were obtained and discussed. In order to evaluate the surface quality of the processed samples, at the different process stages, thickness and cellular perimeter measurements were obtained from CAD, resin and metal samples. The analysis focused on development geometries, used for adjusting manufacturing parameters and prototype geometries intended for geometrical and mechanical validation. The results are indicative of the viability of the method for producing foam structures suitable for mechanical loading eventually allowing further optimization of geometrical structure.

*corresponding author: peixinho@dem.uminho.pt (N. Peixinho)

# METAL NANOCOMPOSITE FOAMS

I. Duarte[1,*], J.M.F. Ferreira[2]
[1]*Department of Mechanical Engineering, TEMA,* [2]*Department of Materials and Ceramics Engineering, CICECO*
*University of Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal*
*Emails: isabel.duarte@ua.pt, jmf@ua.pt*

**Keywords:** Metal foams; Nano reinforcements; Carbon nanotubes

## Abstract

Open-cell and closed-cell metal foams have been reinforced with nano-sized reinforcements to enhance the mechanical properties of the metallic matrix. The idea behind this approach is that the nano-reinforcements will strengthen the matrix of the cell edges and cell walls and provide high strength and stiffness. Nowadays, this becomes one of the most important topics (very hot research topic) in metal foam field. Despite very few, some works on this issue are beginning to be published [**1-5**], including a review paper [**6**]. This paper is intended to highlight the most important novel studies to explore the mechanical behaviour of metal foams reinforced with carbon nanotubes (CNTs). Carbon nanotubes (Fig. 1) have emerged as potentially ideal nano-sized reinforcements to fabricate light weight and high-strength metal-matrix composites due to their low density and high values of aspect ratio, mechanical strength, electrical and thermal conductivities.

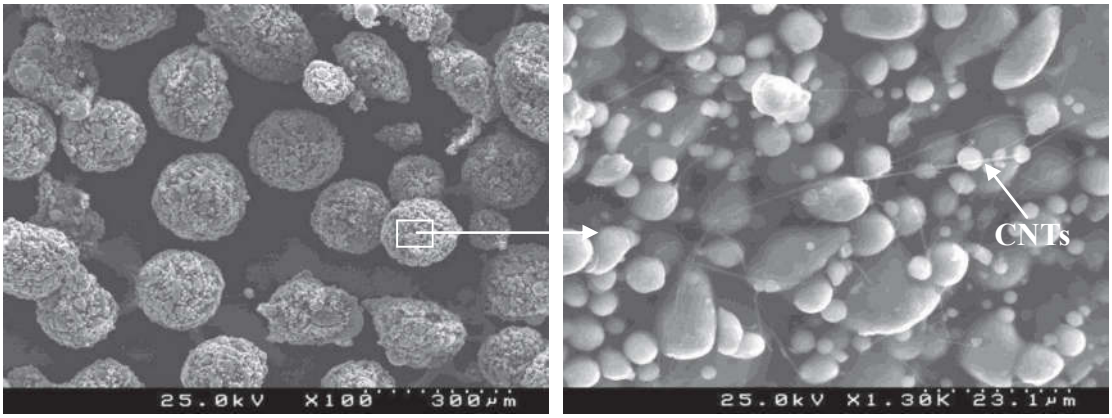


**Fig. 1.** Carbon nanotubes incorporated in the powder mixture of aluminium and titanium hydride.

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[*]corresponding author: isabel.duarte@ua.pt (I. Duarte)

# MECHANICAL PROPERTIES AND ENERGY ABSORPTION OF ALUMINUM FOAMS WITH MODIFIED CELLULAR GEOMETRY

N. Peixinho*, P. Pinto, F.S. Silva, D. Soares
[1]*Department of Mechanical Engineering, Universidade do Minho, 4800-058 Guimarães, Portugal*
*Emails: peixinho@dem.uminho.pt,paulopinto@dem.uminho.pt, fsamuel@dem.uminho.pt, dsoares@dem.uminho.pt*

**Keywords:** Cellular structures; Mechanical properties; Aluminum; Energy absorption

## Abstract

Experimental results on compression testing are presented regarding the behavior of aluminum alloy metal foams with controlled pore morphology. Two types of metal foams were analyzed, having uniform cell structure (US) and with a dual-size cell arrangement (DS) seeking optimized mechanical properties. A commercial AlSi12 alloy (A413.1) was used for the manufacturing of cellular structures. This alloy was selected based on previous experience in manufacturing structures with very thin walls. The structures were manufactured by lost-wax casting using 3D printed components for internal structure definition. Results for stiffness and energy absorption were obtained and compared on weight efficiency basis. The compression tests showed that the specific Pmáx (N/g) withstood by the dual-size (DS) structure was approximately ∼83% higher than that of the uniform size, while stiffness had an improvement of 29%. Specific absorbed energy registered for 5 mm of displacement presented a significant improvement (around 112%). For a higher displacement (15 mm) the specific absorbed energy of the dual size structure was approximately 27% higher than that of the uniform size structure. These results are indicative of a higher efficiency of the dual-size structures that may be therefore considered for use in components subjected to impact or compression.

*corresponding author: peixinho@dem.uminho.pt (N. Peixinho)

# TESTING AND MODELLING THE BEHAVIOUR OF METAL FOAMS, A PATH TOWARDS PREDICTION AND OPTIMIZATION

J. Aquino, T. Rodrigues, I. Duarte, J. Dias-de-Oliveira*
*Department of Mechanical Engineering, Universidade de Aveiro, Aveiro, Portugal*
*Emails: jmra.ua.pt, tiagoarodrigues@live.ua.pt, isabel.duarte@ua.pt, jalex@ua.pt*

**Keywords:** Aluminium foams; Effective properties; Representative unit-cells; Homogenization, Optimization

## Abstract

Metallic foams are widely used as core and/or as filler materials for sandwich panels and thin-walled structures, respectively. In these assemblies thin metal sheets and thin-walled structures ensure the required mechanical strength, while the foam core or filler contribute to the geometrical stabilization and lead to improved crashworthiness. Therefore, a detailed understanding of the mechanical properties and behaviour, and a characterization of the effective properties are necessary for their application in large scale. Nonetheless, there is a great difficulty in predicting the properties of these inhomogeneous materials due to their irregularities and micro-defects. The aim of this work is a set of first steps for the modelling of these materials in depth, within an integrated plan that comprises material testing [1] to correlate to the study analytical models and numerical methods for describing the mechanical behaviour of these foams. To do this, first in an elastic regime, numerical methods and analytical models provided by previous research were used. Accordingly, Kelvin and Weaire-Phelan structures were selected to model the closed-cell and open-cell representative unit-cell geometries. The open and closed-cell geometries were modelled using different numerical simulation approaches, including far field approaches with single freedom constraints and the use of periodic boundary conditions for the Asymptotic Expansion Homogenization (AEH) method. The analytical, numerical and experimental results were compared, in particular for the relative Young's modulus as a function of the relative density [2].

The detail and depth of information that the AEH provides on the orthotropic nature of these materials opens a path to other studies, namely for material optimization. The asymptotic expansion homogenization also integrates a localisation procedure, able to obtain detailed information on the behaviour of the material within the unit-cell, giving way to local sensitivities that can be used to control optimization procedures. This leads to a material topology optimization approach, perfectly suited for the design of this type of material [3, 4]. Within this scope, this work also explores the analysis of effective material properties of cellular materials designed with topology optimization procedures.

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*corresponding author: jalex@ua.pt (J. Dias-de-Oliveira)

# HOMOGENIZATION TECHNIQUES USING MESHLESS METHODS FOR STRUCTURAL AND BIOMECHANICAL ANALYSIS

D.E.S. Rodrigues[1], M. Marques[1], J. Belinha[1,2,*], L.M.J.S Dinis[1,2], R.M. Natal Jorge[1,2]
[1]*Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Porto, Portugal,*
[2]*Department of Mechanical Engineering, Faculty of Engineering of the University of Porto, Porto, Portugal*
*Emails: drodrigues@inegi.up.pt, mcmarques@inegi.up.pt, jbelinha@fe.up.pt, ldinis@fe.up.pt, rnatal@fe.up.pt*

**Keywords:** Anisotropy; Multiscale; Representative volume element (RVE); Meshless methods; Computational homogenization

**Abstract**

In the literature it is possible to find several homogenization techniques capable to assist an efficient multiscale analysis. These homogenization techniques allow to predict the anisotropic macro-scale mechanical properties of heterogeneous materials (at their micro-scale level).

This work presents a new homogenization technique for the biomaterials and composite materials. The technique is based on the Fabric Tensor concept [1]. Thus, using an orientation distribution function (ODF) is possible to define the material preferential direction. Afterwards, using a polar graph combined with the ODF it is possible to define the mechanical properties for each principal direction of the material. Finally, with the material orientation and the mechanical properties for each principal direction, the material anisotropic constitutive matrix is defined.

In this work, the developed homogenization technique is combined with a meshless method [2], which allow to discretize the problem domain with an unstructured nodal distribution. The meshless method uses the Radial Point Interpolators to construct the shape functions, possessing the delta Kronecker property.
Several structural analyses are performed, using both biomaterials (trabecular bone) and composite materials. The results are compared with the literature and with other discrete numerical techniques.

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The authors truly acknowledge the funding provided by Ministério da Ciência, Tecnologia e Ensino Superior – Fundação para a Ciência e a Tecnologia (Portugal), under grants: SFRH/BPD/111020/2015, SFRH/BD/121019/2016, SFRH/BD/110047/2015, and by project funding UID/EMS/50022/2013 (funding provided by the inter-institutional projects from LAETA). Additionally, the authors gratefully acknowledge the funding of Project NORTE-01-0145-FEDER-000022 – SciTech – Science and Technology for Competitive and Sustainable Industries, co-financed by Programa Operacional Regional do Norte (NORTE2020), through Fundo Europeu de Desenvolvimento Regional (FEDER).

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[*]corresponding author: jbelinha@fe.up.pt (J. Belinha)

# MULTIFUNCTIONAL FOAM FILLED TUBES

I. Duarte[1,*], M. Vesenjak[2], L. Krstulović-Opara[3]
[1]Department of Mechanical Engineering, TEMA, University of Aveiro, Aveiro, 3810–193, Portugal
[2]Faculty of Mechanical Engineering, University of Maribor, Maribor, 2000, Slovenia
[3]Faculty of El. Eng., Mech. Eng. and Naval Arch., University of Split, Split, 21000, Croatia
Emails: isabel.duarte@ua.pt, Lovre.Krstulovic-Opara@fesb.hr, matej.vesenjak@um.si

**Keywords:** Foam filled tubes; Aluminum foams; Compression; Bending; Infrared thermography

## Abstract

Multifunctional lightweight tubular structures based on cellular metals are regarded as one of the most promising components for industrial applications in a wide variety of sectors (e.g. transportation, construction). The combination of advantageous properties exhibited by these materials allows to fulfil multiple functions simultaneously when incorporated into a single tubular structure. We developed and tested lightweight, recyclable, non-inflammable *in-situ* FFTs made of light Al-alloys through powder compact foaming method [1] wherein the joining between the foams and tubes is achieved during the liquid foam formation, resulting in good metallic interface bonding, a pre-requisite for better mechanical response of the composite structure. Fig. 1 shows the main results in which the crush performance and the failure mechanisms of specimens were assessed by compression and three-point bending tests supported by infrared thermography. The mechanical response of the *in-situ* FFTs was compared to the individual components and the *ex-situ* FFTs prepared by insertion of the pre-shaped foam into the tube [1-4]. The results clearly demonstrate that the new *in-situ* FFTs have a superior mechanical performance and that they ensure high ductility and very good crashworthiness behavior since they deform under compressive and bending loads without formation of cracks and without abrupt failure. A good interface bonding also contributes to a more axisymmetric deformation. We believe that the incorporation of such structures into the automotive structures can further reduce the vehicle weight, improve the crashworthiness and safety in case of an accident and increase the comfort by reducing the noise and vibrations while driving.

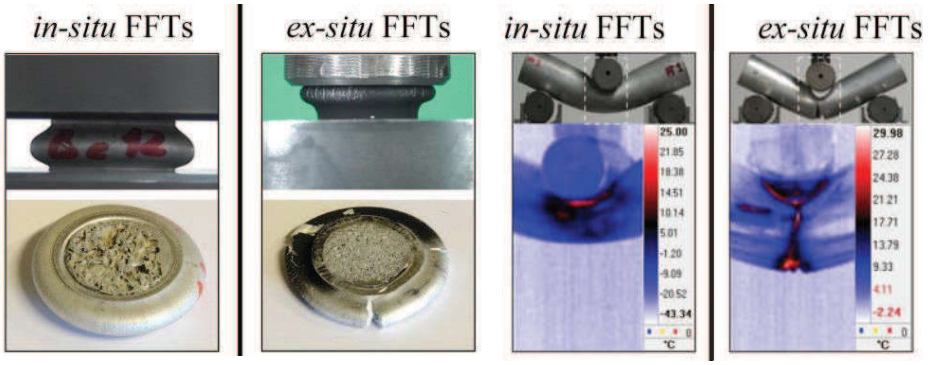


**Fig. 1.** Compressive and bending responses of *in-situ* and *ex-situ* FFTs.

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*corresponding author: isabel.duarte@ua.pt (I. Duarte)

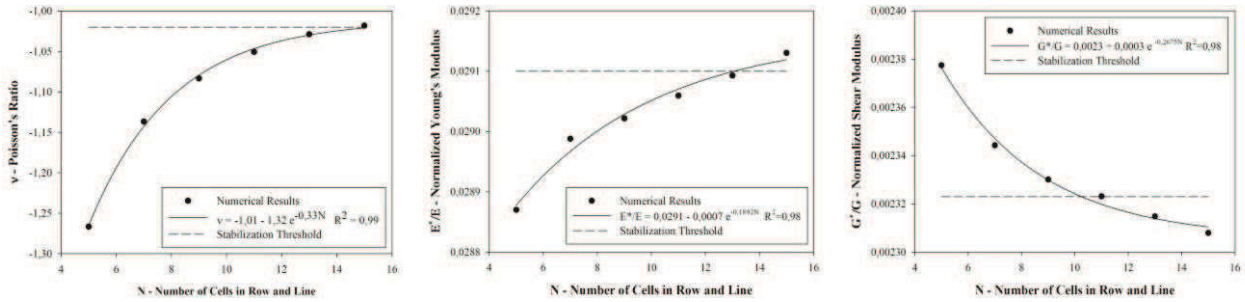
# EFFECT OF THE CELL NUMBER ON THE ELASTIC CONSTANTS OF AUXETIC REENTRANT LATTICES

V.H. Carneiro*, J. Meireles, N. Peixinho
*MEtRiCS - Centro de Engenharia Mecânica e Sustentabilidade de Recursos*
*University of Minho – Campus de Azurem, Guimarães, 4800-058, Portugal*
*Emails: id5544@alunos.uminho.pt,meireles@dem.uminho.pt, peixinho@dem.minho*

**Keywords:** Auxetic; Lattices; Elasticity; Poisson's Ratio.

## Abstract

Auxetic materials are defined by a negative Poisson's ratio, i.e. while in tension/compression they tend to expand/contract. Analysing the Theory of Elasticity, it may be seen by the correlation with the other elastic constants, that this behaviour does not contradict the thermodynamic balance of a body and the Poisson's ratio may assume values -1 and 0.5 [1]. Auxetics are expected to possess high relative shear, fracture resistance, elevated relative hardness and enhanced damping properties [2,3], however, given their absence in an isotropic form there has been an effort to produce artificial auxetics (e.g. using reentrant lattices) [3]. Even though there are several studies that explore the use of these structures [4], there seems to be a shortage of research on the role of number of cells (mxn) relatively to the bulk elastic constants of such lattices. This report presents a study, based on the numerical simulation of reentrant lattices by Finite Element Analysis, to determine the variation of basic elastic constants (Young's modulus, Shear modulus and Poisson's ratio) while the number of cells per column/line is changed. It is concluded that for "regular" auxetic cells, the Young's modulus and Poisson's ratio tend to stabilize for lattices with number of cells superior to 15 per row, while for the Shear modulus this happens for values higher than 13 cells per row. The bulk value of these constants tend to 0.0291, 0.0023 and -1.01, respectively for the Normalized Young's and Shear moduli and the structure Poisson's ratio.

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*corresponding author: id5544@alunos.uminho.pt (V.H. Carneiro)

# STATIC AND DYNAMIC BEHAVIOUR OF 3D PRINTED HONEYCOMB CELLULAR STRUCTURES

J. Magalhães, H. Gonçalves, N. Peixinho*, V.H. Carneiro
[1]*Department of Mechanical Engineering, Universidade do Minho, 4800-058 Guimarães, Portugal*
*Emails: a71479@alunos.uminho.pt, a72371@alunos.uminho.pt, peixinho@dem.uminho.pt, id5544@alunos.uminho.pt*

**Keywords:** Cellular structures; Honeycombs; Energy absorption

**Abstract**

Results on 3D print manufactured honeycombs are presented for static compression and impact loading. The cell arrangement and geometry parameters such as wall thickness were analysed seeking to obtain improved mechanical properties. The material used in the manufacturing 3D print was PLA while the overall geometry was constructed using 15 cell arrangement for significant results. Load-displacement curves were obtained in stacic testsfor two directions of loading being obtained classic load profiles that are indicative of suitability for energy absorption. Particular fracture modes were obtained and analysed as well as mechanical and fracture behaviour in drop tower impact tests.

*corresponding author: peixinho@dem.uminho.pt (N. Peixinho)

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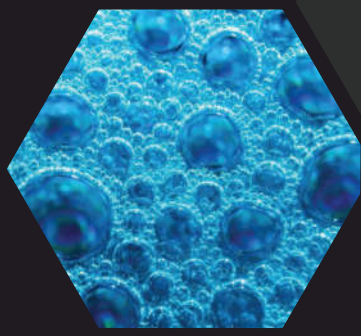

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