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International Conference on

Structural Integrity and Reliability of Advanced Materials obtained through Additive Manufacturing

Conference Programme & Book of Abstracts

International Conference

Structural Integrity and Reliability and Design of Additively Manufactured Materials

SIRAMM23

Central Library, Polytechnic Univ. of Timisoara (UPT)

& online

Timisoara, Romania, 8th - 11th March 2023

Conference Programme & Book of Abstracts

Conference organized by

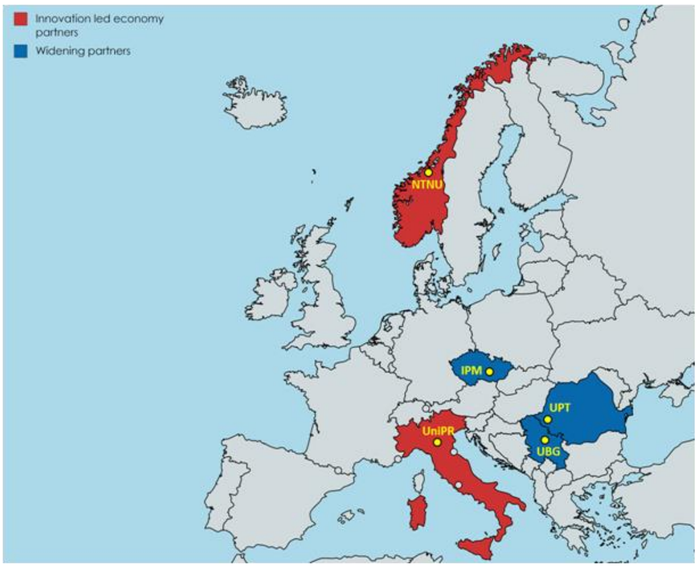
Polytechnic University of Timisoara,
ROMANIA

University of Belgrade,
SERBIA

Institute of Physics of Materials, Brno,
CZECH REP.

University of Parma,
ITALY

Norwegian Univ. of Science and Technology,
NORWAY



Institutions participating in the SIRAMM project

Workshop chairmen:

Prof. Roberto Brighenti	-	Univ. of Parma, Italy
Prof. Liviu Marsavina	-	Polytechnic Univ. of Timisoara, Romania
Prof. Aleksandar Sedmak	-	Univ. of Belgrade, Serbia
Prof. Lubos Nahlik	-	Institute of Physics of Materials, Czech Academy of Sciences, Brno, Czech Republic
Prof. Filippo Berto	-	Norwegian University of Science and Technology, Trondheim, Norway

Conference Programme

(EET Eastern European Time, UTC +2h - Timisoara)

● in presence & online

■ online

Wednesday, 8th March 2023

8:00-9:30	**Registration** Central Library, **Polytechnic Univ. of Timisoara** (UPT), Romania Bulevardul Vasile Parvan 2, Timișoara, Romania (Google map)
9:30-10:00	**Opening of the Conference** and presentation of the SIRAMM project (UPT & online) Prof. Liviu Marsavina, Prof. A. Sedmak, Prof. R. Brighenti
10:00-10:30 ●	**1st Keynote lecture** (UPT & online) - Chairman Prof. Liviu Marsavina ***Active rheology control for additive manufacturing of concrete structures*** Prof. Geert de Schutter - Ghent Univ., Belgium
10:30-11:00 ●	**2nd Keynote lecture** (UPT & online) - Chairman Prof. Roberto Brighenti ***Design of 3D-printed lattice materials and shape-morphing structures*** Prof. Noy Cohen - Technion, Israel Institute of Technology, Haifa, Israel
11:00-11:30	**Coffee break (UPT)**
11:30-13:15	**1st Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Characterization of AM polymer-based materials 1*** Chairman: Prof. Andrea Spagnoli
11:30-11:45	***Effect of process parameters on mechanical properties in fused deposition modelling of polyethylene terephthalate glycol*** B. Mallikarjuna, Musunuri Shanmukha Vardhan, Harshini G V, Vasu M
11:45-12:00	***Effect of the notch opening angle of the static behaviour of PLA and carbon fibers reinforced PLA realized through AM technique*** Pietro Foti, Estera Valean, Liviu Marsavina, Filippo Berto
12:00-12:15	***Accelerated vibration-fatigue characterization for 3D-printed structures: Application to fused-filament-fabricated PLA samples*** Martin Česnik, Janko Slavič, Miha Boltežar
12:15-12:30	***Experimental and numerical investigation of fracture mechanics parameters on samples produced by selective laser sintering on two types of specimens*** Isaak Trajkovic, Milos Milosevic, Milan Travica, Bojan Medjo, Marko Rakin, Aleksandar Sedmak
12:30-12:45	***Compressive and flexural mechanical responses of components obtained through MSLA vat photopolymerization technology*** Matteo Montanari, Aleksa Milovanovic, Mihai P. Marghitas, Aleksandar Sedmak, Roberto Brighenti

12:45-13:00	***Evaluation of wall thickness effect on tensile properties of injected short fiber reinforced polymers*** Dan Micota, Alexandru Isaincu, Liviu Marsavina
13:00-13:15	***Thermo-Mechanical simulation of the powder bed of Polyamide 12 during the SLS Process*** Hanane Yaagoubi, Hamid Abouchadi, Mourad Taha Janan
13:15-14:30	**Lunch break (UPT)**
14:30-15:00	**3rd Keynote lecture** (online) - Chairman Prof. Liviu Marsavina ***Surface post-processing of Additive Manufactured metallic materials for enhanced performance*** Prof. Sara Bagherifard - Polytechnic of Milan, Italy
15:00-17:30	**2nd Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Characterization of AM metallic materials*** Chairman: Prof. Noy Cohen
15:00-15:15	***Effect of post-processing techniques on the surface roughness of Laser powder bed fusion processed Al12Si alloy*** Sai Kumar Balla, Manjaiah Mallaiah, Anand Kumar Subramaniyan
15:15-15:30	***Micro Raman Spectroscopy of apatite of composition La9.5Ge5.5Al0.5O26 calcined and sintered by electric and microwave heating*** Chetan Sharma, Kanchan L Singh, Anirudh P Singh
15:30-15:45	***Effect of laser parameters on the melt-pool dimensions and the thermo-mechanical properties of additively manufactured Inconel 718*** Samrat Rao, Anand Kumar Subramaniyan, Abhishek Shrivastava, Mohit Yadav
15:45-16:00	***Enhanced fatigue performance of laser directed energy deposition fabricated Ti6Al4V alloy using laser shock peening*** Sapam Ningthemba Singh, Ashish B. Deoghare
16:00-16:15	**Coffee break (UPT)**
16:15-16:30	***Post-processing of support structure of LPBF-processed Ti6Al4V part: Effect of process parameters*** Akshay Pathania, S. Anand Kumar, B.K Nagehsa
16:30-16:45	***Densification of Laser Powder Bed Fusion Manufactured Haynes 230: A Design of Experiment Approach*** Shreyas Nandakumar Harithsa, S. Anand Kumar, V. Rajkumar, B.K. Nagesha
16:45-17:00	***Fatigue Life and Crack Growth Rate Prediction of Additively Manufactured 17-4 PH Stainless Steel using Machine Learning*** Bijit Kalita, Abhiraj RC, Jayaganthan R
17:00-17:15	***In-situ neutron diffraction investigation of high-manganese steel with tailored crystallographic texture under cyclic loading*** M. Šmíd, J. Čapek, M. Jambor, D. Koutný, Ch. Haase, E. Polatidis
17:15-17:30	***Understanding the Formation and Impact of Large Particles on Porosity in SLM Processed Austenitic Stainless Steels 304L*** Filip Grygar
19:00-22:00	**Welcome reception at Casa Politehnicii 2** Bd. Mihai Eminescu 11, 300028 Timişoara Vasile Parvan 2, Timișoara, Romania (Google map)

Thursday, 9th March 2023

09:00-9:30 •	**4th Keynote lecture** (UPT & online) - Chairman Prof. Roberto Brighenti ***Programmable materials and 4D printing: advanced modeling and applications*** Prof. Giulia Scalet - Univ. of Pavia - Italy
9:30-11:15	**3rd Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Modeling and simulation of AM materials and processes*** Chairman: Prof. Dan Stoia
9:30-9:45	***Numerical evaluation of the infill pattern upon mechanical proprieties of 3D printed materials*** Laszlo Racz, Mircea Cristian Dudescu
9:45-10:00	***Computational modeling of laser metal deposition of titanium aluminide plate geometries*** B. Mallikarjuna
10:00-10:15	***Homogenization of the mechanical response of FFF-printed parts via RVE numerical model*** Luca Collini, Alberto Corvi
10:15-10:30	***Optimization of the numerical homogenization method for cellular structures manufactured by additive SLM technology*** Kevin Moj, Grzegorz Robak, Robert Owsiński
10:30-10:45	***Numerical and experimental study for DLP printed specimens from dental resin under Charpy impact tests*** Andrei Zoltan Farkas, Sergiu-Valentin Galatanu, Cosmin Florin Popa, and Riham Nagib
10:45-11:00	***A viscoplastic model with non-affine deformation and rotation of a distribution of embedded fibers*** J. Ciambella, M.B. Rubin
11:00-11:15	***Finite element machining simulations of Cu/Ag bicrystal*** Srihari Dodla
11:15-11:30	**Coffee break (UPT)**
11:30-13:15	**4th Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Characterization of AM metallic materials and composites 1*** Chairman: Prof. Aleksandar Sedmak
11:30-11:45	***Fatigue life time assessment and crack growth rate analysis in Ni-based alloy 699 XA at elevated temperatures*** Ivo Šulák, Tomáš Vražina, Mei-Lin Chen, Benedikt Nowak, Bhupesh Verma
11:45-12:00	***Facile production of high-temperature titanium aluminide powders for directed energy deposition technology*** B. Mallikarjuna, S. Anand Kumar, Nagesha BK
12:00-12:15	***Morphological and mechanical characterization of 3D printed hydroxyapatite at micro and nano scale*** Luca D'Andrea, Dario Gastaldi, Francesco Baino, Enrica Verné, Pasquale Vena
12:15-12:30	***Metal Technologies in Additive Manufacturing*** Milan Miščević, Djordje Dihovični, Aleksandra Mitrović, Nada Ratković Kovačević

12:30-12.45	***Influence of post-heat treatment on microstructure and hardness on electron beam welded joint of Ti6Al4V parts manufactured via laser powder bed fusion technology*** S Anand Kumar, R. Damodran, Randhir Kumar Singh, S. Cyril Joseph Daniel, Adarsh K. Hegde, BK Nagesha
12:45-13.00	***Microstructural characterization and mechanical behaviour of laser powder bed fusion stainless steel 316L*** Davide Crisafulli, Stanislava Fintová, Dario Santonocito, Danilo D'Andrea
13:00-13:15	***A technique for estimation of cyclic stress-strain curves using an optical strain measurement and its application to additively manufactured AlSi10Mg*** Halama Radim, Paška Zbyněk, Hajnyš Jiří
13:15-14:30	**Lunch break (UPT)**
14:30-16:15	**5th Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***AM in bio-related applications, health, and medicine*** Chairman: Prof. Giulia Scalet
14:30-14:45	***3D-customized PCL/β-TCP composite scaffold for hard tissues restoration*** Benedetta Ghezzi, Ruben Foresti, Luisa P. Scialoia, Biagio Matera, Matteo Meglioli, Andrea Toffoli, Guido M. Macaluso, Simone Lumetti
14:45-15:00	***The role of 3D printing in rehabilitation*** Andrea Demeco, Cosimo Costantino, Antonio Frizziero, Chiara Martini, Paolo Perini, Ruben Foresti
15:00-15:15	***Fibrous scaffolds for tissue engineering applications: experiments and modeling*** Michele Terzano, Maximilian Wollner, Malte Rolf-Pissarczyk, Gerhard A. Holzapfel
15:15-15:30	***3D Bioprinting of organoid-based scaffolds for toxicology investigation (OBST)*** Amparo Guerrero Gerboles, Maricla Galetti, Stefano Rossi, Francesco Paolo lo Muzio, Silvana Pinelli, Nicola Delmonte, Cristina Caffarra Malvezzi, Claudio Macaluso, Michele Miragoli, Ruben Foresti
15:30-15:45	***Additive Manufacturing for orthopedic implants: morphological and material characterization of SLM Ti6Al4V thin samples*** Francesca Danielli, Francesca Berti, Adelaide Nespoli, Valentina Lo Presti, Edoardo Sironi, Davide Ninarello, Tomaso Villa, Lorenza Petrini
15:45-16:00	***Use of 3D printed models for endovascular treatment planning of peripheral arterial disease. Preliminary results of a single-blinded randomised trial*** Chiara Martini, Paolo Perini, Claudio Bianchini Massoni, Alexandra Catasta, Massimo De Filippo, Andrea Demeco, Cosimo Costantino, Antonio Freyrie, Ruben Foresti
16:00-16:15	***Shelf-life of 4D bioprinted aerogel*** Ruben Foresti, Maria Nicastro, Silvana Pinelli, Giovanna Trevisi, Pasquale D'Angelo, Benedetta Ghezzi, Biagio Matera, Stefano Rossi, Alfredo Annicchiarico, Renato Costi, Guido M. Macaluso, Claudio Macaluso, Domenico Corradi
16:15-16:30	**Coffee break (UPT)**
16:30-17:00 ▪	**5th Keynote lecture** (online) - Chairman Prof. Andrea Spagnoli ***On the inverse design of flexible mechanical metamaterials*** Prof. Katia Bertoldi - Harvard University, Boston, MA, USA
17:00-17:30	**Lecture on European research funding** (UPT & online) ***Widening & ERA Calls 2023 & 2024*** Dana Dragomir, NCP Romania

18:00 -22:00 **Conference Dinner at Recas Winery**

Friday, 10th March 2023

9:00-9:30	**6th Keynote lecture** (UPT & online) - Chairman Prof. Liviu Marsavina ***3D-printed polymers for biomedical application*** Prof. Vadim Silberschmidt - Loughborough Univ., U.K.
9:30-11:15	**6th Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Characterization of AM metallic materials and composites 2*** Chairman: Prof. Aleksandar Sedmak
9:30-9:45	***Cyclic stress-strain behaviour of L-PBF Ni-based superalloy IN939 at 800 °C*** Ivo Kuběna, Tomáš Babinský, Luboš Náhlík, Ivo Šulák
9:45-10:00	***Review of the fatigue behavior in near-threshold conditions for notched and un-notched additively manufactured metallic materials, with a focus on AlSi10Mg lattice structures*** Francesco Collini, Giovanni Meneghetti
10:00-10:15	***Fatigue behavior of SLM maraging steel under variable-amplitude loading*** Zbigniew Marciniak, Ricardo Branco, Wojciech Macek, Cândida Malça
10:15-10:30	***Impact of Electron Beam Melting process recycling on defects and microstructure of Ti-6Al-4V powders*** Larisa Patricia Mocanu, Costanzo Bellini, Filippo Berto, Rosario Borrelli, Vittorio Di Cocco, Stefania Franchitti, Francesco Iacoviello, Seyed Mohammad Javad Razavi
10:30-10:45	***On the evaluation of the fatigue thresholds of additively manufactured metals*** Daniele Rigon, Giovanni Meneghetti
10:45-11:00	***Anomalous fatigue crack propagation behavior in near-threshold region of L-PBF prepared austenitic stainless steel*** Michal Jambor, Tomáš Vojtek, Pavel Pokorný, Daniel Koutný, Luboš Náhlík, Pavel Hutař, Miroslav Šmíd
11:00-11:15	***The effect of PLA fillers on mechanical properties of FDM components*** Dan Ioan Stoia, Cristina Vălean, Emanoil Linul
11:15-11:30	**Coffee break (UPT)**
11:30-13:30	**7th Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Characterization of AM polymer-based materials 2*** Chairman: Prof. Lubos Nahlik
11:30-11:45	***Influence of printing orientation on the tensile strength of specimens made of PA12 using SLS*** Ivana Jevtić, Goran Mladenović, Miloš Milošević, Aleksa Milovanović, Isaak Trajković, Milan Travica
11:45-12:00	***Investigating the effect of raster orientation on fracture behavior of 3D-printed ABS specimens under tension-tear loading*** Amir Nabavi-Kivi, Majid R. Ayatollahi, Seyed Mohammad Javad Razavi
12:00-12:15	***Temperature and Thermal Aging Effects on the Mechanical Response of Polycarbonate Materials*** Tamas Krausz, Cosmin-Denis Topircean, Cosmin-Florin Popa, Lucian Rusu, Liviu Marsavina
12:15-12:30	***Examination of mechanical characteristics of ABS and ABS-like materials*** Zorana Golubovic, Božica Bojovic, Ljubiša Petrov, Aleksandar Sedmak, Aleksa

	Milovanovic, Žarko Mišković, Miloš Milošević
12:30-12.45	***The influence of nutshell on FDM parts in the Shear test*** Cosmin-Florin Popa, Sergiu-Valentin Galaţanu, Tamas Krausz, Liviu Marşavina
12:45-13.00	***On the mixed mode fracture of DLP manufactured SCB specimens*** Mihai Marghitas, Liviu Marsavina, Cosmin Popa, Roberto Brighenti
13:00-13.15	***The influence of wall thickness on the fracture toughness of short fiber reinforced polymers obtained using single edge notch test specimens*** Alexandru Isaincu, Dan Micota, Liviu Marsavina, Viorel Ungureanu
13:15-13.30	***Layer thickness influence on impact properties of FDM printed PLA material*** Aleksa Milovanović, Sergiu-Valentin Galaţanu, Aleksandar Sedmak, Liviu Marşavina, Isaak Trajković, Cosmin-Florin Popa, Miloš Milošević
13:30-14:30	**Lunch break (UPT)**
14:30-16:45	**8th Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***Applications & advancements in AM materials and structures*** Chairman: Prof. Dan Stoia
14:30-14:45	***Inter and Intra-Surface Topography Comparison of Gecko-Inspired features fabricated by 3D printing*** Shubham Sharma, S. Anand Kumar , R. Uma Sankar
14:45-15:00	***3D Printing of the parts of the Library automation system*** Goran Vojnović, Nada Ratković Kovačević, Djordje Dihovični, Dragan Kreculj
15:00-15:15	***A Comprehensive Review of the Additive Manufacturing Process*** Anand Prakash Dwivedi, Charalampos Haris Doumanidis
15:15-15:30	***Structural properties of components manufactured using the Additive Manufacturing process: a review*** Anand Prakash Dwivedi, Charalampos Haris Doumanidis
15:30-15:45	***Tensile properties of 3D-printed PLA specimens: optimization of FDM process parameters*** Cristina Vălean, Marian Baban, Emanoil Linul
15:45-16:00	**Coffee break (UPT)**
16:00-16:15	***Unconventional use of FDM printing method for testing the delamination of PVA material for different layer height*** Mina Šibalić, Aleksandar Vujović, Jelena Šaković Jovanović
16:15-16:30	***Laser Additive Manufacturing Techniques*** Milesa Srećković, Aleksandar Bugarinović, Nada Ratković Kovačević, Željka Tomić, Stanko Ostojić, Aleksander Kovačević
16:30-16:45	***Mechanical Behaviour of Recycled FDM Printed Parts from PETG in the Circular Economy*** Sergiu-Valentin Galaţanu, Mihai-Petru Mărghitaş, Estera Vălean, Corina Şoşdean, Cosmin-Florin Popa, Linul Emanoil, Liviu Marşavina
16:45-17:15 ■	**7th Keynote lecture** (UPT & online) - Chairman Prof. Aleksandar Sedmak ***The critical distance concept to perform static and fatigue assessment of notched additively manufactured polymer*** Prof. Luca Susmel - Univ. of Sheffield, U.K.
19:00 -22:00	**Conference dinner at Casa Politehnicii 2** (SIRAMM Networking event) Bd. Mihai Eminescu 11, 300028 Timişoara Vasile Parvan 2, Timișoara, Romania (Google map)

Saturday, 11th March 2023

9:00-9:30 •	**8th Keynote lecture** (UPT & online) - Chairman Prof. Saveria Spiller ***Upscaled architected carbon and its potential in engineering applications*** Prof. Jan Torgersen - TU Munich, Germany
9:30-11:15	**9th Session** (UPT & online) (12 min presentation + 3 min Qs&As) ***4D printing and AM metamaterials*** Chairman: Prof. Roberto Brighenti
9:30-9:45	***Defect sensitivity mitigation in the mechanical behavior of 3D printed lattice metamaterials through a soft elastomeric matrix*** Matteo Montanari, Roberto Brighenti, Andrea Spagnoli
9:45-10:00	***Numerical and Experimental Analysis of Quilling Inspired Metamaterials*** Vasilica-Ioana Cimpoieș, Mircea Cristian Dudescu
10:00-10:15	***Experimental and numerical investigation on the energy absorbing capability of green additively manufactured multiphase cellular structures*** Alberto Corvi, Luca Collini, Corrado Sciancalepore
10:15-10:30	***Controlling wrinkling patterns in thin sheets coated with 3D printed rigid elements*** Riccardo Alberini, Roberto Brighenti, Matteo Montanari, Fabrizio Moroni, Andrea Spagnoli
10:30-10:45	***Testing of 3D printed precise positioning mechanism's creep*** Marko Horvatek, Filip Posilović
10:45-11:00	***Highlights on the Mechanical Properties of Extruded Filament in FDM 3D Printing*** Dan Ioan Stoia, Anghel Cernescu
11:00-11:15	***Effect of printing orientation on mode I fracture toughness of DLP printed UV sensitive resin specimens*** Marian Baban, Emanoil Linul
11:15-11:45	**Closing of the Conference** Prof. Liviu Marsavina, Prof. A. Sedmak, Prof. R. Brighenti
12:00-13:30	**Timisoara - European Capital of Culture City Tour**

List of Keynote lectures

& Abstracts

Keynote lectures

Keynote lecture

Active rheology control for additive manufacturing of concrete structures

Geert de Schutter

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ABSTRACT

Introduction
Workability of concrete is very important for casting and processing. Reaching a target workability for a specific application is typically based on the use of superplasticizers within the mix design. Nevertheless, the workability achieved on the construction site can deviate from the intended level, without further options for adjustment post-mixing. Another workability challenge is the existence of contradicting requirements in different steps of the process. While pumping, the fresh concrete should be sufficiently flowable, in order to reduce pumping pressures. After filling the formworks, the concrete should be stiff fast enough, to limit formwork pressures. For 3D printing of concrete, the required change in rheological properties is even more crucial: from flowable while pumping, over extrudable within the nozzle, to stiff immediately after extrusion. This is related to the three key requirements: pumpability, extrudability and buildability. A new methodology, developed at Ghent University, is based on active control methods to adjust the rheology of the fresh concrete while processing and is named Active Rheology Control (ARC), also including Active Stiffening Control (ASC) [1].

Active Rheology Control Using Responsive Nanoparticles
The first route to obtain ARC is based on magnetizable solid particles that are added to the cementitious material, e.g. magnetizable nanoparticles (MNP) consisting of Fe_3O_4 or more traditional cement-replacing materials like fly ash with some magnetic response. Upon applying a magnetic field, the magnetizable particles can form clusters, inducing stiffening on demand. Alternatively, the acceleration of the magnetizable particles temporarily gives the cementitious material some more liquid-like properties. Variable magnetic fields can be applied to actively control rheology, using the magnetizable particles as internal actuators. An example is given in Figure 1, showing the window of opportunity for ARC of a cement paste containing MNP of size 200 nm. The storage modulus (indicative for the elastic properties or stiffness of the material) is shown for a reference cement paste with water/cement ratio equal to 0.4, not containing MNP and without magnetic field (0.4-REF-0T). A comparable evolution of storage modulus is obtained in absence of magnetic field for a controllable cementitious paste with water/cement ratio 0.45 containing 3% (by mass) MNP (0.45-3MNP-0T). When a constant magnetic field is applied, a faster stiffening is obtained as shown by the top curve in Figure 1. In case of a varying magnetic field, a reduced stiffening is obtained as shown by the staggered lower curve. For more details, the reader is referred to [1].

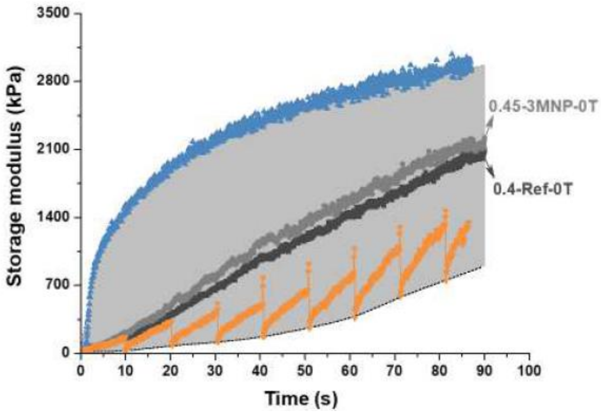

Figure 1: Potential adjustment window of storage modulus by means of a magnetic field with strength 0.5 T applied to cement paste containing magneto-responsive nanoparticles.

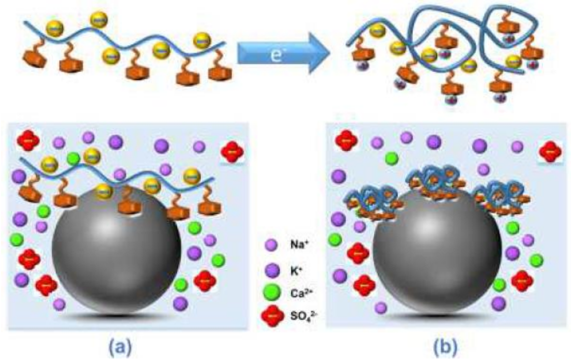

Figure. 2: switchable superplasticizer and mode of action. (a) poly(MAA-co-TEMPO) shows an extended polymer chain adsorbed onto cement particles, and (b) poly(MAAco-TEMPO+) forms coils due to the intramolecular interactions between the positive and negative charges in the polymer.

Active Rheology Control Using Switchable Superplasticizers

Another ground-breaking methodology is the use of switchable superplasticizers. The latest generation type of superplasticizers (also referred to as polycarboxylate ethers, PCE), can be given new functionalities by incorporating responsive elements into the polymer architecture. One example is shown in Figure 2, representing a comb copolymer consisting of a classical backbone with negative charges (MAA) and of side changes of a new type, namely TEMPO.
This side chain on the one hand can provide steric hindrance, and on the other hand can be triggered by an electric signal to become positively charged. Upon electric triggering, the positive charges of TEMPO+ will counterbalance negative charges form the backbone, reducing the adsorption capacity to the cement grain surface. In this way, a controllable superplasticizer is obtained, enabling active rheology control by moderating the adsorption capacity through external electric signals. In principle, this control mechanism is reversible. For more details, reference is made to [1].

Conclusion

At a fundamental materials science level, the concept of active rheology control (ARC), including active stiffening control (ASC), has been shown at paste level following two different routes, following a particles route as well as a polymer-based route. Further upscaling steps are ongoing, also in view of application to 3D printing of concrete.

REFERENCE

[1] G. De Schutter, K. Lesage, *Active Rheology Control of Cementitious Materials*, Taylor&Francis, 2023 (available in Open Access)

Keynote lecture

Design of 3D-printed thermally activated shape-morphing structures

Noy Cohen[1], Tamara Hanuhov[1]

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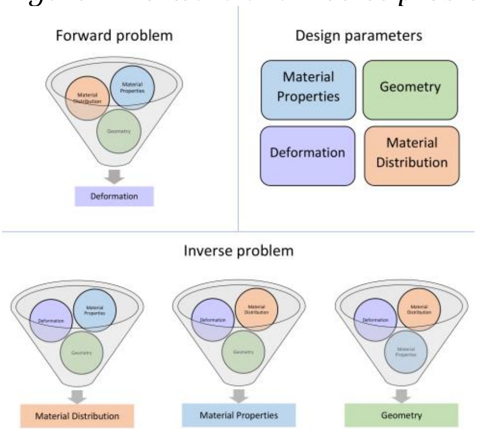
Email: noyco@technion.ac.il [1]

ABSTRACT

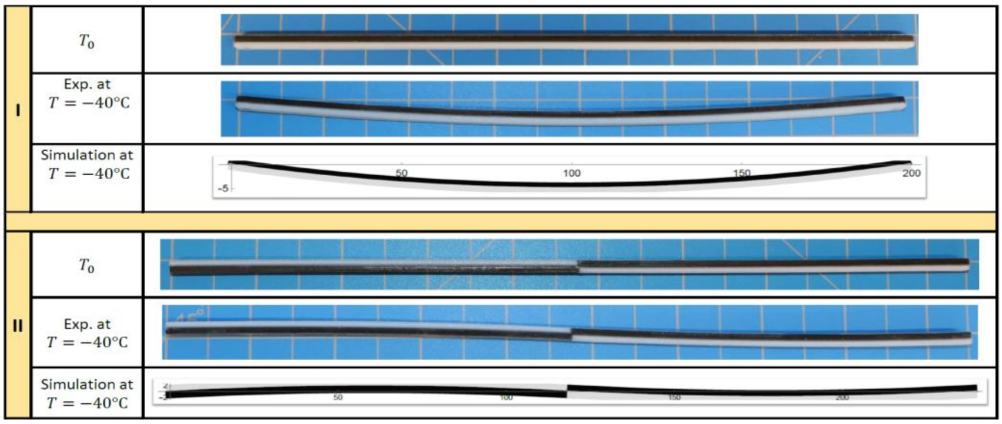
Shape morphing structures can change their shape in response to external stimuli such as thermal excitation and hydration. This ability is often employed to advance functionality and perform work in applications from many fields, including actuators, soft robotics, and biomedical devices. In classical mechanics, the referential configuration and the material properties and distribution of a structure are prescribed, and the deformed configuration that results from the application of an external stimulus can be determined. This case is often referred to as the forward problem. However, to capitalize on the potential of shape morphing structures, an inverse design tool that accepts a target shape as an input and computes the initial material properties, distribution, and geometry is required (see Fig. 1). To tackle this challenge, simple models that can predict the stimulus-driven response must be derived.

Figure 1: Forward and inverse problem



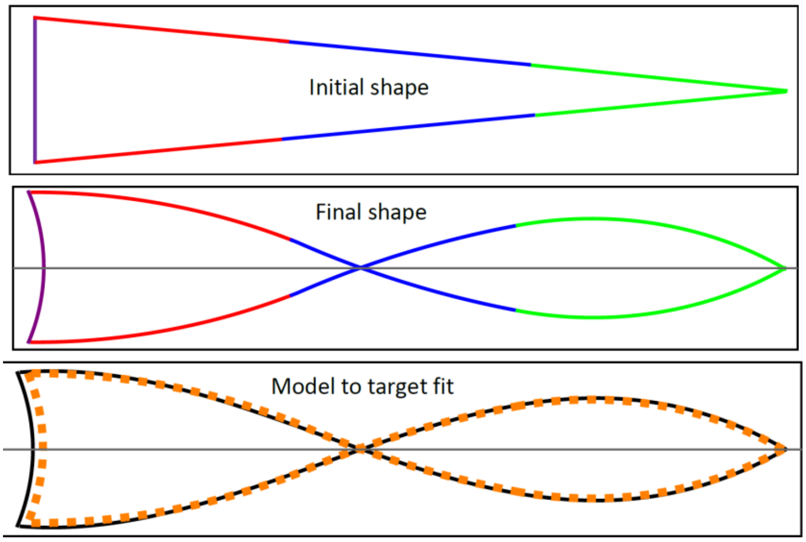
In this presentation I will introduce the moderate rotation theory, which is an extension of

Figure 2: Experimental results and model-based simulations.



linear elasticity that accounts for moderate-to-large rotations, within the context of thermomechanics [1-3]. Using variational principles, implicit relations between the thermo-mechanical response, the thermo-mechanical properties, the geometry, and the material distribution are developed [2]. To validate the model, bi-layer beams with different material distributions were 3D-printed and subjected to thermal excitation. As shown in Fig. 2, the model accurately captures the experimental results.
The model was employed to develop an inverse design algorithm for struts and strut-based structures [3]. This algorithm accepts a target function as an input and computes the required material properties, the distribution, and the geometry that are required to achieve the desired deformation. I show that the solution to the inverse problem is not unique, thereby providing flexibility in the design. To demonstrate the merit of this inverse design tool, two representative examples will be presented – (1) a simple target function and (2) a complex target shape that requires an in-plane deformation of an initial arrangement of struts, as illustrated in Fig. 3.

Figure 3: A representative example of a fit to target shape.



The proposed framework provides principle guidelines for the inverse design of thermally activated shape morphing structures. Thanks to the simplicity of the framework, the concepts presented here can be expanded to other stimuli.

REFERENCES

[1] Cohen N, McMeeking RM, and Begley MR, "Modeling the non-linear elastic response of periodic lattice materials", Mechanics of Materials, 129: 159-168, 2019.
[2] Hanuhov T and Cohen N, " Thermally induced deformations in multi-layered polymeric struts", International Journal of Mechanical Sciences, 215: 106959, 2022.
[3] Hanuhov T and Cohen N, "Inverse design of 3D-printed thermally activated shape-morphing structures", Under Review, 2023.

Keynote lecture

Surface Post-processing of Additive Manufactured Metallic Materials for Enhanced Performance

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ABSTRACT

Introduction
Laser powder bed fusion (LPBF), as one of the widely used additive manufacturing (AM) technologies, offers prominent advantages in fabrication of parts with complex geometries. However, the layer-by-layer nature of fabrication in LPBF, besides the complex thermo-physical phenomena and the high cooling rate, result in the formation of various internal and surface defects. Surface roughness is known as a limiting factor for the performance of additive manufactured materials. The surface of as-built parts are often characterized by high density of randomly positioned or agglomerated partially melted powder particles [1]. Besides wear, scratch and corrosion resistance, fatigue life and endurance are also highly affected by surface quality. Therefore, post-treatments are required to modulate the negative effects of the internal and surface defects on the mechanical properties of LPBF materials. However, their parameters should be customized based on the material properties and shape of the part to be treated.

Objectives
This study evaluates the effect of various impact-based surface treatments and their combination with thermal and chemical post-treatments on fatigue performance of AlSi10Mg specimens prepared using laser powder bed fusion (LPBF).

Methodology
Various post-processing methods including thermal treatment as well as mechanical, laser-based and chemical surface treatments were considered. These post-treatments include T6 heat treatment, shot peening, severe vibratory peening, ultrasonic nanocrystalline surface modification, laser shock peening, chemical polishing and electro-chemical polishing. The combination of these treatments as hybrid processes were also applied to the samples. Experimental characterizations were carried out to study the effects of these post-treatments on microstructure, surface morphology and roughness, porosity, hardness, residual stresses, and fatigue behavior of the AlSi10Mg samples.

Results
The results confirmed the overall favourable effect of the applied post processing treatments in enhancing the fatigue performance of the samples. The surface treatments led to considerable reduction in surface roughness. The mechanical treatments also induced residual stresses, surface layer work hardening, and in some cases led to grain refinement, the

synergistic effects of which contributed to the improved fatigue performance. The heat treatment applied to the bulk of the materials also had an important role in homogenizing the microstructure and releasing the undesirable residual stresses induced during fabrication.

REFERENCES

[1] Maleki E, Bagherifard S, Bandini M, Guagliano M. Surface post-treatments for metal additive manufacturing: Progress, challenges, and opportunities. Additive Manufacturing, 2021;37: 101619.
[2] Maleki E, Bagherifard S, Sabouri F, Bandini M, Guagliano M, Hybrid thermal, mechanical and chemical surface post-treatments for improved fatigue behavior of laser powder bed fusion AlSi10Mg notched samples, Suface and Coatings Technology, 2022; 430: 127962.
[3] Maleki E, Bagherifard S, Unal O, Bandini M, Guagliano M, The effects of microstructural and chemical surface gradients on fatigue performance of laser powder bed fusion AlSi10Mg. Materials Science and Engineering: A, 2022; 840: 142962.

Keynote lecture

Programmable materials and 4D printing: advanced modeling and applications

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ABSTRACT

Programmable materials are next-generation materials with the ability to change their morphology, physical properties, and/or functionalities in a programmable spatial and temporal sequence, under the application of an external stimulus. Programmable behavior is a highly demanded feature since it allows the material to adapt to the application need or to dynamic environmental variables.

When coupled with 4D printing, these materials have a huge potential in realizing innovative structures with both programmable behavior and customized architectures. In fact, 4D printing is a manufacturing approach that produces objects with complex geometries and capable of transforming themselves over time (the fourth dimension) after being manufactured, under the application of external stimuli [1].

However, the design of 4D printed programmable materials and structures is not trivial and requires careful attention at different levels, i.e., during printing, experimental characterization, modelling, and simulation.

This work will present our recent research efforts to achieve programmability in 4D printed structures. Particularly, we will focus on light- and temperature-responsive structures manufactured via extrusion-based and resin 3D printing. Experimental and numerical results will be presented and discussed. A special focus will be given to macroscopic phenomenological material modeling, combined with finite element analysis and density-based topology optimization. New application examples concerning soft actuators, metamaterials, and pharmaceutical devices will be provided [2-4].

REFERENCES

[1] F. Momeni, S.M.M. Hassani, X. Liu, and J. Ni, "A review of 4D printing", Mater. Des., 122, 42−79 (2017).

[2] C. Pasini, N. Inverardi, D. Battini, G. Scalet, S. Marconi, F. Auricchio, and S. Pandini, "Experimental investigation and modeling of the temperature memory effect in a 4D-printed auxetic structure", Smart Mater. Struct., 31, 095021 (2022).

[3] Y. Wang, E. Sachyani Keneth, A. Kamyshny, G. Scalet, F. Auricchio, and S. Magdassi, "4D Multimaterial Printing of Programmable and Selective Light-Activated Shape-Memory Structures with Embedded Gold Nanoparticles", Adv. Mater. Tech., 2101058 (2021).

[4] N. Inverardi, G. Scalet, A. Melocchi, M. Uboldi, A. Maroni, L. Zema, A. Gazzaniga, F. Auricchio, F. Briatico-Vangosa, F. Baldi, and S. Pandini, "Experimental and computational analysis of a pharmaceutical-grade shape memory polymer applied to the development of gastroretentive drug delivery systems", J. Mech. Behav. Biom. Mater., 124, 104814 (2021).

Keynote lecture

On the inverse design of flexible mechanical metamaterials

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ABSTRACT

From wearable devices and energy-absorbing systems to scaffolds and soft robots, many applications would benefit from the inverse design of materials with a target nonlinear mechanical response. For example, to enhance tissue regeneration, scaffolds should be designed to match the nonlinear response of the surrounding native tissue. Further, wearable and flexible electronics must accommodate the large deformations of soft biological tissues and reduce the stresses induced on the skin by their presence. Finally, it has been shown that reusable, rate independent and self-recoverable energy absorbing materials can be realized by engineering structures that display nonlinear responses characterized by sudden snapping-induced load drops.

Mechanical metamaterials have recently emerged as an effective platform to engineer systems with mechanical behaviors that are governed by geometry rather than composition. While initial efforts have focused on the design of metamaterials with negative properties in the
linear regime, more recently it has been shown that highly nonlinear responses (often accompanied by large internal rotations) can be triggered by introducing into the architectures slender elements that are prone to elastic instabilities. These nonlinear behaviors not only display very rich physics but can also be exploited to enable advanced functionalities, such as shape morphing, energy absorption and programmability. Although it is well known that such functionalities can be tuned by altering the underlying geometry, the identification of architectures that result in a target nonlinear response is a non-trivial task.

Here, we present a framework to design mechanical metamaterials with target nonlinear response. Our starting point is a metamaterial based on hinged rotating squares, which has recently attracted significant interest as it displays effective negative Poisson's ratio and supports the propagation of solitary pulses. We first show that changes in the shape of the quadrilateral units lead to a wide range of mechanical responses and identify the key ingredients governing such behaviors. Then, we use optimization algorithms to efficiently identify geometries that exhibit target nonlinear behaviors both in the static and dynamic regime. The proposed strategy holds potential for a range of applications that benefit from systems with a target nonlinear mechanical behavior, as demonstrated by the design of energy absorbing systems, soft robots and morphing structures.

Keynote lecture

3D-printed polymers for biomedical applications

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ABSTRACT

Synthetic polymers have transformed the manufacture of medical devices, implants and soft-tissue prostheses since their conception at the turn of the 20th century [1]. Their widespread adoption in the biomedical sector was driven by their intrinsic functionality (biocompatibility, mechanical robustness, chemical resistance), processability (ease of modification, mould-ability and batch consistency) and their inexpensiveness [2]. Furthermore, their carbon-chain structure is closer to that of human tissues compared to other inorganic materials [2]. Hence, they are the largest and most versatile structural materials in the biomedical field, with a net worth of $1 billion per annum [3, 4]. Unlike present day, whereby materials are fabricated with specific function in mind, the first polymeric biomaterials existed as commercially available plastics, which were used experimentally [5]. Such examples include polymethyl-methacrylate (PMMA), which was used to produce the first intraocular lenses (1930's), after it was noted that the material gave minimal signs of rejection [6]. Decades later, a wealth of polymers were suggested for biomedical application: polydimethylsiloxane (PDMS; breast implants and heart valves), ultra-high molecular weight polyethylene (UHMWPE; acetabular cups and total joint replacement), high-density polyethylene (HDPE; tendon reconstruction), PMMA (bone cement and hard contact lenses), polyurethanes (vascular grafts and stents), polyether ether ketone (PEEK; spinal cages and suture anchors) and polyester (plasters and surgical gowns), which all play a prominent role in current medical practice [7].
Additive manufacture known interchangeably as 3D printing (3DP) is a rapid prototyping technology that enables the user to convert digital design files (STL) into three-dimensional components layer by layer [8]. With relatively short production rates and the ability to fabricate complex, organic geometries with varying compositions (functional grading), the technology has generated significant traction in medical research [9, 10]. As result, this actively growing research area introduced a variety of orthopaedic implants, scaffolds for soft- and hard-tissue generation, drug-delivery platforms, dental products, medical devices, bioinks and coatings via the processing of conventional polymeric biomaterials [11, 12]. Notably, harsh mechanical and thermal processing cycles impact the intrinsic features of these polymers, resulting in the manufacture of components with undesirable properties (chemical, biological, topological, mechanical and thermal) as well as poor surface finish and geometry [13],[14],[15],[16]. Availability of commercial, "off the shelf" polymeric biomaterials for AM is rather limited. Hence, there is need to develop and characterise polymeric materials for 3DP and the production of next-generation medical products.

REFERENCES

[1] D. Feldman, Polymer history, Des. Monomers Polym., 2008, Vol. 11, pp. 1–15. doi:10.1163/ 156855508X292383.
[2] M.F. Maitz, Applications of synthetic polymers in clinical medicine, Biosurf. Biotribol., 2015, Vol. 1, pp. 161–176. doi:10.1016/j.bsbt.2015.08.002.
[3] L.A. Utracki, Introduction to polymer blends. In: Polymer Blends Handbook. Eds: L.A. Utracki, C. Wilkie, Springer, 2014, pp. 1–122. doi:10.1007/0-306-48244-4_1.
[4] W. He, R. Benson, Polymeric Biomaterials. In: Handbook of Polymer Applications in Medicine and Medical Devices. Eds K. Modjarrad, S. Ebnesajjad, Elsevier, 2014, pp. 55-76.
[5] D.E. Heath, S.L. Cooper, The development of polymeric biomaterials inspired by the extracellular matrix, J. Biomater. Sci. Polym. Ed., 2017, Vol. 28, pp. 1051–1069. doi: 10.1080/09205063.2017.1297285.
[6] C.E. Letocha, Follow-up of 3 patients with Ridley intraocular lens implantation, J. Cataract Refract. Surg., 1999, Vol. 25, pp. 587–591. doi:10.1016/S0886-3350(99)80061-3.
[7] A.J.T. Teo, A. Mishra, I. Park, Y.J. Kim, W.T. Park, Y.J. Yoon, Polymeric Biomaterials for Medical Implants and Devices, ACS Biomater. Sci. Eng., 2016, Vol. 2, pp. 454–472. doi: 10.1021/acsbiomaterials.5b00429.
[8] I. Gibson, D.W. Rosen, B. Stucker, Additive Manufacturing Technologies. 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Springer, 2010. doi:10.1007/978-1-4419-1120-9.
[9] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C.B. Williams, C.C.L. Wang, Y.C. Shin, S. Zhang, P.D. Zavattieri, The status, challenges, and future of additive manufacturing in engineering, Comput. Des. 2015, Vol. 69, pp. 65–89. doi:10.1016/j.cad.2015.04.001.
[10] S. Derakhshanfar, R. Mbeleck, K. Xu, X. Zhang, W. Zhong, M. Xing, 3D bioprinting for biomedical devices and tissue engineering: A review of recent trends and advances, Bioact. Mater. 2018, Vol. 3, pp. 144–156. doi:10.1016/j.bioactmat.2017.11.008.
[11] S. V Murphy, A. Atala, 3D bioprinting of tissues and organs., Nat. Biotechnol. 2014, Vol. 32, pp. 773–785. doi:10.1038/nbt.2958.
[12] S.C. Ligon, R. Liska, J. Stampfl, M. Gurr, R. Mülhaupt, Polymers for 3D printing and customized additive manufacturing, Chem. Rev., 2017, Vol. 117, pp. 10212–10290. doi:10.1021/acs. chemrev.7b00074.
[13] J.R.C. Dizon, A.H. Espera, Q. Chen, R.C. Advincula, Mechanical characterization of 3D-printed polymers, Addit. Manuf. 2018, Vol. 20, pp. 44–67. doi:10.1016/j.addma.2017.12.002.
[14] R.D. Goodridge, R.J.M. Hague, C.J. Tuck, An empirical study into laser sintering of ultra-high molecular weight polyethylene (UHMWPE), J. Mater. Process. Technol. 2010, Vol. 210, pp. 72–80. doi:10.1016/j.jmatprotec.2009.08.016.
[15] M. Vaezi, S. Yang, Extrusion-based additive manufacturing of PEEK for biomedical applications, Virtual. Phys. Prototyp. 2015, Vol. 10, pp. 123–135. doi:10.1080/17452759.2015. 1097053.
[16] T.J. Hinton, A. Hudson, K. Pusch, A. Lee, A.W. Feinberg, 3D printing PDMS elastomer in a hydrophilic support bath via freeform reversible embedding, ACS Biomater. Sci. Eng., 2016, Vol.2, pp. 1781–1786. doi:10.1021/acsbiomaterials.6b00170.

Keynote lecture

The Critical Distance concept to perform static and fatigue assessment of notched additively manufactured polymers

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ABSTRACT

Additive Manufacturing (AM) allows complex forms to be incorporated into components to be used in advanced structural applications. As stated by ASTM F42, AM is *"the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"*. As per this definition, AM is an "additive" manufacturing process that can be more effectual than traditional "subtractive" fabrication technologies. This holds true especially in the presence of complex geometries that would be difficult to be fabricated via traditional manufacturing processes.
As far as polymers are concerned, certainly polylactide (PLA) is the most common material that are used along with commercial, low-cost 3D-printers. PLA can be additively manufactured by making use of powders, wires and flat sheets that are melted using a variety of different techniques, with fusion deposition modelling being the most popular technology available in the market. PLA is a biodegradable, absorbable and biocompatible polymer that is widely adopted to manufacture components used in biomedical, automotive and mechanical applications.
As mentioned earlier, one of the most relevant peculiarities of AM is that components having complex forms can be manufactured by reaching a very high level of accuracy in terms of both shape and dimensions. As far as the design problem is concerned, the fact that 3D-printed components can contain very complex geometrical features results in localised stress concentration phenomena, with stress raisers reducing markedly the fatigue strength of the components themselves. Therefore, reliable and straightforward design methodologies are needed to perform both the static and the fatigue assessment of additively manufactured (AM) materials accurately.
The Theory of Critical Distances (TCD) is the name which has been given to a group of design methodologies that all make use of a material length scale parameter to post-process the local linear-elastic stress fields in the vicinity of the crack initiation locations. In the manufacturing scenario depicted above, certainly the TCD is the most powerful candidate to be employed systematically in industry to design AM components against static and fatigue loading because: (i) it is successful independently of shape and sharpness of the notch being designed; (ii) it models the material meso-structural features by using a suitable critical distance to calculate the design stress; (iii) the relevant stress fields can be determined by modelling the mechanical behaviour of the material under investigation by adopting a simple linear-elastic constitutive law; (iv) the design stress can be determined by post-processing the results from

standard linear-elastic Finite Element (FE) models, with the same numerical solid models being used to inform also the manufacturing process.
In this scenario, the present paper reviews the research work we have supervised over the last decade [1-14] to devise a robust TCD-based methodology suitable for performing the static and fatigue assessment of notched 3D-printed PLA.

REFERENCES

[1] Ahmed, A. A., Susmel, L. Additively manufactured PLA: strength and fracture behaviour under static loading. In: Proceedings of The BSSM's 12th International Conference on Advances in Experimental Mechanics, Sheffield, UK, 29-31 August, 2017.

[2] Ahmed, A. A., Susmel, L. Additively Manufactured PLA under static loading: strength/cracking behavior vs. deposition angle. Procedia Struct. Integr. 3, pp. 498–507, 2017.

[3] Ahmed, A. A., Susmel, L. On the use of length scale parameters to assess the static strength of notched 3D-printed PLA. Frattura Integr. Strutt., 11(41), pp. 252-259, 2017.

[4] Ezeh, O. H., Susmel, L. Designing additively manufacture notched PLA against static loading. In: Proceedings of International Symposium on Notch Fracture, Edited by S. Cicero et al., 29-31 March 2017, Santander, Spain, ISBN: 978-84-617-9611-3.

[5] Ahmed, A. A., Susmel, L. Crack paths in plain and notched specimens of additively manufactured PLA under static loading. In Proceedings of: The 6th International Conference on Crack Paths (CP 2018), Edited by: F. Berto, A. Carpinteri, Y. Hong, L. Pook, S. Vantadori, 19-21 September 2018, Verona, Italy.

[6] Ezeh, O. H., Susmel, L. On the fatigue strength of 3D-printed polylactide (PLA). Procedia Struct. Integr. 9, pp. 29-36, 2018.

[7] Ezeh, O. H., Susmel, L. Fatigue behaviour of additively manufactured polylactide (PLA). Procedia Struct. Integr. 13, pp. 728-734, 2018.

[8] Ahmed, A. A., Susmel, L. Estimating static strength of plain/notched PLA additively manufactured with different in-fill levels. In: Proceedings of the Fifth IJFatigue & FFEMS Workshop: Characterisation of Crack Tip Fields, Edited by M. Vormwald, Heidelberg, Germany, 8-10 April 2019, pp. 30-31 – ISBN: 978-3-939195-62-7.

[9] Ahmed, A. A., Susmel, L. A material length scale based methodology to assess static strength of notched additively manufactured polylactide (PLA). Fatigue Fract. Eng. Mater. Struct., 41(10), pp. 2071-2098, 2018.

[10] Ezeh, O. H., Susmel, L. Influence of the printing direction on the fatigue behaviour of 3D-printed polylactide (PLA). In: Proceedings of ESIAM19, Edited by F. Berto and J. Torgersen, Trondheim, Norway, 9-11 September 2019, p. 71.

[11] Ahmed, A. A., Susmel, L. Static assessment of plain/notched polylactide (PLA) 3D-printed with different in-fill levels: equivalent homogenised material concept and Theory of Critical Distances. Fatigue Fract. Eng. Mater. Struct., 42, pp. 883–904, 2019.

[12] Ezeh, O. H., Susmel, L. Reference strength values to design against static and fatigue loading polylactide additively manufactured with in-fill level equal to 100%. Mat. Design Process. Comm., e45, pp. 1-6, 2019.

[13] Ezeh, O. H., Susmel, L. Fatigue strength of additively manufactured polylactide (PLA): effect of raster angle and non-zero mean stresses. Int. J. Fatigue 126, pp. 319-326, 2019.

[14] Ezeh, O. H., Susmel, L. On the Notch Fatigue strength of additively manufactured polylactide (PLA). Int J Fatigue 136, 105583, 2020.

Keynote lecture

Upscaled architected carbon and its potential in engineering applications

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ABSTRACT

The field of architected carbon is a rapidly growing field [1], where the outstanding and tuneable properties of carbon meet geometrical design for performance enhancement. A wide range of applications are envisioned including novel electrode designs, carbon microelectromechanical systems, highly load bearing and lightweight structures, AFM tips and X-ray optical lenses [1–8]. The key enabler of this field are photopolymers that can be structured by photopolithography and that retain their shape during carbonization. Despite the prospect of this field, there are several challenges to be overcome, the main one being the achievable range of feature sizes. Whereas structures with absolute dimensions in the cm scale have been obtained, feature sizes within this domain only range from 160 µm to 200 nm [1,9,10]. Leveraging the knowledge from carbon fibre production, we can divide the carbonization process in two main stages; first, hetero atoms get eliminated and a conjuncted network forms between 300 and 500 °C, later, non-carbon atoms are fully removed and the aromatic content increases between 500 and 1200 °C [3,11].Yet the mechanisms affecting the geometry and feature sizes during this process have been overlooked despite their importance to particularly bulky but geometrically defined carbon structures with large cross sections. The parameter of significance is the surface to volume ratios (SVR), which has a rather high lower bound in the current state of the art. As a result, the current SVR in the field is in the range of 1.5 to 0.01 μm^{-1}, with only highly porous architectures achieved for the lowest SVRs so far [1,9,12,13].

In conventional glassy carbon production, diffusional transport of volatiles through the converting polymer matrix during carbonization sets the upper bound of producible volume [14,15]. This is linked to the transport distance and the degrees of freedom in transport directions within the polymeric feature [16]. In this presentation, we aim to overcome this limit and create the first macroscopic dimensionally stable carbon geometries that comply with a ISO test standard for tensile specimen. To this aim, we first explore and discuss the composition and mechanical properties of a commercial high temperature photopolymer (upCarbon). We study the effects of heating rate and isothermal steps in the temperature program used to carbonize porous scaffolds and rods with mm cross sections produced by two-photon polymerized (2PP). During the carbonization step, we present two thermal regimes with activation energies of ~79 and 169 kJ mol^{-1}, which we reason with mechanisms during the polymer's morphologic conversion between 300 - 500 °C. The temperature range

of the major dimensional shrinkage (300-440 °C, 50%) does not match the range of the largest alteration in elemental composition (440-600 °C, O/C 0.25-0.087%). We therefore optimized the thermal treatment to comprise an initial ramp (2 °C min-1 to 350 °C), an isothermal hold (14h), a post hold ramp (0.5 °C min-1 to 440 °C) and a final ramp (10 °C min-1 to 1000 °C). The resulting carbon structures are dimensionally stable, non-porous at the µm scale, and comprise an unprecedented variation in feature sizes (from cm to µm scale). The composition of the derived carbon material, the dimensional shrinkage and the electrical properties are investigated by energy dispersive x-ray spectroscopy (EDS), scanning electron microscopy (SEM) and four-point probe measurements, and interpreted with respect to the temperature program employed. Finally, we show how to create a dimensionally stable architecture of significantly higher volume as well as differing feature dimensions within one part. The scale achieved in this study reaches the cm domain and constitutes the largest bulk CAD defined carbon structures ever produced, to the best of our knowledge. We also show the fabrication of standard test specimens according to the ISO 527-1 standard and present initial macroscopic mechanical properties and their relation to the size and microstructure of the carbon architecture. The findings shall advance architected carbon to industrially relevant scales.

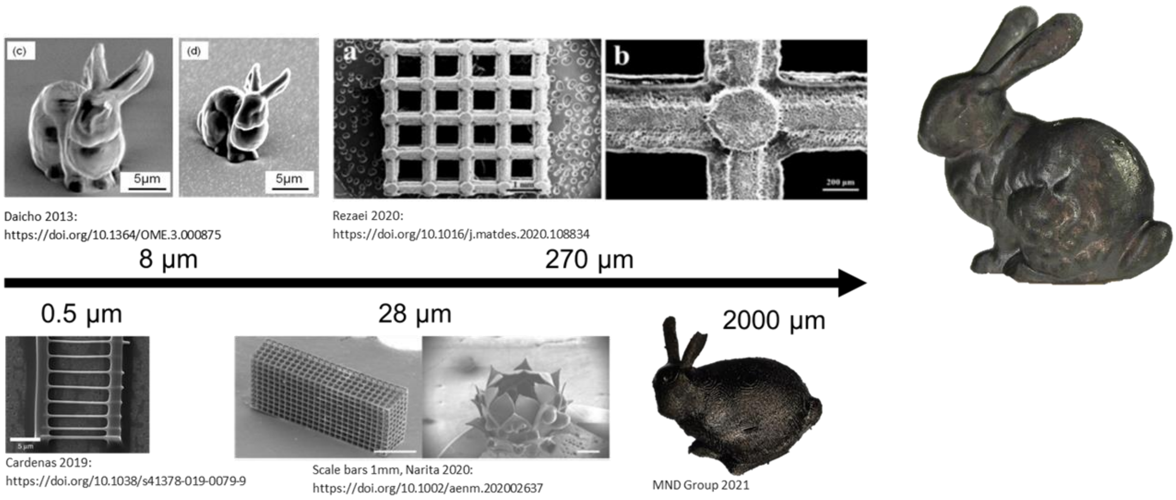

Figure 1: Upscaling architected carbon. On the left, features of the state of the art are presented together with the respective literature references. The two structures on the right (rabbit) are produced by the authors.

REFERENCES

[1] K. Narita, M.A. Citrin, H. Yang, X. Xia, J.R. Greer, 3D Architected Carbon Electrodes for Energy Storage, Advanced Energy Materials. 11 (2021) 2002637. https://doi.org/10.1002/aenm.202002637.

[2] D. Niblett, Z. Guo, S. Holmes, V. Niasar, R. Prosser, Utilization of 3D printed carbon gas diffusion layers in polymer electrolyte membrane fuel cells, International Journal of Hydrogen Energy. 47 (2022) 23393–23410. https://doi.org/10.1016/j.ijhydene.2022.05.134.

[3] R. Martinez-Duarte, SU-8 Photolithography as a Toolbox for Carbon MEMS, Micromachines. 5 (2014) 766–782. https://doi.org/10.3390/mi5030766.

[4] A. Zakhurdaeva, P.-I. Dietrich, H. Hölscher, C. Koos, J.G. Korvink, S. Sharma, Custom-Designed Glassy Carbon Tips for Atomic Force Microscopy, Micromachines. 8 (2017) 285. https://doi.org/10.3390/mi8090285.

[5] M.I. Sharipova, T.G. Baluyan, K.A. Abrashitova, G.E. Kulagin, A.K. Petrov, A.S. Chizhov, T.B. Shatalova, D. Chubich, D.A. Kolymagin, A.G. Vitukhnovsky, V.O. Bessonov, A.A. Fedyanin, Pyrolyzed microstructures made by two-photon polymerization: comparative study, in: 2021 Conference on Lasers and Electro-Optics Europe and European Quantum Electronics Conference (2021), Paper Cm_p_32, Optica Publishing Group, 2021: p. cm_p_32. https://opg.optica.org/abstract.cfm?uri=CLEO_Europe-2021-cm_p_32 (accessed February 20, 2023).

[6] J. Ye, L. Liu, J. Oakdale, J. Lefebvre, S. Bhowmick, T. Voisin, J.D. Roehling, W.L. Smith, M.R. Cerón, J. van Ham, L.B. Bayu Aji, M.M. Biener, Y.M. Wang, P.R. Onck, J. Biener, Ultra-low-density digitally architected carbon with a strutted tube-in-tube structure, Nat. Mater. 20 (2021) 1498–1505. https://doi.org/10.1038/s41563-021-01125-w.

[7] C.M. Portela, B.W. Edwards, D. Veysset, Y. Sun, K.A. Nelson, D.M. Kochmann, J.R. Greer, Supersonic impact resilience of nanoarchitected carbon, Nat Mater. 20 (2021) 1491–1497. https://doi.org/10.1038/s41563-021-01033-z.

[8] M. Islam, A.D. Lantada, M.R. Gómez, D. Mager, J.G. Korvink, Microarchitectured Carbon Structures as Innovative Tissue-Engineering Scaffolds, Advanced Engineering Materials. 22 (2020) 2000083. https://doi.org/10.1002/adem.202000083.

[9] B. Rezaei, J.Y. Pan, C. Gundlach, S.S. Keller, Highly structured 3D pyrolytic carbon electrodes derived from additive manufacturing technology, Materials & Design. 193 (2020). https://doi.org/10.1016/j.matdes.2020.108834.

[10] J. Bauer, A. Schroer, R. Schwaiger, O. Kraft, Approaching theoretical strength in glassy carbon nanolattices, Nature Materials. 15 (2016) 438–443. https://doi.org/10.1038/nmat4561.

[11] M. Al Aiti, D. Jehnichen, D. Fischer, H. Brünig, G. Heinrich, On the morphology and structure formation of carbon fibers from polymer precursor systems, Progress in Materials Science. 98 (2018) 477–551. https://doi.org/10.1016/j.pmatsci.2018.07.004.

[12] B. Bian, D. Shi, X. Cai, M. Hu, Q. Guo, C. Zhang, Q. Wang, A.X. Sun, J. Yang, 3D printed porous carbon anode for enhanced power generation in microbial fuel cell, Nano Energy. 44 (2018) 174–180. https://doi.org/10.1016/j.nanoen.2017.11.070.

[13] Z. Lyu, G.J.H. Lim, J.J. Koh, Y. Li, Y. Ma, J. Ding, J. Wang, Z. Hu, J. Wang, W. Chen, Y. Chen, Design and Manufacture of 3D-Printed Batteries, Joule. 5 (2021) 89–114. https://doi.org/10.1016/j.joule.2020.11.010.

[14] H. Maleki, L.R. Holland, G.M. Jenkins, R.L. Zimmerman, Determining the shortest production time for glassy carbon ware, Carbon. 35 (1997) 227–234. https://doi.org/10.1016/S0008-6223(96)00144-3.

[15] V. Uskoković, A historical review of glassy carbon: Synthesis, structure, properties and applications, Carbon Trends. 5 (2021) 100116. https://doi.org/10.1016/j.cartre.2021.100116.

[16] M.H. Klopffer, B. Flaconneche, Transport Properties of Gases in Polymers: Bibliographic Review, Oil & Gas Science and Technology - Rev. IFP. 56 (2001) 223–244. https://doi.org/10.2516/ogst:2001021.

Abstracts

1st Session

1. Characterization of AM polymer-based materials 1

Effect of process parameters on mechanical properties in fused deposition modelling of polyethylene terephthalate glycol

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ABSTRACT

Fused deposition modelling is one of the most inexpensive and efficient additive manufacturing methods. The products printed via FDM can showcase a varied sample of properties with the changes in the process parameters. The material chosen was Polyethylene Terephthalate Glycol (PETG) for its high impact resistance, chemical resistance, low density, and high ductility. PETG is widely available, having a vast range of applications from defense and medical to daily applications. The general extrusion temperature of PETG is above 240° C and has a glass transition temperature of 77°C. Towards this end, a review of the effects of various process conditions such as extrusion temperature, printing speed, and infill density experiments was designed under the Taguchi L_9 Orthogonal Array. Weight measurements of slicing software were compared against the FDM printed samples, and an error of less than 6% was noticed. About dimensional inspection for printed samples against the CAD files, an error of 10% has been observed. Higher tensile, flexural, and impact strengths have been observed for the samples (S4, S5, S6) having 25% infill density. Sample with 30% infill density, 245° C extrusion temperature, and 25 mm/s print speed has been found to have the highest ultimate tensile strength of 35.46 MPa (as shown in Figure 1). Compression strength has been increased with an increase in infill density from 1.08 kN to 2.1 kN. The impact strength of the samples (S4, S5, and S6) was highest, where the print speed was 25 mm/s.

Keywords: Fused Deposition Modelling, Polyethylene Terephthalate Glycol, Process Parameter, Mechanical Properties, Spectacle Frame

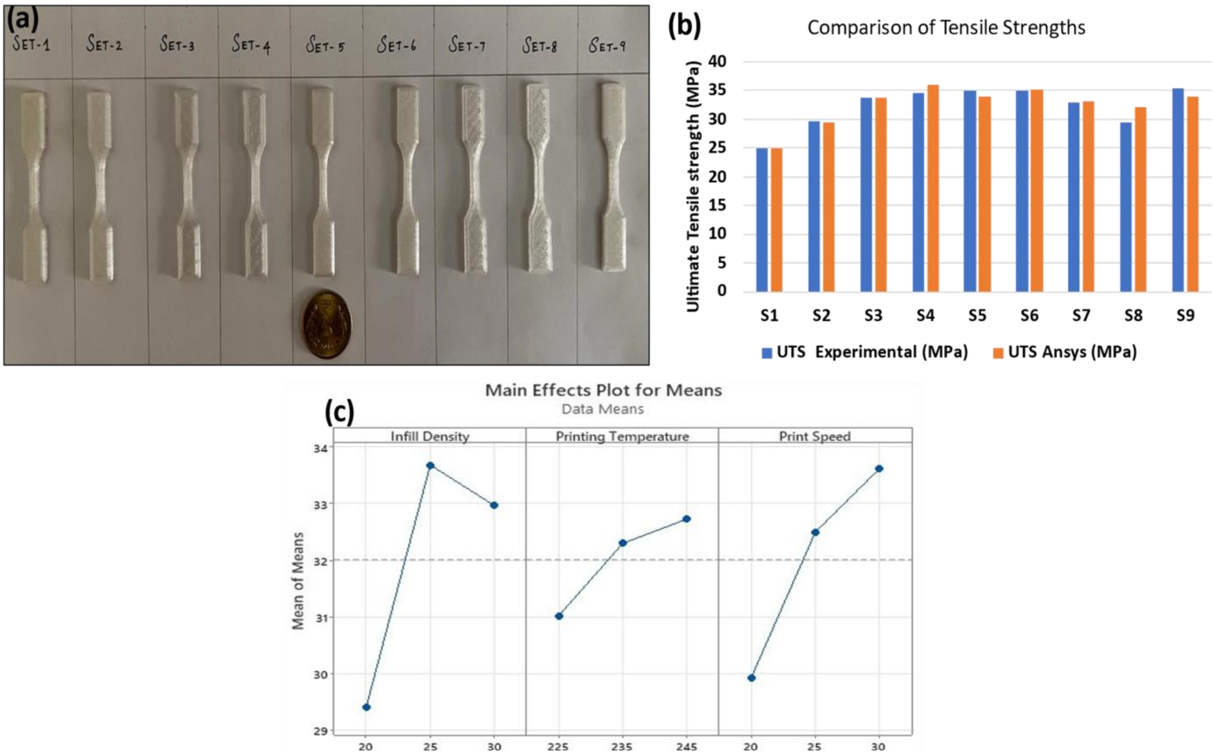

Figure 1 FDM printed (a) Tensile Samples (a) Tensile test results (c) Main effects plot

REFERENCES

1. Bellehumeur, C., Li, L., Sun, Q., and Gu, P. (2004). Modeling of Bond Formation Between Polymer Filaments in the Fused Deposition Modeling Process. Journal of Manufacturing Processes, 6(2), 170–178. https://doi.org/10.1016/S1526-6125(04)70071-7
2. Blaj, M., Zaharia, S., Alin Pop, M., and Oancea, G. (1964). Tensile Properties and Manufacturing Defectives of Short Carbon Fiber Specimens Made with the FDM Process. Mater. Plast, 59(1), 33–43. https://doi.org/10.37358/Mat.Plast.1964
3. Es-Said, O. S., Foyos, J., Noorani, R., Mendelson, M., Marloth, R., and Pregger, B. A. (2000). Effect of layer orientation on mechanical properties of rapid prototyped samples. Materials and Manufacturing Processes, 15(1), 107–122. https://doi.org/10.1080/10426910008912976
4. Guessasma, S., Belhabib, S., and Nouri, H. (2019). Printability and tensile performance of 3D printed polyethylene terephthalate glycol using fused deposition modelling. Polymers, 11(7). https://doi.org/10.3390/polym11071220
5. Jayanth, N., Senthil, P. and Mallikarjuna, B., 2022. Experimental investigation on the application of FDM 3D printed conductive ABS-CB composite in EMI shielding. Radiation Physics and Chemistry, 198, p.110263.

Effect of the notch opening angle of the static behaviour of PLA and carbon fibers reinforced PLA realized through AM technique

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ABSTRACT

Additive manufacturing provides significant advantages over conventional manufacturing. Among the others, it is worth mentioning the almost unconstrained freedom in the geometries that can be realized. However, the geometrical complexness of such components requires for adequate tools to assess both their fracture behaviour and fatigue life. A suitable solution for such a design issue is to rely on the so-called local approaches whose main advantage is to consider a local parameter to evaluate the behaviour of the entire component; besides, such methods have the advantage that their critical value can be assumed to be independent on both the overall geometry of the component and the loading conditions. With this purpose, the present work investigates the fracture behaviour of notched specimens made PLA and carbon fiber reinforced PLA realized through additive manufactured technique. The specimen's geometry considered is flat and double notched while the notch opening angles varies between 30 and 120 degrees. The results of the experimental campaign have been summarised through the averaged strain energy density (SED) method, an energetic local approach, widely proved to be a valid tool to investigate both fracture in static condition and fatigue failure. The critical value of SED has been obtained through the stress-strain curve of smooth specimens for the two different materials considered. After the determination of the control volume characteristic length, R_0, the data have been summarised in terms of averaged SED values. The critical loads for the different geometries and the different materials considered are predicted by the method with an average error of 7%.

Keywords: PLA; Additive manufacturing; local approaches; SED method.

Accelerated vibration-fatigue characterization for 3D-printed structures: Application to fused-filament-fabricated PLA samples

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ABSTRACT

Introduction

Up to date, the research on fatigue of additive manufactured (AM) components has received the least attention among studies related to mechanical properties of AM components mostly due to the longevity of experiments multiplied by the large number of influential parameters, related to processing, material, environmental or loading conditions. This study introduces a novel fatigue testing methodology of AM components, which enables simultaneous testing of multiple specimens at significantly higher loading rate by exploiting the specimen's dynamic response when exited with random-signal acceleration.

Materials and methods

The basic concept of accelerated fatigue testing in this research follows the accelerated vibration testing approach using an electro-dynamic shaker. The test sample is fixed to the shaker armature; for the kinematically excited dynamic system with random signal of known one-sided power spectral density (PSD) $G_{\ddot{y}\ddot{y}}(\omega)$ the response at k-th stress degree-of-freedom can also be obtained in terms of PSD as $G_{\sigma\sigma,k}(\omega)$:

$$G_{\sigma\sigma,k}(\omega) = \left|H_{\sigma\ddot{y},k}(\omega)\right|^2 \cdot G_{\ddot{y}\ddot{y}}(\omega), \qquad (1)$$

which, together with material fatigue parameters, provide sufficient information to obtain a fatigue life estimation [1] with frequency counting methods (Narrowband, Dirlik…). In this research the sample, shown in Fig. 1, is sliced in three spatial directions (x, y and z). With that, one can obtain samples with identical geometry, but different orientations of perimeter filaments and layers compared to the direction of the maximal stress load σ_y. In this way, it is possible to evaluate the influence of perimeter configuration on the sample's fatigue life.

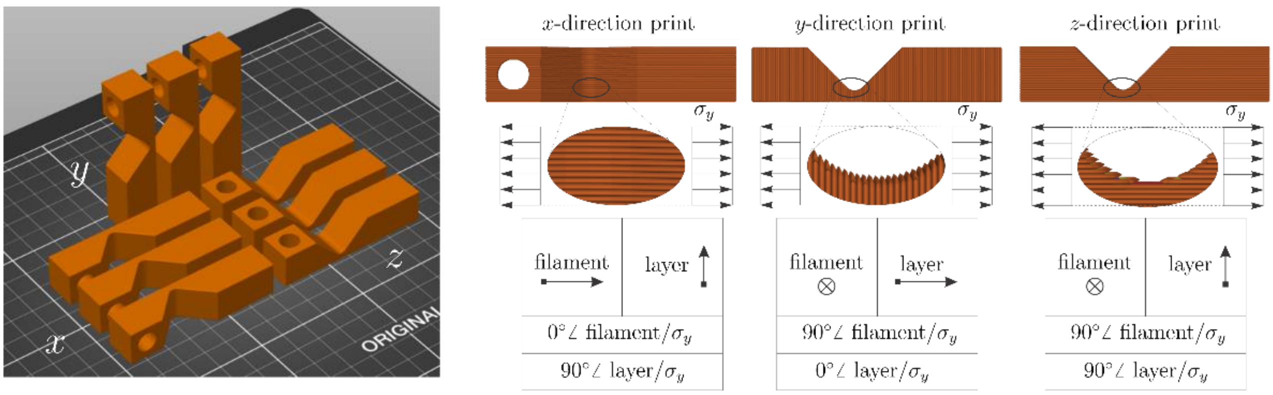

Figure 1. Proposed printing directions and its influence on filament orientation in the sample's fatigue zone.

The experimental setup with 8 simultaneously tested samples is shown in Fig. 2. Laser vibrometer with scanning head monitored the responses for construction of valid simulation model of each tested sample. The proposed method is applied to 4 different types of samples, manufactured from PLA by FFF. The samples differed in printing direction as a variation of processing parameter (x, y or z direction), and in color as a material variation (blue or gray). In total 106 samples were tested.

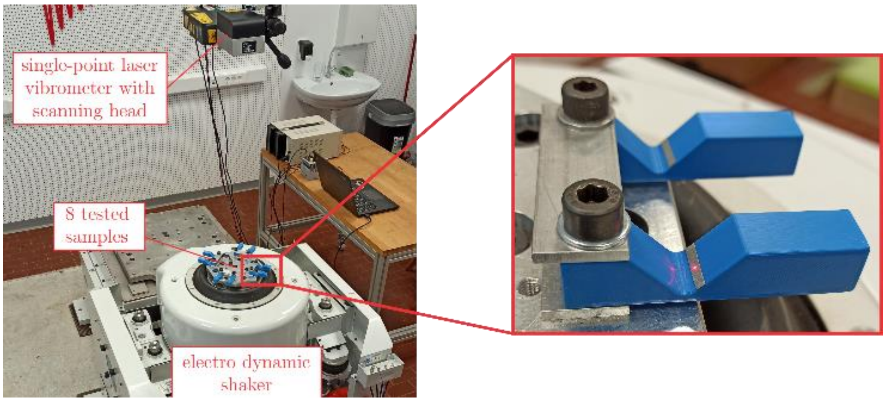

Figure 2. Experimental setup of fatigue test.

Results

The trend of fatigue lives for individual sample set under different loads, characterized by σ_{RMS} is presented in Fig. 3. Evidently, a high number of load cycles can be achieved in a relatively short time; for example, sample SN107 marked in Fig. 4 with f_1=690 Hz reached $2.08\cdot10^8$ load cycles in 83.6 hours. The obtained SN curves for particular sample sets are presented in Fig. 3 together with the relevant results from the literature. Focusing first on the results of the new methodology, it is clear that the printing direction and consequently the orientation of the perimeter filaments have a paramount impact on the durability of the 3D printed structures.

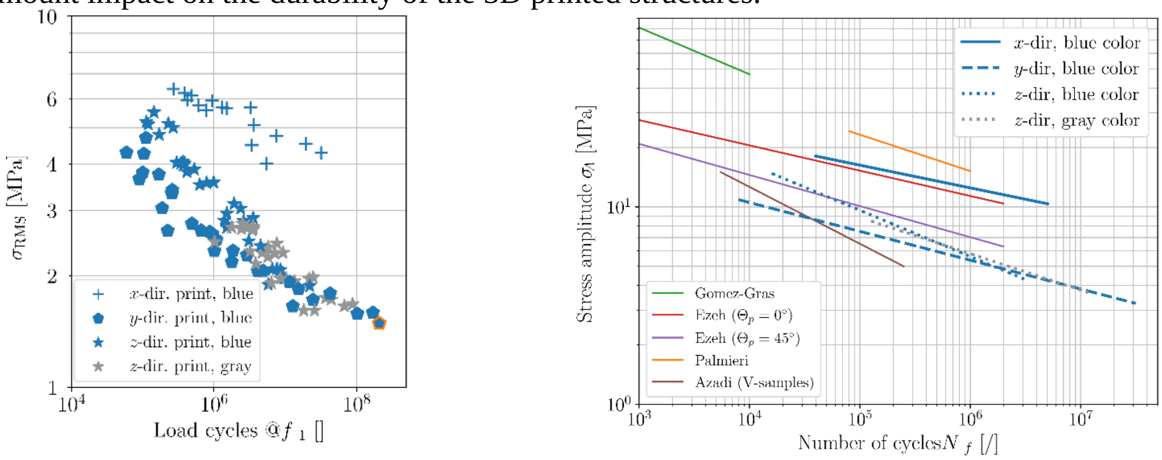

Figure 2: Fatigue lives (left) and SN curves for the sample sets studied and comparison with relevant studies [2-6].

REFERENCES

[1] J. Slavič et al. *Vibration Fatigue by Spectral Methods*, 1st. ed. (2022)
[2] G. Gomez-Gras et al. *Materials & Design* **140** (2018) 278-285
[3] O.H. Ezeh et al. *Int. Journal of Fatigue* **126** (2019) 319-326
[4] M. Palmieri et al. *Materials* **15** (2022) 854
[5] M. Azadi et. al *Forces in Mechanics* **3** (2021) 100016

Experimental and numerical investigation of fracture mechanics parameters on samples produced by selective laser sintering on two types of specimens

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ABSTRACT

The release of fluid due to damage in a pressurized pipeline can cause various types of damage, ranging from environmental contamination to the explosion of entire facilities and fatal outcomes for operators who are in close proximity. The standardized procedure for testing fracture mechanics parameters on pipelines prescribes certain relationships between the thickness of the sample, the width and length of the sample, and the length and width of the crack. The requirements that must be met limit of dimensions of the pipe samples that can be tested. To overcome this problem, various sample geometries have been proposed to test fracture mechanics parameters. However, none of the new sample geometries has completely overcome this problem. The aim of this study is to develop a new method for assessing pipeline integrity and determining fracture mechanics parameters by testing a new type of specimens called the Pipe Ring Notched Tension (PRNT) specimen which has a sharp notch. Experimental and numerical methods were used to investigate the influence of sample geometry on fracture mechanics parameters. The samples were made by selective laser sintering (SLS) of polyamide PA12 on an EOS Formiga P100 machine. In addition to PRNT samples, standard SENT (Single Edge Notched Tension) test specimens were also made under the same conditions. A universal tensile testing machine was used to test all specimens, and a tool was designed to simulate internal pressure by applying contact pressure to the inner walls in the direction of tension while the SENT specimens were tested using a standard tensile tool. The optical measuring system Aramis GOM 2M was used to determine the parameters of geometric fracture mechanics, including CMOD and CTOD and stresses on the surface of the tested samples. This study not only examined the fracture properties of additively manufactured PA12, but also developed a non-standard test procedure based on the relationship between the fracture mechanics parameters of non-standard PRNT type samples and standard SENT samples. This method could later be applied to samples cut from metallic or non-metallic pipes.

Acknowledgement
The authors would like to thank the support from European Union's Horizon 2020 research and innovation program (H2020-WIDESPREAD-2018, SIRAMM) under grant agreement No 857124.

Compressive and flexural mechanical responses of components obtained through MSLA vat photopolymerization technology

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ABSTRACT

In recent years, Additive Manufacturing (AM) has become an increasingly popular method in industrial applications for fabricating components with complex geometries, offering a number of benefits over traditional (subtractive) manufacturing methods. Among all available AM technologies, ''vat photopolymerization'' is still a reliable approach for manufacturing high-resolution components at relatively small costs [1]. Depending on the light source that photopolymerizes liquid resin, there are different subtypes of this technology i.e., SLA, DLP, and MSLA. Among all three listed technologies, the Masked Stereolithography Apparatus (MSLA) technology has emerged as a promising approach due to much simpler AM machine construction compared to the other two, as the LCD screen doesn't require an additional mirror system to spread light over the bottom (transparent) surface of the vat.

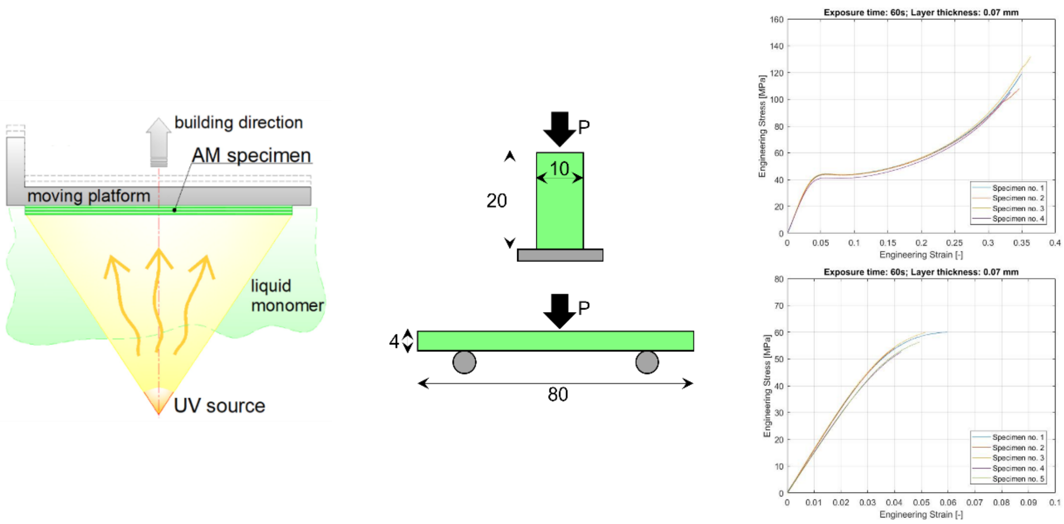

Figure 1. Left- Scheme of the MSLA process employed to fabricate the specimens; Middle- Compressive and flexural specimen front view with applied load direction and dimensions in [mm]; Right- Obtained stress-strain curves from compressive and flexural tests, respectively.

However, the mechanical properties of MSLA components have not been studied extensively, hence there is a lack of knowledge of how AM process parameters and post-processing treatments affect the final mechanical properties of MSLA components. This research presents an experimental investigation of the compressive and flexural mechanical responses of components produced through this relatively new AM technology.

Both compressive and flexural tests were carried out on specimens with different layer thicknesses and post-curing times. There are three layer thicknesses- .03, .05, and .07 mm, and four post-curing times- 10, 20, 30, and 60 seconds. Previous research [2] conducted on DLP tensile specimens showed a higher influence of exposure time over the layer thickness, in such a manner that higher exposure times and lower layer thicknesses produce stiffer components with higher strength values. The effect of layer thickness on DLP component mechanical properties was also investigated in [3], leading to similar conclusions.

Here, both compressive and flexural results show a significant effect of AM process parameters and post-processing treatments on the mechanical properties of AMed components. Therefore, a carefully thought-out optimization of the presented variables is required in order to obtain components with the desired mechanical properties.

Keywords: Additive Manufacturing; MSLA; Compressive properties; Frexural properties.

REFERENCES

1. Milovanović, A., Sedmak, A., Golubović, Z., Zelić Mihajlović, K., Žurkić, A., Trajković, I., Milošević, M. (2021) The effect of time on mechanical properties of biocompatible photopolymer resins used for fabrication of clear dental aligners, *Journal of the Mechanical Behavior of Biomedical Materials* 119, 104494. DOI: 10.1016/j.jmbbm.2021.104494.
2. Brighenti, R., Marsavina, L., Marghitas, M.P., Cosma, M.P., Montanari, M. (2022) Mechanical characterization of additively manufactured photopolymerized polymers, *Mech. of Advanced Materials & Structures.* DOI: 10.1080/15376494.2022.2045655.
3. Hanon, M.M., Shaly, A., Zsidai, L., Szakál, Z., Szabó, I., Kátai, L. (2021) Investigations of the Mechanical Properties of DLP 3D Printed Graphene/Resin Composites, *Acta Polytechnica Hungarica*, Vol. 18, No. 8. DOI: 10.12700/APH.18.8.2021.8.8.

Evaluation of wall thickness effect on tensile properties of injected short fiber reinforced polymers

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ABSTRACT

The aim of this paper is to analyze the effect of increasing the wall thickness in injection molded short fiber reinforced polymer (SFRP) parts, focusing mainly on tensile strain and tensile strength, as these are the most used characteristics for structural analyses.
The phenomena that makes this evaluation of interest has to do with the microstructure of SFRP injection molded parts and how the fibers get oriented along the flow direction at superficial depths with an increasingly less aligned structure down to the mid plane/surface. By increasing the injected part wall thickness the ratio between the thicknesses of highly oriented layers and poorly oriented layers decreases, thus the tensile properties of the material should suffer a decrease as well.
In order to study the mentioned hypothesis two types of materials were tested, PPA GF33 and PPS GF40, dog-bone type specimens were cut at different angles to the flow direction from injection molded plates of 2 and 3 mm wall thickness values. The tensile strains were recoded using a video extensometer and material data was calibrated using Digimat MX reverse engineering module and Ansys properties homogenization tool and finite element solver.

Thermo-Mechanical simulation of the powder bed of Polyamide 12 during the SLS Process

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ABSTRACT

The selective laser sintering process is considered to be a new process among the most innovative processes in the field of the additive manufacturing, to facilitate the development and the technical improvement of this process, a thermo-mechanical simulation by was made under the COMSOL Multiphysics software, using Hook's law with the equilibrium and accounting equations for the calculation of the residual stresses appearing in the sintered layer of polyamide 12. this simulation was made for the prevention of deformations appeared in the final printed parts.

Keywords: Thermo-mechanical simulation, polyamide12, selective Laser Sintering (SLS), COMSOL Multiphysics software, Mechanical Phenomena, Nonlinear Problem.

2nd Session

2. Characterization of AM metallic materials

Effect of post-processing techniques on the surface roughness of Laser powder bed fusion processed Al12Si alloy

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ABSTRACT

The Additive manufacturing (AM) process, especially laser powder fusion (LPBF), could print complex medical implants directly from computer-aided design (CAD) data. LPBF offers numerous benefits compared to traditional methods, such as efficient customized product development, complex shape creation, and lighter components that save time and costs [1]. AM also have some challenges that are usually addressed, such as poor surface quality, physical properties, residual stresses and fatigue [2]. These challenges prevent AM parts from being used in real-life applications.
Surface roughness is a significant issue in many forms of additive manufacturing (AM) because of the layer-by-layer deposition process [3]. This study aims to gain a deeper understanding of the roughness generated during the laser powder bed fusion (LPBF) process. In LPBF, metal powders are melted by a focused laser beam to create each component layer. Despite its ability to produce fine details using a variety of metal powders, LPBF is one of the most widely used metal AM processes across a range of industries, including the automobile, aerospace, and medical fields [4]. However, there are complex physical phenomena in LPBF that contribute to roughness. This study seeks to better understand LPBF and explore post-processing techniques that can improve the surface roughness of additively manufactured parts.
The processing techniques, including traditional machining, wire electro-discharge machining, chemical anodizing, abrasive flow finishing and laser polishing, are customarily applied to resolve these issues. This study has complied with various post-processing techniques and their implementation. The effects of different post-processing techniques on additive-manufactured Al12Si are shown in Table 1 and will be discussed. Micro-milling significantly reduces surface irregularity topography, peaks and roughness. Micro-milling reduced average surface roughness (Sa) by up to 99% and a minimal increase in surface hardness compared to WEDMed, chemical anodizing, sandblasting, and as-printed parts. The 3D surface typographs are shown in Fig.1. The study found that micro-milling is a promising approach for finishing complex metallic additively manufactured parts with minimal complexity.

Keywords: Laser powder bed fusion; WEDM; Chemical Anodizing; Micro Milling; sandblasting, surface roughness

Table 1: Surface average roughness (Sa) and their post-processing conditions

Condition	As printed	Sand blasted	Chemical Anodizing	WEDMed	Micro milled
Sa (μm)	22.74	9.05	11.25	3.98	0.256

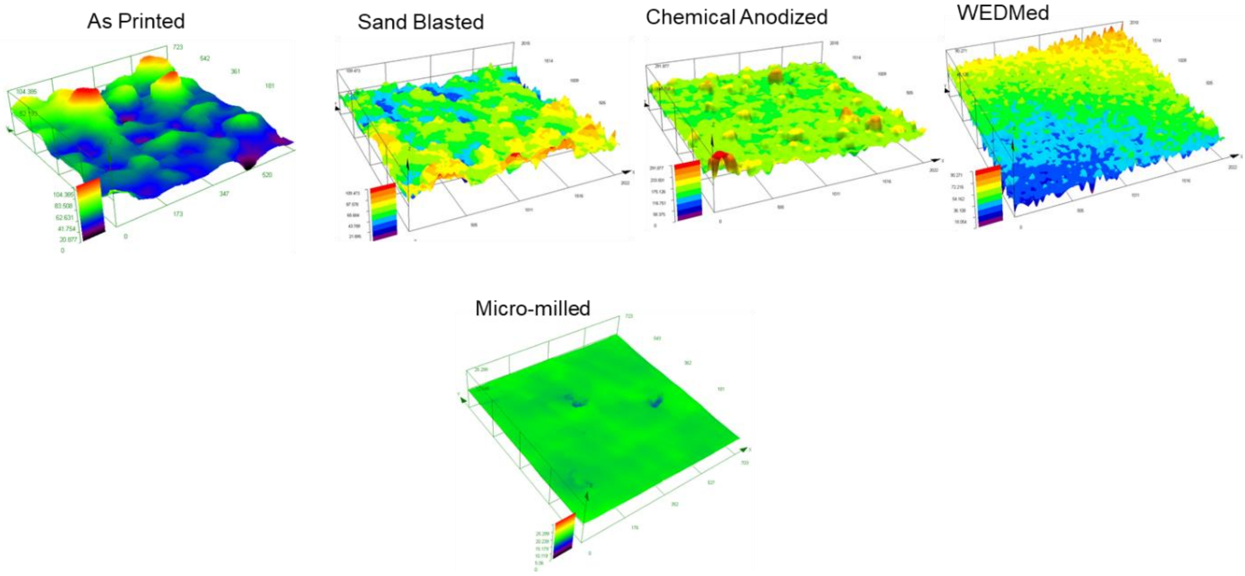

Figure1. 3D Surface topographs of as-printed and post-processed samples

REFERENCES

[1] S.R. Narasimharaju, W. Zeng, T.L. See, Z. Zhu, P. Scott, X. Jiang, S. Lou, A comprehensive review on laser powder bed fusion of steels: Processing, microstructure, defects and control methods, mechanical properties, current challenges and future trends, J. Manuf. Process. 75 (2022) 375–414. https://doi.org/10.1016/j.jmapro.2021.12.033.

[2] C. Ye, C. Zhang, J. Zhao, Y. Dong, Effects of Post-processing on the Surface Finish, Porosity, Residual Stresses, and Fatigue Performance of Additive Manufactured Metals: A Review, J. Mater. Eng. Perform. 30 (2021) 6407–6425. https://doi.org/10.1007/s11665-021-06021-7.

[3] J. Gockel, L. Sheridan, B. Koerper, B. Whip, The influence of additive manufacturing processing parameters on surface roughness and fatigue life, Int. J. Fatigue. 124 (2019) 380–388. https://doi.org/10.1016/j.ijfatigue.2019.03.025.

[4] R. Singh, A. Gupta, O. Tripathi, S. Srivastava, B. Singh, A. Awasthi, S.K. Rajput, P. Sonia, P. Singhal, K.K. Saxena, Powder bed fusion process in additive manufacturing: An overview, Mater. Today Proc. 26 (2020) 3058–3070. https://doi.org/10.1016/j.matpr.2020.02.635.

Micro Raman Spectroscopy of apatite of composition La9.5Ge5.5Al0.5O26 calcined and sintered by electric and microwave heating

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ABSTRACT

The apatite compositions $La_{9.5}Ge_{5.5}Al_{0.5}O_{26}$ was calcined in the range of temperature 900°C-1100°C for 1 h by microwave heating and also by electric heating at 1100°C for 1 h. The samples obtained by microwave and conventional calcination at 1100°C for 1 h were sintered by microwave processing at 1350°C for 30 min and at 1350°C for 4 h by conventional processing. The sintered samples obtained by microwave processing (AlMCMS and AlCCMS) had higher density and more uniform grain growth & higher conductivity value compared to the apatite samples obtained by conventional processing samples (AlMCCS and AlCCCS). The longer heating time was responsible for the loss of germanium, resulting in the formation of La_2GeO_5; it was attributed to conventional heating which reduces the conductivity value of conventionally sintered samples (AlMCCS and AlCCCS).

Effect of laser parameters on the melt-pool dimensions and the thermo-mechanical properties of additively manufactured Inconel 718

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ABSTRACT

We have used ANSYS® software to study the impact of laser parameters on the densification and distortion behaviour of components fabricated from Inconel 718 (In718) using laser powder bed fusion. It was found that the densification behaviour of In718 depends on the melt-pool size. Porosity is eliminated by optimising the laser parameters to ensure that the geometry of the melt-pool formed by adjacent scan tracks resulted in achieving a solid ratio of unity. We propose a strategy to reduce edge distortion of the built part by varying the volume energy density during the fabrication process.

Introduction and computational details

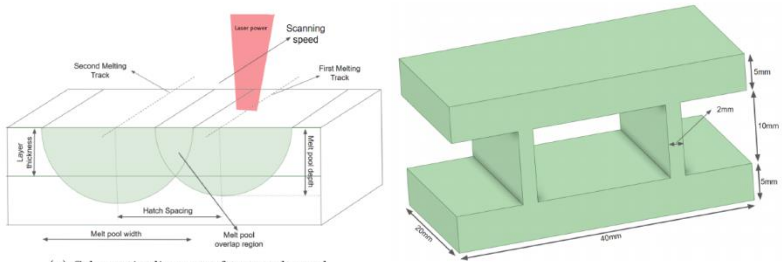
Laser powder bed fusion (LPBF), a technology used for additive manufacturing (AM), involves the fabrication of components by irradiating a laser source on a thin layer of finely powdered material (Fig. 1a), thereby causing the powder to melt and fuse. The component is thus built layer by layer. LPBF allows us to manufacture complex geometries with acceptable precision and allowable distortion. Inconel 718 (In718) is used in high-temperature operating environments, for example, in aero-engines. In view of the importance of In718 in the aero-industry, we have simulated, using the finite element module of ANSYS® software, the effects of laser power, scan speed and hatch spacing on the densification and distortion behaviour of additively manufactured In718 components.
The geometry of the component simulated is shown in Fig. 1b. We have used a 3D Gaussian heat source [1] to mimic the effects of the laser source on the metal powder. The thickness of the powder layers is kept fixed at 40 µm. Conductive heat transfer is assumed to occur through the metal powder, solidified metal and metal substrate. Heat loss to the ambient occurs by natural convection.

Results and discussion

The parameters and their ranges used in the simulations are given in Table 1. Elimination of porosity is a crucial aspect in ensuring good build quality of AM components. We have assumed that the geometry of melt-pool perpendicular to the scan direction is semi-circular. Fig. 1a shows that an overlap region of adjacent melt-pools forms between adjacent scan tracks. The overlap region occurs if, for a given hatch spacing, the laser power is sufficient to melt a region common to both scan tracks. Porosity is eliminated if the vertical extent of the overlap region is equal to or greater than the thickness of the powder layer. In such situations, the solid ratio, which is the ratio of actual density to theoretical density, becomes unity. Table 2 shows the optimised set of laser parameters that result in a solid ratio of unity.

Parameters	value
Laser power (W)	50-250
Scan speed (mm/sec)	350-1550
Layer thickness(micron)	40
Hatch spacing (micron)	80-90
layer rotation	67
Baseplate Temperature (°C)	80

Table1: Parameters used for the simulations



(a) Schematic diagram of two melt pool.
(b) Schematic diagram of 3D model.

Figure 1: (a) Geometric parameters used to achieve a solid ratio of unity, (b) geometry of the simulated component

Layer thickness (μm)	Hatch spacing(μm)	laser power($watt$)	Scanning speed(mm/sec)	Distortion(mm)	Solid ratio
40	80	125	750	0.42313	1
40	80	150	950	0.42375	0.9999
40	80	175	1150	0.42331	0.9999
40	80	225	1350	0.42684	0.9999
40	80	250	1550	0.42507	0.9999
40	90	75	350	0.39123	1
40	90	100	550	0.41785	1
40	90	175	950	0.42635	1
40	90	200	1150	0.42527	1
40	90	250	1350	0.42671	1

Table 2: Optimised set of laser parameters which result in a solid ratio of unity

Thermal stresses are proportional to thermal gradients [2]. As the laser source reverses its direction upon reaching the edge of the component, there is a high amount of energy deposition, which causes higher thermal gradients and stresses, thereby leading to higher distortion in the edges. Lowering the volume energy density (VED) when the laser source is close to the edges reduces the distortion while maintaining the unit solid ratio.
We conclude that a viable strategy to ensure good quality build using LPBF is to (i) optimise laser parameters to achieve a solid ratio of unity, and (ii) reduce the VED at the edges to reduce distortion effects.

REFERENCES

1. H S Carslaw and J C Jaeger, Conduction of Heat in Solids, 2nd Edition (Oxford University Press, 1959).
2. Zhang Y, Wu L, Guo X, et al, Additive manufacturing of metallic materials: a review, 2018, Journal of Materials Engineering and Performance 27:1–13.

Enhanced fatigue performance of laser directed energy deposition fabricated Ti6Al4V alloy using laser shock peening

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ABSTRACT

Additively manufactured parts generally have lower fatigue life than the wrought counterparts due to the nature of deposition, defects, extreme thermal gradients, and residual stresses generated during the process. Thin layer thickness leads to longer manufacturing time. The present study is focused on the fatigue performance of Ti6Al4V alloy fabricated by high layer-thickness laser directed energy deposition (LDED) process and enhances it by employing laser shock peening (LSP). Samples with ASTM E466-21 standard were prepared with LDED process in a Meltio M450 machine with 6 continuous diode lasers of 200 W each at 976 nm wavelength as per Table 1. The average layer thickness was 1.2 mm with an alternate 45^0 scanning pattern and initial peripheral deposition to improve dimensional accuracy in an inert Argon environment. After removing the parts from the substrate using wire-electric discharge machining (wire-EDM), it was polished with a grit range of 200 to 2200. One set of fatigue tests on the LDED fabricated parts and another fatigue test on the LDED+LSPed samples. LSP was carried out in a Litron Nd:YAG laser of 1064 nm wavelength with a laser diameter of 0.8 mm with a repetition of 60% two times on both sides of the fatigue samples. A pulse width of 6 ns and repetition rate of 10 Hz with a maximum energy of 370 mJ was applied on a water overlay with a black tape sacrificial layer. Load of 650 MPa on fully reversed cyclic load at 5 Hz was applied for the fatigue test.

Table 1: Process parameters during the LDED process.

Dataset no.	**1**	**2**	**3**	**4**
Power (W)	800	850	900	950
Speed (mm/s)	10	10	13	13

The polished surface revealed proper deposition except for some isolated very small voids in the boundary between the peripheral deposition and alternate 45^0 deposition pattern. Figure 1 shows the different failed samples under fatigue loading for both LDED and LDED+LSPed samples. The lath like microstructures were observed under the scanning electron microscope (SEM) as seen in Figure 1.f. As seen in Figure 2(a), significant improvement in the fatigue life in samples 1 (56.51%) and 4 (39.26%) were observed for the LDED+LSPed samples as compared to only LDED samples. However, for samples 2 (-0.99%) and 3 (-11.40%), a slight decrease in fatigue life was observed for LDED+LSPed samples. This can be due to internal defects on the LDED+LSPed samples, surface cracks, or due uneven distribution of LSP on the surfaces. Gaps in the LSP were observed on samples 2 and 3, as seen in Figure 2.a. Figure 2.b shows the SEM image of the failed surface during fractography. A

ductile fatigue failure mode was observed with multiple cracks (both point and line cracks) on the failed surface. River lines with multiple tributaries as well as striation regions with clear signs of incremental crack growth. The present paper presented the high layer thickness LDED for faster part fabrication and enhanced fatigue life using LSP as a post-processing method. This will help reduce manufacturing time while also improving fatigue life compared to other AM processes.

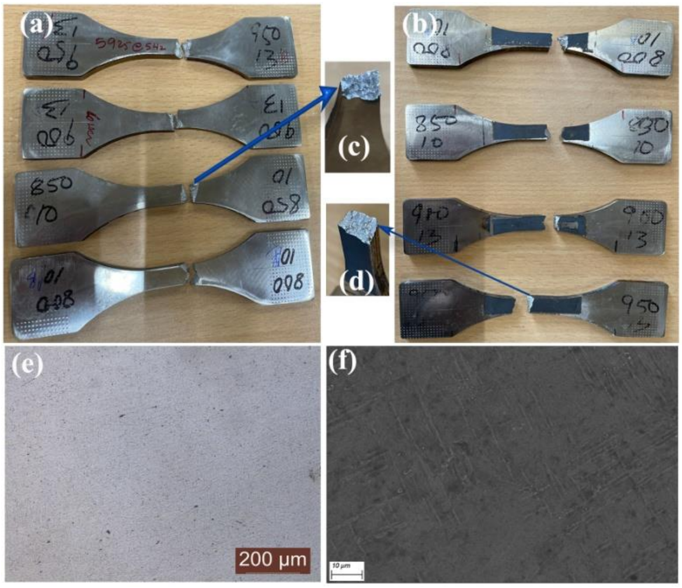

Figure 1. (a) LDED Failed samples, (b) LDED+LSPed failed samples, (c) LDED failed surface, (d) LDED+LSPed failed surface, (e) polished surface, and (f) SEM image of the polished surface.

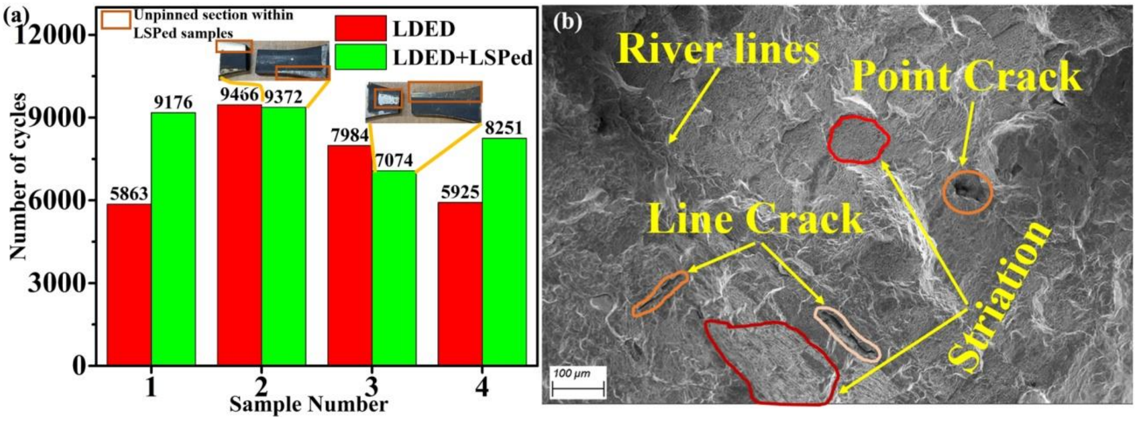

Figure 2. (a) Number of cycles for different LDED and LDED+LSPed samples, and (b) fractured surface under SEM.

Acknowledgments
S. N. Singh acknowledges the Ministry of Education, Govt. of India, for providing fellowship. The authors thank CIF IIT Guwahati for SEM, CFM VIT Vellore for LSP facility, material characterization lab IIT Hyderabad for fatigue test, advanced manufacturing lab, weld and corrosion lab NIT Silchar for the optical microscope and polishing facility.

Post-processing of support structure of LPBF-processed Ti6Al4V part: Effect of process parameters

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ABSTRACT

Additive manufacturing (AM) is the disruptive technology gained its attention in various industrial applications owing to its capability to produce intricate shape parts with least wastage and higher dimensional accuracy. The laser powder bed fusion (LPBF) is the type of manufacturing used to manufacture the metallic parts with high build accuracy. The support structure is essential in LPBF process to provide support from the base plate to the printed part. The support structures serve the purpose of giving supports to the overhangs and dissipate the heat to reduce the thermal stresses. Therefore, supports are inevitable in the AM design to provide stability and prevent the distortions. However, there are negative effects of support structure including high surface roughness on part and possibility of deteriorating the structural integrity of part during their removal. Therefore, processing of supports must be in such a way that they should remove easily without deteriorating the part's structural and dimensional integrity. In present work, process parameters optimization of support structure is part on the LPBF processed Ti6Al4V part. The printed supports from the part are removed through a torque wrench in view of evaluating the torque force required during removal. It was interesting to note that the optimized parameters resulted in lesser (~36%.) force to remove the support structure from the part. Moreover, the dimensional inspection of the part after support removal was performed using 3D white light scanning technique and it was found that the dimensions were closely match with the CAD geometry.

Densification of Laser Powder Bed Fusion Manufactured Haynes 230: A Design of Experiment Approach

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ABSTRACT

Aeroengine nickel-based superalloys are predominantly used for the hot end components of a gas turbine because of their excellent high-temperature strength, superior chemical stability and excellent creep life. To broaden their functioning temperature range, intricate cooling passages are integrated within these components. The inherent properties of poor thermal conductivity and high work hardening rate pose challenges in processing these alloys through conventional processes. Laser powder bed fusion (LPBF) technology is a near-net shape fabrication process capable of efficiently fabricating intricate and complex geometries by employing a successive material layer deposition and laser melting approach. Haynes 230 is a solid solution-strengthened Ni-based superalloy derived from the Ni-Cr-W-Mo alloy system. Its high-temperature strength and corrosion resistance make it a competitive candidate for gas turbines. The current study investigated the effect of LPBF process parameter combinations formulated through a central composite design of experiments on the density of the Haynes 230 cube specimens. The Archimedean density measurement method was employed to quantify the density of each specimen, and relative density was calculated concerning material bulk density. The highest relative density was 99.88% at an energy density of 175J/mm^3, and the lowest value of 98.37% was observed at 42.6J/mm3, which can be attributed to the lack of fusion voids. The ANOVA results for the density values with the treatment combinations indicated that hatch distance was the most significant parameter (P-value of 0.002) affecting density compared to laser power and hatch speed which were also influential. The corresponding quadratic regression equation displayed an R-sq value of 82.43%. From the main effects plot, it was inferred that density was directly proportional to laser power but inversely proportional to scan speed and hatch spacing. The data's interaction plots and contour plots provided a process window of Power: 130-160W, Speed: 800 – 100m/s and hatch spacing: 0.035 – 0.04mm. The relation between energy density and relative density was also studied, which indicated a strong positive relation between them with an R-value of 0.89 and a quadratic regression model with an R-sq value of 85.9%.

Keywords: Central composite design of experiment, Laser Powder bed Fusion, Haynes 230, Archimedean density

REFERENCES

[1] Bauer, Thomas, Karl Dawson, Adriaan Bernardus Spierings and Konrad Wegener. "Microstructure and mechanical characterisation of SLM processed Haynes® 230®." (2015).

[2] Maurer, Michael Thomas, Patricia Sierra and Patrik Meng. "Reheat Burner Front Panel Produced by Additive Manufacturing Challenges: Strategies and Engine Validation." (2016).

[3] Seetharaman, Sankaranarayanan & Krishnan, Manickavasagam & Wen, Francis & Niaz, Khan & Ng, Gary. "RESEARCH UPDATES ON THE ADDITIVE MANUFACTURING OF NICKEL BASED SUPERALLOYS" (2016).

[4] Sundarraj, Suresh, Sion M. Pickard, Alonso D. Peralta, Anil B. Chaudhary, David R. Snyder, Jeff W. Doak, Suraj P. Rawal, Raymond Ruiwen Xu, Seshacharyulu Tamirisakandala, Albert Contreras, John V. B. Meyer, Andrzej L. Wojcieszynski, Derrick Lamm and Edwin J. Schwalbach. "ICME Based Additive Manufacturing of Alloy 230 Components." (2018).

[5] Gaole, Zhao, Jiang Yun, Hu Xiaoan, Huang Jia, Wu Jinwu and Wang Yun. "High-temperature mechanical properties of nickel-based superalloys manufactured by additive manufacturing." *Materials Science and Technology* 36 (2020): 1523 - 1533.

[6] Yang, Bo, Zejin Shang, Jie Ding, Jack Lopez, William Jarosinski, T. Sun, Norwin Richter, Y. F. Zhang, H. Wang and X. Zhang. "Investigation of strengthening mechanisms in an additively manufactured Haynes 230 alloy." *Acta Materialia* (2021).

[7] Liu, Wenjie, Zhensheng Deng, Hui Li, Yicang Huang, Kai Guo and Wei Wei. "Laser Powder Bed Fusion of Haynes 230 Superalloy: Microstructure, Mechanical Properties and Hot Cracking Inhibition." *SSRN Electronic Journal* (2022).

Fatigue Life and Crack Growth Rate Prediction of Additively Manufactured 17-4 PH Stainless Steel using Machine Learning

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ABSTRACT

Additive manufacturing (AM) is a novel manufacturing technology that provides more freedom in design, manufacturing near-net-shaped parts as per demand, and lower cost of production for complex shaped parts. Among various metal AM techniques, Laser Powder Bed Fusion (L-PBF) is the most prominent technique that provides higher accuracy and powder proficiency in comparison to other methods. Particularly, 17-4 PH alloy is a martensitic precipitation hardened (PH) stainless steel characterized by resistance to corrosion up to 300 °C and tailorable strengthening by copper precipitates. The excellent weldability of 17-4 PH stainless steel and its ability to be heat treated to improve mechanical properties make it a good material choice for variety of structural applications in aerospace and chemical industries. Most of the fatigue experiments in AM 17–4 PH stainless steel were conducted under load-control conditions, limiting the analysis to the high-cycle fatigue range where there was no significant cyclic plasticity involved. Strain-controlled fatigue experiments facilitate the analysis of cyclic plasticity behavior, such as cyclic stress-strain relationship, cyclic hardening/softening, and strain range effect. Stress-controlled experiments, particularly in the low-cycle fatigue (LCF) regime, may lead to ratcheting deformation that is not desirable for the study of basic fatigue properties. Very few experimental studies have focused on the cyclic deformation and low-cycle fatigue behavior of the AM 17–4 PH stainless steel. The present work is focused on machine learning-assisted predictions of the low cycle fatigue behaviour and fatigue crack growth rate (FCGR) of 17- 4 PH SS processed through L-PBF and post-processing. Various machine learning techniques reported in the literature provided a flexible approach for explaining the complex mathematical interrelationship among processing-structure-property of the materials. In the present work, four machine learning (ML) algorithms, such as K- Nearest Neighbor (KNN), Decision Trees (DT), Random Forests (RF), and Extreme Gradient Boosting (XGB) algorithms, are implemented to analyze the Fatigue Crack growth rate (FCGR) of 17-4 PH SS alloy. After optimizing the hyperparameters for these algorithms, the trained models were found to estimate the unseen data as equally well as the trained data. The four tested ML models are compared among each other over the training as well as the testing phase based on their mean squared error and R2 scores. Extreme Gradient Boosting model has performed better for the FCGR predictions providing the least mean squared errors and higher R2 scores compared to other models.

In-situ neutron diffraction investigation of high-manganese steel with tailored crystallographic texture under cyclic loading

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ABSTRACT

Processing parameter modifications of laser powder bed fusion (LPBF) technique has recently attracted considerable attention as a promising tool to tailor mechanical properties. This goal can be achieved by the microstructural manipulation in terms of intentional selection of dominant crystallographic texture with the respect to loading axis. Consequently, a certain active deformation mechanism can be hindered or promoted which is especially beneficial in the case of metastable austenitic steels. The study investigates high-manganese steel X30Mn22 processed by LPBF with various final crystallographic textures (<001>, < 011>, <111> and random) subjected to symmetrical cyclic loading. The results indicate distinct differences in cyclic hardening between the crystallographic textures stemming from different magnitude of strain-induced γ-austenite $\rightarrow$ ε-martensite transformation. This diversity is reflected by various hysteresis loop shape asymmetry and distinctively different mean stresses. In order to follow the evolution of underlying deformation mechanisms, the in-situ neutron diffraction low cycle fatigue tests were carried out. In the combination with comprehensive microstructural characterization by electron microscopy, we were able to identify distinct differences in deformation behaviour and address the effect of the dominant crystallographic texture. Neutron diffraction measurements provided a unique insight into load sharing and susceptibility to the strain-induced martensitic transformation between various grain families.

Understanding the Formation and Impact of Large Particles on Porosity in SLM Processed Austenitic Stainless Steels 304L

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ABSTRACT

Porosity of 3D printed austenitic stainless steel is still a major issue, despite significant research efforts in this area. In this study, the 3D printing and testing of 304L steel at low temperatures was initially investigated, but high porosity was encountered. The root cause of the high porosity was identified as the formation of large particles that were many times larger than the layer height. To address this issue, re-melting was employed, leading to a reduction in porosity.
Many studies have used porous specimens from 304L steel to investigate mechanical properties such as yield and ultimate strength or fatigue. Fashanu [1] and Spratt[2] achieved relative densities 98,7% and 98% respectively. Such high porosity can cause deterioration of mechanical properties. For examples Zhang [3] describes that even porosity in a range of 0,5% can cause significant reduction of fatigue life. The porosity of 3D printed parts has been found to vary even when the same processing parameters are used. The porosity of the parts increases with the higher occupancy of the build platform on which they are built. This is caused by particles ejected from the melt pool by the laser, which are subsequently carried away by the circulating inert atmosphere. If these particles land on the part being printed, they can become welded to it, resulting in the formation of particles that are multiple times larger than the layer height as can be seen on Figure a). In subsequent printing, these particles are not fully melted, resulting in pores around these particles due to a lack of fusion Figure b). Additionally, the large particles can cause deformation of the subsequent layers, as they block the deposition of the powder and the coarsening of the grain in its surroundings.
Porosity of manufactured parts varies not only with the occupancy of the platform but also with their position on the platform. It can be said that the more parts on the platform, the higher the probability of a hot particle being ejected and landing on a previously melted part. In the classic scheme, the parts are melted first at the exit of the inert atmosphere and then moved closer to the entry of the inert atmosphere. Therefore, there is a higher risk of porosity in parts that are closer to the output of the inert atmosphere.

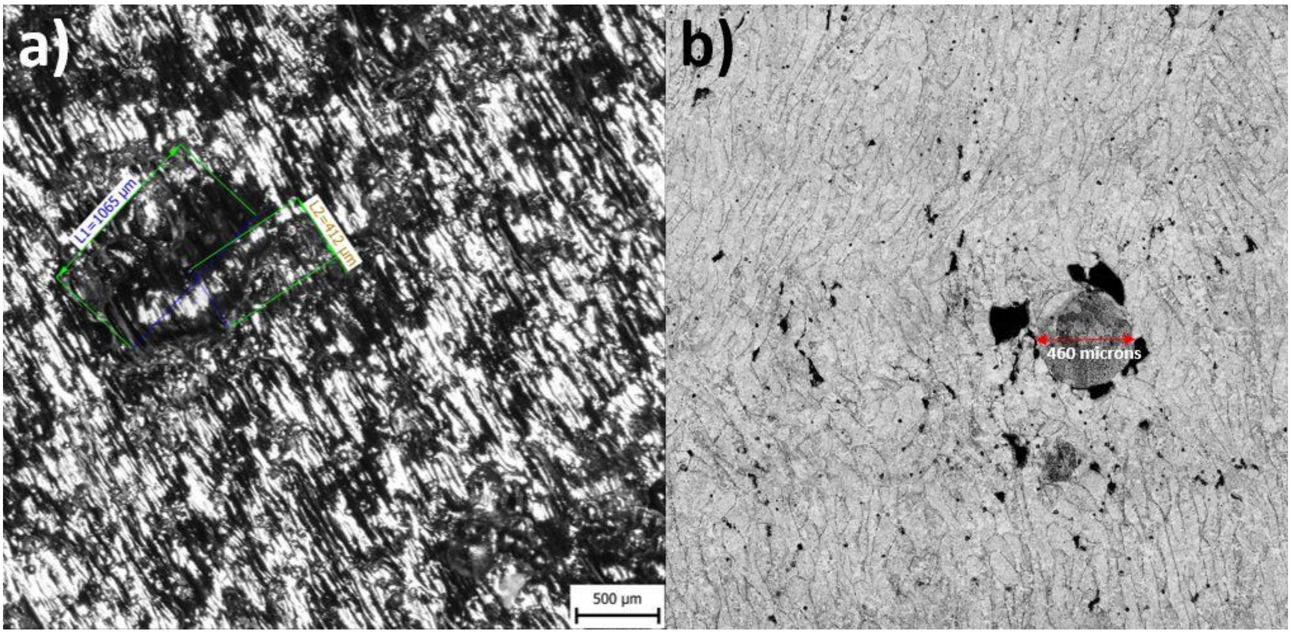

Figure 1. Big particles sintered on specimen a) from a top view b) in cross-section

The effect of sintered particles on the porosity of 3D printed parts was investigated in this study, as well as the effect of the location of the specimen on the filled platform. A solution in the form of re-melting and defocusing the laser was tested, leading to a decrease in porosity down to a value of 0.01% with energy density of 56 J/mm^3 independent on position or occupancy of platform. With such samples, it is possible to proceed to further research.

REFERENCES

[1] Fashanu, Okanmisope, Mario F. Buchely, Myranda Spratt, Joseph Newkirk, K. Chandrashekhara, Heath Misak a Michael Walker. Effect of SLM Build Parameters on the Compressive Properties of 304L Stainless Steel. *Journal of Manufacturing and Materials Processing* [online]. 2019, **3**(2), 43. ISSN 2504-4494. Dostupné z: doi:10.3390/jmmp3020043

[2] Spratt, Myranda, Joseph W. Newkirk, Okanmisope Fashanu a K. Chandrashekhara. Effect of the Melt Pool Boundary Network on the Anisotropic Mechanical Properties of Selective Laser Melted 304L. *Journal of Manufacturing and Materials Processing* [online]. 2021, **5**(4), 110. ISSN 2504-4494. Dostupné z: doi:10.3390/jmmp5040110

[3] Zhang, Hongzhuang, Mengtao Xu, Zhendong Liu, Changyou LI, Punit Kumar, Zhenhua Liu a Yimin Zhang. Microstructure, surface quality, residual stress, fatigue behavior and damage mechanisms of selective laser melted 304L stainless steel considering building direction. *Additive Manufacturing* [online]. 2021, **46**(March), 102147. ISSN 22148604. Dostupné z: doi:10.1016/j.addma.2021.102147

3rd Session

3. Modeling and simulation of AM materials and processes

Numerical evaluation of the infill pattern upon mechanical proprieties of 3D printed materials

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ABSTRACT

The effect of the structure that is printed inside an object, known as infill pattern, on mechanical proprieties of ABS specimens was investigated in this paper. Numerous studies demonstrated that parts created with fused deposition moulding (FDM) technology present inferior mechanical properties due to additional porosity and anisotropy caused by the nature of the manufacturing process. In this regard the influence of printing parameters may be analised for correct evaluation of mechanical behaviour and material constants. The methodology proposed in this paper consists of a numerical simulation of the fused deposition moulding 3D printed specimen, identification of the cross-sectional area and re-evaluation of the strain-stress curves of the materials. There are several infill pattern geometries, each with benefits and compromises between material usage, printing time or mechanical strength of the obtained part. The current paper analysed specimens with 100% density (infill rate) but having different infill patterns: grid 0°-90° and ±45°, triangular 60°, fast honeycomb, full honeycomb and wiggle. The results are showing the dependence of the pecimen's E modulus with the infill pattern and comparisson of the strain-stress curves drawn with full cross-section and numerically calculated ones.

Introduction

Uncertainties in the manufacturing process of FDM, such as the formation of voids or inefficient bonding of layers, increase the probabilities of damage in polymeric structures, the mechanical proprieties of the part being one of main disadvantage of the technology. Among the factors that influence the mechanical characteristics of polymeric printed materials the most relevant ones can be grouped in the manufacturing parameters (infill rate, infill pattern, raster orientation, layer height, number of shells, speed while extruding, speed while travelling), the position of the element in relation to the platform, filament properties and the characteristics of the 3D printer. Many of the studies presented in the literature [1-3] have investigated the influence of printing parameters, such as infill ratio, infill pattern, layer thickness, layer height and other printer settings on the mechanical behaviour of parts made by FDM technology. The novelty of the present study is the methodology used in the analysis and prediction of the mechanical behaviour of FDM specimens.

Materials and methods

In present study a hybrid method (numerical and experimental) was chosen to determine the cross-sectional area of the specimens, thus the single filaments were generated by a script using the G-code of the 3D printer to set-up a finite element model. Based on experimental evaluation of the cross-sectional geometry of a printed tensile specimen the connection between the filaments is determined and the flattening effect of the filaments can be counted. Finite element simulations were validated by experimental tests. The methodology allows on one hand numerical estimation of the real cross-sectional area of a specimen and correction of the experimental stress-strain curves and on the other hand accurate determination of the E-modulus of a printed tensile specimen.

Results

Considering the computed cross-sectional areas of the specimens is possible to draw the real strain-stress curves and to calculate the real E-modulus. In Fig. 1 is presented the strain-stress curve of a tensile specimen with grid 0°-90° infill pattern and in Fig. 2 the variation of the E-moduli obtained considering a full cross-section and the numerically calculated.

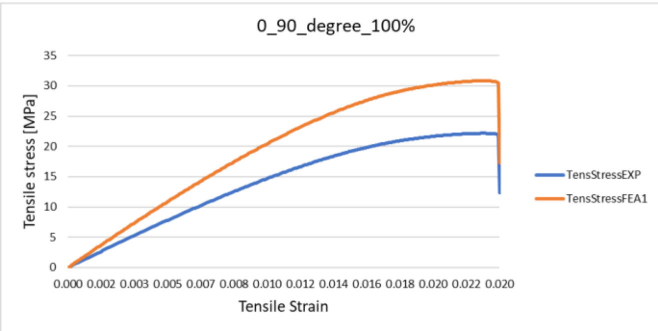

Figure 1. Strain-stress curve of the specimen with 0°-90° infill pattern

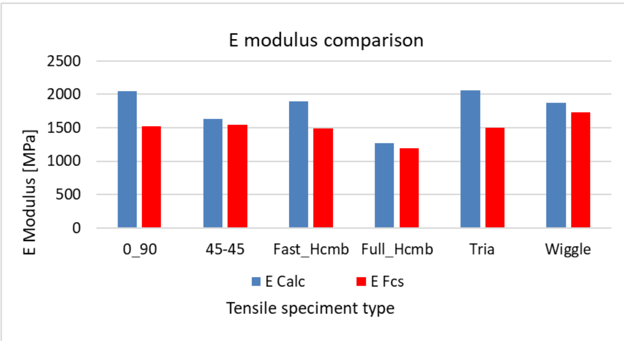

Figure 2. E-moduli comparison (full and computed cross section)

REFERENCES

[1] Bakır, A. A., Atik, R., & Özerinç, S. (2021). Mechanical properties of thermoplastic parts produced by fused deposition modeling: a review. *Rapid Prototyping Journal* 27(3), 537-561. https://doi.org/10.1108/RPJ-03-2020-0061

[2] Khan, I., & Kumar, N. (2021). Fused deposition modelling process parameters influence on the mechanical properties of ABS: A review. *Materials Today: Proceedings*, *44*, 4004-4008. https://doi.org/10.1016/j.matpr.2020.10.202

[3] Popescu, D., Zapciu, A., Amza, C., Baciu, F., & Marinescu, R. (2018). FDM process parameters influence over the mechanical properties of polymer specimens: A review. *Polymer Testing*, *69*, 157-166. https://doi.org/10.1016/j.polymertesting.2018.05.020

Computational modeling of laser metal deposition of titanium aluminide plate geometries

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ABSTRACT

In this work, transient thermomechanical analysis of the laser metal deposition (LMD) process was carried out to predict melt pool dimensions, thermal cycles and residual stress during Titanium Aluminide (TiAl) multitrack and multilayer structures deposition (plate). Towards this end, the computational modelling of laser metal deposited TiAl plate geometries indicate that melt pool length, width, and depth (melt pool dimensions) increased with the laser power increased from 250 to 350 W (as shown in Figure 1). The melt pool dimensions decreased as the travel speed increased from 10 to 20 mm/s. Further, the highest Principal stress of 140 MPa was found in track 1. The predicted principal stress is lower than the yield strength (400 MPa) of the TiAl alloy. However, the magnitude of Principal stresses diminished as track deposition progressed from track 2 to 6.

Keywords: γ-TiAl Alloy, Laser Metal Deposition, Melt Pool, Thermal Cycles

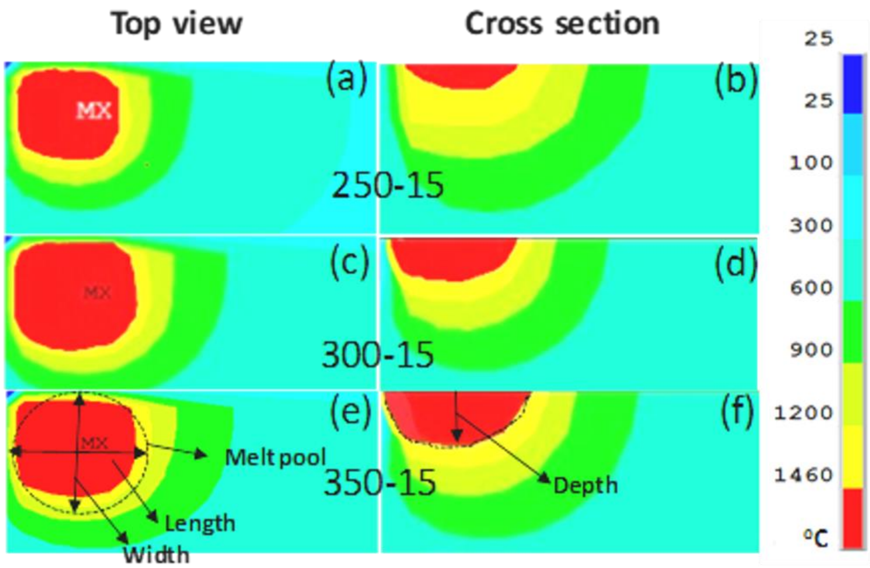

Figure 1. Predicted melt pool top and cross-sectional view while deposiiton of layer 2 and track 3 at constant velocity (V) = 15 mm/s and different laser power (a) and (b) 250 W; (c) and (d) 300 W; (d) and (e) 350 W.

REFERENCES

1. M. Balichakra, S. Bontha, P. Krishna, V.K. Balla, Prediction and validation of residual stresses generated during laser metal deposition of γ titanium aluminide thin wall structures, Mater. Res. Express. 6 (2019) 106550. doi:10.1088/2053-1591/ab38ee.
2. B. Mallikarjuna, E.W. Reutzel, Reclamation of intermetallic titanium aluminide aero-engine components using directed energy deposition technology, Manuf. Rev. na (2022) 1–22. doi:10.1051/mfreview/2022024.
3. H.S. Dhami, P.R. Panda, K. Viswanathan, Production of powders for metal additive manufacturing applications using surface grinding, Manuf. Lett. 32 (2022) 54–58. doi:10.1016/j.mfglet.2022.02.004.
4. K. Kothari, R. Radhakrishnan, N.M. Wereley, Advances in gamma titanium aluminides and their manufacturing techniques, Prog. Aerosp. Sci. 55 (2012) 1–16. doi:10.1016/j.paerosci.2012.04.001.
5. J.C. Heigel, P. Michaleris, E.W. Reutzel, Thermo-mechanical model development and validation of directed energy deposition additive manufacturing of Ti-6Al-4V, Addit. Manuf. 5 (2015) 9–19. doi:10.1016/j.addma.2014.10.003.
6. L. Wang, S. Felicelli, Y. Gooroochurn, P.T. Wang, M.F. Horstemeyer, Optimization of the LENS® process for steady molten pool size, Mater. Sci. Eng. A. 474 (2008) 148–156. doi:10.1016/j.msea.2007.04.119.

Homogenization of the mechanical response of FFF-printed parts via RVE numerical model

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ABSTRACT

Mechanical strength of 3D printed parts dramatically depends on process parameters, which can be controlled over a relatively wide range. In this investigation, a large number of ABS tensile specimens are printed by the well-known FFF technology varying deposition path, temperature, speed, and layer thickness over 3 typical values (3^4 factorial plan), and the mechanical response is evaluated searching for the optimum both in terms of main effects and factors interactions.

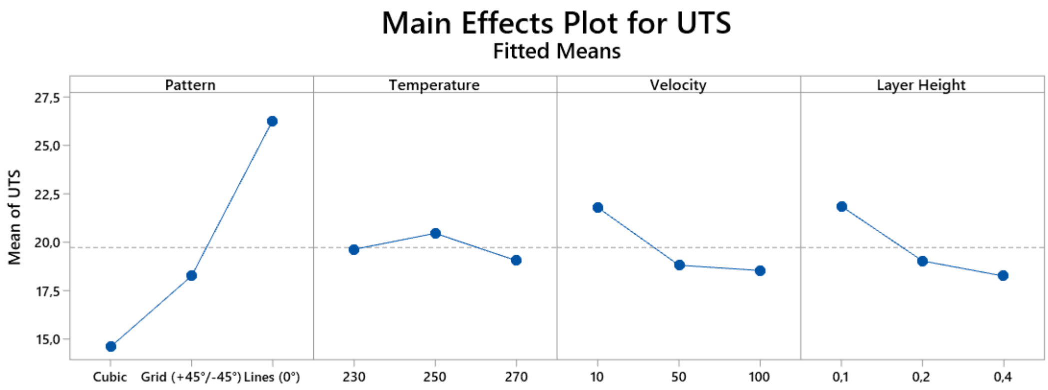

Figure 1. Main effects plot

Unit-cell approach (RVE) applying periodic boundary conditions (PBCs) is an efficient method to homogenize the mechanical behavior of a complex material (composite layer, lattice structure, porous material, etc..), reflecting on the meso-scale the effect of the micro-structure [1]. In this work, the finite element model is developed starting from microscope analysis, with the aim to evidence the effect of structure morphology on the mechanical strength.
The main controllable parameters show a significant influence on the porosity between deposited filaments, and also on the quality of the bonding between filaments (belonging to the same layer or to the following one). These aspects are accurately modelled as they primary affect the specimen response at the macro-scale [2]. Also, the damaging of the part is studied, emphasizing the difference between the material damage (intra-layer) and the failure of the bonded/melt zone (inter-layer).

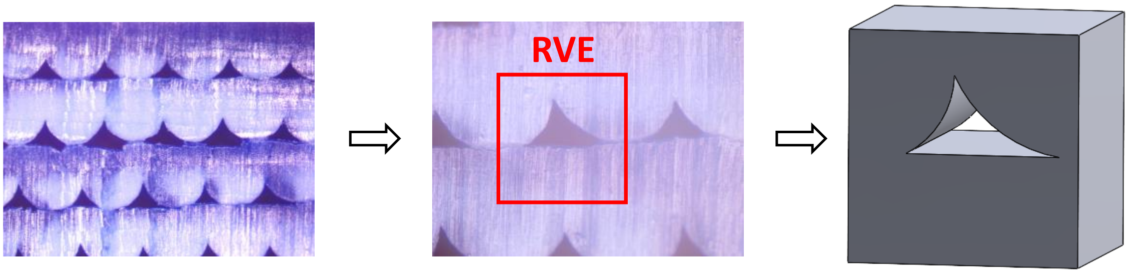

Figure 2. RVE definition from microscope observation

Here the will to homogenize the part in order to have more precise and reliable numerical simulations of 3D-printed components [3]. Results and following interpretation can be of great use in maximizing efficiency of components obtained with this widely adopted manufacturing technology.

REFERENCES

[1] L. Collini, A. Pirondi, Microstructural, multilevel simulation of notch effect in ferritic ductile cast iron under low cycle fatigue, *International Journal of Fatigue,* 162 (2022) 106993.

[2] A. Corvi, *et al.,* Analysis and modelling of damage mechanism in FDM 3D-printed lattice structure under compression loading, *Journal of Mechanical Science and Technology,* 37(4) (2023).

[3] M.S. Anoop, P. Senthil, Homogenisation of elastic properties in FDM components using microscale RVE numerical analysis, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 41 (2019) 540.

Optimization of the numerical homogenization method for cellular structures manufactured by additive SLM technology

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ABSTRACT

1. Introduction

The article focuses on studying cellular structures in 3D printing, which can help optimize components' design to reduce weight. By using cellular networks, we can achieve a cost-effective, lightweight, and durable product. Cellular structures have properties such as high strength, stiffness, and thermal conductivity, which makes them an excellent choice for various applications. As 3D printing enables the creation of complex cellular structures, it is essential to develop numerical analysis techniques for modeling them. The article presents how to optimize the numerical homogenization method. To improve, the minimum number of cells of the structure was determined depending on the shape of a single cell and the relative density. Researchers are constantly working to improve these techniques to unlock the full potential of cell structures in 3D printing.

2. Optimization of the numerical homogenization method for cellular structures

The homogenization method is a numerical technique employed to analyze the properties of cellular structures. This method involves calculating the effective properties of the entire structure by considering the properties of the individual cells that constitute it. It treats the structure as a homogeneous medium with uniform composition, and determines its effective properties, such as stiffness, strength, and thermal conductivity by averaging the properties of the constituent cells. In this method, a mathematical model is formulated to describe the geometry and properties of the cells. The properties of the cells are then averaged over the entire structure, taking into account their spatial distribution and orientation. This results in a precise description of the overall behavior of the structure, without the need to analyze each cell individually.

In considering the homogenization method, it was assumed that the modeling of cellular structures involves determining the constitutive equations on a macroscopic scale based on knowledge of the material properties of a minimum number of unit cells, thus creating a structure, according to the developed algorithm (Fig. 1). The actual shape of the cell structures produced by the SLM/DMLS additive technique was determined using computed tomography. The base material was MS1 tool steel. Using techniques for non-invasive measurements, actual models were obtained along with the porosity occurring. The determination of material parameters is carried out by appropriate averaging against a selected representative volume. In this case, the representative volume is defined as a model consisting of a minimum number of cells, thus forming a cellular structure. In addition, the model contains information on the porosity of the actual geometry of the manufactured element.

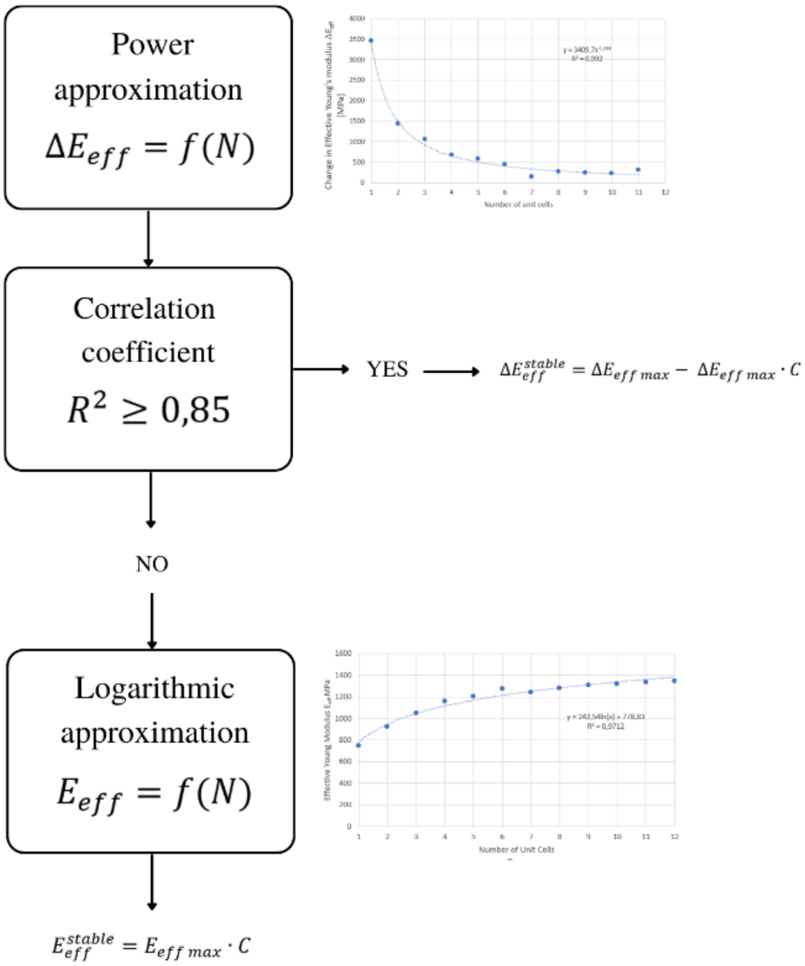

Figure 1. An algorithm to compute the minimum number of cells for cellular structures.

The homogenization approach is particularly suitable for complex and large cellular structures. It provides an efficient and streamlined analysis process while ensuring high accuracy. The improvements have resulted in more accurate results that are consistent with those from the experiment. This technique finds broad applications in the numerical analysis of cellular structures across various fields, such as engineering, material science, and biology.

Numerical and experimental study for DLP printed specimens from dental resin under Charpy impact tests

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ABSTRACT

Technological advances are closely related to the development of new materials and their processing and manufacturing technologies [1]. Additive manufacturing (AM) technology, 3D printing, besides being adopted for rapid prototyping is also used for rapid manufacturing and shows great potential for applications in aerospace engineering, biomedical engineering, and conceptual model preparation [2]. The most important aspect of AM is that there is no more material wastage, costs are reduced, and it is starting to be used in many fields, including the dental field. Most of the high complexity geometrical designs for dental crowns, bridges and other dentistry products are currently realised using digital light processing (DLP) 3D printable biocompatible resins [3]. The 3D printing market is constantly on the rise, and it is projected that it will continue to thrive in the future [4]. Reason why there is a need for a deep understanding of the mechanical proprieties and behaviour of these materials.

The aim of the present study is to assess the Charpy impact tests proprieties of a DLP 3D printable dental resin for specimens printed according to the ISO 179-1 "A" standard [5]. The printing of the samples was done using the "ANYCUBIC Photon Mono X" 3D printer [6], this is a printer model considered at par with the industry standard in the field [7]. The resin used for this study is the NextDent C&B Micro-Filled Hybrid (MFH) dental resin [8]. From which 24 specimens were printed, of which 12 specimens were notched and 12 specimens were unnotched. For each type of specimen there were 4 specimens printed for each printing layer orientation (0°, 45° and 90°(Fig.1).

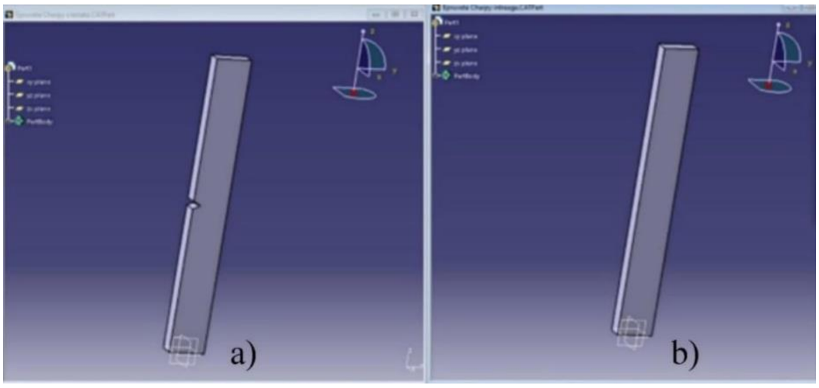

Figure 1. a) Notched Charpy samples; b) unnotched Charpy samples

We can conclude that in the case of the notched samples, we observe the maximum value of both the impact energy and the displacements among the printed samples at an angle of 0˚.

The samples printed on the other two directions, respectively 45˚ and 90˚ show considerably lower values of the overshoots and the energy required to break is somewhere around 75% of that required to break the samples with an orientation of 0˚. The lowest values of both energy and displacements are recorded for the samples printed at 90˚, the impact occurring in the direction of printing the layers of these samples.

REFERENCES

1. Ashutosh T. ş.a., Advanced Engineering Materials and Modeling (Advanced Material Series), Wiley Hoboken, United States, 2016; 528.
2. Gibson I., Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing 2nd ed., Springer, 2015; 498.
3. Hanon, M. M., A. Ghaly, L. Zsidai, Z. Szakál, I. Szabó, and L. Kátai. 2021. "Investigations of the Mechanical Properties of Dlp 3d Printed graphene/resin Composites." Acta Polytechnica Hungarica 18 (8): 143-161. doi:10.12700/APH.18.8.2021.8.8
4. Maines, E. M., Porwal, M. K., Ellison, C. J. and Reineke, T. M. Sustainable advances in SLA/DLP 3D printing materials and processes. Green Chemistry 2021, Vol. 23 Issue 18 Pages 6863-6897 DOI: 10.1039/D1GC01489G
5. International standard ISO 179-2, Plastics — Determination of Charpy impact properties, 1997
6. nycubic.com. https://www.anycubic.com/products/photon-mono-x-6k (accessed 25. December 2022)
7. Nulty A. A comparison of trueness and precision of 12 3D printers used in dentistry. BDJ open, 2022, 8(1), 14. https://doi.org/10.1038/s41405-022-00108-6
8. Nexdent.com. https://nextdent.com/products/cb-mfh-micro-filled-hybrid/ (accessed on 25. December 2022)

A viscoplastic model with non-affine deformation and rotation of a distribution of embedded fibers

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ABSTRACT

A large deformation continuum model for an isotropic visco-plastic matrix reinforced by a distribution of fibres has been formulated. The fibre distribution is a symmetric positive-definite tensor with unit trace that is determined by an evolution equation. This evolution equation includes a competition between tendencies for affine evolution of the distribution and non-affine evolution causing the distribution to align with the elastic distortional deformation tensor or to become isotropic. Two elastic deformation measures are introduced associated with the fibre distribution. Specifically, non-affine measures of elastic stretch of the fibre distribution and non-coaxiality of the fibre distribution cause anisotropic stress response. The resulting model describes a number of effects that may be relevant to additive manufacturing of artificial materials. For example, the equations model the smooth transition from isotropic to anisotropic response seen in fibre spinning and other engineering processes.

Finite element machining simulations of Cu/Ag bicrystal

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ABSTRACT
Materials with microstructure lead to anisotropic deformation behavior and machining characteristics. In this work, a crystal-plasticity-based finite element model for the machining of Cu/Ag bicrystal. In particular, the effect of the Cu/Ag phase boundary on the microscopic deformation behavior with the macroscopic machining results [1,2]. The crystal plasticity-based material model has been implemented in the VUMAT subroutine, and the element deletion technique is followed to describe the material removal and the chip formation [3]. The anisotropic machining characteristics are studied in terms of the chip morphology and the cutting force.

Keywords: Crystal plasticity model, Machining, Finite element modeling, Cutting force

REFERENCES

[1] A. Bertram*: Elasticity and Plasticity of Large Deformations – an Introduction, Third Edition*. Springer Verlag, Berlin (2012).
[2] S. Dodla, A. Bertram, M. Krüger: Finite element simulation of lamellar copper-silver composites, *Computational Materials Science*, 101, (2015a), 29-38.
[3] Liu Q., Dodla S., Roy A., Silberschmidt, V. V. Crystal-plasticity simulation of micromachining of single-crystal metal: Methodology and analysis, Advanced Structured Materials, vol. 60, 165-183 (2016).

4th Session

4. Characterization of AM metallic materials and composites 1

Fatigue life time assessment and crack growth rate analysis in Ni-based alloy 699 XA at elevated temperatures

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ABSTRACT

The present study investigates high temperature fatigue behaviour of Ni-based alloy VDM 699 XA manufactured by laser powder bed fusion (L-PBF) and cold rolling. Isothermal high temperature fatigue experiments were performed on miniature cylindrical specimens in a symmetrical push-pull cycle under stress control in laboratory air at 650 °C and 750 °C. Testing frequency was set to be 5 Hz. S-N curves were obtained for both materials with interesting outcomes. At 650°C, the S-N curve of L-PBF VDM 699 XA is considerably shifted to longer lifetimes whereas at 750°C, the fatigue curves are comparable as shown in Fig. 1a. To explain this behaviour, a thorough microstructural scrutiny as well as fracture surface observations of selected specimens was utilized by means of advanced electron microscopy techniques. Particular attention was paid to the γ´ formation, identification of fatigue crack initiation sites (Fig. 1b) and a quantitative fractography analysis of fatigue crack growth. Crack growth rates evaluated from striation spacing (Fig. 1c) were related to cyclic stress intensity factor range through Paris law. Difference in fatigue life performance and fatigue crack growth behaviour is further discussed and correlated with consideration of microstructural specifics typical for both L-PBF and cold rolled material.

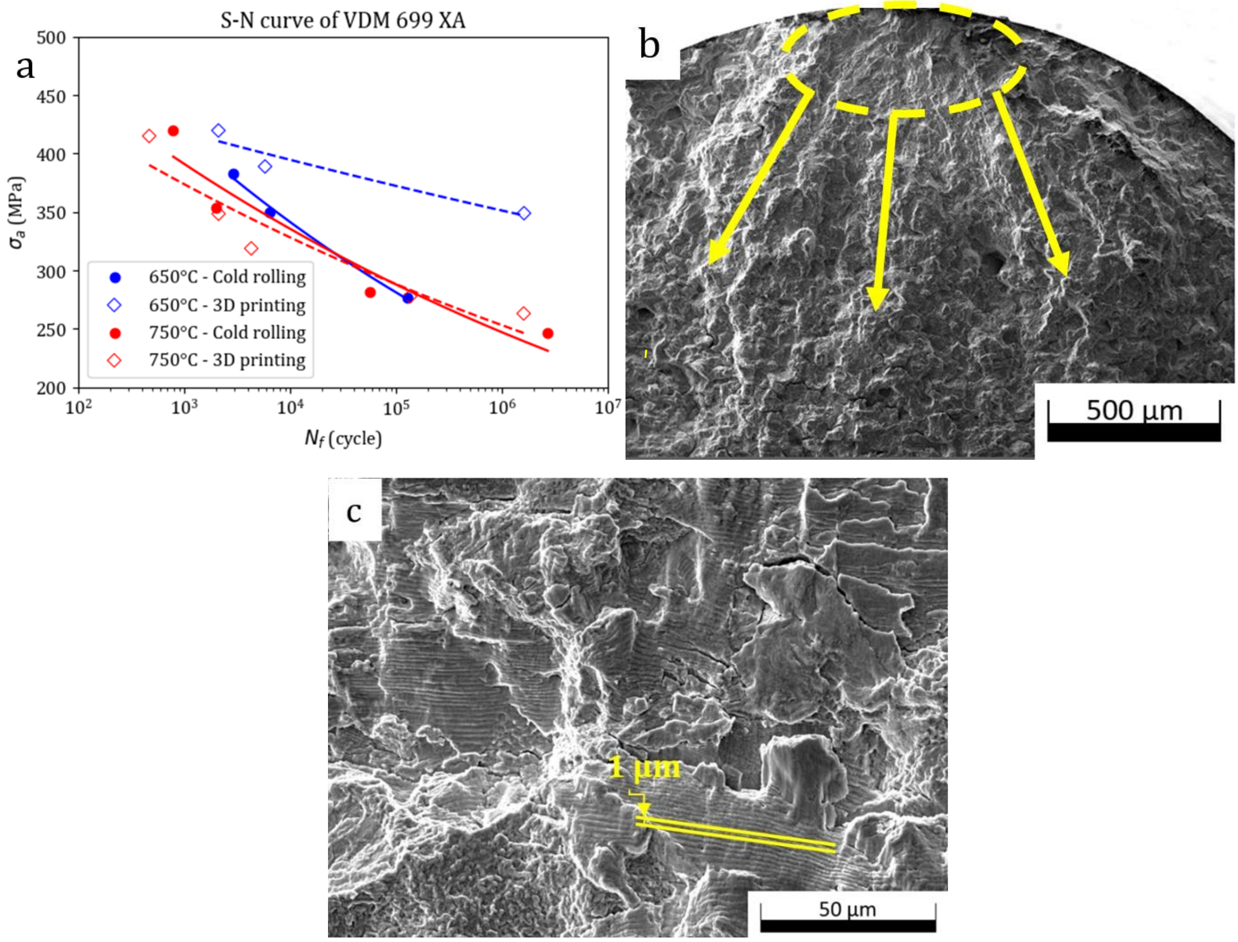

Figure 1. a) S-N curves of VDM 699 XA manufactured by L-PBF and cold rolling; b) representative fracture surface with surface fatigue crack initiation; c) fatigue crack propagation area with typical striations.

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Facile production of high-temperature titanium aluminide powders for directed energy deposition technology

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ABSTRACT

An attempt was made to produce high-temperature Gamma-Titanium Aluminide (γ-TiAl) high-energy ball milling (HEBM). The γ-TiAl solid samples are used in HEBM methods to produce the powders for directed energy deposition (DED) part realization. The powders were characterized by their morphology, elemental composition, and particle size distribution. The elemental composition of the HEBM powders found all four alloying elements, such as Ti, Al, Cr, and Nb. It was observed that the HEBMed powder exhibits a nearly spherical shape (Figure 1). The average sizes of the powders were between 1 to 80 µm. The morphology was quite irregular in contrast to the powders employed in powder bed- based AM technologies. The XRD (Figure 2) results of the powders indicate the presence of γ and α_2 phases. It can be concluded that the HEBM process is a potential low-cost technique for producing the TiAl alloy powder.

Keywords: High Energy Ball Milling, γ-TiAl Alloys, Particle Size Distribution

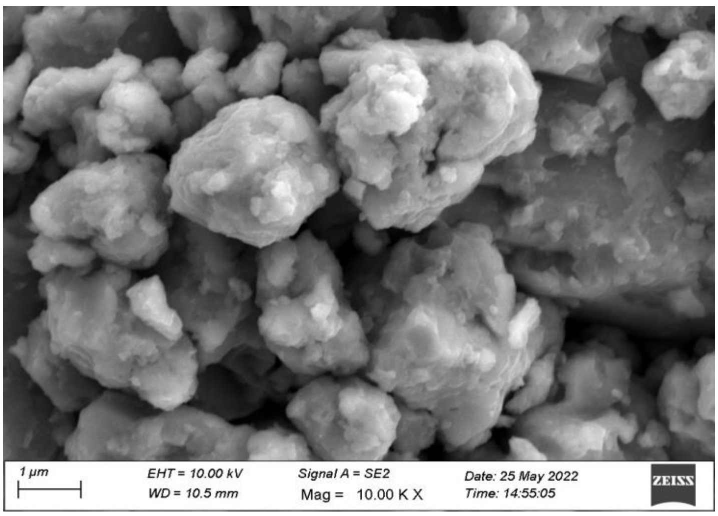

Figure 1. High-temperature intermetallic powder produced via High energy ball milling for directed energy deposition part manufacturing.

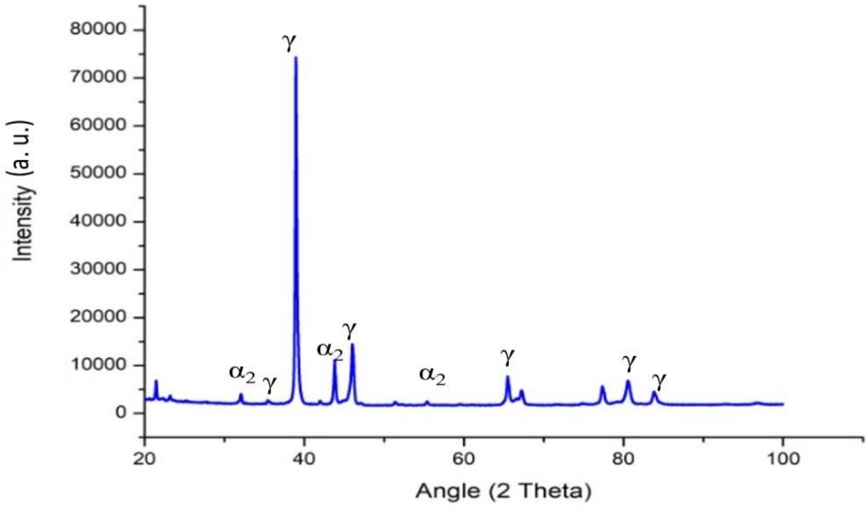

Figure 2. XRD spectra of HEBMed powder

REFERENCES

1. M. Balichakra, S. Bontha, P. Krishna, V.K. Balla, Prediction and validation of residual stresses generated during laser metal deposition of γ titanium aluminide thin wall structures, Mater. Res. Express. 6 (2019) 106550. doi:10.1088/2053-1591/ab38ee.
2. B. Mallikarjuna, E.W. Reutzel, Reclamation of intermetallic titanium aluminide aero-engine components using directed energy deposition technology, Manuf. Rev. na (2022) 1–22. doi:10.1051/mfreview/2022024.
3. H.S. Dhami, P.R. Panda, K. Viswanathan, Production of powders for metal additive manufacturing applications using surface grinding, Manuf. Lett. 32 (2022) 54–58. doi:10.1016/j.mfglet.2022.02.004.
4. K. Kothari, R. Radhakrishnan, N.M. Wereley, Advances in gamma titanium aluminides and their manufacturing techniques, Prog. Aerosp. Sci. 55 (2012) 1–16. doi:10.1016/j.paerosci.2012.04.001.

Morphological and mechanical characterization of 3D printed hydroxyapatite at micro and nano scale

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ABSTRACT

Introduction

Bone is a biological composite tissue combining extraordinary strength and toughness with respect to its weight, thanks to its microarchitecture [1]. Some pathologies and trauma may cause a critical-size bone defect, affecting bone's naturally self-healing property. These conditions can be treated using bioceramic scaffolds, able to stimulate bone growth. Among bioceramic materials, hydroxyapatite (HAP) is a good candidate for scaffold production for its chemical affinity with the native bone's mineral component, thus ensuring biocompatibility and promoting osteointegration. DLP-stereolithography is a printing technology allowing for very fine spatial resolution and high printing fidelity [2]. Since the technological process includes a sintering phase at high temperature, the properties of the obtained material are strongly affected by the intrinsic defects which characterize the final product [3]. In this study, we propose the mechanical characterization of the material samples, which have a simple geometrical shape and the same characteristic size of the microstructural features of the scaffolds. Furthermore, the samples were obtained through the same process as that used for the scaffold production.

Materials and methods

We 3D-printed three different kinds of beams: simple beams, notched beams and cantilever beams (Figure 1) with a rectangular cross-section of approximatively 0.3 mm x 1 mm.

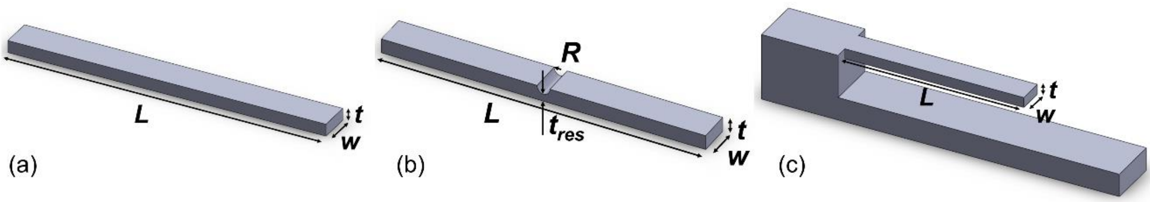

Figure 1. three designs of samples: (a) simple beam, (b) notched beam and (c) cantilever beam.

The samples have been subjected to confocal laser imaging, micro-Computer Tomography scanning and mechanical tests. The confocal laser scanning provided the size of the samples having the purpose to complement mechanical tests and to assess printing fidelity; the micro-CT analyses had the purpose to quantify the intrinsic porosity of the material resulting from the sintering process. The mechanical tests were micro-bending tests and Berkovich nanoindentations. The micro-bending tests were used to assess the stiffness and the flexural strength, while the nanoindentation tests have been used to verify whether elastic property exhibits a scale effect, expected in case micro-defects occur in the material.

Results and discussion

Micro-CT scans have shown a highly dense material with isolated porosity; pore diameter spanned from approximately 2 µm to 25 µm. The overall porosity was as low as 0.35%, indicating that the pores were isolated at a large mutual distance (Figure 2a). Confocal laser scans have shown a surface roughness of Ra = 254 nm ± 31 nm and Rq = 315 nm ± 37 nm (Figure 2b). This surface roughness results adequate for bone cell attachment and proliferation. It is worth mentioning that this porosity and surface features are obtained directly after the sinterization stage, without other external treatments.

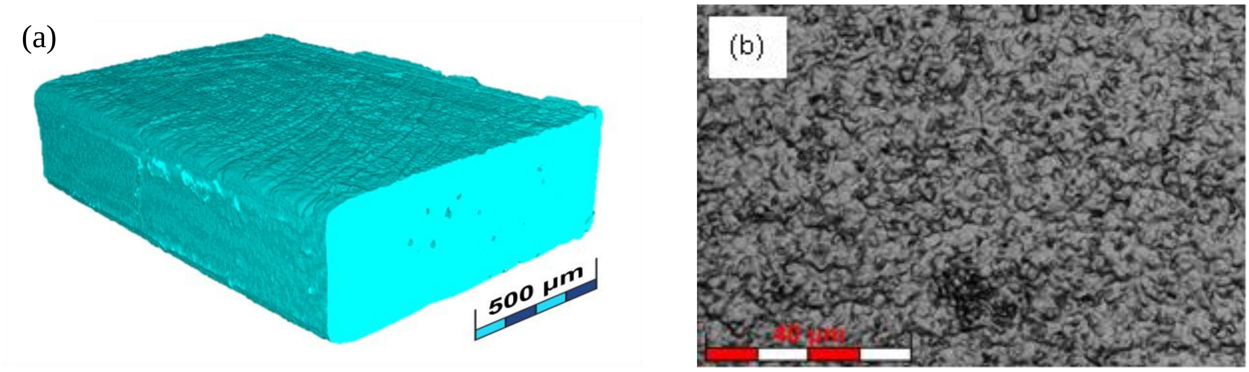

Figure 2. (a) micro-CT rendering of a beam showing the intrinsic porosity and (b) surface roughness of HAP.

Material stiffness estimated through micro-bending tests was E = 98 ± 22 GPa and flexural strength was σ = 115 ± 37 MPa. The notched beams were used for flexural strength assessment only, resulting in σ = 135 ± 58 MPa. Results obtained from nanoindentations show a Young modulus of 102 ± 27 GPa (Possion ratio of 0.3 is assumed). In order to quantify the scattering of the strength, the Weibull modulus has been evaluated, resulting in m = 2.6 and a shape factor of 143 MPa. The knowledge of the intrinsic material properties will represent a relevant piece of information for the design and *in-silico* modeling of bioceramic scaffolds.

REFERENCES

1. Liu Y. et al., *Hierarchical Structures of Bone and Bioinspired Bone Tissue Engineering*, Small 2016.
2. Baino F. et al., *Digital light processing stereolithography of hydroxyapatite scaffolds with bone-like architecture, permeability, and mechanical properties*, Journal of the American Ceramic Society 2022.
3. D'Andrea L. et al., *Estimation of elastic modulus, fracture toughness and strength of 47.5B-derived bioactive glass-ceramics for bone scaffold applications: a nanoindentation study*, Materials Letter 2022.

Metal Technologies in Additive Manufacturing

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ABSTRACT

According to the predictions of the global management consulting company McKinsey & Company, in the next decade we will witness technological progress that will have the scope of the complete progress achieved in the past 100 years. Ten technological trends will dominate this period, and one of them is 3D printing [1].

Metal 3D printing is an advanced technology that enables the production of complex metal parts in one step. This is achieved by adding thin layers of material to the printer platform, which enables precise modelling and fabrication of complex shapes. This process also enables rapid testing and development of prototypes, rapid delivery of new products to the market and improvement of existing ones. By using 3D metal printing, manufacturers can reduce costs, increase production speed, and improve product quality. Several technologies for 3D metal printing exist [2]. Metal 3D printing also requires precision and accuracy, as well as high quality printing materials. This means that the costs of this process can be increased as well as the quality and efficiency. These technologies can help solve complex engineering problems and enable the production of parts that would be difficult or impossible to manufacture using traditional methods. Metal 3D printing also enables personalized production, meaning that parts can be custom-made for the individual needs of the user. [3], [4], [5].

One of the advantages of 3D metal printing is the ability to create parts of high strength and durability, which makes them ideal for use in highly critical applications, such as aeronautics, automotive and medicine [3], [4]. Another important aspect of 3D metal printing is its flexibility and ability to be used in combination with other technologies, which increases its possibilities and applications. For example, 3D metal printing can be combined with other machining processes such as turning, drilling, milling or others to create a finished product with the desired properties and quality. In addition, 3D metal printing significantly reduces production time. Components can be printed directly from the CAD model, which eliminates the need for tooling and models, leading to a faster manufacturing process. This can help to develop products faster and create a competitive advantage. Figure 1. shows 3D printed prototypes - elements of the machine for the rubber processing, made of 316L steel.

Figure 1. 3D printed prototypes, made of 316L steel - elements of the machine for the rubber processing; 3D printing and photos courtesy of M. Eng. Milan Miščević and Teximp d.o.o.

However, metal 3D printing is still a relatively new and developing technology, including some drawbacks (e. g. limitations in the size and shape of printed parts, as well as the high cost of equipment and materials). Either way, 3D metal printing is a significant technology that will continue to evolve in the future. With increased speed, precision and product quality, this technology will have a significant impact on numerous industries and help solve complex engineering challenges.

REFERENCES

[1] McKinsey & Company, "The top trends in tech – executive summary download", [accessed on 10. 02. 2023.] https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/The%20top%20trends%20in%20tech%20final/Tech-Trends-Exec-Summary

[2] Thomas Duda, L. Venkat Raghavan, "3D Metal Printing Technology", IFAC-PapersOnLine, Volume 49, Issue 29, 2016, Pages 103-110. https://doi.org/10.1016/j.ifacol.2016.11.111

[3] Alper Kanyilmaz, Ali Gökhan Demir, Martina Chierici, Filippo Berto, Leroy Gardner, Sastry Yagnanna Kandukuri, Paul Kassabian, Takuya Kinoshita, Andrea Laurenti, Ingrid Paoletti, Anton du Plessis, Seyed Mohammad Javad Razavi, "Role of metal 3D printing to increase quality and resource-efficiency in the construction sector", Additive Manufacturing, Volume 50, February 2022, 102541. https://doi.org/10.1016/j.addma.2021.102541

[4] M. C. Zang, H. Z. Niu, S. Liu, R. Q. Guo, D. L. Zhang, "Achieving highly promising strength-ductility synergy of powder bed fusion additively manufactured titanium alloy components at ultra-low temperatures", Additive Manufacturing, Volume 65, 5 March 2023, 103444. https://doi.org/10.1016/j.addma.2023.103444

[5] Henry Merrow, Justin D. Beroz, Kaihao Zhang, Ulrich P. Muecke, A. John Hart, "Digital metal printing by electrohydrodynamic ejection and in-flight melting of microparticle", Additive Manufacturing, Volume 37, January 2021. https://doi.org/10.1016/j.addma.2020.101703

Influence of post-heat treatment on microstructure and hardness on electron beam welded joint of Ti6Al4V parts manufactured via laser powder bed fusion technology

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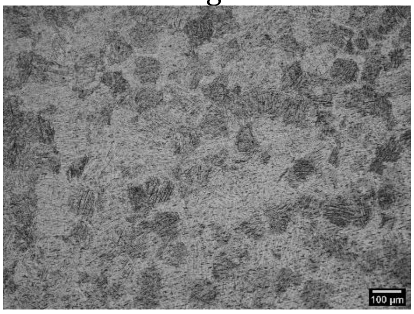
ABSTRACT

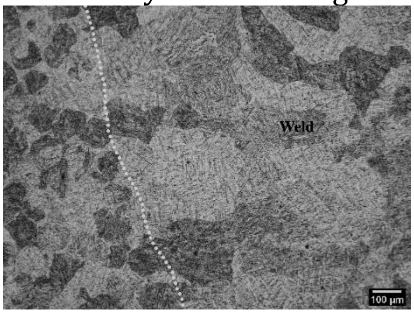
Laser powder bed fusion (LPBF) technology is a layer-based deposition method using a laser to selectively melt successive layers of metal powder in an inert-gas-filled chamber [1,2]. It provides a better alternative manufacturing route than traditional manufacturing techniques in aspects like high flexibility, high material use efficiency and near-net-shape geometries [3]. LPBF has been widely used in bio-medical, military, aerospace, and automobile manufacturing. Titanium alloys such as Ti6Al4V, due to their high weight-to-strength ratio and superior mechanical properties, have been widely used in both the biomedical and aerospace industries [4]. This research studies the influence of heat treatments on the microstructure and hardness of the electron beam(EB) welded joint of Ti6Al4V alloy processed by the LPBF technique. During the LPBF fabrication, the laser power used was 170 - 200W, and the scanning speed was set at 500 - 1250 m/s, whereas layer thickness was controlled at 30μm, and a 67° rotation scanning strategy was adopted. In the present study, the welding was performed using a 6 kW, 60-kV electron beam welding (EBW) setup. A circular beam oscillation at 200Hz having a diameter of 100 microns was used. EBW was done at surface focus conditions. The welding speed of 1500 mm/min with a beam current of 20mA was employed.

The welding was carried out on two state-of-condition samples i.e. i) as-printed (AP) Ti6Al4V parts were welded (AP+AP), and ii) stress-relieved (SR) Ti6Al4V LPBF parts were welded with as-printed LPBF processed parts (SR+AP). The optical microstructure of SR+AP is shown in Fig.1. After the welding, heat treatment was performed on the welded parts to study the effect of heat treatment on the microstructure and hardness of the welded joints. The heat treatment was performed on the EBW samples at three different temperatures of 850°C, 950°C and 1050°C. The welds were analyzed and compared in terms of weld microstructures, bead profile, microhardness and macro examination. The size of the lamellar mixture

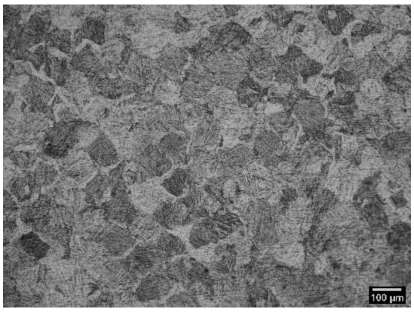
structure inside the Ti6Al4V part gradually grows with the increase in heat treatment temperature. Due to the steep cooling rate during the heat treatment above the T_0 temperature, β phase recrystallization transforms into a compact secondary α phase. A basketweave structure is seen because of the primary α phase, which connects or crosses each other with different orientations. Both α phase and β phase tend to coarsen with an increase in the temperature. An increase in the microhardness is observed as welded part was heat treated at a higher temperature of 1050°C. The hardness profile of the welded samples in all three heat-treated conditions and the fabricated condition is shown in Fig.2. The results revealed specific differences between the welds of AM parts and the welds of AP+AP and SR+AP samples. Significant differences were found in the weld fusion zone (FZ) and the material's thermal conductivity below the β transus. The FZ boundary on the AM side of the joint was wider and straight than the neck-shaped FZ boundary on the wrought material side.



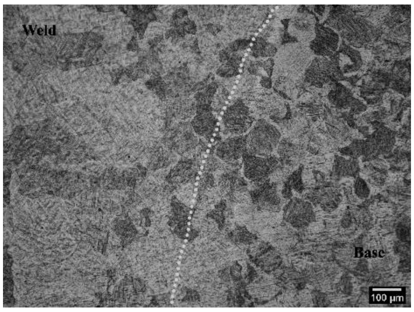
a) Base in as fabricated side



b) HAZ on fabricated side



c) Base in as fabricated SR side



d) HAZ on fabricated SR side

Figure 1. The optical microstructure of welded joint in as-fabricated condition and SR condition

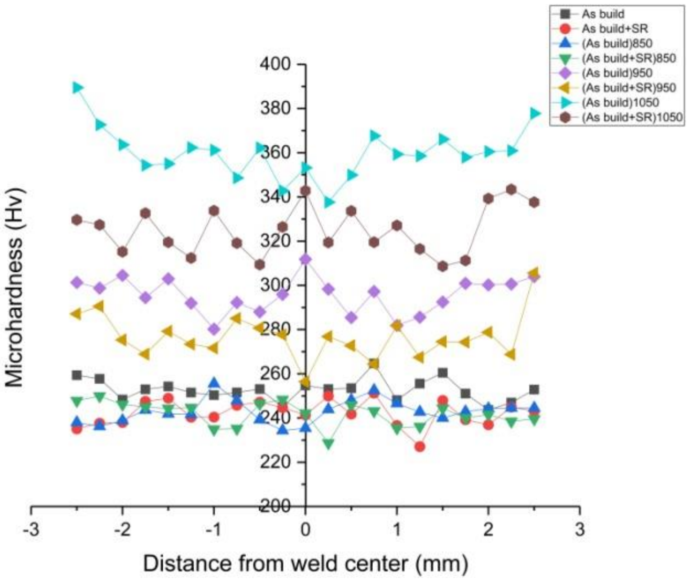


Figure 2. The hardness profile of the LPBF+EBM welded joint

REFERENCES

[1] Herzog, D.; Seyda, V.; Wycisk, E.; Emmelmann, C.; Additive manufacturing of metals. Acta Mater. 2016, 117, 371–392.

[2] Prashanth, K.G.; Scudino, S.; Ecker, J.; Defining the tensile properties of Al-12Si parts produced by selective laser melting. Acta Mater. 2017, 126, 25–35.

[3] Kiel-Jamrozik, M.; Szewczenko, J.; Basiaga, M.; Nowinska, K. Technological capabilities of surface layers formation on implants made of Ti-6Al-4V ELI alloy. Acta Bioeng. Biomech. 2015, 17, 31–37.

[4] Kiel-Jamrozik, M.; Jamrozik, W.; Witkowska, I.; The heat treatment influence on the structure and mechanical properties of Ti6Al4V alloy manufactured by LPBF technology. Innov. Biomed. Eng. 2018, 623, 319–327.

Microstructural characterization and mechanical behaviour of laser powder bed fusion stainless steel 316L

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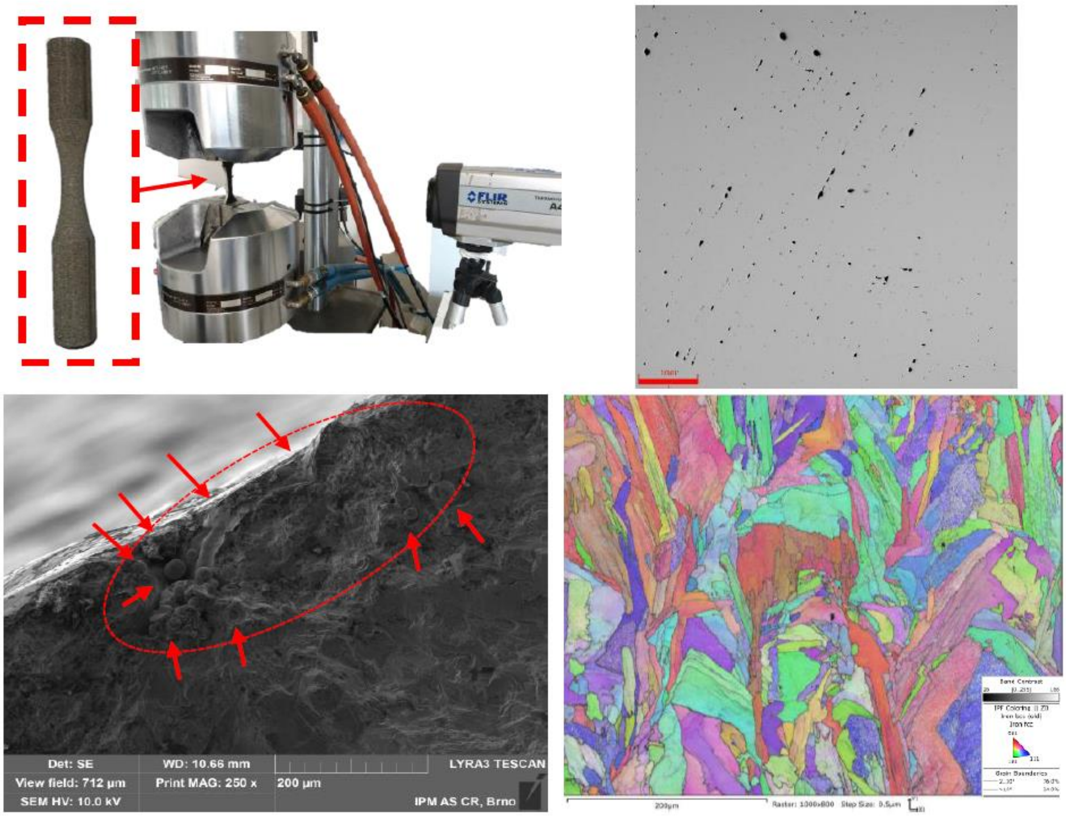
ABSTRACT

Additive manufacturing (AM) techniques represent a revolutionary process for rapid prototyping but also to create ready-to-use components that do not require further processing, even with very complex shapes. Nowadays, the applications of AM process cover almost all of the manufacturing fields, from the automotive and aerospace up to bioengineering to obtain lighter and cheaper prosthesis [1,2].
Laser Powder Bed Fusion (LPBF) is a highly precise and customizable manufacturing technique that uses a high-energy laser to selectively melt and fuse powdered material into a three-dimensional object. This process is also known as selective laser melting (SLM) or direct metal laser sintering (DMLS). However, depending on the process parameters, such as laser power, scanning speed, powder quality, and support structure design, the final components will have potential problems that can affect the quality and mechanical properties.
Some LPBF-prepared components may contain porosity and some other structural defects due to melting and incomplete fusion of powder particles; and because the process involves local heating and sometimes uneven heat transfer, the processed components may warp or crack due to residual stresses or thermal gradients [3]. It is well known, that the manufacturing process itself reflects in the final component structure having a significant effect on the properties usually reducing strength, durability, fatigue resistance, and/or corrosion. Therefore, the mechanical behavior of AM-manufactured components must be investigated to provide their integrity and reliability during operating time.
In this work, constant stress amplitude fatigue tests were performed on AISI 316L stainless steel LPBF processed specimens. The energetic release has been evaluated with an infrared camera during the fatigue tests aiming to identify material response to the loading and predict the failure [4,5]. Differences were observed comparing the fatigue data of the LPBF processed specimens. However, analysis of internal structure, porosity, and also surface characteristics of the AM material in combination with fractographic analysis helped to explain the differences in the number of cycles reached by tested the material. The results show, that the surface roughness was less detrimental than the widely present structural defects, usually acting as fatigue crack initiation sites.



REFERENCES

[1] Milone, D., Risitano, G., Pistone, A., Crisafulli, D. and Alberti, F. (2022) A New Approach for the Tribological and Mechanical Characterization of a Hip Prosthesis Trough a Numerical Model Based on Artificial Intelligence Algorithms and Humanoid Multibody Model. *Lubricants 2022*, **10**, 160. https://doi.org/https://doi.org/10.3390/lubricants10070160

[2] Lowther, M., Louth, S., Davey, A., Hussain, A., Ginestra, P., Carter, L. et al. (2019) Clinical , industrial , and research perspectives on powder bed fusion additively manufactured metal implants. *Additive Manufacturing*, Elsevier. **28**, 565–84. https://doi.org/10.1016/j.addma.2019.05.033

[3] Zhang, M., Sun, C., Zhang, X., Chin, P., Wei, J. and Hardacre, D. (2017) Fatigue and fracture behaviour of laser powder bed fusion stainless steel 316L : In fl uence of processing parameters. *Materials Science & Engineering A*, Elsevier B.V. **703**, 251–61. https://doi.org/10.1016/j.msea.2017.07.071

[4] Santonocito, D., Gatto, A., Risitano, G. (2021) Energy release as a parameter for fatigue design of additive manufactured metals. *Material Design & Processing Communications*, 1–7. https://doi.org/10.1002/mdp2.255

[5] Santonocito, D. (2020) Evaluation of fatigue properties of 3D-printed Polyamide-12 by means of energy approach during tensile tests. *Procedia Structural Integrity*, Elsevier B.V. **25**, 355–63. https://doi.org/10.1016/j.prostr.2020.04.040

A technique for estimation of cyclic stress-strain curves using an optical strain measurement and its application to additively manufactured AlSi10Mg

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ABSTRACT

Introduction

Low-cycle fatigue (LCF) of additively manufactured AlSi10Mg are still rare in literature [1]. The aim of standard strain controlled LCF tests is to evaluate the e-N curve and cyclic stress-strain curve. In this contribution, ASTM inspired practise and an accelerated technique based on an optical measurement were applied to determine the cyclic stress-strain curve under three loading cases: push-pull, torsion and 90 degrees out of phase axial-torsion combination. Results obtained for AlSi10Mg vertically built specimens show very good correlation.

DIC technique description

The dependence of the stress amplitude on the strain amplitude can be obtained by optical measurement on the rounded part of the sample [2]. Thanks to Digital Image Correlation (DIC), hysteresis loops for different stress levels can be evaluated, see Fig.1.

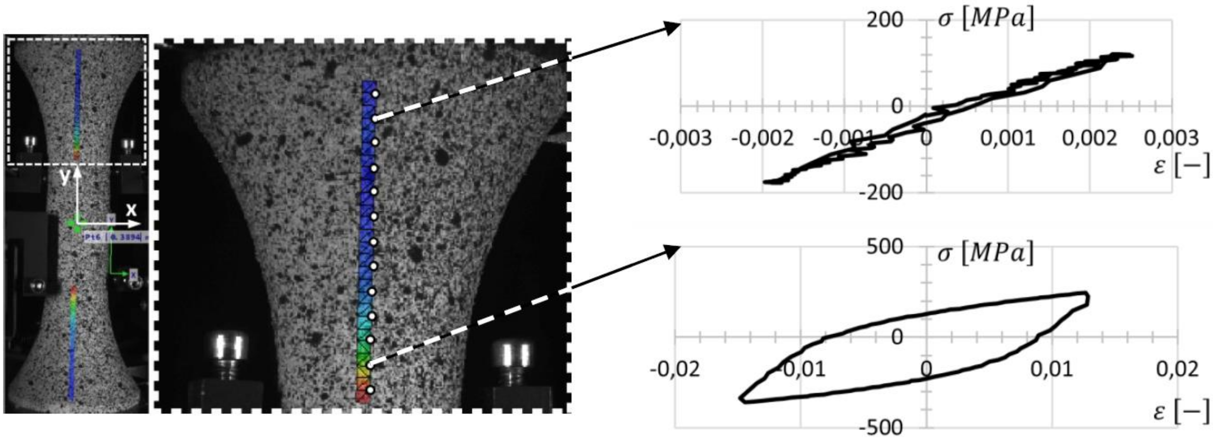

Figure 1. Example of strain contours captured by DIC and corresponding hysteresis loops.

RESULTS

The main benefit of the DIC technique application is estimation of the cyclic stress-strain curve from a single LCF test with a constant (large) strain amplitude. As an example, the results for AlSi10Mg are presented in the form of cyclic stress-strain curves for bottom/upper part of specimen, averaged and the conventional one in the Fig.2. Similarly, good correlation was achieved also for the case of torsion and the non-proportional loading case.

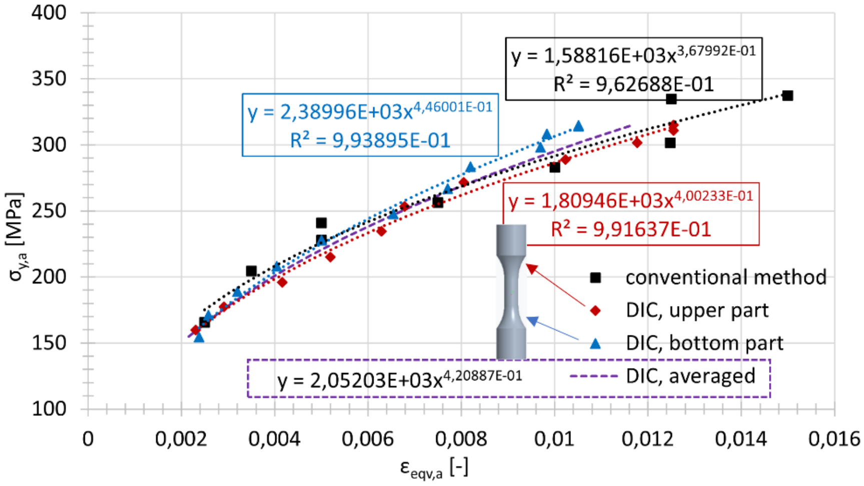

Figure 2. Resulting cyclic stress-strain curves from the DIC technique in comparison with the conventional one for uniaxial loading case.

Conclusion

A new approach for cyclic stress-strain curve estimation was developed. Any full-field optical method suitable to measure plastic strains can be used. Developed technique can help to lower energy consumption and number of specimens, which is very useful in research in the field of additive manufacturing. AlSi10Mg shows a cyclically stable behaviour. Authors will focus on a transient behaviour investigation in a future study.

Acknowledgment

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REFERENCES

[1] A. Raja, S.R. Cheethirala, P. Gupta, J. V. Nilesh, R. Jayaganthan. A review on the fatigue behaviour of AlSi10Mg alloy fabricated using laser powder bed fusion technique. Journal of Materials Research and Technology, 2022, 17 (1013-1029).

[2] Paška, Z. Application of appropriate optical methods for strain field determination in elasto-plastic domain. Dissertation Thesis. VSB - Technical University of Ostrava. Tutor: prof. Ing. Radim Halama, Ph.D. (In Czech)

5th Session

5. AM in bio-related applications, health, and medicine

3D-customized PCL/β-TCP composite scaffold for hard tissues restoration

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ABSTRACT

Background
Grafting materials for bone regeneration aim to facilitate new tissue formation and require peculiar characteristics as well as biodegradability, porosity, interconnectivity, adequate surface topography and elastic modulus, which play a pivotal role in the clinical performance of the biomaterial. Remarkable results have been obtained in bone tissue engineering for the treatment of degenerative and disruptive diseases using highly customized 3D-printed constructs (scaffolds). 3D-printing enables the creation of grafts designed with the specific shape of patient's defect by using a huge variety of biomaterials.
In detail, Poly-Ɛ-caprolactone (PCL) and β-tricalcium phosphate (β-TCP) are among the most studied biomaterials for scaffold customization through 3D-printing due to their many biological properties (e.g, biocompatibility, biodegradability/resorption) and mechanical features.

Objective
The objective of this study is to optimize printable PCL/β-TCP composite biomaterials with balanced porosity and specifically designed internal architecture aiming to resemble human cancellous bone, maintaining adequate mechanical strength, and eliciting positive cellular responses. The main goal of this work is to define the higher amount of β-TCP capable to guarantee an ideal PCL/β-TCP biomaterial combination, in terms of both biological and mechanical properties. This approach allows to provide good structural features (e.g., printability, resistance to compressive stress, porosity, etc.) and improved osteogenic properties, desirable leading to a faster healing of the bone defect.

Materials and methods
Medical grade PCL (Evonik) and β-TCP (Sigma-Aldrich) powders have been used to produce the PCL/β-TCP filaments needed for the printing of customized scaffolds. Initially, all the parameters for filament extrusion (i.e. speed, temperature and cooling) have been set to create three different filaments with PCL/β-TCP relative ratios of 100/0, 60/40 and 30/70.
Subsequently, 3D-printed scaffolds (dimensions 10x10x2mm), with an ad-hoc designed internal architecture, have been obtained through fused deposition modeling (FDM) technology by using a customized 3D printer and extruder. Materials morphology has been

observed through micro-computed tomography; contact angle measurements have been performed to evaluate their wettability and murine osteoblastic cells (MC3T3-E1) have been employed to evaluate their behaviour in biological microenvironment. In particular, scaffolds were tested for their cytocompatibility responses by direct and indirect contact cytotoxicity tests (following ISO 10993-5 Guidelines), cell adhesion and cell morphology (SEM) analysis. Additionally, osteoblastic differentiation has been studied through the analysis of key genes, directly or indirectly involved in bone formation (i.e., OCN, OPG and BSP), via RT-PCR analysis.

Results

All the tested PCL/β-TCP ratios and their ad-hoc printing protocols ended up in high quality printed scaffolds. Micro-computed tomography showed a well-defined internal architecture, consisting with the projected parameters - which resembles in thickness and porosity the interconnectivity of trabecular bone. The internal structure showed an average wall thickness of about 250μm which is analogous to native osteons dimensions [1]. Biological data showed a great scaffold biocompatibility, non-toxicity, with a progressive increase of cell proliferation and osteoblastic differentiation on PCL/β-TCP structures if compared to neat PCL. These results were confirmed through the analysis of cell morphology performed by scanning electron microscopy (SEM) which showed that PCL/β-TCP scaffolds provided to a more favourable microenvironment for cell attachment and proliferation if compared to PCL scaffolds. The presence of β-TCP powder also on the edge of the scaffold, at the interface with the biological environment might lead to a controlled release of calcium ions, thus favouring cell differentiation and new bone formation, as the presence of ceramic powder induced a more marked differentiation, signal of the essential role of β-TCP powder in the cellular differentiation process.

Discussion and conclusion

The PCL/β-TCP scaffolds produced through this process should represent the perfect combination of structural integrity and bioactivity, accelerating the regeneration of the site of interest in an anatomically functional way. In this work has been proved that all the samples loaded with ceramic powder showed a greater proliferative and differentiative effect compared to 100/0 PCL scaffold, providing a microenvironment particularly suitable for cell adhesion, colonization, and proliferation. The biomaterial obtained could therefore represent an ideal candidate for the future development of scaffolds for bone and periodontal regeneration.

Acknowledgements

PNRR-M4C2-I1.5, Project ECS00000033, CUP D93C22000460001, Italian Ministry of University and Research funded by the EU – NextGenerationEU

REFERENCES

1. Vashisth, P.; Bellare, J.R. Development of hybrid scaffold with biomimetic 3D architecture for bone regeneration. Nanomedicine 2018, 14, 1325-1336, doi:10.1016/j.nano.2018.03.011.

The role of 3D printing in rehabilitation

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ABSTRACT

Over the past two decades, 3D printing (3DP) has emerged with a wide range of applications and promising results in medicine. In particular, 3DP deeply changed the production of orthoses [1], movement analysis systems [2], and pre-operative surgeon training [3]. This led to a growing scientific interest, with 345 articles found entering the keywords "3D-printing" and "rehabilitation" into major scientific databases.
The great advantage of 3DP is the possibility to personalize the devices, adapting them in several rehabilitation context. More in details,_3DP was exploited in the customization of orthoses, representing a more cost- and time-efficient process, providing an individualized orthosis shape, optimization of pressure points, high ventilation surface, good aesthetics, and light weight, overcoming the limitations of traditional and standard orthoses, e.g., cutaneous and circulatory complications, muscle loss and joint stiffness, user discomfort which results in less adherence to treatment and discontinuous use. Thanks to these characteristics, 3D printed orthoses showed good clinical results in biomechanical and functional parameters. In particular, it is shown a reduction in plantar pressure and a better load distribution when compared with commercial device. Moreover, in neurorehabilitation, stroke patients showed improvements when treated with 3DP wrist orthosis, e.g., reduction in spasticity and swelling, passive range of motion increase, and improved sensorimotor function [4]. In hand diseases, 3DP devices showed improvements in hand function and pain. The augmented design possibilities can meet the needs of individualized treatment also in pediatric or complex cases, at a significantly lower cost compared to conventional custom-made device. However, one of the main challenges is represented by the choice of materials used to print the orthoses. In general terms, the results in literature showed good technical features in durability and resistance. The choice of the right material grants a higher smoothness and material comfort, increasing wearing time and user satisfaction[5].
In addition, the technological advancement of rehabilitation encourages the use of monitoring devices mounted on 3DP tools or 3DP sensors, which can provide immediate feedback on the activity of the patients, to objectify the results of rehabilitation and build an exercise plan based on the patient's needs. [6] In detail, monitoring systems produced with 3DP for upper and lower limb rehabilitation showed interesting results in hand rehabilitation, improving e.g., pinching amplitude and speed. Furthermore, thanks to 3DP biofeedback system is possible to improve balance and proprioception. However, one of the most important features of 3DP devices is the possible application in tele-rehabilitation, with tools that the patients can manage in autonomy, with a continuous monitoring of healthcare professionals. This approach has shown interesting results, improving the patient's independence during activity of daily life. In addition, 3DP can be used also to print scaffolds to guide tissue reparations with initial evidence from in vivo animal studies, e.g., bone tissue, and cartilage scaffolds, or peripheral nervous system scaffolds, but there are still few in-vivo studies.
However, one of the most interesting fields of application of 3DP is the surgical training. Especially in complex surgeries, a 2D pre-operatory planning has notable limits compared to

3DP customized anatomical models on which the surgery team can study the right surgical approach. 3DP also has the potential to train new medical student by overcoming the observational learning method. The student will be able to perform the invasive procedure on the model without consequences, with positive results in wound complications, patient recovery time and post-operative pain. In literature, there are already interesting results, e.g., in face trauma surgery improving the success of 18.5% when surgery was performed after 3D simulation [7]; in calcaneal fractures, with a 20% reduction observed in wound lesions, shortening of hospitalization time, reduction in post-operative pain, and improved ankle function; and intertrochanteric femur fractures, reducing the operating time, hospitalization, and sarcopenia, with a faster healing time and a better hip range of motion. The potential of training with 3D printing can improve the outcome of invasive procedure, allowing a better learning curve and operatory planning.
On the other hand, there are still some limitations to address on 3DP, e.g., need for calibration and technical assistance; new studies are needed to compare the characteristics of the different materials for 3DP, the software utilized and the new solutions to spread the use of 3DP in clinical practice.
In conclusion, although the potential of 3DP has still to be fully explored, it represents an innovative and personalized tool with beneficial effect for motor recovery, rehabilitation outcomes and quality of life in a wide range of patients.

REFERENCES

1. Guida, P.; Casaburi, A.; Busiello, T.; Lamberti, D.; Sorrentino, A.; Iuppariello, L.; D'Albore, M.; Colella, F.; Clemente, F. An Alternative to Plaster Cast Treatment in a Pediatric Trauma Center Using the CAD/CAM Technology to Manufacture Customized Three-Dimensional-Printed Orthoses in a Totally Hospital Context: A Feasibility Study. *J Pediatr Orthop B* **2019**, *28*, 248–255, doi:10.1097/BPB.0000000000000589.
2. Borghese, N.A.; Essenziale, J.; Mainetti, R.; Mancon, E.; Pagliaro, R.; Pajardi, G. Hand Rehabilitation and Telemonitoring through Smart Toys. *Sensors (Basel)* **2019**, *19*, 5517, doi:10.3390/s19245517.
3. Zhao, Y.; Liu, Y.-H.; Mao, S.-G.; Zhang, X.-X. Evaluation of the Clinical Efficacy of 3D Printing Technology Assisted Surgery Combined with Early Postoperative Comprehensive Rehabilitation in the Treatment of Senile Intertrochanteric Fractures. *Pak J Med Sci* **2021**, *37*, 740–745, doi:10.12669/pjms.37.3.3988.
4. Kim, S.J.; Kim, S.J.; Cha, Y.H.; Lee, K.H.; Kwon, J.-Y. Effect of Personalized Wrist Orthosis for Wrist Pain with Three-Dimensional Scanning and Printing Technique: A Preliminary, Randomized, Controlled, Open-Label Study. *Prosthet Orthot Int* **2018**, *42*, 636–643, doi:10.1177/0309364618785725.
5. Huang, T.-Y.; Pan, L.-L.H.; Yang, W.-W.; Huang, L.-Y.; Sun, P.-C.; Chen, C.-S. Biomechanical Evaluation of Three-Dimensional Printed Dynamic Hand Device for Patients With Chronic Stroke. *IEEE Trans Neural Syst Rehabil Eng* **2019**, *27*, 1246–1252, doi:10.1109/TNSRE.2019.2915260.
6. Foresti, R.; Statello, R.; Delmonte, N.; Lo Muzio, F.P.; Rozzi, G.; Miragoli, M.; Sarli, L.; Ferrari, G.; Macaluso, C.; Maggio, M.G.; et al. Bionic for Training: Smart Framework Design for Multisensor Mechatronic Platform Validation. *Sensors* **2022**, *22*, 249, doi:10.3390/s22010249.
7. Khomutinnikova, N.E.; Durnovo, E.A.; Vyseltseva, Y.V.; Gorbatov, R.O. Digital Technologies in the Surgical Treatment of Post-Traumatic Zygomatico-Orbital Deformities. *Sovrem Tekhnologii Med* **2021**, *12*, 55–61, doi:10.17691/stm2020.12.3.07.

Fibrous scaffolds for tissue engineering applications: experiments and modeling

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ABSTRACT

Biodegradable polymers are increasingly used for cardiovascular in situ tissue engineering devices, which offer relevant advantages over traditional prosthetic solutions in terms of age-related deterioration and biocompatibility. In this contribution, we present the state of our research on a soft fibrous polymeric network fabricated by an electrospinning technique and used as a temporary scaffold for tissue-engineered aortic valves [1].

Cyclic uniaxial and biaxial extension revealed a highly nonlinear material behavior characterized by mechanical anisotropy, time-dependent hysteresis, stress softening, and permanent deformation. We propose a novel constitutive model for the short-term response of the scaffold, developed in the framework of finite strain continuum mechanics and its numerical implementation in a commercial finite element software. The anisotropic response is introduced by second-order structure tensors [2]. The time-independent inelastic effects are accounted for by the concept of pseudo-elasticity [3], while the time-dependent behavior is modeled with internal variables according to the theory of finite strain viscoelasticity [4]. The model is able to accurately reproduce the experimental results. In addition, a large-scale application consisting of a parallel-plate compression test is simulated with a finite element model and validated by comparison with the corresponding experiments.

REFERENCES

[1] De Kort, B.J., Marzi, J., Brauchle, E.M., et al. (2021). Inflammatory and regenerative processes in bioresorbable synthetic pulmonary valves up to two years in sheep. *Acta Biomater.*, 135, 243–259
[2] Schroder, J., Neff, P., & Ebbing, V. (2008). Anisotropic polyconvex energies on the basis of crystallographic motivated structural tensors. *J. Mech. Phys. Solids*, 56(12), 3486–3506
[3] Dorfmann, A., & Ogden, R.W. (2004). A constitutive model for the Mullins effect with permanent set in particle-reinforced rubber. *Int. J. Solids Struct.*, 41(7), 1855–1878
[4] Holzapfel, G.A., & Gasser, T.C. (2001). A viscoelastic model for fiber-reinforced composites at finite strains: Continuum basis, computational aspects and applications. *Comput. Methods Appl. Mech. Eng.*, 190(34), 4379–4403

3D bioprinting of organoid-based scaffolds for toxicology investigation (OBST)

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ABSTRACT

The toxicity of nanoparticles absorbed by contact or inhalation is a major concern for public health, hence it is mandatory to evaluate the toxicity of nanomaterials [1]. In-vitro nanotoxicology studies are conventionally restricted by the two dimensions. While 3D bioprinting has been recently adopted for three-dimensional culture in the context of drug release and tissue regeneration, little is known regarding 3D nanotoxicology investigation. Aiming to simulate the exposure of nanoparticles to lung cells, we developed organoid-based scaffold for long-term studies in immortalized cell lines, printing the viscous cell-laden material via a customizable 3D bioprinter [2], and subsequently, covering the scaffold by 40 nm either latex-fluorescent or 11-14 nm silver nanoparticles.

Background

Engineered nanomaterials (ENMs) are becoming a persistent component of the air we breathe and are used for intentionally administering drugs via inhalation. Inhaled and contact ENMs [3] are a major public health concern: workers and the entire population are daily exposed to these new materials, by direct interaction with the skin or mucous membranes, or simply by breathing [4]. Hence, a nanotoxicology investigation on the effects/problems caused by ENMs over time is mandatory. The in-vitro nanotoxicology approaches (conventional two-dimensional (2D) cell-based models) are limited to the lack of a Z-dimension, avoiding the possibility of examine NPs diffusion, distribution, penetration and the ability to mimic some properties of normal and pathological tissues. Rodents, rabbits and pigs are widely used for in-vivo nanotoxicology and nanomedical preclinical studies, with certain advantages in understanding bioavailability and biodistribution among organs but are not exempt from limitations related to the evaluation of the number of nanoparticles interacting with cellular populations, the kinetics and diffusion of nanoparticles-membrane internalization, and the related animals/facilities costs. These limitations could be overcome by using 3D printed organoids that reproduce the micro-architecture of extracellular matrix (ECM), enabling cells interaction to recapitulate biological functions and consequently reducing the number of animals experiment.

Materials and methods

The 3D bioprinter, customized in our laboratory, was designed for the best fitting between the 3D printer dimensions and the dedicated biosafety cabinet (Heraeus, Herasafe, Germany) [5], provided with UV light for the sterilization procedures before printing. The multilayer 3D model was made via SolidWorks 2015 and saved as a standard triangulation language (.stl) file, for the trajectory generation with Slic3r™. Then, the aforementioned file was converted into .g-code format, useful for the motion control customized firmware (Marlin™). Human Non-Small Cell Lung Cancer line Calu-3 (hereafter Calu-3), purchased from American Type Culture Collection (ATCC, Manassas, VA), were cultured in D-MEM (high glucose) with 0.01 mmol/L nonessential amino acid, 1 mM sodium pyruvate, with 2mM glutamine, 10% fetal bovine serum (FBS, Euroclone, Milano, Italy) and 1% penicillin/streptomycin (5,000 U/mL). Then, the cultured cells were maintained under standard and recommended cell culture conditions. The bioinks were composed by mixing SA (Sigma Aldrich, St.Louis, MO, USA) at different concentration (1% to 5%), 10% Matrigel® (Tewksbury, MA, USA) and 10% Porcine Gelatine (Type A, Sigma Aldrich, St.Louis, MO, USA), diluted in 2 ml of DMEM (w/o phenol red) with 10% FBS and 10 mM HEPES buffer, 2 mM Glutamine and 1% Penicillin/Streptomycin. Cell proliferation was quantified by cell counting by trypan blue exclusion and evaluated under a phase contrast upright microscope (Leica Microsystems, Germany). The viability of cells in the 3D construct was also confirmed using Calcein-AM staining (Thermo Fisher, Waltham, MA, USA). The oxidative stress assay was quantified via intracellular ROS levels by flow cytometer using. Moreover, the Thiobarbituric Acid Reactive Substances (TBARS) was detected to monitor lipid peroxidation, using a Cary Eclipse fluorescence spectrophotometer (Varian, Inc., Palo Alto, CA, USA) (excitation 515 nm, emission 545 nm). Finally, images of the assembly containing Calu-3 cells with 20 μg/ml nanoparticles administration have been performed utilizing two-photon microscopy (res. 0.5-1 μm) at 25x magnifications (Nikon, Balsamo Strumenti, Italy).

Results

The SA concentration adopted for the toxicology experiments was 2% (viscosity 900cP), perfectly fitting those adopted for 2D cell culture, and the extrusion speed was fixed at 13 mm/s. The number of live cells was $5\times10^5\pm5\times10^2$ at the beginning of culturing and increased to $1.27\times10^6\pm9.19\times10^4$ after 21 days. Moreover, the number of dead cells was low at each time point, ranging from $4.78\times10^4\pm7.95\times10^3$ on Day 0 to $8.25\times10^4\pm2.19\times10^4$ on Day 21 ($p=0.044$). Results showed, after 1, 7 and 14 days of 3D culture printing, a significant and progressive decrement of TBARS values. Moreover, 3D printing affects the cell cycle reaching values of cells, after 72 h, of 80.5% in the G2/M phase, while 10.5% are in S and 8.9% in the G2/M phase. Then, once confirmed that printed cells embedded in the hydrogel could survive and proliferate over time, by reducing drastically oxidative stress, we further decided to investigate the potential use of our "organoids" for nanotoxicology approaches, analysing the NPs (red fluorescent 40 nm latex, negatively charged) internalization in 2D and 3D multicellular structures. The OBST shows a direct interaction between nanoparticles and the cells. The cells are widely distributed in the entire thickness of the multilayer and for this type of cell-laden bioprinted hydrogel, the maximal penetrated nanoparticles numbers were achieved at Z=680 μm. Finally, we evaluated the polydispersity of colloidal toxic AgNPs, known as a potential agent for antitumor possible therapies. AgNPs concentrations denote an increment of the concentration necessary to inhibit 50% of cell viability ($IC_{50}=6.88\text{x}10^9$) similar to in-vivo toxicological investigation on rats, where, silver nanoparticles became toxic with concentration over 100 μg/ml

Conclusion

In our study, we demonstrated a significant increment of cell viability from 3D vs 2D cultures exposed to nanoparticles, denoting on the 14th day lipid peroxidation reduction over time and minimal cell death throughout 21 days. Finally, whereby both cells and nanoparticles were not equally distributed the cells entrapped nanoparticles in all layers, showing toxicology responses that recapitulate the in-vivo tests of AgNPs inhaled by rats. The results open a new perspective in 3D protocols for nanotoxicology investigation supporting 3R's.

REFERENCES

1. Malakar, A.; Kanel, S.R.; Ray, C.; Snow, D.D.; Nadagouda, M.N. Nanomaterials in the environment, human exposure pathway, and health effects: A review. *Sci. Total Environ.* **2021**, *759*, 143470, doi:10.1016/j.scitotenv.2020.143470.
2. Foresti, R.; Rossi, S.; Pinelli, S.; Alinovi, R.; Sciancalepore, C.; Delmonte, N.; Selleri, S.; Caffarra, C.; Raposio, E.; Macaluso, G.; et al. In-vivo vascular application via ultra-fast bioprinting for future 5D personalised nanomedicine. *Sci. Rep.* **2020**, *10*, 3205, doi:10.1038/s41598-020-60196-y.
3. Bandala, E.R.; Berli, M. Engineered nanomaterials (ENMs) and their role at the nexus of Food, Energy, and Water. *Mater. Sci. Energy Technol.* **2019**, *2*, 29–40, doi:10.1016/j.mset.2018.09.004.
4. Foresti, R.; Ghezzi, B.; Vettori, M.; Bergonzi, L.; Attolino, S.; Rossi, S.; Tarabella, G.; Vurro, D.; Zeppelin, D. von; Iannotta, S.; et al. 3D printed masks for powders and viruses safety protection using food grade polymers: Empirical tests. *Polymers (Basel).* **2021**, *13*, 1–13, doi:10.3390/polym13040617.
5. Foresti, R.; Rossi, S.; Pinelli, S.; Alinovi, R.; Barozzi, M.; Sciancalepore, C.; Galetti, M.; Caffarra, C.; Lagonegro, P.; Scavia, G.; et al. Highly-defined bioprinting of long-term vascularized scaffolds with Bio-Trap: Complex geometry functionalization and process parameters with computer aided tissue engineering. *Materialia* **2020**, *9*, doi:10.1016/j.mtla.2019.100560.

Additive Manufacturing for orthopedic implants: morphological and material characterization of SLM Ti6Al4V thin samples

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ABSTRACT

Introduction

The advantages of Additive Manufacturing (AM) applied to the orthopedic industry are nowadays well recognized. The production of a new generation of devices mimicking bone morphology is an outstanding example: lattice structures in the order of hundreds of microns are conceived to resemble trabecular bone. These implants are commonly manufactured by using Selective Laser Melting (SLM) technology and Ti6Al4V powder. Uncertainties in producing thin struts approaching the accuracy limit of AM technologies (about 300 μm) affect their mechanical behavior. Indeed, recent works [1,2] outlined how the dimensions of such small samples lead to a significant discrepancy from the bulk material (dimensions in the order of centimeters), hindering their characterization. In this scenario, morphology and mechanical behavior (static and fatigue) of AM thin struts should be investigated together. Thus, the current study aims at providing an exhaustive morphological and material characterization of Ti6Al4V thin struts produced via SLM, coupling a pure experimental approach adopted in the literature with Finite Element (FE) analyses. These results will be used for designing a safe and efficient implant for talus substitution, as discussed in [3].

Material and methods

(i) Specimens manufacture. Cylindrical samples (0.6 mm of diameter, approaching the thickness of bone trabeculae) were manufactured via SLM using a biomedical grade Ti6Al4V ELI powder. Three batches of material specimens were used, different for the print direction (45°, 60°, 90° w.r.t. the build plane), reasonably chosen based on the struts inclinations of the trabecular cells commonly used for orthopedic devices and compatibly with the AM limits (the 0° case was precluded) (*Fig. 1a*). *(ii) Morphological characterization*. The quality of the as-built samples was investigated by performing: 1) density analysis to assess the presence of internal pores w.r.t. a machined Ti6Al4V, 2) global geometry evaluation to assess mismatches of the AM samples from the nominal ones (e.g. cross-section area, *Fig. 1b*), 3) local geometry evaluation of the surface texture. *(iii) Material characterization*. Uniaxial tensile tests were performed under displacement control on three samples for each batch to determine static

mechanical properties (*Fig. 1c*). Given the small dimensions of the samples, extensometers were not applied to measure strains. To avoid this limitation, experiments were coupled with numerical analyses: FE models of the samples were developed considering the actual cross-section areas derived from the morphological characterization. Finally, fatigue tests were performed under force control (stress ratio 0.1, mean force 40 N) until either sample failure or runout ($5{\cdot}10^5$ cycles). To date, three load levels have been considered and five samples for each level and for the 60°- and 90°- batches have been tested (*Fig. 1d*). The runout was chosen based on the final aim of this study: the design of a talus prosthesis. Considering an average of 10^6 steps/year, the time to guarantee an osseointegrated implant is about half a year ($5{\cdot}10^5$ cycles), during which the prosthesis is the only element bearing the body weight. This condition represents the worst-case scenario to be investigated during the fatigue analysis.

Results and discussion

The AM peculiarities in producing thin struts are currently open issues. The outcomes of the current work confirmed the few findings available in the literature. The underrated cross-section area (5%-20% difference w.r.t. the nominal one, *Fig. 1b*) and the surface roughness led to a reduction in the effective load-bearing section. A decrease of about 40% was found for the elastic modulus and a reduction of 7% was observed for the yield stress in the static tests. In the fatigue tests, a reduction varying between 20% to 40% of the limit stress within the range of $4{\cdot}10^4$ and 10^5 cycles was observed w.r.t. to the results obtained testing bulk Ti6Al4V samples (specimens diameter ranging from 3 mm to 6 mm, [4]) (*Fig. 1d*). The introduced parameters were not affected by the print direction, with the exception of the cross-section area: lower was the print direction (45°), higher was the mismatch w.r.t the nominal sample.
A deep insight into the material and geometrical properties of AM thin struts is crucial for predicting the mechanical behavior of an AM prosthesis characterized by trabecular parts.

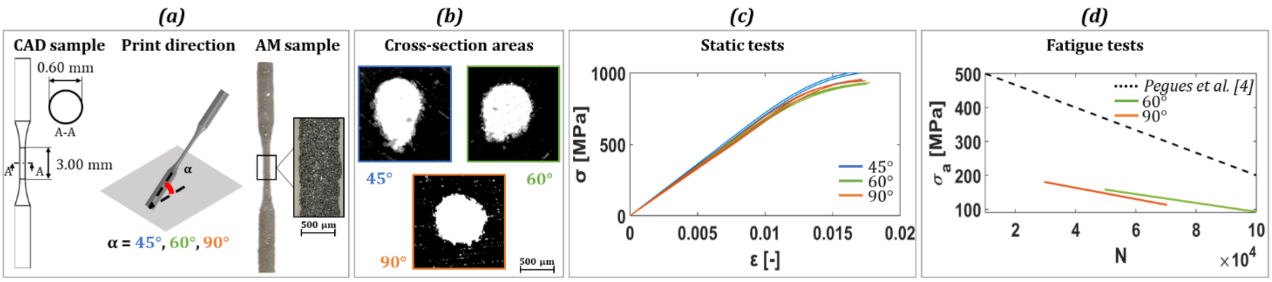

Figure 1. (a) Ti6Al4V cylindrical specimens manufactured via SLM, (b) cross-section areas of the printed samples, (c) stress–strain curves (σ–ε) obtained in the uniaxial tensile tests, (d) stress–number of cycles (σ–N) obtained in the fatigue tests compared with the literature results obtained testing bulk Ti6Al4V [4].

REFERENCES

[1] S. Murchio *et al.*, *Journal of the Mechanical Behavior of Biomedical Materials*, 2021.
[2] U. Hossain *et al.*, *Additive Manufacturing*, 2021.
[3] F. Danielli *et al.*, *Journal of Mechanical Science and Technology*, 2023.
[4] J. Pegues *et al.*, *International Journal of Fatigue*, 2018.

Use of 3D printed models for endovascular treatment planning of peripheral arterial disease. Preliminary results of a single-blinded randomised trial

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ABSTRACT

Background and Purpose

The preoperative planning of chronic peripheral artery diseases (PAD) undergoing endovascular treatment is generally performed based on data obtained by Computed Tomography Angiography (CTA), or directly during the procedure through digital subtraction angiography (DSA) assessment.
The aim of this study is to evaluate the advantage of custom-printed 3D models in preoperative planning and training in terms of perioperative results.

Material and Methods

Three-dimensional (3D) printing applications in medicine have been limited for a long time due to the high cost and technical difficulty of creating 3D printed objects. It is now known that patient-specific, hollow, and small-caliber vascular models can be manufactured with 3D printing and used for endoluminal device testing. Previous studies have shown that the production of anatomically accurate, medium and small-caliber arterial models have been printed using a patient's Computed Tomography scan data, free open-source software, and low-cost Internet 3D printing services.
In our study, since January 2022, all patients undergoing endovascular treatment of aorto-iliac-femoral-popliteal arteriopathy with an available preoperative Computed Tomography Angiography were randomised 1:1 (Figure 1). In group 1 (cases), a 3D model was printed for planning and training before treatment. In group 2 (control), the angioplasty/stent procedure was planned and performed according to the usual local protocols. Urgent treatments were excluded. For the reproduction of the 3D models, custom-made hybrid printers in a climate chamber, resins polymerisation printers and rapid-freeze prototyping were used (Figure 2, 3). Perioperative data were compared in the two groups. Operating time, amount of contrast medium, radiation dose, technical success and complications were compared.

Results or Findings

All 12 included patients presented with iliac lesions (Table 1). The mean duration of surgery was 46.80±17.00 min in group 1 vs. 81.70±11.5.00 min in group 2 ($p=0.03$). Amount of contrast medium: 100.00±62.70 mL vs. 196.70±221.40 mL ($p=0.43$). Radiation dose 9900±2068 cGy/cm2 vs. 36350±10468 cGy/cm2 ($p=0.004$); sweep time 7.80±2.10 min vs. 25.00±11.50 min ($p=0.03$). Only one intraoperative complication was recorded in group 1 ($p=0.35$). Technical success was 100% in both groups. No periprocedural deaths occurred.

Conclusion

Our preliminary results suggest that preoperative planning and training using custom-printed 3D models for iliac revascularization surgery may have a significant benefit in terms of reduction of endovascular procedure duration, scoping time, and radiation dose.

Main points

- In customized medicine, it is possible to create precise, patient-specific 3D models of thin vascular structures.
- 3D printed vascular models may be helpful for planning before endovascular surgery.
- 3D printed vascular models can be produced virtually and inexpensively.

REFERENCES

1. Itagaki MW. Using 3D printed models for planning and guidance during endovascular intervention: a technical advance. Diagn Interv Radiol. 2015 Jul-Aug;21(4):338-41. doi: 10.5152/dir.2015.14469. PMID: 26027767; PMCID: PMC4498430.
2. Zhang H, Lu T, Guo W, Liu X, Jia X, Xiong J, Ma X, Wang L. [Three-dimensional print of aortic aneurysm models aid preoperative planning in complicated endovascular repair procedure]. Zhonghua Wai Ke Za Zhi. 2015 Apr;53(4):300-4. Chinese. PMID: 26269166.
3. Namba K, Higaki A, Kaneko N, Mashiko T, Nemoto S, Watanabe E. Microcatheter Shaping for Intracranial Aneurysm Coiling Using the 3-Dimensional Printing Rapid Prototyping Technology: Preliminary Result in the First 10 Consecutive Cases. World Neurosurg. 2015 Jul;84(1):178-86. doi: 10.1016/j.wneu.2015.03.006. Epub 2015 Mar 14. PMID: 25779852.
4. Namba K, Higaki A, Kaneko N, Mashiko T, Nemoto S, Watanabe E. Microcatheter Shaping for Intracranial Aneurysm Coiling Using the 3-Dimensional Printing Rapid Prototyping Technology: Preliminary Result in the First 10 Consecutive Cases. World Neurosurg. 2015 Jul;84(1):178-86. doi: 10.1016/j.wneu.2015.03.006. Epub 2015 Mar 14. PMID: 25779852.
5. Kang J, Yang M, Kwon Y, Jeong C, Kim N, Heo S. Case report: Application of three-dimensional technologies for surgical treatment of portosystemic shunt with segmental caudal vena cava aplasia in two dogs. Front Vet Sci. 2022 Aug 12; 9:973541. doi: 10.3389/fvets.2022.973541. PMID: 36032305; PMCID: PMC9411943.

Shelf-life of 4D bioprinted aerogel

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ABSTRACT

3D bioprinting aims to the fast customization of drug delivery systems useful for personalised medicine applications, in particular for laparoscopic procedures. Indeed, printed scaffolds are very similar to polypropylene gauze, typically inserted via trocars, but presenting the ability to modulate the in situ release of different kind of drugs. Regrettably, additive manufacturing requires long fabrication times, not always congruous with surgical duration. Moreover, the fabrication procedures that might go towards long-term storage have to be planned before the surgery. Despite of the ability of hydrogels to be preserved in a 5% ethanol suspension[1], it is not possible to change or modulate the active principle concentration after the printing phase. Aerogels may overcome these problems, thanks to rehydration procedures merged with the shape-memory properties, typically obtained during the hydrogel gelation [2]. In conclusion, to ensure the ability of aerogels to be adopted for in-vivo drug release validation and for personalized medicine, it is mandatory to test the biomaterial after several months from the synthesis.

Background

Laparoscopic approaches adopted to surgically treat abdominal structural diseases allow to perform resections without making major incisions of the abdominal wall. Anastomoses can be performed either manually (hand-sewn) or by means of a mechanical stapler. In addition, some suturing devices can be provided with biocompatible materials which are automatically fixed to the suture thereby reducing the anastomotic leak, the bleeding rate, and the infection risk. The aim of this study is to develop an aerogel scaffold, useful for the aforementioned applications and presenting a high quality shape memory. In fact, 3D printing fabrication process takes a long time to develop a given material [3], which makes it difficult to produce the device in parallel with the duration of the surgery. Moreover, biomaterials are playing a pivotal role in the development of complex and highly customizable structures able to mimic the target tissue morphology, thus it is mandatory to identify hydrogels able to resemble ECM structure, composition, and the internal architecture of the native tissue as closely as possible.

Materials and methods

The hydrogels were prepared by dissolving sodium alginate powder into complete high

glucose DMEM w/o Phenol Red (Gibco®, ThermoFisher scientific, Waltham, MA, USA) at a final concentration of 7%, 9%, and 11% wt/vol. Subsequently, the scaffolds have been printed (speed of 6 mm/s) onto an aluminium plate, with a 26 G needle at RT and −24°C of printing platform temperature. The alginate-based scaffolds were washed in EtOH, dehydrated at 40°C and through scanning electron microscopy the surface topography was analysed in terms of micro-porosity, before and after 4 years of storing.
Finally, HT29 cells in their logarithmic phase were cultured on 96-well plates and allowed to adhere overnight at 37°C, before the addition of alginate scaffold 11% for 24–48h after cells seeding. At the end of the treatment, cell morphology was visualized with an inverted phase contrast microscope and cellular viability was assessed by (3-(4,5-dimethyl-thiazol-2-yl)2,5-diphenyl tetrazolium bromide) (MTT) assay. The above-mentioned cells-scaffold have been processed for histology, using a conventional cryostat and by fixation/embedding, in formalin 10% and paraffin respectively. Finally, the histological sections obtained by both methods were stained by a Giemsa dye and observed under a bright-light microscope.

Results
Our results demonstrate that, alginate scaffolds, obtained via liquid frozen deposition manufacturing, dehydration and ethanol cleaning, can be stored up to 48 months after fabrication, preserving the micro-porosity. By changing the concentration of the hydrogel, the scaffold rehydration process showed a linear increase of the time required to regenerate the shape, regaining the original structure and preserving the macro-porosity. The scaffold, as demonstrated by Scanning Electron Microscopy analysis, after rehydration, supported HT29 cells attachment and proliferation. Moreover, replication and toxicity tests on cells cultured onto the scaffolds, performed via histological analysis, gave good results, showing cell groups with well-preserved nucleus and cytoplasm were identifiable. Lastly, cells during mitosis, specifically in advanced metaphase, have been identified, strongly suggesting a viable and active state of these cells/scaffold complexes.

Discussion and conclusion
In our study, we demonstrated that aerogels scaffold can be printed and stored for up to 4 years, without loss of properties, overcoming the typical problem related to the fabrication time. Furthermore, the scaffold can be rehydrated, recovering the initial shape, with active ingredients useful for the surgery activity, i.e. drugs that favour tumour regression. Thus, our approach can assure tissue regeneration after cancer removal and based on its shape should be easily scaled in laparoscopic surgery.

REFERENCES

1. Foresti, R.; Rossi, S.; Pinelli, S.; Alinovi, R.; Barozzi, M.; Sciancalepore, C.; Galetti, M.; Caffarra, C.; Lagonegro, P.; Scavia, G.; et al. Highly-defined bioprinting of long-term vascularized scaffolds with Bio-Trap: Complex geometry functionalization and process parameters with computer aided tissue engineering. *Materialia* **2020**, *9*, doi:10.1016/j.mtla.2019.100560.
2. Foresti, R.; Rossi, S.; Selleri, S. Bio composite materials: Nano functionalization of 4D bio engineered scaffold. In Proceedings of the 2019 IEEE International Conference on BioPhotonics, BioPhotonics 2019; 2019; Vol. 2019-Janua.
3. Avventuroso, G.; Foresti, R.; Silvestri, M.; Frazzon, E.M. Production paradigms for additive manufacturing systems: A simulation-based analysis. In Proceedings of the 2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation Management Beyond 2020: New Challenges, New Approaches, ICE/ITMC 2017 - Proceedings; 2018; Vol. 2018-Janua.

6th Session

6. Characterization of AM metallic materials and composites 2

Cyclic stress-strain behaviour of L-PBF Ni-based superalloy IN939 at 800 °C

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ABSTRACT

The present study focuses on the cyclic stress-strain behaviour of additively manufactured polycrystalline Ni-based superalloy IN939 fabricated via laser powder bed fusion (L-PBF). Cylindrical fatigue specimens with gauge length and diameter of 9 mm and 3 mm, respectively, manufactured with loading axis (L.A.) oriented parallel and perpendicular to the building direction (B.D.) were tested in heat-treated conditions (solution annealing + 2-step precipitation hardening). Cyclic loading was performed in a fully reverse symmetrical push-pull cycle at 800 °C in laboratory air under strain control mode using a computer-controlled MTS 810 testing machine. The strain was monitored via a sensitive extensometer equipped with extended ceramic tips. A heating was provided by a three-zone resistance furnace, and temperature was controlled using four K-type thermocouples. A cyclic stress-strain curve was obtained using a short-cut procedure. This method uses only one fatigue specimen, which is subjected to a gradual increase in strain amplitude every 10 cycles until fracture. Thorough microstructural scrutiny was conducted employing scanning electron microscopy, energy-dispersive X-ray spectroscopy, electron backscatter diffraction, and transmission electron microscopy. Conventionally cast IN939 was subjected to the same experimental routine to reveal differences in both microstructures and cyclic stress-strain behaviour. The columnar grain structure with a preferential orientation of <001> in the building direction is typical for L-PBF IN939, whereas for cast alloy coarse dendritic grains without any specific texture are typical. Both L-PBF and cast IN939 exhibited bimodal distribution of coherent γ´ precipitates (Fig. 1b). Selected hysteresis loops for all modifications of IN939 in the representation of stress vs. strain are shown in Fig. 2a-c. The specimen with columnar gains oriented parallel to L.A. withstand deformation up to 1.3% whereas cast material with polyhedral grains and L-PBF IN939 with columnar grains oriented perpendicular to L.A. endure only 0.5% and 0.4% of total deformation. The cyclic stress-strain curves that determine the behaviour of the material for most of its fatigue lifetime are shown in Figure 1d. The curves are consistent with the hysteresis loops (Fig. 2a-c) and show that the IN939 with L.A. oriented parallel to the B.D. has the highest plasticity, which is most likely caused by the strong texture of the longitudinal grains in the ⟨001⟩ direction.

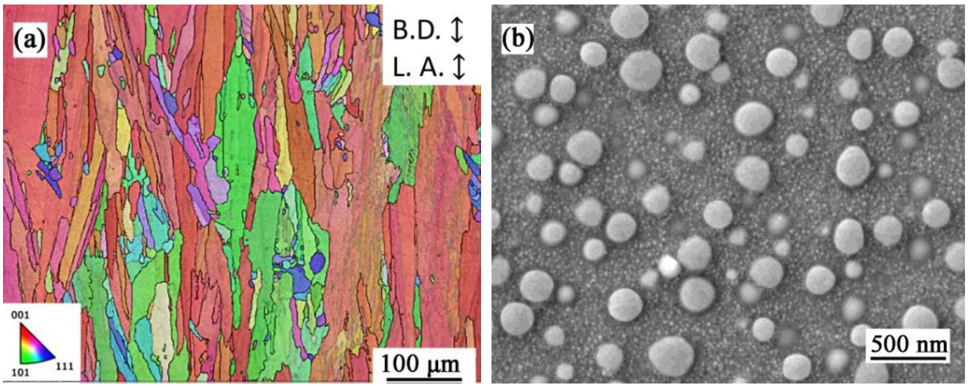

Figure 1. Microstructure of IN939. (a) IPF EBSD map of L-PBF material with columnar grains and <001> texture along the building direction. (b) Coherent γ´ precipitates.

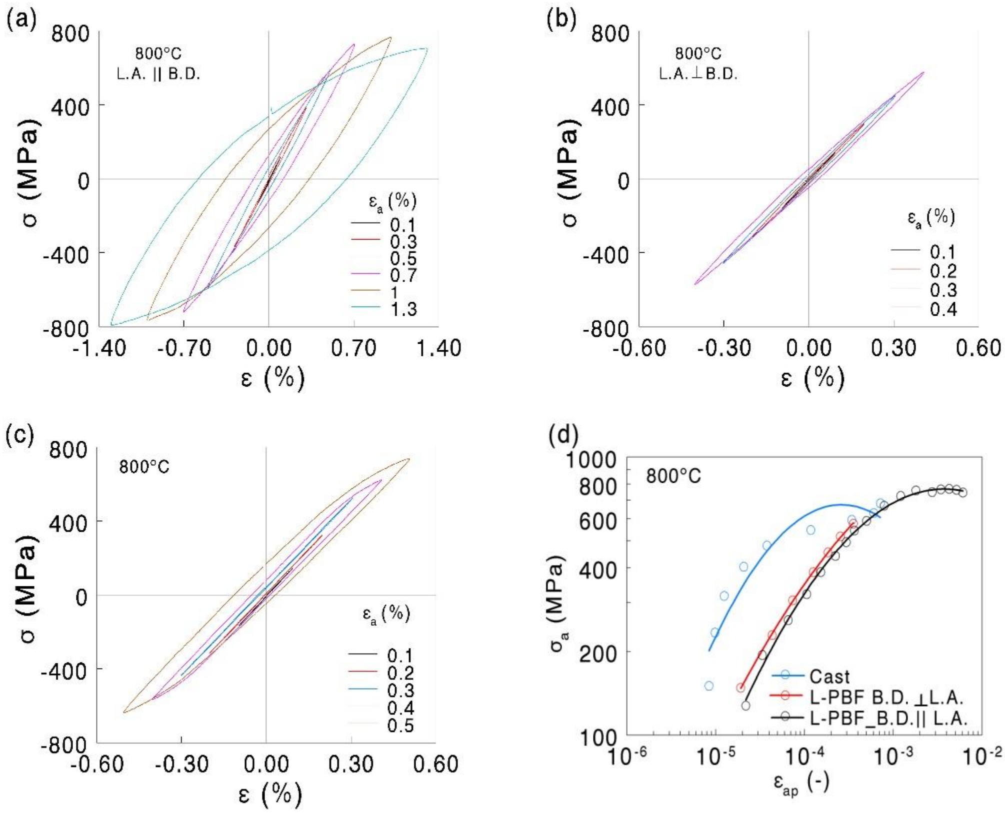

Figure 2. Representative hysteresis loops of IN939 obtained at 800 °C for (a-b) L-PBF specimens with (a) parallel and (b) perpendicular loading to building direction, and (c) cast specimen; (d) Comparison of cyclic stress-strain curves of IN939 at 800 °C.

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Review of the fatigue behavior in near-threshold conditions for notched and un-notched additively manufactured metallic materials, with a focus on AlSi10Mg lattice structures

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ABSTRACT

Additive manufacturing (AM) technologies are at the forefront of technological development in machine design, as they allow the creation of artifacts that are just not possible with conventional production processes, given the almost complete absence of geometric limitations. Among the possibilities offered by AM, lattice structures in particular (or cellular structures, metamaterials) stand out. These structures are obtained by the periodic repetition of an elementary cell of struts or surfaces in space and are characterized by macroscopic mechanical properties that are different from those of the base material of which they are composed. The ability to vary the elementary cell size and obtain stiffness-to-weight and strength-to-weight ratios with composite materials make such structures particularly suitable for the aerospace, automotive, and biomedical industries.

The potential of AM, especially for lattice structures, is currently limited by concerns related to their structural integrity, due to mechanical peculiarities closely linked to the production process. In particular: (i) the presence of surface defects (e.g., surface roughness, deep sharp notches similar to cracks) and sub-surface defects (e.g., porosity, Lack Of Fusion – LOF), (ii) the potentially significant discrepancy between the as-designed and as-built geometry, (iii) the presence of strong residual stresses in the As-Built (AB) conditions.

All these factors contribute to poor fatigue resistance of AMed structures compared to their counterparts obtained through conventional processes. Furthermore, the fatigue assessment is even more complex considering (i) the significant statistical dispersion of data and (ii) the difficulty in transferring information from small-sized laboratory test specimens to the real components.

At the current state of the art, the fatigue assessment of AMed lattice structures is typically performed with a nominal approach [1], [2]. It requires the calculation of the applied nominal stresses using the beam theory and comparing the stresses obtained with an experimentally calibrated sN curve. The method's main limitation is that it does not consider the effects of the stress concentrations at (i) the strut junctions and (ii) the surface and internal defects. This results in the necessity to calibrate the sN curve for each loading condition and geometry of the real component, resulting in costly and time-consuming experimental campaigns.

Experimental results show that lattice structure fatigue cracks initiate from either surface defects or internal defects close to the surface characteristic of the AM process (typically LOFs). Assuming the presence of non-propagating cracks originating from the defects at the fatigue limit (as experimentally seen for various metallic alloys typically used to produce lattice structures [3], [4]), one should use a Damage Tolerant (DT) approach based on the Linear Elastic Fracture Mechanics (LEFM) for the fatigue assessment. In the literature, there

are several successful applications of DT models, mainly based on Murakami's sqrt(area) [5] and the Atzori-Lazzarin-Meneghetti model [6], to predict the fatigue limit of un-notched AM defective specimens under uniaxial loading [7]–[9], but very few for notched materials [10], [11].

This work first proposes a thorough review of the fatigue resistance of fully dense AMed plain and notched metallic specimens with a DT approach based on LEFM. Then it covers the fatigue behavior of AMed lattice structures in AlSi10Mg, highlighting qualitative results showing the validity of predictions based on DT models.

REFERENCES

[1] M. Benedetti, A. du Plessis, R. O. Ritchie, M. Dallago, S. M. J. Razavi, and F. Berto, "Architected cellular materials: A review on their mechanical properties towards fatigue-tolerant design and fabrication," *Materials Science and Engineering: R: Reports*, vol. 144, p. 100606, Apr. 2021, doi: 10.1016/J.MSER.2021.100606.

[2] A. Cutolo and B. van Hooreweder, "Fatigue behaviour of diamond based Ti-6Al-4V lattice structures produced by laser powder bed fusion: On the effect of load direction," *Mater Today Commun*, vol. 33, p. 104661, Dec. 2022, doi: 10.1016/J.MTCOMM.2022.104661.

[3] H. Matsunaga, Y. Murakami, M. Kubota, and J. H. Lee, "Fatigue Strength of Ti-6Al-4V Alloys Containing Small Artificial Defects," *Materials Science Research International*, vol. 9, no. 4, pp. 263–269, Dec. 2003, doi: 10.2472/jsms.52.12appendix_263.

[4] Y. (Yukitaka) Murakami, "Metal fatigue : effects of small defects and nonmetallic inclusions".

[5] M. Yukitaka and E. Masahiro, "Quantitative evaluation of fatigue strength of metals containing various small defects or cracks," *Eng Fract Mech*, vol. 17, no. 1, pp. 1–15, Jan. 1983, doi: 10.1016/0013-7944(83)90018-8.

[6] B. Atzori, P. Lazzarin, and G. Meneghetti, "Fracture mechanics and notch sensitivity," *Fatigue Fract Eng Mater Struct*, vol. 26, no. 3, pp. 257–267, Mar. 2003, doi: 10.1046/J.1460-2695.2003.00633.X.

[7] S. Beretta and S. Romano, "A comparison of fatigue strength sensitivity to defects for materials manufactured by AM or traditional processes," *Int J Fatigue*, vol. 94, pp. 178–191, Jan. 2017, doi: 10.1016/J.IJFATIGUE.2016.06.020.

[8] D. Rigon and G. Meneghetti, "Engineering estimation of the fatigue limit of wrought and defective additively manufactured metals for different load ratios," *Int J Fatigue*, vol. 154, p. 106530, Jan. 2022, doi: 10.1016/J.IJFATIGUE.2021.106530.

[9] D. Rigon and G. Meneghetti, "An engineering estimation of fatigue thresholds from a microstructural size and Vickers hardness: application to wrought and additively manufactured metals," *Int J Fatigue*, vol. 139, Oct. 2020, doi: 10.1016/J.IJFATIGUE.2020.105796.

[10] S. Beretta *et al.*, "A benchmark activity on the fatigue life assessment of AlSi10Mg components manufactured by L-PBF," *Mater Des*, vol. 218, p. 110713, Jun. 2022, doi: 10.1016/J.MATDES.2022.110713.

[11] M. Benedetti and C. Santus, "Building the Kitagawa-Takahashi diagram of flawed materials and components using an optimized V-notched cylindrical specimen," *Eng Fract Mech*, vol. 224, p. 106810, Feb. 2020, doi: 10.1016/J.ENGFRACMECH.2019.106810.

Fatigue behavior of SLM maraging steel under variable-amplitude loading

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ABSTRACT

Introduction

Maraging steel is a special class of advanced high-strength steels, widely used in the aircraft, aerospace, military, offshore, tooling and mould making industries, due to the combination of unusual properties, namely high-strength, toughness, ductility, and weldability along with dimensional stability [1]. Because of their martensitic matrix, these materials require a rapid quench from the austenitic region to temperatures below the martensite start temperature, which makes them particularly suited for the selective laser melting technology.
In the above-mentioned areas of application, most components experience variable-amplitude loading which makes them prone to fatigue failure. Under these service conditions, engineering design against fatigue requires not only a detailed knowledge on the loading history but also a deep understating of the cyclic deformation response [2]. Nevertheless, so far, very few studies have addressed the loading sequence effect and the damage accumulation mechanisms in fatigue life of maraging steel produced by selective laser melting. Thus, this paper studies the uniaxial fatigue behaviour of 18Ni300 maraging steel produced by selective laser melting under variable-amplitude loading.

Material and methods

The material selected for all experiments performed in this study was the 18Ni300 maraging steel produced by selective laser melting. The specimen geometries were fabricated with a vertical orientation, on the base plate, using a Concept Laser M3 linear printing system equipped with a Nd:YAG fibre laser (see Figure 1). The building strategy comprised the deposition of 40 μm thick layers, with a hatch spacing of 100 μm, at a scan speed of 200 mm/s.
The loading history consisted of two blocks of three cycles each. In the first block, the amplitude increased, and in the second they decreased. The amplitudes of the individual

cycles were 50%, 75% and 100% of the maximum strain amplitude. The tests were carried out at four load levels at the maximum value of the strain amplitude: 1.00%, 0.75%, 0.50% and 0.35%.

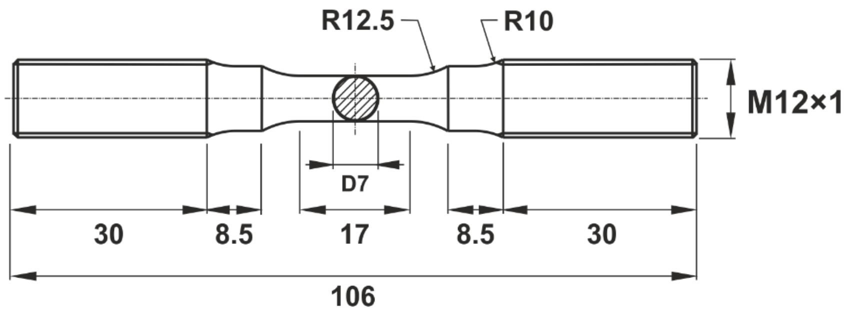

Figure 1. Specimen geometry used in the low-cycle fatigue tests.

Results and discussion

Based on the obtained test results, it was noticed that for the two highest load levels, where the maximum strain amplitude was 1.00% and 0.75%, the material cyclically softened, which was evident by about a 20% decrease in the stress amplitude while for the other two, it behaved stably. The average fatigue life increased, concerning the life at the maximum strain amplitude of 1.00%, three times (0.75%), eight times (0.05%) and over thirty times (0.035%).

REFERENCES

1. Kempen K, Yasa E, Thijs L, Kruth JP, Van Humbeeck J (2011). Microstructure and mechanical properties of selective laser melted 18Ni-300 steel. Physics Procedia 12, 255-263.
2. Marciniak Z, Rozumek D, Macha E (2008). Fatigue lives of 18G2A and 10HNAP steels under variable amplitude and random non-proportional bending with torsion loading. International Journal of Fatigue 30, 800-813.

Impact of Electron Beam Melting process recycling on defects and microstructure of Ti-6Al-4V powders

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Keywords: Electron Beam Melting; Ti-6Al-4V; Recycling powders; Defects; Microstructure; Powder morphology; Plasma atomization process; ELI powders.

ABSTRACT

Metal powders are used as the feedstock material during an Electron Beam Melting process. The process involves using an electron beam as the energy source to produce intricate parts with complex shapes in a layer-by-layer production system. The electron beam is directed by information from an STL file, and the process takes place in a pre-heated chamber that is maintained under vacuum. Once the production cycle is complete, the process yields the desired components along with a certain amount of residual powders that were not melted.
To improve process efficiency and reduce costs associated with powder atomization, it is feasible to repurpose the excess powder for subsequent production cycles. Prior to starting a new cycle, the excess powder is initially sieved to ensure a more uniform powder batch, and subsequently, the sieved powder can be mixed with other virgin powder to decrease oxygen content.
This study examines the microstructure and defects present in a batch of virgin powders, produced through plasma atomization, and a batch of powders that were reused five times and mixed with Ti-6Al-4V grade 23 (ELI powders) at each cycle. The ELI powders are characterized by a low oxygen content.
The results of the analysis indicate a clear correlation between the powder atomization process and the formation of porosities in virgin powders resulting from trapped gas, as well as surface irregularities, including the presence of satellites. With an increase in the number of reuses, there is a reduction in the number of satellites, potentially due to surface partial melting due to the pre-heating of the EBM chamber, leading to rougher surfaces on the recycled particles.
The microstructure of virgin powders is predominantly characterized by a fine acicular α' phase, known as martensitic, formed due to the rapid cooling rate during the atomization process. Conversely, recycled powder tends to exhibit a coarser grain microstructure due to lower cooling rates. However, it is common to observe particles with a microstructure similar to that of newly manufactured powders, indicating that each individual particle has undergone a distinct thermal history.

On the evaluation of the fatigue thresholds of additively manufactured metals

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ABSTRACT

The studies on the structural integrity of additively manufactured (AM) metals have increased significantly in recent years, driven by advances in technology and the need for lighter and more efficient components. Despite the growing interest in AM metals, their fatigue behaviour remains an area of concern, mainly due to a lack of knowledge regarding the interplay between the peculiar microstructure, residual stress state, poor surface quality, and defects.
The most employed approaches to investigate the influence of defects and the surface asperities on the fatigue behaviour of such materials are based on fracture mechanics.
This work aims to summarize the authors' previous works on the effect of defects on the fatigue behaviour of AM specimens.
The fatigue threshold of several AM metals was estimated using the Atzori Lazzarin and Meneghetti (ALM) model, which is an extension to the notches with different opening angles of the well-known model proposed by the El Haddad Smith Topper (EHST) [1,2]. The ALM model needs two material parameters, namely the plain fatigue limit of the defect-free material $\Delta\sigma_0$ and the threshold value of the long crack stress intensity factor range $\Delta K_{th,LC}$.
The accurate evaluation of $\Delta K_{th,LC}$ would require standardised fatigue crack growth procedures for a given load ratio, R. However, in absence of experimental data, the authors calibrated a parametric empirical equation based on Vickers hardness (HV) and a properly defined microstructural length parameter (l), able to estimate $\Delta K_{th,LC}$ of both wrought and AM metals within an error band of +-20%. The equation coefficients were calibrated on experimental data taken from the literature for three different load ratios, namely, -1, 0 and 0.5 [3,4].
The standard method for obtaining $\Delta\sigma_0$ is to perform high cycle fatigue tests on polished specimens using the staircase procedure. However, owing the presence of defects in AM materials, the experimental determination of the defect-free plain material fatigue limit $\Delta\sigma_0$ is unpracticable. Therefore, the Murakami's correlation based on HV ($\Delta\sigma_0$=3.2HV) was assumed to be valid also for AM alloys, such as Ti6Al4V, stainless steels and tool steels. In addition, to take into account the effect of the load ratio, an empirical equation $\Delta\sigma_0$=f(HV,R) was derived by means of the Goodman's correction.
Given the empirical equations $\Delta K_{th,LC}$ =f(l, HV) and $\Delta\sigma_0$=f(HV), the ALM model can be simply estimated from measurements of l and HV.
The ALM model proved accurate by comparison with constant amplitude fatigue test results on AM maraging steel specimens performed by the authors and fatigue test results of several AM alloys reported in the literature.

The advantage of the proposed engineering approach is that it relies only on l and HV material parameters, making it a cost-saving and efficient tool for estimating fatigue thresholds in additively manufactured materials.

REFERENCES

[1] Atzori B, Lazzarin P, Meneghetti G. Fracture mechanics and notch sensitivity. Fatigue Fract Eng Mater Struct 2003;26:257–67. https://doi.org/10.1046/j.1460-2695.2003.00633.x.

[2] Atzori B, Lazzarin P, Meneghetti G. A unified treatment of the mode I fatigue limit of components containing notches or defects. Int J Fract 2005;133:61–87. https://doi.org/10.1007/s10704-005-2183-0.

[3] Rigon D, Meneghetti G. An engineering estimation of fatigue thresholds from a microstructural size and Vickers hardness: application to wrought and additively manufactured metals. Int J Fatigue 2020;139:105796. https://doi.org/10.1016/j.ijfatigue.2020.105796.

[4] Rigon D, Meneghetti G. Engineering estimation of the fatigue limit of wrought and defective additively manufactured metals for different load ratios. Int J Fatigue 2022;154:106530. https://doi.org/10.1016/j.ijfatigue.2021.106530.

Anomalous fatigue crack propagation behavior in near-threshold region of L-PBF prepared austenitic stainless steel

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ABSTRACT

Laser powder bed fusion (L-PBF) process produces a specific non-equilibrium microstructure with properties significantly different from those of conventionally processed materials. In the present study, the near-threshold fatigue crack propagation in austenitic stainless steel 304L processed by L-PBF was investigated. Three series of specimens with different orientation of initial notch with respect to build direction were manufactured in order to evaluate the effect of specimen orientation on the near-threshold fatigue crack propagation behavior. The results showed absence of the orientation dependence of the fatigue crack propagation behavior. However, abnormally low threshold stress intensity factor values were recorded, which was attributed to the absence of crack closure even at low load ratios (R = 0.1). In order to explain recorded behavior, the selected orientation was subjected to heat treatment to relieve build-in residual stresses (HT1) and create recrystallized microstructure (HT2) comparable with conventionally processed materials. It was found that the characteristic microstructure produced by L-PBF is the reason for the absence of crack closure and low threshold values at low load rations. As-built microstructure containing sub-micron dislocation cell-substructure is prone to cyclic instability. In the crack tip region, cyclic plasticity results in strain-induced phase transformation and the continuous thin martensitic layer is formed in the crack vicinity. The induced martensite phase is softer compared to the austenite matrix with cell-substructure. Together with cyclic instability of the matrix, the macroscopic cyclic softening occurs as the result within the crack tip region. Under such conditions, the formation of the plasticity-induced and roughness-induced crack closure is significantly reduced and macroscopic resistance to the fatigue crack propagation is low.

The effect of PLA fillers on mechanical properties of FDM components

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ABSTRACT

Fused Deposition Modelling (FDM) is the most accessible additive technology up to now because it combines the low cost and simplicity of the machine with the low cost and availability of the thermoplastic polymers. This class of polymers are however limited and in order to increase the applicability of the products, mixing the polymeric matrix with various fillers can be a solution.

The purpose of this study is to identify the effect of the functional fillers incorporated in PLA thermoplastic on the mechanical properties of the obtained components. In addition, the layer orientation in relation to the loading direction will be considered as a study variable also. All samples were manufactured on the same conditions using three identical FDM machines. The effect of carbon and glass-fibers fillers on the PLA matrix in comparison with the parental PLA filament was evidenced by tensile and bending testes. The results were then interpreted based on the two variables: filler and layer deposition in accordance to the loading direction.

7th Session

7. Characterization of AM polymer-based materials 2

Influence of printing orientation on the tensile strength of specimens made of PA12 using SLS

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ABSTRACT

The aim of this study is to analyze the mechanical characteristics of specimens produced by selective laser sintering. Using a Fuse 1 (FormLabs, Summerville, MA) machine, all specimens were made. Here, the mechanical characteristics of a single specimen geometry made in accordance with ISO 527-2 are determined. In general, polymer materials are tested for tensile strength using this specific standard. The bulk dimensions of the chosen specimen are 170x20x4 mm. Two sample batches with different printing orientations—vertical and horizontal—were created. The material used in this method is Polyamide 12, which is used often in manufacturing. In the tensile testing machine, specimens are evaluated in their as-built condition.

The obtained research shows that the elasticity and tensile strength values of the horizontal specimens have a lower value scatter than the vertically constructed specimens. Moreover, specimens produced horizontally have greater strain values than those produced vertically.

Investigating the effect of raster orientation on fracture behavior of 3D-printed ABS specimens under tension-tear loading

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ABSTRACT

Most of the engineering components are servicing under complex loading conditions or have complex geometries that lead to a multiaxial stress state in the component [1]. Thus, the fracture behavior of parts under mixed-mode loading conditions should be investigated. The Fused Deposition Modeling (FDM) is a subcategory of the Additive Manufacturing (AM) techniques that has some important manufacturing parameters [2]. The raster orientation (or raster angle) is one of fabricating parameters that significantly affect the mechanical behavior of fabricated parts [3]. Therefore, this study aims to investigate the fracture behavior of FDM specimens made of Acrylonitrile Butadiene Styrene (ABS) under mixed-mode I/III loading conditions. To this goal, four different raster configurations of ψ_R = 0/90°, 15/-75°, 30/-60°, and 45/-45° were selected for FDM fabrication of edge cracked rectangular specimens, and five loading angles of β= 0° (mode I), 40°, 65°, 72°, and 90° (mode III) were used for performing mixed-mode I/III fracture experiments on the pre-cracked specimens. Besides, some tensile experiments were performed on dog-bone specimens fabricated with the mentioned raster configurations. In order to theoretically predict the failure loads in the tested cracked specimens, a theoretical model named Equivalent Material Concept (EMC) was utilized for equating the ductile behavior of FDM-ABS material with a brittle one [4]. The mentioned concept was coupled with J-integral (EMC-J) and Maximum Tangential Stress (EMC-MTS) criteria to predict the failure loads under mixed-mode loading conditions. The results showed that both EMC-J and EMC-MTS criteria could predict the experimental failure loads well. Additionally, Scanning Electron Microscopy (SEM) was performed on the fracture surfaces to analyze the failure mechanisms of the tested specimens. SEM analysis confirmed the presence of three failure features namely air gaps, filament pullouts, and hackle regions that were discussed comprehensively.

Keywords: Fused Deposition Modeling (FDM); Equivalent Material Concept (EMC); J-integral method; Maximum Tangential Stress (MTS) criterion; Tension and tear loading

REFERENCES

[1] B. Bahrami, M.R. Ayatollahi, I. Sedighi, M.A. Pérez, A.A. Garcia-Granada, The effect of in-plane layer orientation on mixed-mode I-II fracture behavior of 3D-printed polycarbonate specimens, Eng. Fract. Mech. 231 (2020) 107018.
[2] R. Singh, J.P. Davim, Additive Manufacturing: Applications and Innovations, CRC Press, 2018.
[3] J. Torres, M. Cole, A. Owji, Z. DeMastry, A.P. Gordon, An approach for mechanical property optimization of fused deposition modeling with polylactic acid via design of experiments, Rapid Prototyp. J. 22 (2016) 578586.
[4] A.R. Torabi, Estimation of tensile load-bearing capacity of ductile metallic materials weakened by a V-notch: The equivalent material concept, Mater. Sci. Eng. A. 536 (2012) 249–255.

Temperature and Thermal Aging Effects on the Mechanical Response of Polycarbonate Materials

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ABSTRACT

Thermoplastic materials, due to their nature, are sensible to temperature variations. This sensibility restrains their usage to a limited number of applications, such as interior automotive products, household and consumer electronics, where temperature and humidity conditions are limited to a certain range, thus ensuring their structural stability.
Although these materials find their places in controlled environmental conditions, during their lifetime they can be submitted to various extreme temperatures.
There are several international standards which specify that all the electronic products, which rely on the usage of such thermoplastics, must withstand high numbers of thermal cycles, within the -40°C +85°C temperature range, without producing mechanical failures.
The polycarbonate grades from the Makrolon family are frequently met in various automotive electronic products, therefore their mechanical parameters should be thoroughly investigated before designing the mechanical components these materials will be used for.
The scope of this study is to investigate the variation of the mechanical properties of the unreinforced Makrolon 2405, and of the glass fibre reinforced Makrolon 9415 and Makrolon 8035 polycarbonate grades, in terms of elasticity modulus, tensile strength and Poisson's ratio, by subjecting standard, dogbone type specimens, to traction tests combined with various temperature loads. In addition, the long-term effect of the thermal cycles is also analysed by conducting a material aging test for the proposed polycarbonate grades. Measurements are done using video extensometer and digital image correlation techniques.

REFERENCES

[1] K. Cao, Y. Wang, Y. Wang, Effects of strain rate and temperature on the tension behavior of polycarbonate, Materials & Design, Volume 38, 2012, p. 53-58.
[2] T. Krausz, D. Serban, R. Negru, A. Radu, L. Marsavina, The effect of strain rate and temperature on the mechanical properties of polycarbonate composites, Materials Today: Proceedings, Volume 45, Part 5, 2021, p. 4211-4215.
[3] S. Redjala, S. Azem, N. Ait Hocine, The effect of the thermal aging on polycarbonate, Materials Today: Proceedings, Volume 47, Part 11, 2021, p. 3073-3076.

Examination of mechanical characteristics of ABS and ABS-like materials

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ABSTRACT

Additive manufacturing, i.e., 3D printing is widely used technology, utilized in different prototyping processes and fabrication of complex shapes and geometries. With this technology it is possible to rapidly manufacture different parts and objects directly from computer-designed drawing data. Manufacturing process with product development and production cycle is significantly shortened with 3D printing, while usability of materials is at the same time greatly improved with this production approach. There are seven types of AM technologies, such as (1) binder jetting, (2) directed energy deposition, (3) material extrusion (i.e. fused deposition modeling (FDM)), (4) material jetting, (5) powder bed fusion (i.e. selective layer sintering (SLS)), (6) sheet lamination, (7) vat photopolymerization (i.e. stereolithography (SLA), digital light processing (DLP)), according to ISO/ASTM 52900:2021.
In this research FDM, SLA and DPL printers produced standardized specimens for mechanical examinations. FDM is one of the most commonly used process for plastic models manufacturing where layer-by-layer is extruded while forming the particular shape. SLA is a process where photosensitive liquid resin is cured by laser beam of UV light in layers (Voet et al., 2018). Although it belongs to same technology of photopolymerization, DLP in contrast to SLA have layers exposed to an image to simultaneously cure the desired voxels in a 2D plane (Shah et al., 2020).
As the range of 3D printing possibilities and applications becomes broadly diverse, examination of different materials and their characteristics is continuously spreading and developing. Polymers are being particularly interesting in engineering, leading to a development of different mixtures and types in order to achieve desired mechanical properties of printed parts. ABS is beside PLA mostly used thermoplastic polymer for FDM technology. It has good mechanical properties, high stress and strain, but are emitting unpleasant odor while printing (Ngo et al., 2018). In order to make the parallel with material used on SLA and DLP printers, in this research is used ABS-like resin material. It is a thermoplastic resin which can be utilized for 3D printing of parts with the moderate detail performance, high strength, and realized functionality (Zhu et al., 2020).
The aim of this research was to observe and compare mechanical properties of ABS and ABS-like specimens, designed according to the corresponding standards for three types of conducted mechanical testing's, i.e., tensile testing, three point bending, compression testing.

Table 1. Sample distribution by material and technology

	FDM					DLP				SLA				
	T	**3 p.b.**	**C**	**Σ**		**T**	**3 p.b.**	**C**	**Σ**	**T**	**3 p.b.**	**C**	**Σ**	
ABS	5	5	5	15	**ABS-like**	5	5	5	15	5	5	5	15	45

All samples were made with 100% infill density and grid infill pattern. Experiments were conducted at about 23℃ and humidity of 55% RH.

Figure 1. Mechanical testing was done on Shimatzu AGS-X universal tensile testing machine: left - ISO 527-2 tensile testing specimen, middle - ISO 604:2002 compression testing sample, right - ISO 178:2019 three point bending testing specimen.

Further analysis included optical 2D and 3D microscopy in order to observe topography and morphology of examined materials. Images taken showed textures and differences in printing regimes.

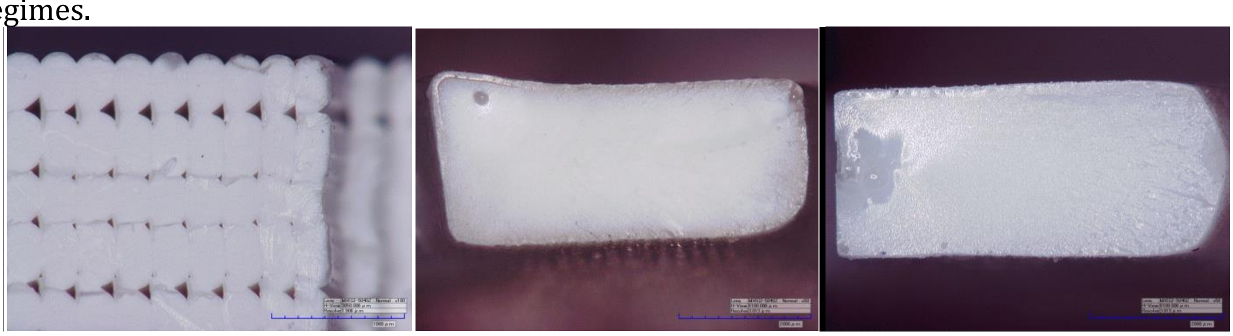

Figure 2. Images made with 3D microscope Xirox KH-7700 – left: ABS printed on FDM printer, middle - ABS-like printed on SLA printer, right – ABS-like printed on DLP printer.

Finally, Atos Core 200 3D optical scanner was used to determine whether the geometry of printed specimens matched digital models made in CAD software.
This research made a detailed analysis of the behavior and characteristics of the same ABS material in the form of filament and resin, leading to the more comprehensive understanding of the differences between them.

REFERENCES

1. Voet V.S.D, Tobias Strating T., Schnelting G.H.M., Dijkstra P., Tietema M., Xu J., Woortman A.J.J., Loos K., Jager J., Folkersma R. (2018) Biobased Acrylate Photocurable Resin Formulation for Stereolithography 3D Printing, ACS Omega 2018, 3, 1403−1408. doi: 10.1021/acsomega.7b01648
2. Shah D.M., Morris J., Plaisted T.A., Amirkhizi A.V., Hansen C.J. (2020) Highly Filled Resins for DLP-based Printing of Low Density, High Modulus Materials, Additive Manufacturing, doi: https://doi.org/10.1016/j.addma.2020.101736
3. Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D. (2018) Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Compos. Part B Eng., 143, 172–196
4. Zhu Z.H., Zhang N., Wang T., Hao M.Y. (2020) Short Review of Polymer Composites for 3D Printing, IOP Conf. Ser.: Mater. Sci. Eng. 758 012046. doi: 10.1088/1757-899X/758/1/012046

The influence of nutshell on FDM parts in the Shear test

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ABSTRACT

Additive manufacturing (AM) is a process that can achieve many complexities in the production of a part. The most important aspect of Additive manufacturing is that there is no more material wastage, so costs are reduced. Additive manufacturing is starting to be used in many fields, including medicine, automotive, aircraft, etc. The method of adding layer by layer or Additive manufacturing is used for a wide range of materials: plastics, metals, and ceramics. Additive manufacturing materials can be tested by stretching, Charpy or Izod impact, bending, shearing, etc. [1 – 3]

In this paper, was investigated the influence of nutshell on shear specimens. Prussa 3D printer and PETG filament were used. The specimens were made using Fused Deposition Modeling (FDM) technology. The parameters used were: the extruder temperature was set at 240˚C and 85˚C on the printing platform and infill density was set at 100%. Two types of specimens, with nutshell fig.1 a) and without nutshell fig. 1 b) at 0˚, the specimens were according with AMS B 831 05 standard.

Was investigated the difference between with nutshell and without nutshell specimens in the stress-strain curve. It has been seen that the specimens have different behavior when the nutshell existed or not. On the other hand, digital image correlation was used to calibrate the strain that appears on the fracture. In the end, we propose the best approach for shear testing on 3D printing specimens.

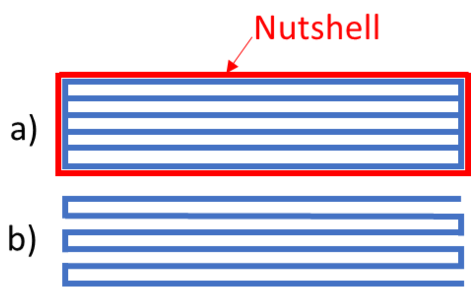

Figure 1. a) printing with nutshell and b) printing without nutshell

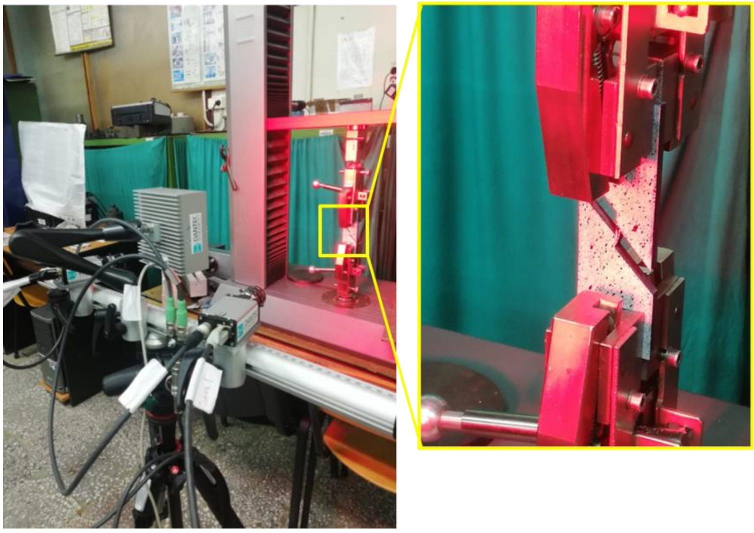

Figure 2. Test perform

The test was performed on the Zwick machine, with maximum load of 5kN, at room temperature and with a loading speed of 2 mm/min. The digital images were recorded with Dantec system, which has two cameras that can capture the deformation in 3D. A frequency of 30 Hz was used to capture the crack propagation and for good quality results. Using Istra 4D software, we were able to extract the maximum principal strain in the critical area.

In conclusion, was seen that the specimen without a nutshell is more suitable than the directional layup specimen for pure shear tests. Although a delamination mode was observed on the specimen with a nutshell.

Acknowledgment
The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 857124.

REFERENCES

[1] Cosmin-Florin P., Mihai-Petru M., Sergiu-Valentin G., Liviu M., Influence of thickness on the IZOD impact strength of FDM printed specimens from PLA and PETG, January 2022Procedia Structural Integrity, pp. 557-563.
[2] Dan Ioan S., Sergiu-Valentin G., Liviu M., Impact properties of laser sintered polyamide, according to building orientation.
[3] Josef K. Chao G., Controlling toughness and strength of FDM 3D-printed PLA componentsthrough the raster layup, Composites part B: Engineering, Volume 180, 1 January 2020.
[4] Standard Test Method for Shear Testing of Thin Aluminum Alloy Products.
[5] Li H., Wang T., Sun J., Yu Z., The effect of process parameters in fused deposition modelling on bonding degree and mechanical properties, Rapid Prototyp J, 24 (1) (2018), pp. 80-92.
[6] Qinglin W., Gonghe Z., Xiaodong Z., Yinxu N., Fenghua L., Yang L., Luoyu Roy X., Efficient characterization on the interlayer shear strengths of 3D printing polymers, Journal of Materials Research and Technology, Volume 22, January–February 2023, pp. 2768-2780.

On the mixed mode fracture of DLP manufactured SCB specimens

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ABSTRACT

The scope of this study is to investigate the mixed mode fracture of components manufactured from a photo-sensitive resin using the Digital Light Processing (DLP) additive manufacturing technology.
Our previous studies highlighted a brittle behaviour of the considered resin characterized by a fracture toughness K_{IC} value equal to about 1 MPa m$^{0.5}$ [1, 2].

In the present study, mixed mode fracture tests were performed on Semi Circular Bend (SCB) specimens loaded symmetrically for Mode I, and asymmetric for mixed mode and mode II loading, respectively. The specimens manufactured via DLP have a radius of 40 mm, a thickness of approximately 4 mm and an initial crack, introduced during the manufacturing process, with length 18 mm. Static fracture tests were performed at room temperature, using a Zwick Roell Z005 universal testing machine with three point bending grips, by adopting an applied displacement speed of 2 mm/min, Fig. 1. Four tests were carried out for each supports position.

The Stress Intensity Factors evaluation for K_I and K_{II} was obtained numerically with Finite Element Analysis by using singular elements to model the singularity at the crack tip.

The effective stress intensity factors obtained for all range of modes resulted to be in the range 0.73 – 1.15 MPa m$^{0.5}$ which is in agreement with our previous tests performed on Single Edge Notched specimens [2].

The experimental results, expressed as K_{II}/K_{IC} versus K_I/K_{IC}, are plotted in Fig. 2 by adopting four different mixed mode fracture criteria: 1) Maximum Tensile Stress (MTS), 2) Strain Energy Density (SED), 3) Maximum Energy Release Rate (G_{max}), 4) Equivalent Stress Intensity Factor (ESIF), Fig. 2. Most of the experimental results fall in the range of the fracture envelope curves.

Figure 1. View of the asymmetric loading of SCB specimen

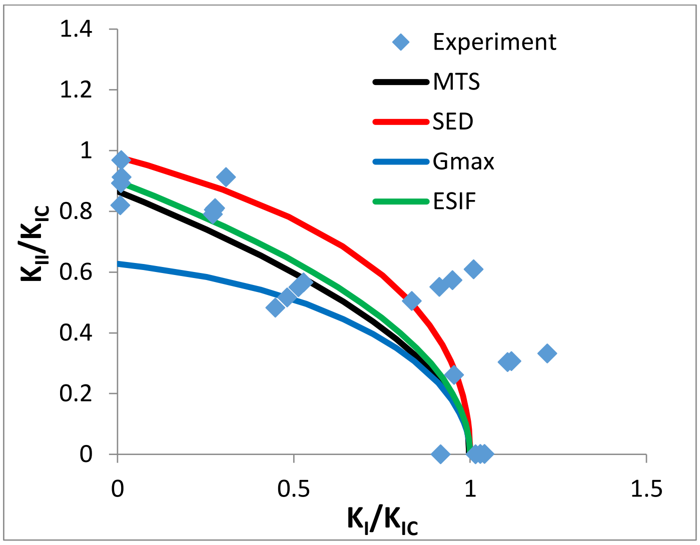

Figure 2. Fracture envelope curves

Some differences with respect to the theoretical envelopes can be observed for cases characterized by low value of the K_{II}/K_I ratio. Among the various theoretical envelopes mentioned above, the SED seems to be the most appropriate for the material being considered.

REFERENCES

1. Brighenti R., Marsavina L., Marghitas M.P., Cosma M.P., Montanari M. (2022) Mechanical characterization of additively manufactured photopolymerized polymers. Mech. of Advanced Materials & Structures, doi:10.1080/15376494.2022.2045655.
2. Brighenti R., Marsavina L., Marghitas M.P., Montanari M., Spagnioli A., Tatar F. (2023) The effect of process parameters on mechanical characteristics of specimens obtained via DLP additive manufacturing technology, Mat. Today: Proceedings, doi:10.1016/j.matpr.2023.01.092.

The influence of wall thickness on the fracture toughness of short fiber reinforced polymers obtained using single edge notch test specimens

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ABSTRACT

In this paper, the fracture behaviour of two short fiber reinforced polymers is discussed. The two investigated materials are a polyphthalamide (PPA) with glass fiber inclusions of 33% (GF33) and a polyphenylene sulfide (PPS) with glass fiber inclusions of 40% (GF40). Due to the highly anisotropic behaviour of these types of materials, most of the mechanical properties, including fracture toughness, are dependent on the fiber orientation. One parameter that directly affects the fiber orientation is the wall thickness. Single edge notch test specimens were used to determine the cracking force under mode I (opening mode) loading conditions. The specimens were milled from plates at different orientations. Three fiber orientations were considered: 0°, 45° and 90°. Two different thicknesses of the plates were used: 2.0 mm and 3.2 mm. A comparison of the fracture toughness obtained using single edge notch test specimens and edge cracked triangular specimens will be accomplished. Numerical simulations were performed using FRANC2D and Ansys Mechanical.

Layer thickness influence on impact properties of FDM printed PLA material

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ABSTRACT

At first, Additive Manufacturing (AM) technology was used for rapid prototyping purposes, because of its faster and cheaper production compared to conventional (subtractive) methods. Over time, with the increase in available production methods and materials, the utilization of this technology in the production of functional components was also taken into consideration. Now, the importance of particular AM technology is not measured only by fabrication time, production energy consumed, and quantity of material used, but also by the potential of a particular AM technology to deliver components for functional applications.

For this estimation material's mechanical properties have to be obtained using standardized tests, and the most probable first choices are tensile, compressive, and flexural tests. For a better insight into the material's behaviour impact properties could also be considered for the assessment. Standardized impact tests include Charpy and IZOD tests. These two methods differ in specimen geometry and placement on the impact machine, but they both evaluate the same material property [1,2].

Here, the material of interest is PolyLactic Acid (PLA), widely used in Fused Deposition Modeling (FDM) technology. AM parameters are known to affect on mechanical properties of final components, hence some of the most influential ones have to be taken into consideration. In FDM, the layer thickness is a known AM parameter that influences the properties of the final component. Lower layer thicknesses are known to have better mechanical properties, as air gaps here have a lower share in total volume. However, also the over-compression of layers has to be taken into account when choosing the appropriate layer thickness [3]. In this investigation, three different layer thicknesses are considered: 0.1, 0.2, and 0.3 mm. All specimens have full (100 %) infill. For Charpy impact property assessment specimens have all been prepared according to ISO 179 standard, namely specimen dimensions are 80x10x4 mm in bulk, with Type A notch (45° notch angle and tip radius of 0.25 ± 0.05 mm). All notches of the specimen were AMed, and prepared for the edgewise direction of the test.

Instron CEAST 9050 instrumented Charpy test rig was used in this research with a mounted 5 J hammer. The particular hammer weight is 1.186 kg, and it is placed on the 229.7

mm long pendulum. The hammer start position is at a 150° angle, and the hammer velocity at the moment of impact is approx. 2.9 m/s. The length between specimen supports is 60 mm.

Charpy instrumented pendulum outputs are detected force, energy, and deflection values with a sampling rate of 1000 Hz. Hence, the results include force-deflection and energy-deflection diagrams for all 3 specimen groups, containing 7 specimens each. The initial plan was to use results from 5 specimens per group, with 2 additional serving as a replacement. But, due to sufficient repeatability all tested specimens were included in the research. Thereafter, energy, maximum force, deflection, and impact strength were observed between groups to have an insight into the beneficial influence of lower layer thicknesses on impact properties and lower result scatter that finer layer resolution should produce.

Figure 1. Instron CEAST 9050 Charpy instrumented pendulum during the PLA material testing.

Acknowledgment

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REFERENCES

1. Popa, C.F., Mărghitaș, M.P., Galațanu, S.V., Marșavina, L. (2022) Influence of thickness on the IZOD impact strength of FDM printed specimens from PLA and PETG. *Procedia Structural Integrity* 41, pp. 557–563. DOI: 10.1016/j.prostr.2022.05.064.
2. Ailinei, I., Galațanu, S.V., Marșavina, L. (2022) The effects of layers orientation on impact energy evaluation of FDM printed specimens. *Material Design & Processing Communications* 3(10). DOI: 10.1002/mdp2.267.
3. Spoerk, M., Arbeiter, F., Cajner, H., Sapkota, J., Holzer, C. (2017) Parametric optimization of intra- and inter-layer strengths in parts produced by extrusion-based additive manufacturing of poly(lactic acid). DOI: 10.1002/app.45401.

8th Session

8. Applications & Advancements in AM materials and structures

Inter and Intra-Surface Topography Comparison of Gecko-Inspired features fabricated by 3D printing

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ABSTRACT

Geckos are lizards renowned for their remarkable ability to stick and unstick to various surfaces using hair-like setae on their feet. This trait can be studied and used to create robots with similar adhesive capabilities through bioinspired Engineering [1]. Additive Manufacturing (AM) is a digital manufacturing process that creates components directly from a digital file. It offers advantages such as increased design freedom and making intricate and complex geometries.[2]. SLA is a 3D printing process that produces highly accurate and detailed parts. However, this technique can be limited in terms of accuracy and repeatability, particularly in fabricating intricate and fine bio-inspired features[3]. Optodigital microscopy is an imaging technique in which an optical image is coupled with a digital camera to produce a high-contrast image to investigate the surface roughness properties in non-contact mode. SLA printer is used here to fabricate a Bio-inspired sample mimicking the gecko foot.[4]. The primary focus of our experiment was to perform inter and intra-surface topography analysis of 3D-printed bio-inspired features. The CAD model prepared is shown in Figure 1(a). The Ra (H-Horizontal) and Ra (V-Vertical) were taken from the features described in Figure 1(a). Figure 1(b) is the 3D image of the SLA-printed samples._The sample's roughness varies horizontally and vertically in inter and intra-samples, as shown in Table 1. The Std. deviation for Sa, intra and inter samples were 0.07 and 0.06, respectively. Our research also shows the potential of using the SLA technique in creating the intricate geometries of Bio-inspired designs.

Table 1. Inter and Intra-Surface Topography Comparison of Gecko-Inspired features.

Average Intra roughness value, Ra (µm)		Average Inter roughness value, Ra (µm)		Sa intra sample (µm)	Sa inter-sample (µm)	Ra Std. deviation intra		Ra Std. deviation inter		Std. deviation Sa (intra)	Std. deviation Sa (inter)
H	V	H	V			H	V	H	V		
0.59	0.62	0.58	0.64	0.74	0.74	0.14	0.12	0.59	0.62	0.07	0.06

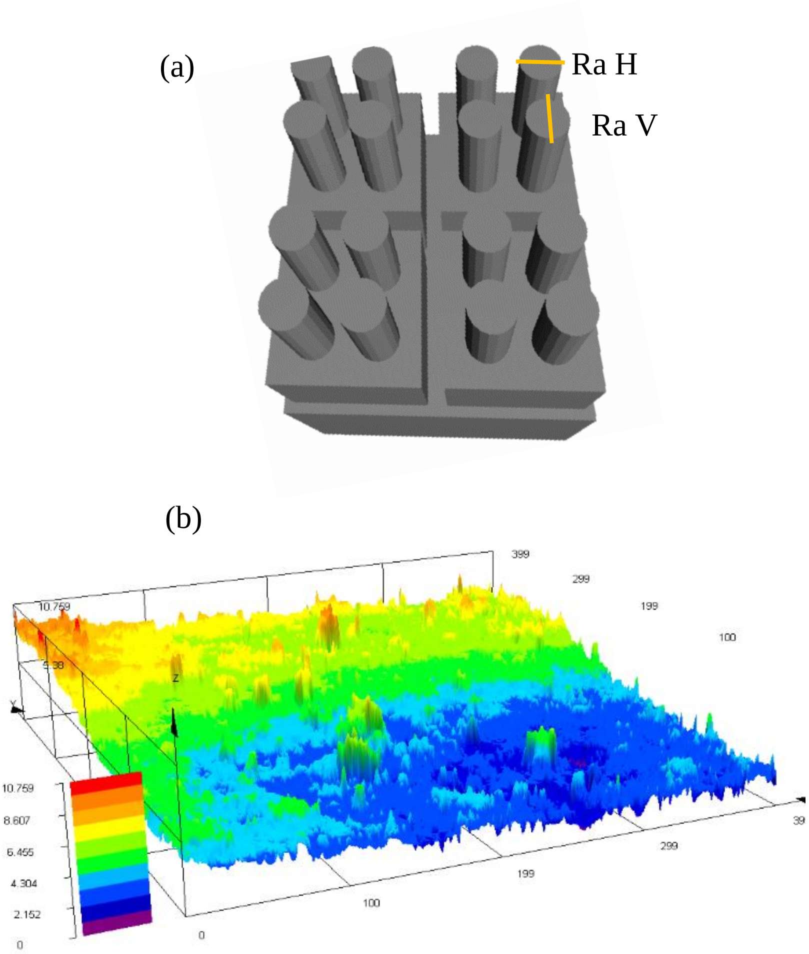

Figure 1. (a) CAD model of Bio-inspired Gecko features; (b) 3D image of the top surface

REFERENCES

1. Congcong Hu and P. Alex Greaney. Role of seta angle and flexibility in the gecko adhesion mechanism. Journal of Applied Physics, August 12, 2014 DOI: 10.1063/1.4892628
2. Davoudinejad, A., M. Ribo, M., Pedersen, D. B., Islam, A., & Tosello, G. (2018). Direct fabrication of bio-inspired gecko-like geometries with vat polymerization additive manufacturing method. Journal of Micromechanics and Microengineering, 28, [085009].
3. Green, D. W. *et al*. High Quality Bioreplication of Intricate Nanostructures from a Fragile Gecko Skin Surface with Bactericidal Properties. *Sci. Rep.* **7**, 41023; doi: 10.1038/srep41023 (2017).
4. Méndez Ribó, M., & Islam, A. (2017). 3D Printing of Bio-inspired surfaces. Poster session presented at Wilhelm und Else Heraeus Seminar, Bad Honnef, North Rhine-Westphalia, Germany.

3D Printing of the parts of the Library automation system

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ABSTRACT

Automation has permeated nearly every industry and each aspect of life. 3D printing technology has come a long way in recent years, and it has opened up many new possibilities for the creation of custom parts and devices. One exciting application of 3D printing is in the creation of robot hands, which can be used for a variety of tasks, including retrieving items from bookshelves. Here a system for Library automation exploiting scanning of bookshelves is being planned and built using 3D printing of some of its parts [1] - [6].

Barcode and QR code (Quick Response) can be used to identify books [2]-[6]. Bookshelf scanning mechanism consists of a barcode scanner mounted onto a sliding track. The barcode scanner can be mounted on a carriage that is able to slide along a track. The track can be mounted above or below the bookshelf, with the carriage positioned such that the scanner is able to read the barcodes of the books as it is slid along the track. A motor or manual crank can be used to move the carriage along the track, and sensors can be used to detect when the carriage has reached the end of the track. The scanned barcode data can be sent to a computer or other device for processing.

Carriage and base plate that hold scanner can be 3D printed [7]. One possible example of the carriage consists of: a base plate carrying all other components, mounted on two wheels which ride on the track; a barcode scanner which is mounted on the base plate; a motor or manual crank that is attached to one end of the base plate, which can be used to move the carriage along the track; a sensors mounted on the base plate to detect when the carriage has reached the end of the track; a support structure attached to the base plate to hold the barcode scanner in place and provide stability to the carriage. Here, a base plate is 3D printed (shown in figures 1.a - 1.c) having dimensions: length 10 cm, width 6 cm and thickness 1.5 cm. Figures 1.b and 1.c show the 3D printer, WANHAO Duplicator 6, which was used.

Additional auxiliary robotic arm can also be 3D printed and used for grasping the books. To create a robot hand using a 3D printer, the first step is to design the hand using a 3D modelling software. There are many different software options available, each with its own set of features and capabilities. Once the hand is designed, 3D printer can be used to create the physical parts, which can then be assembled into a functional hand [2], [7]. When designing a robot hand for grasping books from bookshelves, one important part to consider is the gripping mechanism. This should be strong enough to hold onto even the heaviest books, but not so strong that it risks tearing the book. One approach to designing a gripping mechanism for this purpose is to use a two-finger hand, with one finger on either side of the

book. Simpler robotic arm is chosen here, having a hand with two fingers (which can be 3D printed). This allows for a secure grip on the book, while minimizing the risk of damaging it.

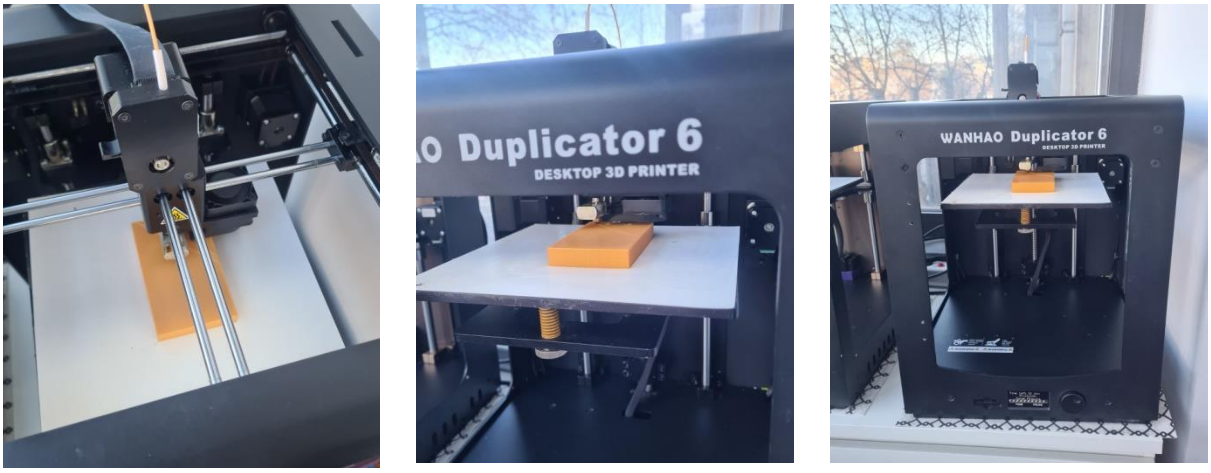

Figure 1. A base plate while being 3D printed; a) a view from above; b) side view; c) A 3D printer used for the experiment is WANHAO Duplicator 6. (3D printing and photos courtesy of Librarian Ms Milica Ćirović)

REFERENCES

[1] N. Ratkovic Kovacevic, G. Vojnovic, and Dj. Dihovicni, "Autonomous Shelf Scanning System for Library", The Book of Abstracts of International Conference on Experimental and Numerical Investigations and New Technologies in Engineering, Springer, M. Balać et al. (Eds.): CNNTech 2022, Zlatibor, Serbia, July 05 – July 08 2022, pp. 91. http://cnntechno.com/docs/Book%20of%20Abstracts%202022.pdf

[2] X. Yu, Z. Fan, H. Wan, Y. He, J. Du, N. Li, Z. Yuan, G. Xiao, "Positioning, Navigation, and Book Accessing/Returning in an Autonomous Library Robot using Integrated Binocular Vision and QR Code Identification Systems", Sensors. 2019; 19(4):783. https://doi.org/10.3390/s19040783 https://www.mdpi.com/1424-8220/19/4/783

[3] Jian Lan Liu and Li Zhu, "Library Intelligent Bookshelf Positioning System Research", Proceedings of the 4th International Conference on Mechatronics, Materials, Chemistry and Computer Engineering 2015. Atlantis Press, 2352-538X, pp. 1237- 1242. DOI: https://doi.org/10.2991/icmmcce-15.2015.238

[4] A. Dani and R. N. Patil, "QR Code based Library Management System", International Journal of Emerging Technologies and Innovative Research JETIR (www.jetir.org), ISSN: 2349-5162, Vol. 7(6), June-2020, pp. 1876-1883, http://www.jetir.org/papers/JETIR2006271.pdf

[5] A. Chanda, "Barcode Technology and its Application in Libraries", Library Philosophy and Practice (e-journal), 3619. November 2019, DOI: 10.2139/ssrn.3649957 https://digitalcommons.unl.edu/libphilprac/3619

[6] S. K. Tahil, "Library Automation: An Emerging Technology for State University and Colleges in Sulu Province", Natural Sciences Engineering and Technology Journal NASET, Vol. 2(1), 2021. pp. 85-89. https://doi.org/10.37275/nasetjournal.v2i1.16

[7] Y. Kanada, '3D-Printing Plates without "Support"', International Journal of Computer, Control, Quantum and Information Engineering, WASET, Vol. 9, No. 5, pp. 568-574, 2015. https://www.kanadas.com/3dprint/3D-Printing-Plates-without-Support.pdf

A comprehensive review of the Additive Manufacturing process

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ABSTRACT

Additive Manufacturing (AM) also known as the 3D Printing, Layer Manufacturing Process or the Rapid Prototyping (RP) technique has witnessed a tremendous growth over the last few decades, because of its major advantages of design flexibility, intricate feature designing, high level of accuracy precision and tolerances and mass customization with minimum waste. This paper presents a comprehensive review of the additive manufacturing process with the aim to provide a holistic overview of various aspects of this process highlighting the basic principle, applications advantages and major advancements during the past two decades.
Additive Manufacturing is a high precision production process, which does not use a particular tool for manufacturing the specimen. This process is based on a digital design file, which later during the process gets converted to a stereolithographic file. AM offers a plethora of applications in almost all the manufacturing domains, which are widely used in each and every aspect of life. It will not be incorrect to say that slowly and gradually, the additive manufacturing technique will supersede the conventional manufacturing techniques in the near future. Therefore, this research paper provides vital state of the art about this modern manufacturing technique and introduces the readers with the benefits, challenges and research avenues in the area of additive manufacturing.

Keywords: Additive Manufacturing, Metals, Polymers, Ceramics, Composites.

Structural properties of components manufactured using the additive manufacturing process: a review

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ABSTRACT

Additive Manufacturing (AM) is an advanced manufacturing technique, which is gaining a lot of appreciation because of its simplicity, accuracy, precision and low cost. It uses the concept of incremental material addition for the specimen building process, the component is manufactured in layer by layer form, and therefore, it is easy to create any complex geometry using the AM technique. AM can be used for a variety of materials like, metals, polymers, ceramics, composites, smart materials etc., hence, the application sector of this technique is far and wide, and further growing day by day exponentially.
This research paper presents an exclusive review of the surface properties of the components manufactured by the additive manufacturing technique. It included the mechanical properties like, hardness, toughness, compression, tension, fatigue crack growth etc. of different alloy components produced by this technique. The outcome of various printing parameters like the orientation of the specimen, infill, raster angle etc. are also discussed in detail. Moreover, this work also includes the scope of additional future research work in AM.

Keywords: Additive Manufacturing, Structures, Materials, Properties, Fracture, Fatigue.

Tensile properties of 3D-printed PLA specimens: optimization of FDM process parameters

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ABSTRACT

Due to the possibility to manufacture complex parts with superior properties, in recent years Additive Manufacturing (AM) technology has experienced a very rapid development and growth [1]. Of all the AM processes, the Fused Deposition Modeling (FDM) process is the most commonly used [2]. The work carries out an optimization study of the process parameters in order to improve the tensile characteristics of the specimens printed by FDM technology. The tensile tests were performed on Polylactic acid (PLA) dog-bone specimens according to the ISO 527-2 standard. Overall, 7 process parameters have been investigated, namely infill pattern, part orientation, infill density, layer height, extrusion speed, number of shells and nozzle temperature. It was found that all the investigated parameters influence the tensile properties of the 3D printed specimens. However, it was noted that the infill density parameter has the greatest influence on the properties, and the infill pattern parameter the least. Moreover, it was observed that the dimensional accuracy is also influenced by the investigated process parameters, especially the thickness of the specimens.

Acknowledgments
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REFERENCES

[1] C. Vălean, L. Marșavina, M. Mărghitaș, et al., Effect of manufacturing parameters on tensile properties of FDM printed specimens, Procedia Structural Integrity, 26 (2020) 313–320.
[2] L. Marșavina, C. Vălean, M. Mărghitaș, E. Linul, S.M.J Razavi, F. Berto, R. Brighenti, Effect of the manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens, Engineering Fracture Mechanics 274 (2022) 108766.

Unconventional use of FDM printing method for testing the delamination of PVA material for different layer height

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ABSTRACT

The need to change the material for the production of certain parts arose with the development of technology, more precisely additive manufacturing technologies. The desire to improve these objects, both their physical and mechanical characteristics. The new materials are expected to provide the elements with greater resistance, durability, and in some cases elasticity, which increases the lifespan and thus the utility value. Also, from the environmental aspect, it is important that these new materials are suitable for recycling. The goal of this work is to test and form the initial base of optimal parameters for printing PVA material. This paper will present the results of material delamination of samples printed by the FDM method, varying the height of the layer. The object of this work is the PVA material, which will later be enriched with particles of a certain biological origin in order to obtain a new polymer, which would have a wider use and better mechanical properties.

Keywords: Additive manufacturing, PVA material, FDM method

Laser Additive Manufacturing techniques

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ABSTRACT

Lasers used in versatile industries and aspects of life [1]-[10], in manufacturing are exploited for decades in various ways: for material characterization, for measurement and control, "subtractive" or classical processing\ machining, post processing and for LAM. LAM can be elaborated and classified with respect to: materials used, design, technologies, or applications. Variations in terminology exist, since the term Laser-based additive manufacturing (LBAM) can be found also, referring to a versatile manufacturing technique, extensively adopted to fabricate metallic components of enhanced properties [11].
Laser techniques, being one of ELION techniques, could be compared in many ways with respect to the specified role. An operational range of the processing methods grouped within ELION techniques should be expanded with respect to their emerging point. Comparison can or should be made, especially for large endeavours, where potentially positive and negative aspects can be easily found without consequences.
The comparison having more generalized or more sophisticated nature is performed for the chosen cases and for at least two techniques in paper presented. Special attention is paid to metrological aspects of more or less destructive laser applications and techniques, i.e. the list of some kind is presented in generalised manner in *descending order of provoked damage*. There are also many of laser-material interactions which are of destructive nature, however these are either potentially used or serve only as a replacement for incoherent methods, which gained in accuracy. A selection of results, obtained from several experimental testing of few processes, is presented.
In particular the paper considered chosen applications of LAM technologies in Biomedical Sciences and Medicine. Attention is paid to the analytical methods as well and some results with the laser interaction will be given.

REFERENCES

[1] M. Srećković, A. Sedmak, N. Ivanović, Z. Fidanovski, S. Ostojić, M. Dragićević, Contemporary approach to the beam interaction and disintegration of material with

emphasis on laser processing, Proceedings of CNTN, Timişoara, Romania, October 28-29, 1993, Vol. 6, pp. 125-130.

[2] Ž. Tomić, Interaction of laser beams with specific ceramic and composite materials, (In Serbian), PhD Thesis, University of Belgrade, Faculty of Electrical Engineering, Belgrade, Serbia, 2007.

[3] M. Srećković, M. Kutin, M. Hribšek, M. Pavlović, S. Polić Radovanović, V. Zarubica, Application of ELION and other techniques in measurements, control and processing of materials and procesess, (In Serbian), Institut Goša d.o.o., Belgrade, Serbia, 2009.

[4] M. Srećković, S.Pantelić, N. Borna, A. Janićijević, A. Bugarinović, S. Bojanić, R. Aleksić, M. Kovačević, Contemporary materials, laser and other ELION techniques, (in Serbian), International scientific conference Contemporary Materials, Banja Luka, July 2.-4., 2010., pp. 157- 189.

[5] M. Srećković, S. Pantelić, S. Stanković, S. Polić, A. Kovačević, N. Ivanović, A. Bugarinović, S. Ostojić, Ž. Tomić, Elion techniques in application and science with the accent on ecology and cultural heritage, RAD, Book of Abstracts, ISBN:978-86-6125-160-3, May 23.-27., 2016, Nais, Serbia, 2016.

[6] Z. Karastojković, M. Dereta, N. Bajić, M. Srećković, S. Ostojić, Electrospark and 3D laser cladding for repair of thermopower plant turbine blades, International Conference Innovative Technologies for Joining Advanced Materials – TIMA 16, June 2.-3., 2016, Timisoara, Romania.

[7] M. Ž. Srećković, S. N. Pantelić, S. J. Stanković, S. R. Polić, N. B. Ivanović, A. R. Bugarinović, and S. M. Ostojić, Gamma Irradiation Effects in Optical Fibres, Splitters, and Connectors, Nuclear Technology & Radiation Protection, 2017, Vol. 32, No. 4, pp. 375-380. http://www.doiserbia.nb.rs/img/doi/1451-3994/2017/1451-39941704375S.pdf

[8] M. Srećković, Z. Karastojković, N. Ivanović, S. Pantelić, S. Polić, S. Ostojić, A. Kovačević, Chosen Contemporary Problems in Fields of Coherent Optics, Photophysics and Interactions With Elion Radiation, Proc. of the 7th International Conference on Renewable Electrical Power Sources ICREPS, 2019., pp. 83-99. https://www.izdanja.smeits.rs/index.php/mkoiee/article/download/5932/6144

[9] M. Srećković, N. Ivanović, S. Ostojić, A. Kovačević, N. Ratković Kovačević, Z. Karastojković, S. Jevtić, Application of lasers in automotive industry, Proc. of the 8th International Conference on Renewable Electrical Power Sources - ICREPS, Belgrade, October 15. - 16., 2020., pp. 223-240. http://smeits.rs/?file=00466

[10] M. Srećković, S. Pelemiš, S. Ostojić, S. Jevtić, S. Pantelić, M. Đurić, B. Kaluđerović, Z. Latinović, N. Ratković Kovačević, Theoretical support of modern issues related to laser techiques, applications of coherent radiation and modern technologies, VII International Congress Engineering, Environment and Materials in Process Industry - EEM2021 March 17.-19., 2021 Jahorina, Republic of Srpska, B & H

[11] N. Ur Rahman, D. T. A. Matthews, M. de Rooij, A. M. Khorasani, I. Gibson, L. Cordova, and G. Romer, An Overview: Laser-Based Additive Manufacturing for High Temperature Tribology, Front. Mech. Eng., Sec. Tribology, Vol. 5 – 2019, 2019, 16 April, 5:16, https://doi.org/10.3389/fmech.2019.00016 https://www.frontiersin.org/articles/10.3389/fmech.2019.00016/full

Mechanical Behaviour of Recycled FDM Printed Parts from PETG in the Circular Economy

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ABSTRACT

In the last decade, 3D printing technology using Additive Manufacturing (AM) technology, became more and more popular, due to the various industrial applications in the field of rapid manufacturing to fabricate prototypes and concept models. However, most of the materials used in 3D printing are non-biodegradable; therefore, in order to achieve a circular economy, the sustainability issue must be taken into consideration. The aim of this research is to produce recycled 3D printed PETG models with high mechanical properties.

To extrude the recycled grains into a filament, used in fused deposition modeling (FDM) technology a Felfil evo filament extruder was used, Figure 1. The recycled filament was extruded from polyethylene terephthalate glycol (PETG) at a temperature of 195°C and with a speed of 7 rpm according to the manufacturer's requirements. Subsequently, the filament was printed on 6 tensile specimens using Prusa i3 MK3S Original, Figure 2. The parameters used to print the specimens were: infill speed 80mm/s, layer thickness 0.2mm, 100% rectilinear infill, nozzle temperature for the first layer 240°C and 250°C for other layers, bed temperature 85°C for the first layer and 90°C for other layers respectively.

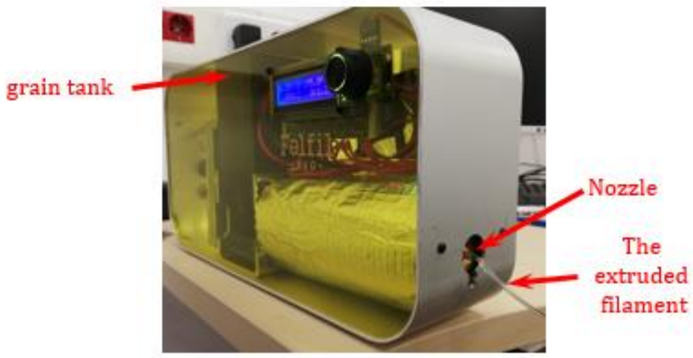

Figure 1. Felfil evo filament extruder

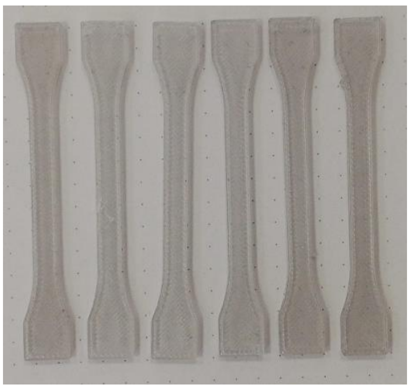

Figure 2. Tensile specimens from the recycled grains

Similarly, six tensile specimens were printed using PETG prusament filament to compare the results between the recycled filament and the manufacturer filament.

After printing the specimens the test was performed on the Zwick machine, with a capacity of 5KN. To determine the strain state in the test specimens digital image correlation was used. This paper presents a comparison between the results obtained using raw and recycled PETG filament.

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The authors want to acknowledge the E^{3}UDRES^2 alliance for supporting this research. This research was supported by the ERASMUS+ Programme [101004069].

REFERENCES

[1] Kumar, Rishi, et al. "A Comparative Study on the Life Cycle Assessment of a 3D Printed Product with PLA, ABS & PETG Materials." Procedia CIRP 107 (2022): 15-20.
[2] Szykiedans, Ksawery, Wojciech Credo, and Dymitr Osiński. "Selected mechanical properties of PETG 3-D prints." Procedia Engineering 177 (2017): 455-461.

9th Session

9. 4D printing and AM metamaterials

Defect sensitivity mitigation in the mechanical behavior of 3D printed lattice metamaterials through a soft elastomeric matrix

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ABSTRACT

Engineered materials, commonly referred to as "architected" materials (or metamaterials), are materials that offer a range of features such as customizable stiffness and strength [1], auxetic behavior [2], and energy absorption [3], just to mention a few. This work focuses on the classic two-dimensional lattice metamaterial configuration, composed of triangular unit cells. A combination of two dissimilar materials was employed in the design process: the "primary" material that constitutes the lattice structure is made of thermoplastic polyurethane (TPU), while an incompressible silicone elastomeric rubber serves as the "secondary" functional material, manually poured inside the lattice cells to form a consistent filling pattern throughout all the examined cases (Fig. 1).

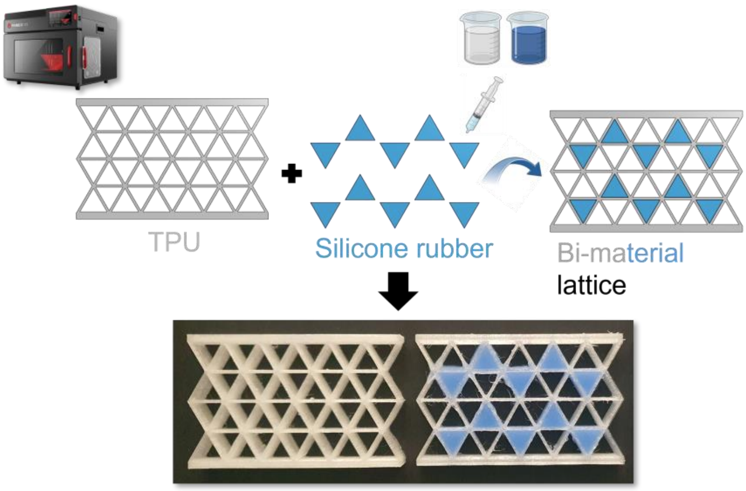

Figure 1. Schematic of the lattice metamaterial with an embedded regular filling pattern of a second highly deformable material and manufactured finite-size specimens.

In order to investigate the mechanical response of such lattice structures to intrinsic defects, geometric imperfections were intentionally introduced during printing. Three distinct types of geometric anomalies, namely curvature of some elements, reduced beam thickness, and lateral shift of some lattice nodes, were randomly introduced.
Additively manufactured perfect and defective lattices have been subjected to compressive tests before and after introducing the filling pattern with the secondary material. Fig. 2 shows the response of an imperfect lattice (caused by shifting nodes from the initial positions) with and without the filling material. The results reveal that perfect lattices display similar response regardless of whether or not they are filled, while imperfect lattices show significant

response improvement with the assumed reinforcing filling pattern, helping to prevent the buckling collapse of the defective beams under compression.

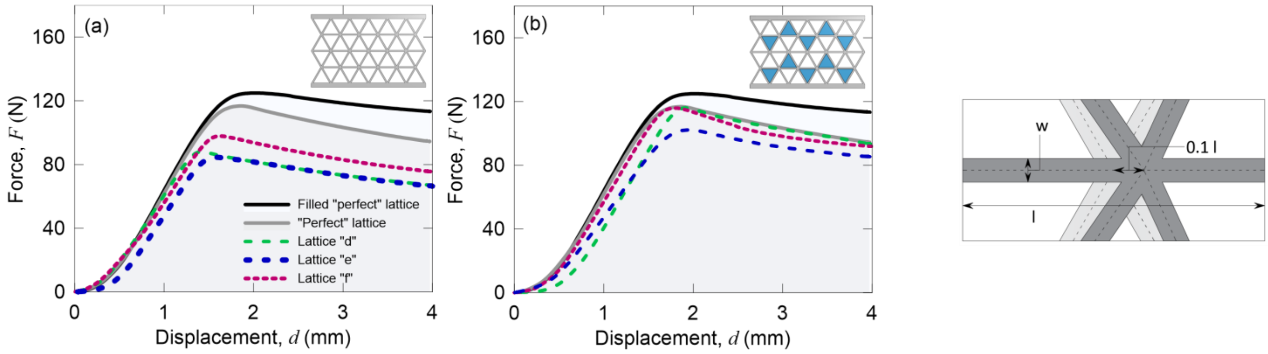

Figure 2. Response of the latticeS with node position imperfections (a): empty lattices (b) and filled ones (b).

Lastly, some FE analyses have been performed to demonstrate how the filling pattern enhances the overall defect tolerance of the structure (Fig. 2).

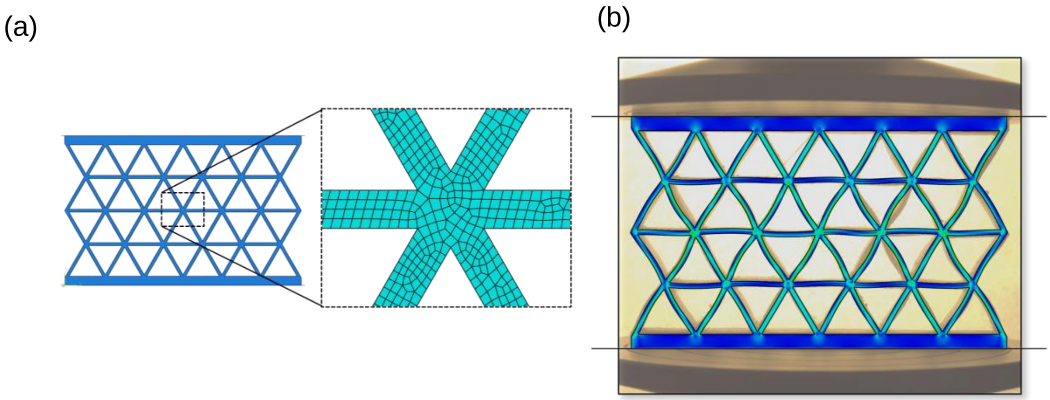

Figure 3. Detailed view of the mesh employed in the FE model (a) and buckled configuration of a "perfect" lattice (b).

REFERENCES

[1] Mueller, J., Lewis, J., & Bertoldi, K., "Architected Multimaterial Lattices with Thermally Programmable Mechanical Response", Advanced Functional Materials, 2105128 (2021).

[3] Kim, Y., Son, K., & Lee, J., "Auxetic structures for tissue engineering scaffolds and biomedical devices", Materials, 14, 6821 (2021).

[3] Zhang, P., Qi, D., Xue, R., Liu, K., Wu, W., & Li, Y., "Mechanical design and energy absorption performances of rational gradient lattice metamaterials", Composite Structures 277, 114606 (2021).

Numerical and Experimental Analysis of Quilling Inspired Metamaterials

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ABSTRACT

In the current paper is presented the behavior of a quilling inspired metamaterial with a nonlinear response to deformation loads. As the art of paper quilling relates on curved shapes, circles and spirals that generates 3D multilayered structures that have the ability to autosustain. The model generated has resulted in spiral shapes layers that are able to undergo a significant load, presenting high deformation rate and instant shape recovery [1]. The metamaterial has been tested through different methods with the purpose to research if a correlation between the results is possible and also to validate the theoretical data obtained through physical tests.

Materials and methods

Firstly the metamaterial was developed and analysed with Finite Element Method using Ansys Wokbench softeware, being subjected to static loads. Afterwords the samples have been printed with 3D printer, using Z-ultrat HDPE filament, and tested in compression with a universal testing machine. The results in terms of displacement corresponding to an applied force resulted by the two investigation methods have been similar. The research went further to obtain the displacements of elements inside the structure. Due to the spiral shapes, the inside cells presented in-plane displacements and rotations around the vertexes of the spiral centers. The movements have been visible during the experiment but we were limited to measure the displacements on the testing machine. In order to compare the FEM simulations with physical tests has been used the Digital Image Correlation (DIC) method which relates on pixels movement from successive frames attained while recording images of the real physical tests [2-5].

The fullfield in-plane deformations of an object are obtained with an enhanced digital correlation technique, by quantitatively correlating a chosen set of points represented by pixels. The DIC testing starts from a digitized intensity pattern of the undeformed sample, as a reference, followed by a set of frames that caught each movement of the physical tests [5-6]. The deformations are identified by the software used in the next scenes, giving the movement path of the pixels and reports back the deformation distance between each frame and the reference.

In the images below are presented the behavior of the metamaterial under the compressive load, a comparison between the FEM simulation and the pixels movement using DIC method.

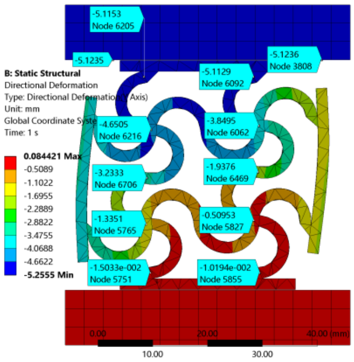

Figure 1. Numerical analysis of the structure

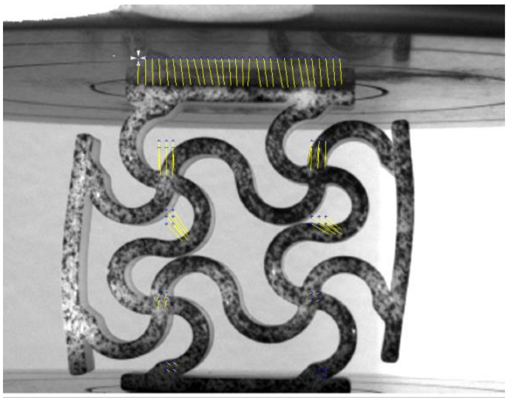

Figure 2. Metamaterial deformation analysed by DIC method

Results & conclusion

The aim of the current study was the validation of numerical data with experimental methods and understanding the mechanical behavior of metamaterials based on quilling-inspired structures. The comparison between the testing and measuring techniques highlighted the similitude of the results, with a recorded small acceptable error. Was concluded that the displacement of intersections of spiral arms suppressed under loads and the movement on rows and columns of the spirals can be evaluated numerically and experimental, changing the geometrical parameters and boundary conditions will produce a significant influence upon the mechanical behavior of such structures.

REFERENCES

[1] Bingbing, G. and others ,(2017), *Vertical Paper Analytical Devices Fabricated Using the Principles of Quilling and Kirigami*, Nature, 2017.
[2] Moreira, D. C., Sphaier, L. A. and others, (2012), *Determination of Young's modulus in polyester-Al2O3 and epoxy-Al2O3 nanocomposites using the Digital Image Correlation method*, Composites Part A: Applied Science and Manufacturing, Volume 43, Issue 2.
[3] Bing Pan, Kai Li, (2011), *A fast digital image correlation method for deformation measurement*, Optics and Lasers in Engineering.
[4] Hursa, A., Rolich, T., (2009) *Determining Pseudo Poisson's Ratio of Woven Fabric with a Digital Image Correlation Method*, Volume 79, Issue 17, Sage Journals, September 18.
[5] Luo, H., Cheng, Y. Z. & Gong, R. Z., (2011)*Numerical study of metamaterial absorber and extending absorbance bandwidth based on multi-square patches*, The European Physical Journal B volume 81
[6] Vanlanduit, S., Vanlanduit, J. and others (2009) *A digital image correlation method for fatigue test experiments*, Optics and Lasers in Engineering Volume 47, Issues 3–4, March–April.

Experimental and numerical investigation on the energy absorbing capability of green additively manufactured multiphase cellular structures

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ABSTRACT

The wide spread of Additive Manufacturing in recent years has paved the way to adopting innovative design in functional applications, together with the appearance of new materials into the 3D-printing world. To date, many engineering applications, from the structural to the biomedical, have greatly benefited from these advancements. Three-dimensional cellular structures, together with Lattice and TPMS structures, are the result of AM capability to embrace complex designs otherwise impossible to obtain with traditional technologies [1-2]. Among their applications, one of the most relevant concerns the energy absorption feature, with practical employs spacing from lifestyle products to crashworthiness components.

Finding inspiration in the natural world, where structures with multifunctional properties are the result of adaptation of the species over millions of years, multi-material structures with a foamlike soft layer in between rigid layers present the most enhanced mechanical properties related with energy absorption.

Recent studies about the interactive effect between the foam and the external shell provide improved properties compared to the algebraic sum of the contributions of single constituents [3]. Also, a multi-material AM technique has been developed to fill thin-walled structures, proving that foam-filled lattices show enhanced properties compared to empty and equivalent-weight lattice structures [4].

In this work, a nature-inspired closed cellular structure is printed in Poly(Butylene Adipate-co-Terephthalate) bio-polymer. Its biodegradability is giving PBAT an emerging position as the preeminent flexible bioplastic; despite not being available among commercial filaments, it has been recently introduced in the 3D-printing world for a more environmentally sustainable production [5].

The structure is functionalized with Poly-Urethane foam, and characterized under static and cyclic compressive loadings: compared to the original cell structure, a consistent Improvement of the energy absorption capability is noted for the foam-filled configuration.

In parallel, a numerical methodology based on Finite Elements modeling is introduced to deeply analyze, explain, and possibly optimize the mechanisms that take place during the deformation process.

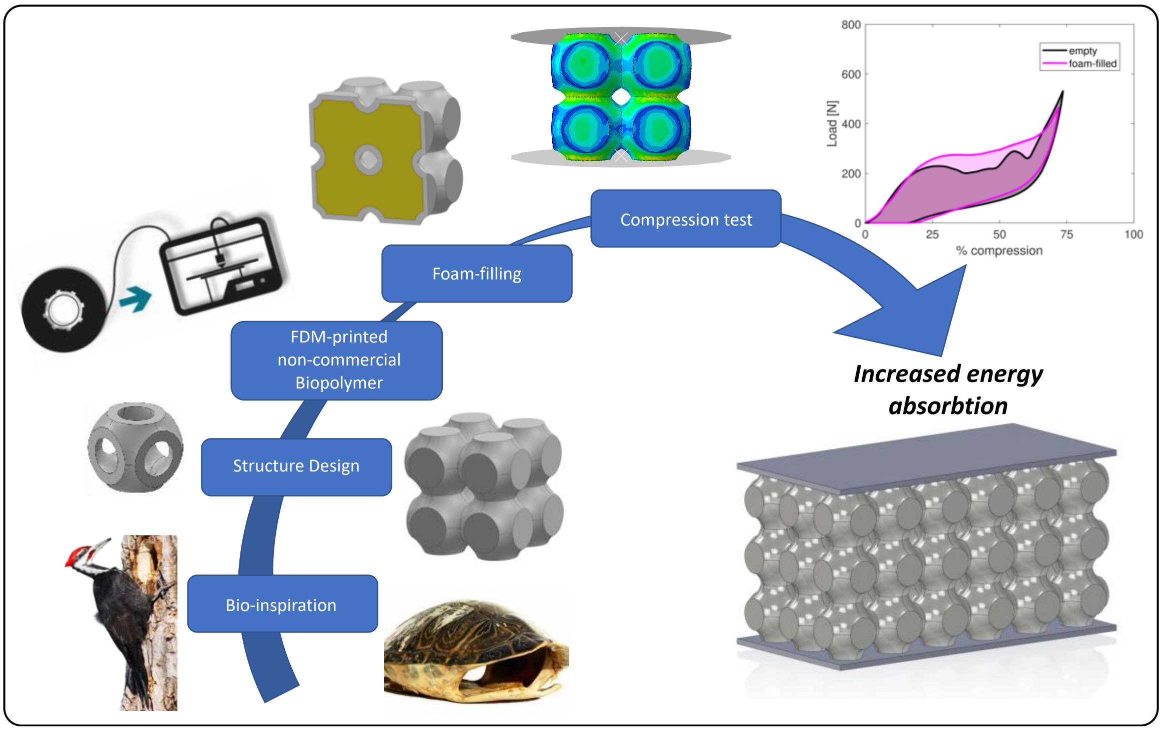

Figure 1. Graphical abstract

REFERENCES

[1] A. Kumar, *et al.*, Design and additive manufacturing of closed cells from supportless lattice structure, *Additive Manufacturing*, 33 (2020) 101168.

[2] A. Corvi, *et al.*, Analysis and modelling of damage mechanism in FDM 3D-printed lattice structure under compression loading, *Journal of Mechanical Science and Technology*, 37(4) (2023).

[3] R. Yao, *et al.*, A bio-inspired foam-filled multi-cell structural configuration for energy absorption, *Composites Part B*, 238 (2022) 109801.

[4] M.J. Prajapati, *et al.*, Multi-material additive manufacturing with lightweight closed-cell foam-filled lattice structures for enhanced mechanical and functional properties, *Additive Manufacturing*, 54 (2022) 102766.

[5] C. Sciancalepore, *et al.*, Flexible PBAT-Based composite filaments for tunable FDM 3D Printing, *ACS Applied Bio Materials*, 5(7) (2022) 3219–3229.

Controlling wrinkling patterns in thin sheets coated with 3D printed rigid elements

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ABSTRACT

Membranes are thin bidimensional structures prone to instability phenomena, forming wrinkles in those regions where the material cannot bear compressive loadings. The realization of controllable wrinkle pattern is of great importance in a number of engineering application, ranging from cell culture surfaces (Li et al., 2015), organic systems for active self-cleaning (Pocivavsek et al., 2019), adaptive aerodynamic drag control (Terwagne et al., 2014), high-level anti-counterfeiting strategies (Bae et al., 2015), and camouflage systems (Xu et al., 2020). Different techniques have been analysed for tailoring prescribed wrinkling patterns, including arrangements of cuts in the membrane (Yan et al., 2014), and controlling the swelling of the substrate in bi-layer materials (Ilseng et al., 2019). Among the non-destructive techniques, the use of additive manufacturing technologies to directly attach deployable lattice structures on the membrane represents a new frontier in control of wrinkling pattern. For instance, structures with auxetic properties might be used to counteracts in a targeted way the effects of wrinkling under specific loadings configurations. In the present work, we explore different arrangements of simple rigid elements (circular inclusions, rods, unit lattice cells) bonded to a thin sheet under uniaxial tension to control its wrinkle pattern. A set of simplified FE analysis, in which the loss of membrane stiffness in compression is treated as material non-linearity (Alberini et al., 2021), is carried out to select the ideal geometrical configurations prior the mechanical testing. Proof-of-concept experimental tests are carried out on sheets made by polyethylene terephthalate with adherent elements 3D printed using FDM technique. Full-field three-dimensional displacements are acquired during the tests using DIC. The results of the present work might be relevant in a number of applications, in particular in the field of cultural heritage, in which artworks made on natural supports susceptible to environment-induced wrinkling, such as parchments and fabrics, require localized and non-destructive interventions to restore the smoothness of the surface (Papanikolaou et al., 2022; Zilberstein et al., 2020).

REFERENCES

- Alberini, R., Spagnoli, A., & Terzano, M. (2021). Numerical modelling of wrinkled hyperelastic membranes with topologically complex internal boundary conditions. *International Journal of Mechanical Sciences*, *212*(July), 106816.
- Bae, H. J., Bae, S., Park, C., Han, S., Kim, J., Kim, L. N., Kim, K., Song, S.-H., Park, W., & Kwon, S.

(2015). Biomimetic Microfingerprints for Anti-Counterfeiting Strategies. *Advanced Materials*, *27*(12), 2083–2089.
- Ilseng, A., Prot, V., Skallerud, B. H., & Stokke, B. T. (2019). Buckling initiation in layered hydrogels during transient swelling. *Journal of the Mechanics and Physics of Solids*, *128*, 219–238.
- Li, M., Hakimi, N., Perez, R., Waldman, S., Kozinski, J. A., & Hwang, D. K. (2015). Microarchitecture for a Three-Dimensional Wrinkled Surface Platform. *Advanced Materials*, *27*(11), 1880–1886.
- Papanikolaou, A., Dzik-Kruszelnicka, D., & Kujawinska, M. (2022). Spatio-temporal monitoring of humidity induced 3D displacements and strains in mounted and unmounted parchments. *Heritage Science*, *10*(1), 15.
- Pocivavsek, L., Ye, S. H., Pugar, J., Tzeng, E., Cerda, E., Velankar, S., & Wagner, W. R. (2019). Active wrinkles to drive self-cleaning: A strategy for anti-thrombotic surfaces for vascular grafts. Biomaterials, 192, 226-234.
- Terwagne, D., Brojan, M., & Reis, P. M. (2014). Smart Morphable Surfaces for Aerodynamic Drag Control. *Advanced Materials*, *26*(38), 6608–6611.
- Xu, C., Colorado Escobar, M., & Gorodetsky, A. A. (2020). Stretchable Cephalopod-Inspired Multimodal Camouflage Systems. Advanced Materials, 32(16), 1905717.
- Yan, D., Zhang, K., Peng, F., & Hu, G. (2014). Tailoring the wrinkle pattern of a microstructured membrane. *Applied Physics Letters*, *105*(7), 071905.
- Zilberstein, G., Zilberstein, S., Maor, U., & Righetti, P. G. (2020). Surface analysis of ancient parchments via the EVA film: The Aleppo Codex. *Analytical Biochemistry*, *604*, 113824.

Testing of 3D printed precise positioning mechanism's creep

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ABSTRACT

Glass scales are important standard of length in precision measurement applications due to their high accuracy, stability, and reliability. In the calibration, stability of linear scale measurement system during the time of calibration is important characteristic, as the procedure may take up to an hour to finish. As additive manufacturing gets more popular over the last years, precise adjustment systems are started to be made of polymer materials using different additive technologies [1], [2]. Therefore, the accuracy of length measurements can be affected by the phenomenon of creep that may appear in the scale holders. This study investigates the creep behaviour of compliant mechanisms fabricated with additive manufacturing (SLA technology) used for fine alignment of linear scale height [3].
Compliant mechanisms are mechanical structures that can transform the motion through the elasticity of their members under load. They are commonly used in applications where precise motion or force control is required. However, the performance of these mechanisms over a period of time is often limited by creep, which is the time-dependent deformation of a material under constant load [4], which is by default present in most of the compliant mechanism states. In this study, we conduct creep tests on 3D printed compliant mechanism made of polymer resin material (Formlabs Grey V4) to investigate their application limitations in metrology mechanisms.
It is worth noting that environmental factors, such as humidity and temperature, have significant effect on the creep behaviour. However, as this research is focused on application of additively produced mechanisms only in the laboratory conditions, where environmental factors are generally well controlled, only the contribution of temperature as external factor will be discussed in this paper.

The measurements were taken on experimental setup using Mahr P2004 M inductive probe with nanometre resolution and temperature sensors PT100 connected to the acquisition system. For mounting of the equipment on the vibration dampened bench rigid Thorlabs optical workbench components were used. Measurements were taken in temperature stabilized environment with temperature deviation under 1,5°C in 24 hours. Duration of 24 hours was chosen as generally the ambient temperature makes full circle and get to the value very similar to the original which allows comparison with the starting position.
Results were taken in 24-hour cycles and the measurements were repeated 3 time. The results showed significant influence of the ambient temperature with the displacement, where change of the 1°C corelated to change of around 7 micrometres.
After temperature influence was eliminated, results showed unwanted mechanism displacement of 1,8 micrometres after 24 hours measurement cycles.

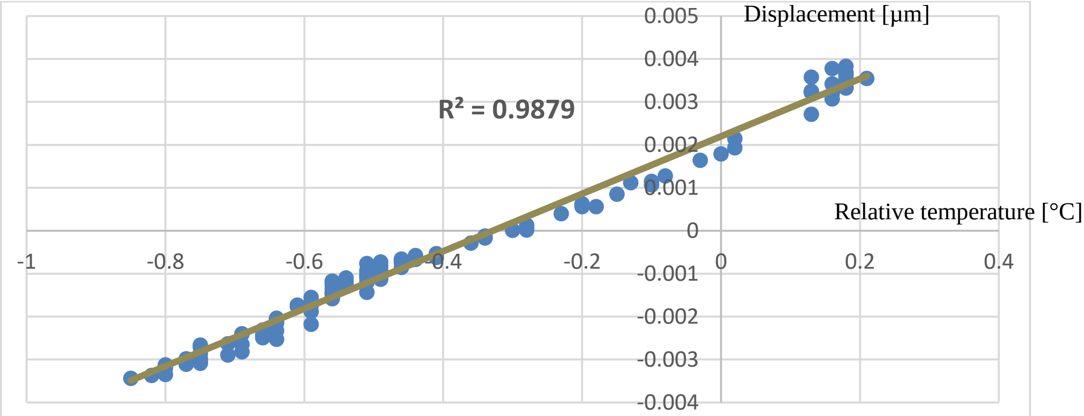

Figure 1. Relationship between displacement and temperature in the first 12 hours of measurement

From the results, it can be calculated that in one hour interval creep might cause sample displacement of 75 nanometres, which is generally insignificant in the calibration of glass scales. However, in other applications where long-term stability over several days or weeks might be important, detected creep could notably affect results.

To conclude, additive technology has emerged as a promising technology for the fabrication of complex parts of length measuring devices and fixtures. However, the creep behaviour of 3D printed parts can limit the application potential. Further research could be conducted in development of materials with low creep rates as well as optimization of printing parameters for reducing the influence of creep.

REFERENCES

[1] J. P. Sharkey, D. C. W. Foo, A. Kabla, J. J. Baumberg and R. W. Bowman, “A one-piece 3D printed flexure translation stage for open-source microscopy,” *Review of Scientific Instruments,* vol. 87, no. 2, 2016.

[2] M. Cui, Z. Zhen and Y. Peng , “Tracking control of a large range 3D printed compliant nano-manipulator with enhanced anti-windup compensation,” *Mechanical Systems and Signal Processing,* vol. Volume 131, pp. Pages 33-48, 2019.

[3] S. Medić, Razvoj sustava za umjeravanje mjernih skala, Zagreb: Fakultet strojarstva i brodogradnje, 2011.

[4] J. A. Crews, Methodology for analysis of stress, creep, and fatigue behavior of compliant mechanisms, Missouri: Missouri University of Science and Technology ProQuest Dissertations Publishing, 2016.

Highlights on the Mechanical Properties of Extruded Filament in FDM 3D Printing

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ABSTRACT

FDM is one of the most popular additive manufacturing techniques through 3D printing. Within this technique, one of the intensively studied subjects is the analysis of the factors that influence the mechanical behavior of the 3D printed parts. However, despite numerous studies that show the influence of parameters such as raster orientation, layer height/thickness, build orientation, number of layers, there are some other process parameters which are less analyzed. Due to some interactions between the effects due to different parameters, it becomes challenging to analyze influences on the mechanical behavior of 3D printed materials. One of the less studied subjects is the mechanical behavior of the extruded filament through the nozzle.

The mechanical behavior of the extruded filament at the nozzle of a 3D printer and the filament before entering the printer (the virgin filament) is experimentally analyzed in this paper by tensile tests. The virgin filament is typically a continuous, uniform strand of filament, with consistent diameter and composition. However, when the filament is extruded from the nozzle during the 3D printing process, its mechanical behavior is significantly changed. The filament is subjected to high temperatures and pressures, which can cause it to soften, deform, and even break. Additionally, the extrusion process can lead to variations in filament diameter and composition, which can affect the strength of the resulting 3D prints. The mechanical behavior of the extruded filament can also depend on other factors such as printing temperature, print speed, and layer height. The printing parameters influence the flow rate and viscosity of the filament, which can affect the adhesion between the layers and the strength of the printed object.

Effect of printing orientation on mode I fracture toughness of DLP printed UV sensitive resin specimens

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ABSTRACT

Additive manufacturing (AM), also known as 3D printing, is a process used to create a physical (or 3D) object adding layer by layer materials based on a digital model [1]. There are a number of processes with their own standards which AM is based on; Digital Light Processing (DLP) is one of them. However, parts obtained through DLP are deprived of comprehensive characterization. DLP prints are above and beyond what is capable from almost any FDM 3D printer. Extremely intricate and difficult geometries can be created using this technology, which is why it has so many applications in 3D printed jewelry and prototyping. Advantages of DLP are very intricate designs - more accurate than FDM or SLS, fast - faster than SLA printing and less running costs than SLA as usually uses a shallower resin vat, reducing waste.
The present paper investigates the mode I fracture toughness (K_{IC}) of Ultraviolet (UV) sensitive resin specimens obtained through DLP printing process. The fracture tests were performed on a 5 kN Zwick Roell 005 universal testing machine. To determine the K_{IC}, three-point bending (3PB) tests were performed on Single Edge Notched Bending (SENB) specimens [2]. The 3PB tests were carried out in the displacement control, using a crosshead loading speed of 2 mm/min. The geometry of the SENB specimen and the experimental setup complied with the provisions indicated by the ASTM D5045 standard [3]. Specimens were printed after 9 different loading directions using flat, on edge and upright positioning. Each positioning presented three printing angles, namely 0, 45 and 90. All investigated directions show major influences on the K_{IC} of the SENB specimens, the highest values obtained in the case of the on-edge orientation.

REFERENCES

[1] C. Vălean, L. Marșavina, M. Mărghitaș, E. Linul, J. Razavi, F. Berto, R. Brighenti, The effect of crack insertion for FDM printed PLA materials on Mode I and Mode II fracture toughness, Procedia Structural Integrity 28 (2020) 1134-1139.
[2] L. Marșavina, C. Vălean, M. Mărghitaș, E. Linul, S.M.J Razavi, F. Berto, R. Brighenti, Effect of the manufacturing parameters on the tensile and fracture properties of FDM 3D-printed PLA specimens, Engineering Fracture Mechanics 274 (2022) 108766.
[3] ASTM D5045 – 14, Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials, 2014.

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