SIRAMM
H2020-WIDESPREAD-2018-03
Project No. 857124

2nd International Workshop on

Structural Integrity of Additively Manufactured Materials

Modelling and Simulation of Additively Manufactured Elements

Hotel Continental Brno
& online

Brno, Czech Republic
4th - 5th February 2022

Workshop Programme & Book of Abstracts

Workshop organized by:

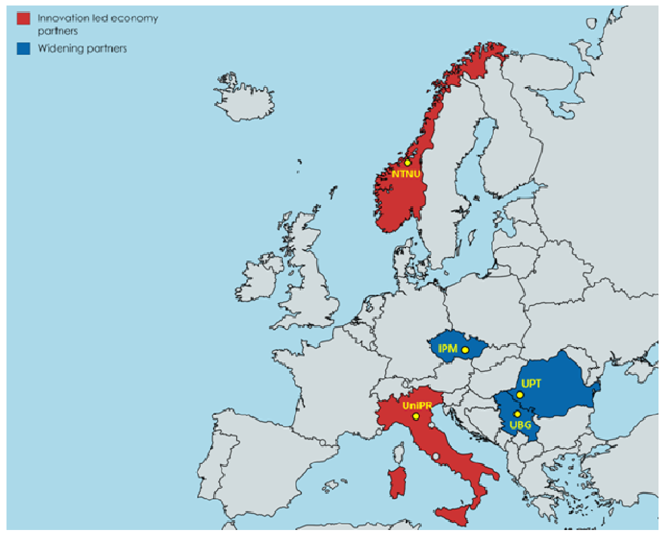
Polytechnic University of Timisoara,
ROMANIA

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 Programme

(Central European Time - Rome, Paris, Prague)

Friday, 4th February 2022

8:30-9:30 Registration
Hotel Continental Brno (HCB)
Kounicova 6, 602 00 Brno, Czech Rep.

9:30-10:00 Opening of the Workshop and presentation of the SIRAMM project (HCB & online)
Prof. Liviu Marsavina

10:00-10:30 **1st Keynote lecture** (HCB & online)
Chairman Prof. Liviu Marsavina
Fatigue of additively manufactured lattice materials: a design and manufacturing challenge
Matteo Benedetti, Simone Murchio, Raffaele De Biasi – Univ. of Trento, Italy

10:30-10:45 *Coffee break* (HCB)

10:45-13:00 **1st Session** (HCB & online) (12 min presentation + 3 min Qs&As)
Chairman: Prof. Andrea Spagnoli
Characterization of AM polymer-based materials

10:45-11:00 Comparison of roughness of different parts obtained by Additive Manufacturing
Miloš Milošević, Ivana Jevtić, Isaak Trajković, Žarko Mišković, Tihomir Ćuzović, Aleksa Milovanović, Milan Travica

11:00-11:15 Analysis of different process parameters of 3D printing and micro-EDM for fabricating precise micro-hole in CFRP composites
Kishore Debnath, Bikash Chandra Behera, Matruprasad Rout

11:15-11:30 Tensile properties of FDM printed PLA specimens: influence of printing parameters
Emanoil Linul, Marian Baban

11:30-11:45 Immersed thermo-mechanical analysis of laser powder bed fusion processes
M. Carraturo, J. Jomo, S. Kollmannsberger, E.Rank, A. Reali, F. Auricchio

11:45-12.00 Influence of temperature on the tensile behavior of FDM printed ABS at different spatial orientations
Daniel Foltut, Estera Valean, Monica Buzdugan, Liviu Marsavina

12:00-12.15 CANCELLED Influence of wall layer number around brass inserts in 3D printed specimens subjected to axial pull-out force
Milica Ivanović, Miloš Vorkapić, Aleksandar Simonović, Toni Ivanov, Igor Stamenković

12:00-12.15 Delamination effect on the mechanical behavior of 3D printed polymers
Fatima Majid, Rajaa Rhanim, Hassan Rhanim

12:15-12:30 Impact properties of laser sintered polyamide, according to building orientation
Dan Ioan Stoia, Sergiu Galatanu, Liviu Marsavina

12:30-12:45 RRAM - A round-robin on additively manufactured plastics - Experiment
Matteo Vettori, Lorenzo Bergonzi, Luca Sentimenti

12:45-13:00 The influence of dog-bone shaped specimen geometry on tensile test results of fused

	filament fabricated PA12 Marius Nicolae Baba, Călin Itu
13:00-14:00	*Lunch break* (HCB)
14:00-14:30	**2nd Keynote lecture** (online) Chairman: Prof. Roberto Brighenti ***Trends in Additive Manufacturing for Medical Devices: Applications and Challenges*** F. Danielli, F. Berti, V. Finazzi, A. G. Demir, T. Villa, Lorenza Petrini – Polytechnical Univ. of Milan, Italy
14:30-16:00	**2nd Session** (HCB & online) (12 min presentation + 3 min Qs&As) Chairman: Prof. Roberto Brighenti ***Fatigue and fracture of AM materials***
14:30-14:45	Low cycle fatigue behaviour of 304L stainless steel fabricated by selective laser melting Miroslav Šmíd, Michal Jambor, Daniel Koutný, Stanislava Fintová
14:45-15:00	Analysis and modelling of damage mechanism in FFF 3D printed Lattice structure during compression loading Luca Collini., Alberto Corvi, Aijeet Kumar
15:00-15:15	Mode I fracture toughness of FDM printed PLA specimens: influence of printing parameters Emanoil Linul and Răzvan Paul Bercuci
15:15-15:30	Fracture Mechanics parameters assessment of quasi-brittle PLA polymer and PLA-X composite Aleksa Milovanovic, Tomas Babinsky, Aleksandar Sedmak, Lubos Nahlik, Milos Milosevic
15:30-15:45	Energy-based method for analysing fatigue properties of additively manufactured AlSi10Mg Martin Matušů, Katharina Dimke, Jan Šimota, Jan Papuga, Jakub Rosenthal, Vladimír Mára, Libor Beránek
15:45-16:00	Experimental determination of fracture mechanics parameters on ring-shaped specimens with different crack lengths Isaak Trajkovic, Milos Milosevic, Bojan Medjo, Marko Rakin, Aleksandar Sedmak, Marko Goreta
16:00-16:15	*Coffee break* (HCB)
16:15 -17:30	**Materials research trends & perspectives** (HCB & online) ***The research focus at the Institute of Physics of Materials (IPM)*** Prof. Ludvik Kunz, head of IPM, Brno, Czech Rep.

Saturday, 5th February 2022

9:00-9:30	**3rd Keynote lecture** (HCB & online) Chairman: Prof. Aleksandar Sedmak ***Additive Manufacturing in Aerospace Propulsion*** Toni Ivanov – Univ. of Belgrade, Serbia
9:30-11:15	**3rd Session** (HCB & online) (12 min presentation + 3 min Qs&As) Chairman: Prof. Aleksandar Sedmak ***Characterization of AM metallic materials***
9:30-9:45	Effect of heat treatment on the TRIP behavior of additive manufactured stainless steel Michal Jambor, Miroslav Šmíd, Ivo Kuběna, Jan Čapek, Efthymios Polatidis, Daniel Koutný
9:45-10:00	Effect of building direction and heat treatment on tensile properties of Inconel 939 prepared by additive manufacturing Ivo Šulák, Tomáš Babinský, Alice Chlupová, Aleksa Milovanović, Isaak Trajkovic, Jakub Poloprudský, Luboš Náhlík
10:00-10:15	Study of heat treatment of Selective Laser Melted AlSi10Mg specimens Alexandra Morvayová, Emanuela Palmieri, Giuseppe Casalino, Luigi Tricarico
10:15-10:30	NiTi-powders behavior at LASER interaction Ana-Maria Scripcariu, Iulian Ioniță, Silviu Gurlui, Alexandru Cocean, Cristian Micu, Nicoleta Monica Lohan, Nicanor Cimpoeșu
10:30-10:45	The evolution of thermal distortion and stresses at macro scale for metal additively manufactured part Muhammad Mashhood, Andreas Zilian, Bernhard Peters, Davide Baroli, Eric Wyart
10:45-11:00	A comparison on static and fatigue behaviour between traditional and SLM AISI 316L Danilo D'Andrea, Andrea Gatto, Eugenio Guglielmino, Giacomo Risitano, Dario Santonocito
11:00-11:15	Role of surface finish on the fatigue behaviour of L-PBF IN718 using miniature specimen Uriati Federico, Gianni Nicoletto, Martina Meisnar
11:15-11:30	*Coffee break* (HCB)
11:30-13:15	**4th Session** (HCB & online) (12 min presentation + 3 min Qs&As) Chairman: Dr. Lubos Nahlik ***Properties and models of AM materials and metamaterials***
11:30-11:45	2D triangular-like additively manufactured lattices: an experimental study Andrea Spagnoli, Roberto Brighenti, Matteo Montanari
11:45-12:00	Influence of infill topology on the flexural stiffness of FDM produced PLA Lorenzo Bergonzi, Matteo Vettori
12:00-12:15	Mechanical behaviour of soft membranes: simulation and possible AM biomimicking tissues Andrea Spagnoli, Riccardo Alberini, Roberto Brighenti
12:15-12:30	Additively Manufactured Triply Periodic Minimally Surface Structures for Biomechanical Application Reza Noroozi, Farzad Tatar, Mahdi Bodaghi, Ali Zolfagharian, Roberto Brighenti, Mohammad Amin Shamekhi, Abbas Rastgo Ghamsari, Amin Hadi
12:30-12:45	CFD-DEM approach towards a multi-track selective laser melting Navid Aminnia, Davide Baroli, Alvaro Estupinan, Bernhard Peters
12:45-13:00	Design of cellular structures fabricated by the additive manufacturing method Kevin Moj, Grzegorz Robak
13:00-13:15	Analysis of mechanical properties of bulk architectured materials Filip Šiška, Luděk Stratil, Zdeněk Chlup, Helena Kotoulová
13:00-14:15	*Lunch break* (HCB)

14:15-17:00 **5th Session** (HCB & online) (12 min presentation + 3 min Qs&As)
Chairman: Prof. Milos Milosevic
AM technologies: advancements & new experiences

14:15-14:30 Surface welding as an additive manufacturing technique to improve rail crack resistance
Olivera Popović, Radica Prokić-Cvetković, Aleksandar Sedmak

14:30-14:45 3D Digitalization and modelling of Cultural and Historical treasures of Montenegro
Mina Šibalić, Jelena Šaković-Jovanović, Aleksandar Vujović

14:45-15:00 Center for Optical Measurements and Rapid Prototyping - Challenges in Additive Manufacturing
Milos Milosevic

15:00-15:15 New methods for CAD development of parts adapted to additive production technologies
Goran Mladenovic, Milos Milosevic, Ivana Jevtic, Mihajlo Popovic, Milos Pjevic

15:15-15:30 Implementation of additive manufacturing at TechLab Tehnopolis
Tihomir Cuzovic

15:30-15:45 Challenges of 3D printing implementation in Civil Engineering
Aleksandar Savić, Aleksandra Mitrović, Nada Ratković Kovačević, Sanja Jevtić, Marina Aškrabić, Miša Stević

15:45-16:00 Prototyping of clamping mandrel for pipe welding by method FSW
Marko Mumović, Nikola Šibalić

16:00-16:15 CANCELLED 3D metal printing - Development and innovation
Aleksandra Joksimovic, Mladen Regodic, Isaak Trajkovic, Ivana Jevtic

16:15-16:30 3D printing applications in civil engineering
Jan Sampor, Nada Ratković Kovačević, Djordje Dihovicni, Dragan Kreculj, Aleksandra Mitrović, Aleksandar Savić

16:30-16:45 Production park Torpedo - how to become the main center of additive technology in Croatia
Dario Zoric

16:45-17:00 Experimental AM drawing tool
Marko Horvatek

17:00-17:15 Closing of the Conference and presentation of future SIRAMM events (HCB & online)
Prof. Liviu Marsavina

17:15-18:30 ***Post Conference tour***

List of Keynote lectures & Abstracts

Keynote lectures

Keynote lecture

Fatigue of additively manufactured lattice materials: a design and manufacturing challenge

Matteo Benedetti[1], **Simone Murchio[1]**, **Raffaele De Biasi[1]**

[1] Department of Industrial Engineering - University of Trento, Trento, Italy

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Architected cellular materials show enormous potential for innovative applications in several high-tech industrial fields, such as biomedical and aircraft components [1]. Despite a growing body of research aiming to shed light on the mechanical properties of lattice structures and their outstanding tunability, a full comprehension of the fatigue response of these materials is still far from being reached. This lack of knowledge is a major concern for industries, thus limiting additive manufacturing (AM) application on a large scale. It has been stated that fatigue is an orientation-dependent property since the building orientation of lattice cell units and single struts influences the morphological outcome of the latter, and consequently their fatigue behavior [2,3]. In this scenario, the possibility of directly designing a fatigue-improved lattice structure before the manufacturing stage could be of enormous advantage for a more robust and faster scale-up of metal AM to the industrial field.
In this work, the authors propose an optimization process able to design a fatigue-improved three-point bending specimen composed of Octet Truss (OT) cells. The approach is based on the fatigue enhancement of the weakest struts of the structure since it is the typical location of the initial lattice failure. A bottom-up approach has been adopted starting from an experimental investigation of the fatigue properties of Ti6Al4V strut-junction specimens (sub-unital lattice elements), additively manufactured via laser powder bed fusion (L-PBF), according to four different building orientations (Figure 1A). Once their fatigue behavior is derived (S-N curves in a fully reversed fatigue regime R=-1, see Figure 1B), a prediction model of the stress amplitude at 10^7 cycles as a function of the building angle was generated by a 3-grade polynomial fitting (Figure 1C). This correlation between fatigue life and building orientation is fundamental for the structural optimization at a macroscopic level. Indeed, the orientation of the specimen can be optimized in order to improve the fatigue life of the most critical struts. As reported in Figure 2A, two angles, γ and ψ, describing the specimen orientation can be defined as optimization variables. A formal optimization problem can now be written and solved using Finite Element (FE) and a gradient-based approach. The solution strategy is iterative and based on the formulation of approximated linear subproblems. The initial conditions are evaluated by an FE simulation and the optimal orientation angles are defined step by step by solving subsequent linear approximations around a new FE solution as proposed in [4].
The outcome of the optimization model on the OT lattice specimen suggests a rigid rotation of γ = 70° and ψ= 90° , as reported in Figure 2B. Additionally, the fatigue life safety factor of the most critical strut in this configuration has an improvement of +61%.

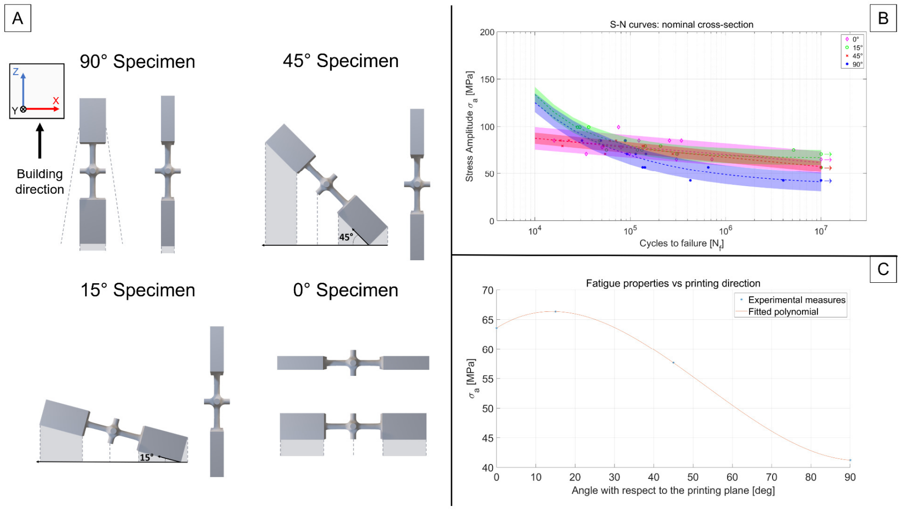

Figure 1 - A) Strut-junction specimens, printed according to four different building orientations, their S-N fatigue curves (1B) and the polynomial fitting model (1C).

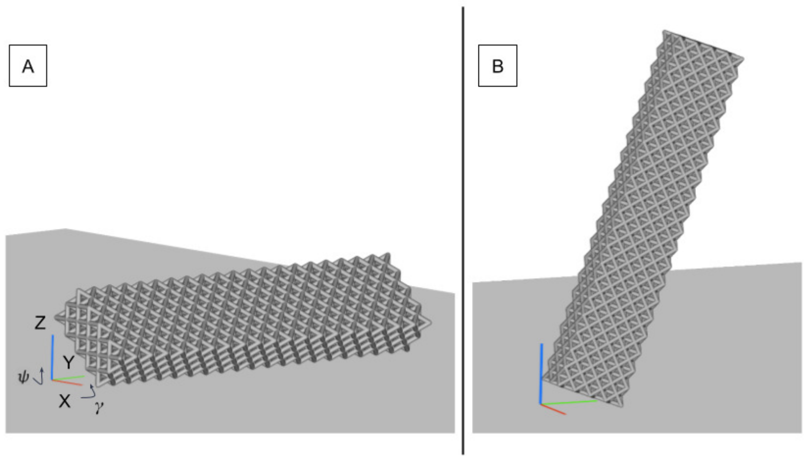

Figure 2 - A) The three point bending specimen in its initial position on the printing plane. B) The specimen optimal orientation.

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Keynote lecture

Trends in Additive Manufacturing for Medical Devices: Applications and Challenges

Francesca Danielli[1], Francesca Berti[1], Valentina Finazzi[2], Ali Gokhan Demir[2], Tomaso Villa[1], Lorenza Petrini[3]

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ABSTRACT

Additive manufacturing technologies for biomedical applications

In the last decade, additive manufacturing (AM) has been recognized with great potential in the medical sector. Looking at the specific application, there are several materials that satisfy the mechanical and compatibility properties required for the development of a varierty of products, such as anatomical mock-up models for preoperative planning (polymers), implants and prostheses (metals and ceramics), surgical instruments (metals and polymers) and tissue engineering products (polymers and cells). With respect to conventional manufacturing processes, the advantages of AM in the production of medical products address both mass-production devices and custom products. Concerning the first, AM technologies allow a higher and cost-effectively parallel production as compared to the series production of the standard fabrication processes. As regards the customized production, the personalized medicine industry is a currently growing market and is expected to revolutionize healthcare system (1). Indeed, it allows the production of medical devices that well-fit even complex anatomical sites, resulting in higher benefits for the patient. **Figure 1** shows the typical pipeline to design and manufacture customized medical products: its starting point is the acquisition of patient images used to define the CAD model of the device to realize (2).

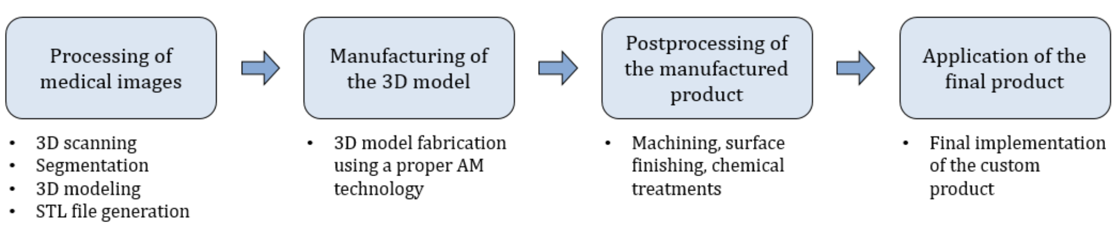

***Figure 1** Typical workflow for the development of a custom medical product made by AM*

New 2017/745 Medical Device Regulation recently introduced a further need of safety demonstration for custom made implantable devices, officially involving a Notified Body that aseesses the fulfilment of the safety requirements This activity is not trivial since there is not a defined methodology to assess the quality of a bespoke product, since each device is intended only for a single time use. Given the ethical and clinical need to guarantee the safety of the product end-users, a well-structured methodology is required to test and verify such devices. Within this scenario and according to the latest scientific investigations, an approach integrating Finite Element (FE) analysis and AM custom production can be a viable tool for the quality assessment of a personalized design (3). Among the several biomedical applications of AM, the current work will focus on implantable metallic devices, which are usually manufactured using powder bed fusion processes, such as Laser Powder Bed Fusion (LPBF) and Electron Beam Melting (EBM) (4). Namely, the authors will highlight the potentialities and the open issues of AM applied to the realization of custom implants in both the well-established orthopaedic field and to the still unexplored cardiovascular sector. On one hand, AM offers unique capabilities for designing and manufacturing devices to fit complex anatomical sites. On the other hand, inherent problems of the manufacturing process may arise, as defects that affect the fatigue life of the product. Regarding this aspect, reasonable considerations on the need of proper surface treatments will be discussed.

Orthopedic implants: design & verification

In orthopaedics, AM allows to manufacture lattice structures mimicking trabecular bone, which results in an enhanced bone ingrowth and post-surgery implant stability in fast times. This is relevant when complex anatomical sites, as the ankle joint, are treated. Standard implants for talus replacement are invasive, affected by a high failure rate, and require technically demanding surgeries. The authors are currently working on the design of a novel AM bespoke implant for talus resurfacing, involving an external solid shell and a trabecular core. The manufactured device should have a properly treated external layer to allow a frictionless articulation of the prosthesis on the surrounding tissues and a functional rough trabecular surface for osseointegration. Within this scenario, FE modelling was chosen as a robust tool for investigating the safety of different design solutions.

The frontiers of personalized solutions: cardiovascular ni-ti stents

Cardiovascular devices are a currently emerging AM application. Within this context, the design of functional Ni-Ti stents by LPBF, aimed at improving treatments of paediatric heart diseases, is a valuable example (5). AM of super-elastic devices require particular care, especially for i) the process parameter selection for realization of micrometric structures; ii) the design rules for AM; iii) the adjustment of temperature-dependent material properties; and iv) the surface finishing to improve hemocompatibility and fatigue resistance.

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Keynote lecture

Additive Manufacturing in Aerospace Propulsion

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ABSTRACT

There are extensive commercial and technical benefits of using additive manufacturing (AM) for aerospace propulsion: reduction of cost and lead time, design of more complex components achieving reduction in mass and number of components, providing better cooling and thermal management etc. There is also the possibility of using novel materials and material modelling.

In this paper a review of the state-of-the-art of additive manufacturing for aerospace propulsion as well as some of the key factors for selection of AM method and the corresponding technical difficulties involved are presented.

Abstracts

1st Session

1. Characterization of AM polymer-based materials

Comparison of roughness of different parts obtained by Additive Manufacturing

Miloš Milošević[1], Ivana Jevtić[1*], Isaak Trajković[1], Žarko Mišković[2], Tihomir Ćuzović[3], Aleksa Milovanović[1], Milan Travica[1]

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The aim of this paper is to compare the roughness of different parts obtained using Additive Manufacturing (AM). Five dissimilar parts were printed on Metal X 3D printer (Markforged Inc., Watertown, MA, USA). This AM technology is extrusion-based FFF (Fused Filament Fabrication), with one key difference: all parts have to be sintered in an oven after printing. For this study all parts were printed with 0.125 mm layer height after sintering. Due to sintering process the reduction along Z-axis is 20%. All parts have triangular infill pattern with 44% density. Used device can manufacture components using several metallic materials, such as stainless, tool steels, Inconel, copper. Of all these metallic materials, the most frequently used are 17-4 PH stainless steel, H13, A2 and D2 tool steels and Inconel 625. In this research 17-4 PH stainless steel is used to make specimens.
The device for measuring roughness used in this research is MarSurf SD26 (Mahr GmbH, Gottingen, Germany). The roughness of these specimens is measured in three different directions: along the printing direction, transverse to it and on lateral surfaces. The results for part no. 5 have identical values of R_z (mean roughness depth) and R_{max} (maximum roughness depth), thus showing that the printing accuracy along the Z-axis is sufficiently high. Also, the roughness values are compared between specimens no. 2 and 5, where the measurements are performed on the raft and directly on the model transverse to the printing direction. Interesting conclusion is that specimen roughness on raft is twofold higher, than on the manufactured part. Just to mention, rafts are constructions formed below the part, used to achieve better adhesion of parts during AM process. Higher value divergence between values of R_{max} and R_z is measured on specimen no. 1, along the printing direction, where R_{max} is twofold higher than R_z.

Analysis of Different Process Parameters of 3D Printing and Micro-EDM for Fabricating Precise Micro-Hole in CFRP Composites

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ABSTRACT

Carbon fibre-reinforced polymer (CFRP) composites have extensive application in several industries, including the automotive and aerospace industries. Fabrication of micro features in CFRP composites is an important process which is frequently performed for various applications including fabrication of micro-products and micro-components. The fabrication of precise micro features in CFRP composite is difficult to achieve by conventional means, even by additive manufacturing. Thus, in this study, the machinability characteristics of CFRP composite was experimentally investigated. CFRP composite was fabricated by using the additive manufacturing (AM) technique. A 3D printer (Make: Markforged and Model: x7) was used to manufacture the continuous carbon fibre-reinforced composites as shown in Fig. 1(a). The micro-hole fabrication in CFRP composite was performed by using a micro-machining centre (Make: Sinergy Nano Systems and Model: Hyper 15) as shown in Fig. 1(b). The different process parameters of 3D printing (infill density, layer thickness, infill pattern, etc.) and micro-EDM (voltage, capacitance, tool rotation, etc.) were considered to investigate their effect on the hole circularity, hole aspect ratio, and productivity. The optimization of the different parameters chosen for the purpose of the investigation was also carried out. The important process parameters that have an impact on the process have been identified and analysed.

Key words: 3D Printing; micro-EDM; CFRP; AM material; Machining

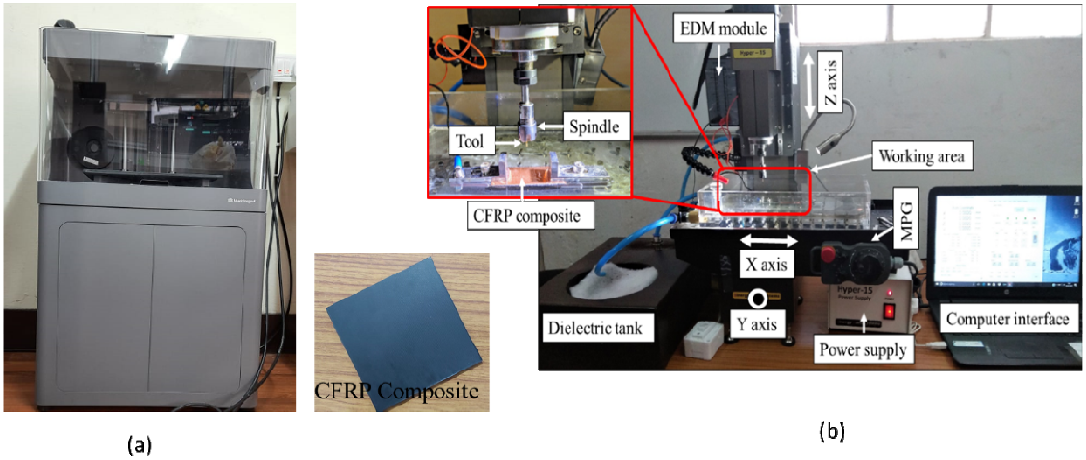

Fig. 1 Experimental setup (a) 3D printer and (b) micro-machining centre

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Tensile properties of FDM printed PLA specimens: influence of printing parameters

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ABSTRACT

Additive manufacturing (AM) is the name of industrial production for 3D printing, a computer-controlled process that creates 3D objects by depositing materials [1]. Fused deposition modelling (FDM) is one of the low lost 3D printing processes, which is based upon the AM concept. The main advantage of FDM over other AM processes is that it does not require any organic solvents and does not require the subsequent removal of excess polymers [2]. In this study, a commercial FDM printer Infitary i3 was used to manufacture Dog Bone (DB) specimens from polylactic acid (PLA). The influence of the printing direction (0, 45 and 90°), the infill pattern (grid, honeycomb and triangular) and the infill density (40, 70 and 100%) on the tensile properties are investigated in detail. The main mechanical properties referred here are Young's modulus, tensile strength and the corresponding strain, and fracture energy. The quasi-static tensile tests were performed on the 5 kN Zwck Roell 005 universal testing machine with a loading speed of 2 mm/min. The DB specimens were fractured under normal temperature conditions (25°C), according to ISO 527-1 [3]. Following the tensile tests, the specimens were subjected to microstructural analyzes. It was observed that all process parameters influence the tensile behavior of the printed specimens. The fracture mechanisms differ depending on the factor under investigation [4].

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Immersed thermo-mechanical analysis of laser powder bed fusion processes

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ABSTRACT

Introduction

The capability to correctly predict part deflections and residual stresses are important to assess the quality of the final artifact produced by Laser Powder Bed Fusion (LPBF) technology. Finite Element Methods (FEM) are usually employed to perform thermo-mechanical analysis of an LPBF process to predict possible process-induced excessive deformations or build failure. Many thermo-mechanical models can be found in the literature which allows simulating LPBF processes at both meso and macro-scale. Meso-scale models resolve the melt pool length scale, i.e., the time step increment directly follows the laser scan path allowing for a detailed description of the anisotropic residual stress distribution, whereas macro-scale models usually activate a cluster of agglomerated powder layers leading to a lower resolution which allows for simulations of the complete process at part scale.

Methodology

All the aforementioned FEM-based approaches require a conforming mesh generation process, which, for complex, optimized geometries, can be very time-consuming. Immersed boundary methods represent an attractive way to effectively handle the numerical analysis of complex geometrical components. In particular, the Finite Cell Method (FCM) has been already applied to simulate thermal [1] and thermo-mechanical [2] problems of both welding and additive manufacturing processes. However, for LPBF processes, these studies were limited to small length scales of approximately 1 mm^3. The present contribution discuss an immersed numerical framework, based on the FCM concept, to effectively simulate an LPBF process both at the meso and macro scale. The novelty of the presented methodology is the possibility to directly simulate the LPBF process starting from the original geometry (in the .stl file format). Therefore a fully automatic and straightforward discretization process can be achieved even for simulations of complex geometries [3, 4].

Results

The obtained numerical results show the effectiveness of the proposed numerical method, which can deliver solutions in excellent agreement with experimental measurements. For instance, for the 3D printed part depicted in Figure 1 the correlation coefficient between the simulated and the measured displacements after support removal is approx. 99%, but a very good agreement with experimental data is obtained also for the mesoscale model (see Figure 2).

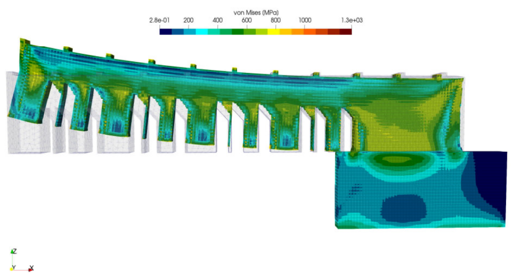

Figure 1: von Mises stress distribution after base plate removal

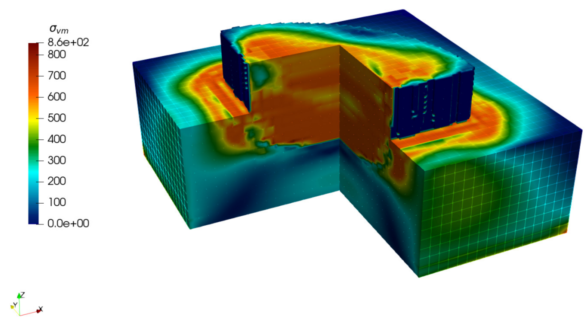

Figure 2: von Mises stress distribution after ten layer process

Conclusions

The proposed immersed boundary approach opens a new possibility to the simulation of LPBF processes, allowing a simple yet reliable workflow which does not suffer mesh generation burdens.

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Influence of temperature on the tensile behaviour of FDM printed ABS at different spatial orientations

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ABSTRACT

In the last years, the additive manufacturing (AM) technology has attracted the interest of many researchers. Fused Deposition Modelling (FDM) is the most widely used AM method of printing thermoplastics, mainly due to its ease of handling, fast processing, simplicity, and low-cost efficiency [1]. FDM is based on fine filament extrusion of mainly thermoplastic materials to build layer-by-layer 3D objects. The main objective of this work is to investigate the tensile properties of acrylonitrile butadiene styrene (ABS) 3D printed specimens obtained through FDM printing. The influence of the spatial printing direction (0°, 45°, 90°) on the main mechanical properties was investigated [2]. The specimens were tested at two different temperatures: room temperature (25°C) and maximum operating temperature (80°C), with a loading speed of 5 mm/min, according to the ISO 527-1 Standard. The main tensile properties were determined based on the data obtained from the experimental tests. It has been observed that the spatial orientation has an important influence on the mechanical properties both at room and glass transition temperatures. Due to the softening process of the specimens, the temperature leads to a significant decrease in the investigated properties. Finally, the results were compared with the ABS filament data sheet.

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Influence of wall layer number around brass inserts in 3D printed specimens subjected to axial pull-out force

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ABSTRACT

The use of threaded inserts embedded in plastic parts is very common in variety of industries including electronics, automotive, aerospace, medical, transportation, defense etc., particullary where frequent assembly and disassembly are required. Performed technique of placement the inserts in specimens is heat staking - pressing the heated insert into the mounting hole to melt the material surrounding the insert. Specimens were made of PLA and obtained using a commercial Creality Ender-6 3D printer. The square-shaped samples have dimensions of 20 x 20 x 4 [mm] with a 4.6 [mm] diameter central hole for placing brass inserts with M3 thread.

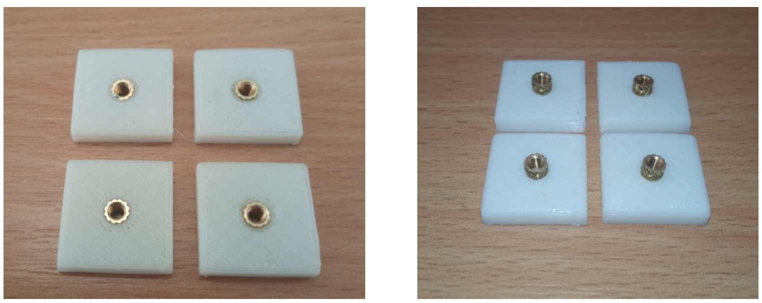

Figure 1. AM test specimens with brass inserts

In most application the load on the insert introduces cracks due to stress concentration in the material around the insert, so the tension load was aplied through the insert to investigate the effects on stresses in the specimens. The objective of this work is to evaluate maximum axial pull-out force in the load increased test. In particular, test was caried out on speciments with different number of wall layers around hole. After performed test, specimens were examined in order to understand how the damage progressed under tension loading. Finally, from the standpoint of crack propagation and maximum force increasement, a recommended number of walls is specified.

Keywords
Brass insert, axial force, stress concentration, crack, wall layer

Delamination effect on the mechanical behavior of 3D printed polymers

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ABSTRACT

The delamination effect is widely studied in composites and multilayer materials [1]. For composites, this phenomenon is recognized as a principal matter and much research tried to deal with the heterogeneity of composite and the study of the interactions between layers [2]. Additive manufacturing of polymers has a similar concept of a concatenation of layers according to specific parameters of temperature, pressure, and speed [3]. In fact, the manufacturing consists of printing the specimens layer by layer of a maximum thickness of 2 mm until reaching the normalized one [4]. Thus, the structure of the specimens is not homogenous and a particular phenomenon could occur in the zones between layers. The delamination effect is one of the cases barely studied for ADF polymers [5-8].

This work investigates the mechanical phenomenon occurring due to the delamination of the layers of 3D printed thermoplastic polymers using developed theories for laminated materials [9]. Thus, standard specimens of additively manufactured polymers is prepared and subjected to tensile tests for mechanical characterization, figure 1. The printing method uses the process of Fused Deposition Modelling (FDM) of many layers according to specific service parameters of the printer, figure 2. The mechanical behaviour of the layers and the adherence between the layers are studied in this paper. The deposition of the layers is modelled as a laminated material. The delamination effect on the resistance of printed material compared to the mechanical characteristics of commercialized polymers, which are compact and homogenous, is evaluated theoretically and experimentally. The delamination effect is investigated along with the effect of the density, the filling rate and the crosshead speed on tensile properties and on the rupture propagation [10-12].

Figure. 1. Geometry and the tensile test of a layers (45°,0°,90°)

Table 1. 3D printer setting of ABS polymers

Infill density (%)	100,60,40,20
Feed rate (mm/s)	20 mm/s
Layer thickness (mm)	0.2
Extruder temperature (°C)	250
Bed temperature (°C)	80
Raster angles	1.2

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Impact properties of laser sintered polyamide, according to building orientation

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ABSTRACT

Introduction

Determining the mechanical behaviour of additively manufactured components manifests high interest for researchers nowadays. The attractivity of the domain is based on the inconsistency obtained in mechanical and geometrical properties, when the manufacturing parameters are changed. Also, the type of additive technology used for manufacturing will highly impact the outcome [1-3]. Many authors focus on determining the elastic and strength properties of additively manufactured materials, but fewer studies concerning static and dynamic fracture behaviour of parts can be found [4-7].
The purpose of this study was to determine the impact energy and strength of polyamide PA2200 samples, according to the building orientation.

Material and methods

The polyamide PA2200 samples were built by selective laser sintering on EOS Formiga P100 machine. The process variable was the arrangement of the sample inside the building envelope. The sample size and shape were designed according to ISO 179 standard [8]. The notched beams were then arranged in the following way: horizontal 1, horizontal 2, vertical and 45° to the XY plane (figure 1 a).
The impact strength was experimentally determined by Charpy V-notch test, using Instron CEAST 9050 Charpy machine, equipped with a 1.186 kg hammer that impacts the sample at a velocity of 2.9 m/s. The pendulum was automatically calibrated and the symmetrical support of the samples measured a 60 mm span (figure 1 b).

a) b) c)

Fig. 1 Sintered samples a) Charpy machine b) and loading configuration c)

Results and conclusions

Twenty samples, five for each considered orientation were tested under the same conditions, according to the ISO 179 standard. The impact force was recorded both in time and deflection domain. All samples experienced brittle fracture no matter the building orientation. Also, the energy data are very well grouped in the elastic impact domain (0 to 0.6 mm) while they start spreading during the crack propagation.

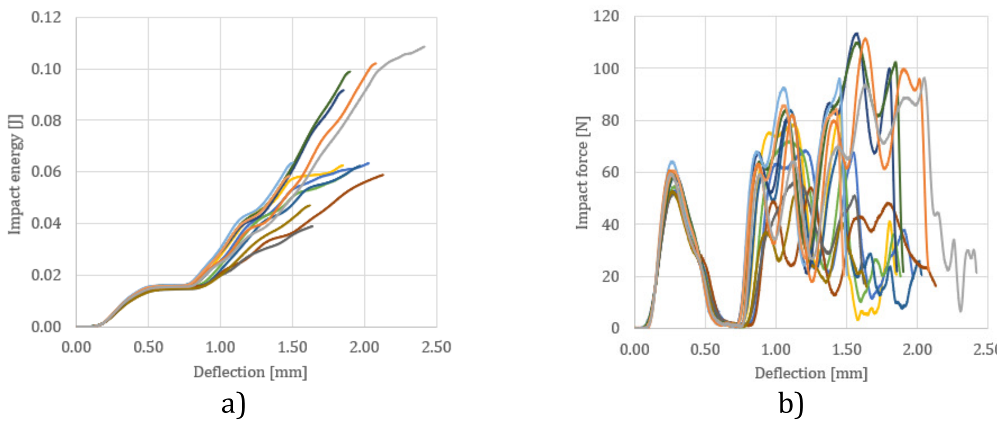

Fig. 2 Impact energy vs. deflection a) and impact force vs. deflection b) curves

In conclusion, highly consistent data are recorded especially for the elastic domain of the impact, where no difference in energy or force can be associated with sample orientation. Also, all samples experience brittle fracture. The crack propagation phase instead manifests some particularities linked with sample orientation.

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RRAM - A round-robin on additively manufactured plastics - Experiment

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ABSTRACT

Mechanical properties of the materials produced through additive manufacturing (AM) are influenced by a multitude of parameters [1-2]. In particular, filament based technology (FFF or FDM) followed recently by resin based technologies (SLA, MSLA and DLP) are the most adopted technologies in many professional applications, due to low machine cost and a general ease of use. In recent years, a lot of printers and manufacturers emerged as well as many slicer softwares. This proliferation led to the development of non-standardized ways of printing, such as different machines architecture or software algorithms to control the printing process: in this way, an object produced with a combination of a printer and a slicer is rarely directly comparable - in terms of mechanical behaviour - with the same object produced using a different combination. The RRAM project aims to investigate possible variations in material mechanical properties due to different combinations of printers, technologies, raw material and more.

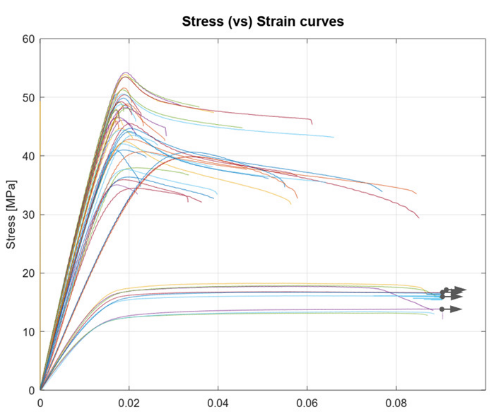

Figure 1. stress-strain curves for 3D printed PLA from the first RRAM experiment.

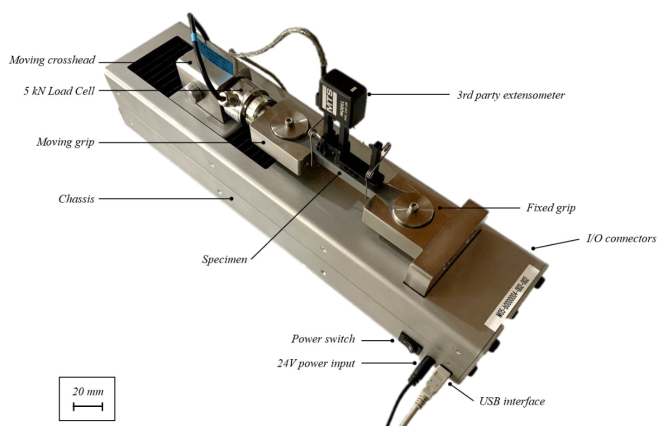

Figure 2. Experimental setup.

A first experiment [3] was carried out onto the mechanical properties of PLA material transformed by FFF/FDM process. Thanks to the involvement of a network of makers (professional and hobbyist) different 3D printers and different filament materials suppliers were compared at fixed process parameters. A large variability in results was emerged (Figure 1).

In this second experiment, conduced in partnership with Fenice Prototipi, a wider set of raw materials from different manufacturers and with different characteristics is compared being processed by a unique 3d printer. The experiment involved more than 200 tests for about 35 materials varying in type, manufacturers and 3d printing technology. Tensile tests are performed onto a MaCh5 UTM [4], a novel conception tensile testing machine with up to 5kN capacity (Figure 2). The main outcomes from tests regards the confirmed variability on mechanical properties from nominally identical materials supplied by different manufacturers (Figure 3) and the ability to draw material selection maps (Ashby diagrams) by comparing together different materials properties.

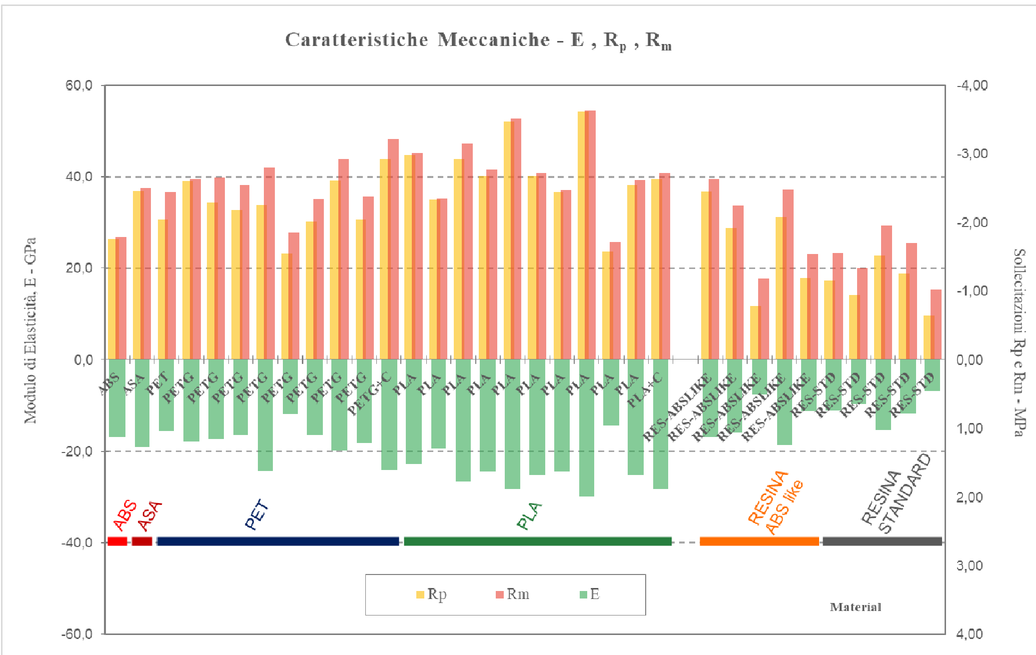

Figure 3. Mechanical properties of different 3d printed materials, grouped by material type.

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The influence of dog-bone shaped specimen geometry on tensile test results of fused filament fabricated PA12

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ABSTRACT

Introduction

Over the past few years, numerous investigations on the mechanical properties of AM PA12 produced by fused deposition modeling (FDM) using the well-known tensile test have been reported in the scientific literature [1, 2, 3, 4, 5]. For almost all these experiments, the dog-bone-shaped specimens were primarily used. However, widely divergent specimen geometry and dimensions can be found. The present study investigates the influence of specimen geometry on the tensile test results of fused filament deposited PA12. A series of static tensile tests were performed on the dog-bone PA12 fused filament fabricated specimens with rectangular and circular cross-sections. The characteristic stress-strain curves, the modulus of elasticity, and the ultimate strength were determined, compared, and critically analyzed. The results show that the influence of the specimen geometry on the obtained mechanical properties of fused filament deposited PA12 cannot be neglected.

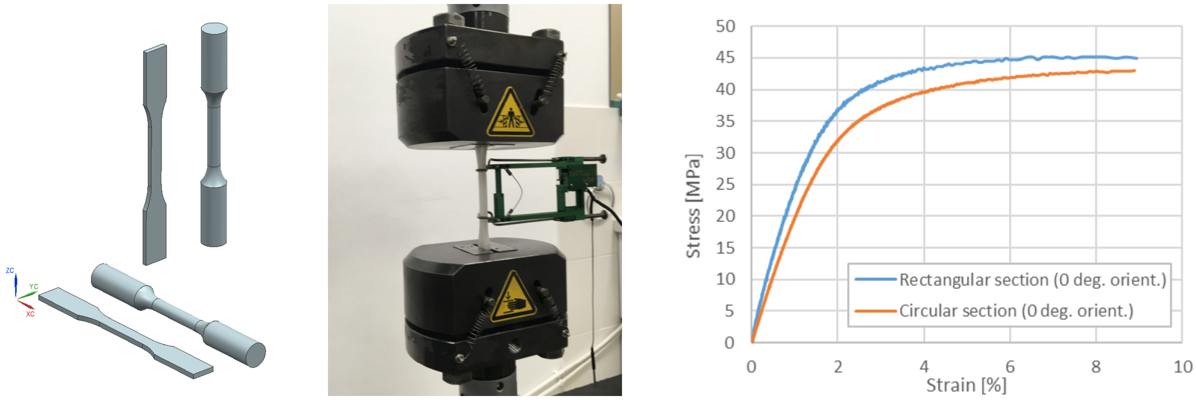
Materials and methods

Polyamide 12 (PA12) commercially available filament was selected to 3D-print the dog-bone specimens. The printing and bed temperatures, as well as the printing bed material were selected based on pre-tests that revealed the best qualities of printed specimens. The characteristic printing parameters are listed in the table below.

Material specs.	Printing Temperature [°C]	Bed Temperature [°C]	Print Bed Material	FFF Printer type	Filament diameter [mm]	Layer height [mm]	Print Speed [mm/s]
Fiberlogy Nylon PA12 natural	250	70	PEI with PVA Coating	Prusa i3 MK3S	1.75	0.2	80

The gage dimensions of rectangular cross-section specimens were 50 mm x 10 mm x 4 mm, while the circular cross-section specimens were 50 mm x ∅10 mm. For each type of specimen having the total length of 170 mm, two different orientations (0° and 90°) were produced. The 0° specimens of unidirectional filament strings printed in X direction, whereas 90° specimens were printed standing upright in Z direction filled circumferentially (see Figure 1-a)
The tensile tests were performed at room temperature using a dual column closed-loop Multipurpose Servohydraulic Universal Testing Machine, type LVF 50-HM (Walter-Bai A.G.) equipped with a loading cell of 50 kN capacity (Figure 1-b). The testing routine followed

strictly the specifications described by the ISO standard 527-1:1993.



(a) (b) (c)

Figure 1

Figure 1-c shows the representative stress-strain curves recorded for 0° oriented specimens. Different behaviour of specimens having rectangular cross-section relative to the circular ones can be observed.

Research outcomes

This study's outcomes are helpful for practical design applications since the directionally dependent stress-strain curves alongside the associated elastic properties and the ultimate strength values of fused filament fabricated PA12 represent the primary input data for the more sophisticated CAE analysis and simulations.

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2nd Session

2. Fatigue and fracture of AM materials

Low cycle fatigue behaviour of 304L stainless steel fabricated by selective laser melting

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ABSTRACT

Additive manufacturing techniques have multiple unique features impossible to achieve by any conventional processing technique. Besides well-known unprecedented design freedom, a microstructure with non-polyhedric grains containing fine subgrain domains is one of them. These domains contain a sub-micron cellular network characterized by locally different chemical composition, due to chemical microsegregation of prominent alloying elements, and highly heterogeneous dislocation distribution stemming from high solidification rates experienced during fabrication. This study presents an insight into the cyclic behaviour of selective laser melted (SLM) austenitic stainless steel 304L and its relation to the observed evolution of as-built microstructure upon cyclic straining. Fatigue tests were carried out in fully reversed mode under constant total strain amplitude ε_a (in the range $0.3 \leq \varepsilon_a \leq 1$ %) until final failure. Additionally, a series of fatigue tests held at $\varepsilon_a = 0.7$ % were interrupted at selected stages of fatigue life ($N = 5$, 25, 50 and 400 cycles) to follow microstructural evolution. In general, cyclic behaviour consisted of initial cyclic softening regardless of total strain amplitude. Subsequently, saturation or mild cyclic softening until final failure was observed at low total strain amplitudes ($\varepsilon_a \leq 0.4$ %). The tests held at $\varepsilon_a \geq 0.4$ % experienced a gradual growth of cyclic hardening with increasing ε_a. The microstructure of interrupted and failed specimens was examined by a combination of electron microscopy techniques, namely ECCI, EBSD and TEM. It was possible to relate the certain stages of fatigue life with observed microstructural evolution. The high strength of 304L is a consequence of cellular microstructure containing high-density dislocation walls. Initially, dislocation movement was significantly hindered by this dislocation arrangement. With further cyclic straining, an onset of cyclic deformation localization takes place resulting in observed cyclic softening. The localization evolves from individual mobile dislocations and partial dislocations along favourable slip systems to distinct bands intersecting cellular microstructure with low dislocation density in their interior. The occurrence of martensite nuclei within the bands was observed subsequently. Martensitic islands growth with additional cyclic loading and their increasing volume fraction is reflected by cyclic hardening. Moreover, numerous stacking faults and deformation twins contributed further to cyclic strength.

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Analysis and modelling of damage mechanism in FFF 3D printed Lattice structure during compression loading

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ABSTRACT

Fused filament fabrication (FFF), also known as fused deposition modeling (with the trademarked acronym FDM), is a widely spread 3D printing process that uses a continuous filament of a thermoplastic material. The big advantage of FFF lies in the customized production of printed objects and relatively low cost and good speed, but at the same time various limitations prevent their dominance in the production of fully functional mechanical components, as the limited size of produced parts and the resulting mechanical properties that are, at the meso- and macro-scale, not homogeneous [1–3]. In particular, various grades of anisotropy in elastic [4–6] and plastic/strength behaviour [5–10] have been recently studied, finding their difficult predictability being extremely various the combinations of printing parameters' set [11–14].
In this work, the anisotropy of cellular "open-cell" structures printed in ABS by the FFF technology is studied and a model of mechanical response up to the damage regime is tried. Cellular structures have at date big consideration, since light in weight and, being mimicked from natural designs, optimize the effective stiffness ratio. More, the possibility of 3D printing with no-support [15] makes these structures effective meta-materials, extending their applicability to several applications, as dampers, shells, and functionally graded structures.
Mechanism of stress distribution at the micro-scale is not fully understood, because of the mentioned anisotropy due to the filament deposition and layering. Resulting structure strongly depends on printing parameters, but, in general, produces anisotropy in the homogenized response and shows damage mechanism which depends on direction, see Fig. 1.

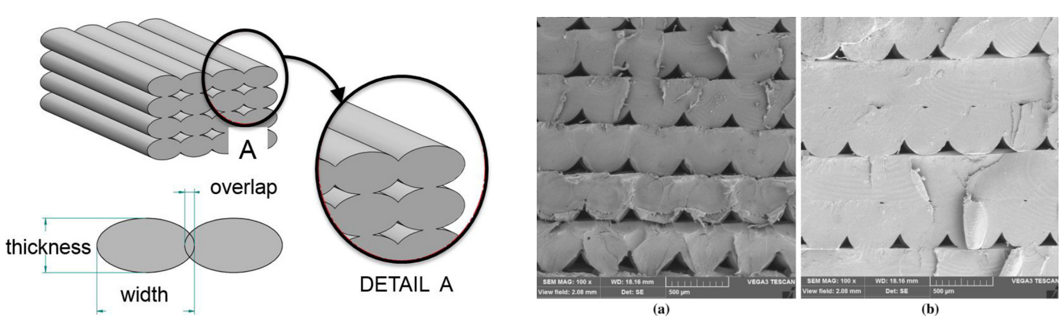

Fig. 1 – Scheme of FFF 3D printing and damage in layered structure.

The present investigation starts from the observation of damage at the micro-scale of 4x4x4 cell structures with different geometrical configurations loaded in compression, and tries to reproduce the anisotropy at both elastic and plastic regimes by FE modelling in ABAQUS© environment. Normal and shear elasticity is being modelled firstly as fully isotropic, and then as general stiffness along the 3 directions, with distinction between tensile and compressive regime, using constants obtained from specific flexural tests of small prismatic ABS specimens; damage is modelled as of the ductile type, again firstly isotropic and then customized by a proper user subroutine to reproduce anisotropy. Results of simulations confirm that treating the material as isotropic is highly reductive, and that by the FE advanced modelling the structure morphology can be optimized acting on the printing parameters.

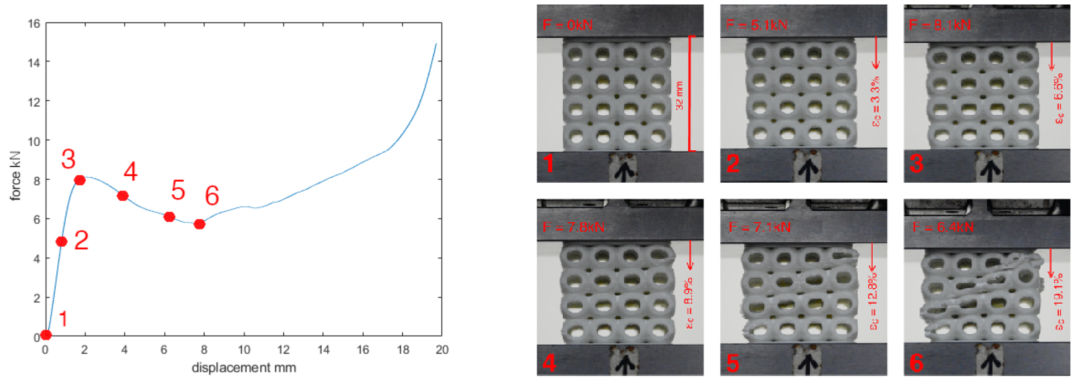

Fig. 2 – Compression testing of FFF lattice structure under investigation.

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Mode I fracture toughness of FDM printed PLA specimens: influence of printing parameters

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ABSTRACT

3D printing, also known as Additive Manufacturing (AM) technology, allows the production of simple or complex three-dimensional objects [1]. AM covers a wide range of manufacturing processes; however Fused Deposition Modelling (FDM), also called Fused Filament Fabrication (FFF), is the most widely used process. FDM builds the 3D model layer-by-layer by depositing the molten material in a predetermined way [2]. This paper investigates the fracture properties of 3D printed FDM components. Single Edge Notched Bend (SENB) specimens made of a PLA (polylactic acid) thermoplastic material were used for this purpose. Various printing parameters, such as infill density (40, 70 and 100%), infill pattern (grid, cubic and concentric) and printing direction (0, 45 and 90°), were used to obtain the SENB specimens. Three-point bending (3PB) tests were performed at room temperature (25°C) according to ASTM D5045-14 standard [3]. It was observed that the fracture toughness values are strongly influenced by the investigated printing parameters. The biggest differences are found in the case of infill density, followed in order of infill pattern and printing direction. Also, the fracture mechanisms, corresponding to the specimens with various parameters, show notable differences [4].

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Fracture Mechanics parameters assessment of quasi-brittle PLA polymer and PLA-X composite

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ABSTRACT

This research involves fracture mechanics parameters assessment tests for two thermoplastic materials available for use in FDM (Fused Deposition Modeling) AM (Additive Manufacturing) technology i.e., PLA and so-called PLA-X material. PLA is a globally available thermoplastic material, with certain advantages over some other thermoplastics used in FDM, such as high dimensional accuracy, low odor during 3D printing, its renewable resource origin, biocompatibility and biodegradability, etc. With combination of different materials during thermoplastic filament fabrication, addition of second-phase particles (for filament pigmentation and mechanical property enhancement) or with addition of carbon or glass fibres in the polymer matrix, certain mechanical properties can be achieved that original material doesn't possess. Quasi-brittle PLA processed in one of before-mentioned methods can achieve overall better mechanical properties, such as higher ductility, toughness, etc. Manufacturer of PLA-X filament (Mitsubishi Chemical, Kyoto, Japan) states that this composite filament has similar mechanical property values as widespread ABS material, but still holds all the material advantages of PLA. Hence, such mechanically enhanced material may have more functional applications than regular PLA material.
These two materials are tested for fracture toughness assessment according to ASTM D5045-14 standard. Tests are conducted on SENB (Single Edge Notched Bending) specimens, using 3-point bending test fixture, on five specimen batches for each material- with variation in layer height, infill density, printing orientation and one batch had previously dried filament, to see the drying effect on material properties. Also, DIC (Digital Image Correlation) cameras were used as an addition to see the deformation fields on specimen ligaments and using ''point-to-point'' option in Aramis software (GOM, Braunschweig, Germany, EU) COD (Crack Opening Displacement) parameters, at specimen mouth and tip, can be assessed. All-in-all, the tensile testing machine with appropriate adaptors combined with DIC setup can offer a broad assessment of fracture mechanics properties of, in this case, thermoplastic AM materials. After the conducted tests SEM microscopy is used to analyse the fracture surfaces of broken SENB specimens.

Energy-based method for analysing fatigue properties of additively manufactured AlSi10Mg

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ABSTRACT

The material used in this study was AlSi10Mg aluminium alloy (CL 31AL). Fatigue specimens of six different geometries (see Figure 1), but with the same area at the critical cross section, were designed for cyclic experiments that included thermal monitoring of surface temperature. Samples were printed by Concept Laser M2 printer. The method of printing was SLM (Selective Laser Melting) with a random criss-cross pattern in the ZXY direction according to ISO / ASTM 52921: 2013. All series were left as built in the active zone, while the heads of samples had M18x1 threads machined. To reduce residual stress, stress relief annealing was applied with the parameters recommended by the CL 31AL manufacturer (according to GE standards).
The samples can be divided into two groups. Series with a 20mm prismatic section in the middle (series B, D, and F) to extend the volume with the critical cross-section area were tested at the CTU in Prague, while the series A, C and E with the minimum cross-section reached in one longitudinal position only were tested at OTH Amberg-Weiden. Both laboratories used their Amsler 100kN resonant pulsators under load control at the load ratio of $R = 0.1$.
The geometry of series A and B conform to typical bar samples of circular cross-section with the transition radius of 60mm between the active part and the head (see again Figure 3). The C and D series are designed to be an inverse hourglass to enlarge the area of the visible surface available for thermal imaging, but with the same area in the active cross section. Series E and F are flat specimens with the same active cross section but in the shape of an oval; the intention of designing these specimens was to minimize the change in the view angle that can alternate the thermal imaging quality.

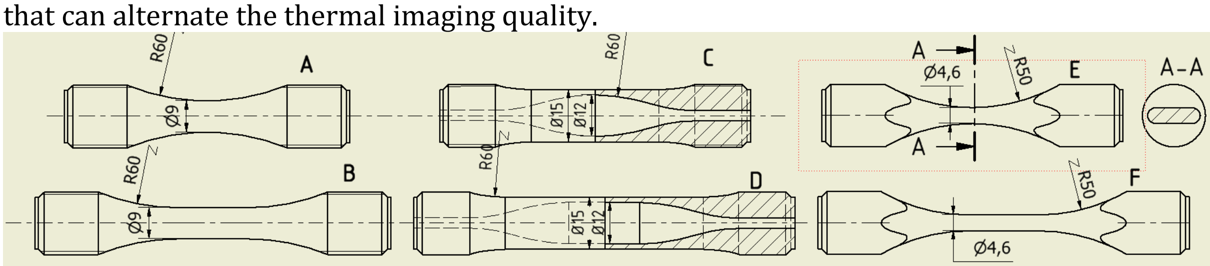

Figure 3 Display of individual geometries from series A-F.

Thermal Analysis

For thermal imaging, FLIR A315 and FLUKE RSE600 thermal cameras were used. The surface of samples was painted with LabIR black coat paint (HERP-LT-MWIR-BK-11) with measured emissivity to ensure precise surface temperature reading (see also Figure 4).

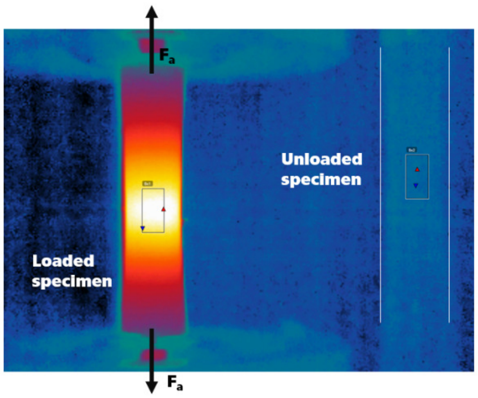

Figure 4 Thermal image of the F series.

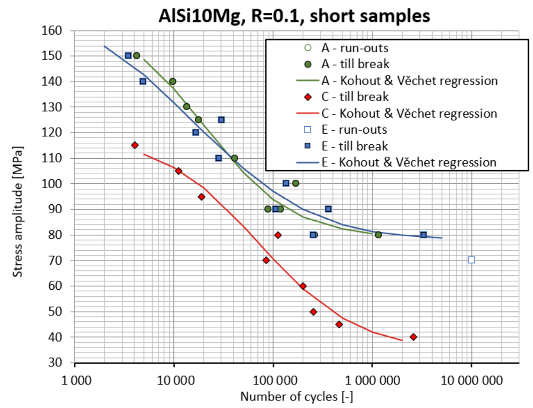

Figure 5 S-N curve of short samples series A, C, and E.

Thermal analysis was performed to check its applicability to replace expensive fatigue experiments. First, the S-N curve for each series was obtained (see also Figure 5). The self-heating test was run on an additional sample to monitor the temperature evolution in the sample during subsequently increased stress steps to derive the fatigue limit [1]. To estimate the fatigue response of each geometry, the method of analysing the evolution of the temperature on the surface was carried out on the basis of an alternative damage criterion [2]. At last, the heat dissipated on the surface of the sample during fatigue testing in the cooling phase was observed [3]. The results of all three methods are described in the prepared paper.

Acknowledgement

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Experimental determination of fracture mechanics parameters on ring-shaped specimens with different crack lengths

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ABSTRACT

In this paper, the effect of crack length change on the parameters of CMOD (Crack Mouth Opening Displacement) and δ-5 (CTOD - Crack Tipe Opening Displacement). Crack is initiated on PRNT (Pipe Ring Notched Tension) type with one crack.. For the purposes of this test, samples were made by FDM (Fused Modelig Deposition) additive production technique. The samples were made of PLA material using a layer height of 0.20 mm, 2 outlines on all sides and 100% infill. Initial cracks were applied with a hammer blade in two length variations. The tests were performed on a machine for testing the mechanical properties of materials (Shimadzu 100KN, Japan) . Experimental determination of fracture mechanics parameters was performed by digital image correlation (DIC) method using Aramis 2M system(GOM, Germany). The obtained results show a certain influence both on the values of the force measured during the test and on the values of the CMOD and CTOD parameters. Based on the values of these parameters, the extremely brittle behavior of the samples was concluded. Obtained results will be used as parameters for the finite elementmethod to analyze the influence of the crack length change on parameters KI and J integral.

3rd Session

3. Characterization of AM metallic materials

Effect of heat treatment on the TRIP behavior of additive manufactured stainless steel

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ABSTRACT

Additive manufacturing is a novel processing method, providing ultimate design freedom while maintaining competitive mechanical properties of processed materials. Due to the extremely high solidification rates, materials prepared by additive manufacturing methods exhibited non-equilibrium microstructure with characteristic cell-substructure evolved. Variation of the processing parameters and post-process heat treatment application can significantly affect produced microstructure, and thus the resulting properties.

Austenitic stainless steels are frequently processed via additive manufacturing methods, due to their interesting combination of mechanical properties and high damage-tolerance characteristics. Carefully chosen chemical composition can even enhance these properties by introduction of TRIP effect when the additional plastic deformation is accommodated by ongoing phase transformation. Magnitude of the TRIP effect strongly depends on the actual microstructural state - mainly presence of macroscopic crystallographic texture, dislocation density, and local chemical heterogeneity.

In the present study, authors examined the TRIP behavior of austenitic stainless steel AISI 304L prepared using selective laser melting (SLM) process. Series of specimens with different crystallographic textures were prepared by SLM and then subjected to annealing heat treatment in the range of 800°C to 1100°C. Application of the heat treatment affects evolved cell-substructure resulting in the formation of microstructures ranging from as-built state with sub-micron cell-substructure to fully recrystallised microstructure with polyhedral grain structure. Specimens processed in this way were then subjected to the uniaxial tension loading until fracture. Neutron diffraction was deployed to in-situ evaluation of the phase transformations during the straining experiment. Microstructures of different series were then evaluated post-mortem, using EBSD and TEM techniques. Present study aims to elucidate effect of the heat treatment application on the TRIP susceptibility of the austenitic stainless steel processed via SLM.

Effect of building direction and heat treatment on tensile properties of Inconel 939 prepared by additive manufacturing

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ABSTRACT

The present work aims to investigate the effect of building direction on the tensile properties of a nickel-based superalloy Inconel 939 produced by additive manufacturing (AM) and to reveal the differences to the conventional cast superalloy. Horizontal (parallel to specimen axis) and vertical (perpendicular to specimen axis) building directions were applied. Furthermore, the effect of three-step heat treatment (1160 °C/4h; 1000°C/6h; 800°C 4h) on the microstructure and tensile properties was analysed. Tensile tests were conducted at room temperature and at elevated temperatures up to 900 °C. Thorough microstructural scrutiny was conducted by means of light microscopy, scanning electron microscopy, energy-dispersive X-ray spectroscopy, electron backscatter diffraction, and transmission electron microscopy. Comparative material testing and characterization of the AMed and the cast Inconel 939 revealed differences in both microstructures and mechanical properties. The columnar grain structure with a preferential orientation of <001> was typical for AMed alloy, whereas for cast alloy polyhedral grain without any specific orientation is typical. Experiments have shown that the AMed material has much better mechanical properties than the material prepared by conventional casting, mainly due to the absence of large casting defects that negatively affected the mechanical properties of the cast material. Heat treatment resulted in a considerable increase in yield strength, ultimate tensile strength and a drop in ductility. This can be attributed to the formation of fine spherical γ′ precipitates with an average size of 180 nm and very fine dispersion of γ′ nanoprecipitates up to 5 nm in diameter. The best material properties were achieved for horizontal building direction.

Study of heat treatment of Selective Laser Melted AlSi10Mg specimens

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ABSTRACT

1. Introduction

Complex thermal phenomena occur to Selective Laser Melted AlSi10Mg during the building process. AlSi10Mg can react unexpectedly during post processing thermal heat treatment (THT). By optimising old THT and designing news THT mechanical properties can be improved. [1,2]

A literature review was carried out to identify methods of THT, which are the most beneficial for mechanical properties of SLM manufactured AlSi10Mg. Several post-processing heat treatment methods were carried out and mechanical properties of SLM were tested through the tensile test.

Finally, a thermoelastic mathematical model was created for virtual THT and tensile test experiment. In fact, the elastoplastic behaviour of heat treated AlSi10Mg SLM specimens have been studied.

2. Material and methods

The specimens were manufactured by EOSINT M280 (EOS, Germany) metal printer, with the following process parameters.

Laser power (P) [W]	**Scanning speed** (v) [mm/s]	**Layer thickness** (d) [mm]	**Hatch space** (h) [mm]
275	600	0.03	0.08

Tab. 1: Process parameters used to build the specime

Heat treatments and setting parameters were chosen as follows.

Thermal treatment method	Parameters
Stress relief (SR)	2 hours/573,15 K
Direct aging (DA)	4 hours/423,15 K
HPT6	2 hours/793,15 K + 2 hours/ 428, 15K / everything under 150 MPa
HIP+T6	2 hours/793,15 K/Under 150 MPa + 2 hours/793,15 K + 2 hours/428,15 K

Tab. 2: Parameters of applied heat treatment

The tensile properties were tested by INSTRON 5869 universal testing machine.

3. Numerical model

The Mathematical model has been created in Comsol Multiphysics 5.4. In the model, the gouverning heat equation were [3]

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p v \nabla T + \nabla q - d_z Q + q_0 \quad (1)$$

$$q = -d_z k \nabla T \quad (2)$$

The heat source was applied as the Gaussian heat flux and 2 phase changes were included in the model. The intermediate cooling of the top surface and lateral surfaces was modelled as

the natural and forced heat convection, as well as the radiation from the surfaces. However, mass losses due to evaporation and the fluid dynamics were neglected.
The small plastic strain mode was considered, while the hardening function was substracted from experimentally gained stress-strain curve as follows.

$$\sigma_h(\varepsilon_{pe}) = \left(\varepsilon_{pe} + \frac{\sigma_{ms}}{E}\right) - \sigma_{y0} \tag{3}$$

For the plasticity model, it was assumed that

$$\dot{\varepsilon_{pl}} = \lambda\frac{\partial Q}{\partial s},\ \lambda \geq 0, \quad F(\sigma, \sigma_{ys}) \leq 0 \text{ and } \lambda F = 0 \tag{4}$$

4. Results and discussion

Results of after treatment tensile tests are showed in tab. 3.

	Ultimate tensile strength (MPa)	**Expected elongation at break** (%)	**Source**
Stress relief	286	7,24	simulation
Direct Aging	392	3,58	simulation
HPT6	363	4,22	simulation
HIP+T6	357	2,63	simulation
As built	381	3,51	experiment
As casted	193	6,52	literature

Tab. 3: Tensile properties of TTed, as built and as casted specimen

The most beneficial heat treatment for PBF manufactured AlSi10Mg specimen is HPT6. When compared with the traditional approach, including cycle of HIP, followed by T6, the novel THT method facilitates almost the double improvement of the ductility while preserving the ultimate tensile strength at around same level. On the other hand, stress relief at low temperature facilitates a significant improvement of ductility, while the UTS remains significantly higher than one of as casted specimen [5, 6, 7].

5. Conclusions

The mathematical model was able to successfully simulate the heat treatment and its effect on mechanical properties of AlSi10Mg SLM specimens.
The mathematical model will be extended with the aim to incorporate and predict the effect of heat treatment on the microstructure and hardness of the specimens.

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NiTi-powders behavior at LASER interaction

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ABSTRACT

Shape memory alloys are intelligent materials that use martensitic transformation from nanoscale to perform a movement at macroscale. Nitinol (NiTi) alloys have various uses in many industrial and medical applications. Based on expected difficulty in the obtaining and machining of these materials the appliance of Additive Manufacturing (AM) methods can be a real great accepted solution method for their realization [1]. The interaction of a LASER beams with Ni and Ti and NiTi particles was performed on the installation in the Atmosphere Optics, Spectroscopy and Lasers Laboratory [2] using the YG 981E/IR-10 laser system, with the parameters τ = 10 ns pulse width, λ = 532 nm wavelength, α = 45 incident angle and υ = 10 Hz pulse repetition time and $3x10^{-2}$ Torr pressure, in a stainless steel chamber. The NiTi powders before and after interaction with the LASER beam was structurally analyzed using optical (MO) and electronic (SEM) microscopy. Differential scanning calorimetry (DSC) was used to analyze the thermal behavior of the material in solid state.

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The evolution of thermal distortion and stresses at macro scale for metal additively manufactured part

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ABSTRACT

The Selective Laser Melting (SLM) involves the melting of the metal powder resulting in melt-pool. When this very melt-pool solidifies, the solidified metal undergoes cooling and reheating in the presence of air and multiple laser passes for continuous material consolidation. In result of such thermal cycles, manufactured part develops the permanent thermal deformation and residual stresses[1]. The current study, involves the evaluation of part deformation and development of residual stresses at macro scale. The multi-physics solution is performed by coupling of transient thermal heat equation with structural solver equipped with the elastoplastic material model. The FeniCS[2] Finite Element Modelling platform is utilized in the development. To mimic the consolidation of material, the elements are activated as per the pattern of metal consolidation under the influence of G-code. The results are gathered to track down the evolution of plastic strain and residual stresses throughout the course of part manufacturing. The significance of temperature dependent material properties is also focused. The generation of permanent deformation and the thermal stress is studied among the cases of constant material properties and the material properties as a function of temperature. Moreover, the the upscaling of material deposition and the parallelization of the simulation platform is currently under focus for enhanced computational efficiency of the developed algorithm.

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A comparison on static and fatigue behaviour between traditional and SLM AISI 316L

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ABSTRACT

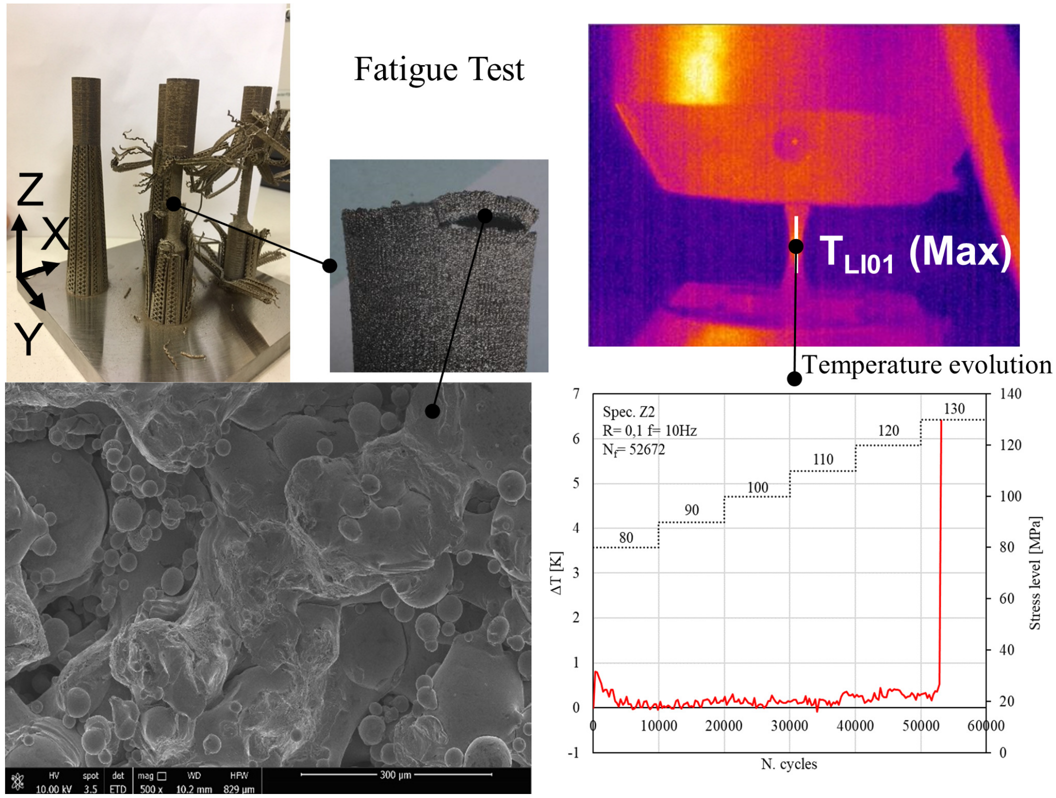
Additive Manufacturing (AM) is a novel production process, initially think as a prototyping technique, now moving to the production stage of final products. Design for Additive Manufacturing (DfAM) means it is possible to design new devices with complex shape, less and well-distributed material compared to traditional Design for Manufacturing (DfM) [1]. It allows the production of lightweight and customizable devices, especially in the aeronautic and bioengineering fields. Such capacity requires a high grade of reliability under the action of service loads, in particular under fatigue loads.

Several materials, both polymeric and metallic, can be adopted for AM processing. One of the high-performance steels adopted is the stainless steel AISI 316L, which is suitable for Selective Laser Melting (SLM) process. Such process consists in a laser beam which sinters metal powder, layer by layer, to obtain the final product. The process is severally affected by laser beam power and velocity. This is also reflected in a different material microstructure compared to the traditional manufacturing process. Hence, mechanical properties must be deeply investigated to provide reliability for final products. Static tensile and fatigue tests must be performed to assess the performance of such material; however, they require a large set of specimens to test and time to be spent, which in turn requires high production costs.

In the recent years, besides traditional testing systems, the adoption of Infrared Thermography allowed the assessment of fatigue properties, in a very short amount of time and adopting few specimens, by monitoring the energy release of the material during fatigue test (Thermographic Method, TM [2]). More recently, a novel procedure has been developed to link the internal damage of the material with the macroscopic applied stress, by monitoring the energy release during a static tensile test (Static Thermographic Method, STM [3]). Such methodology could provide useful information, severally shortening the testing time [4].

In the present work static tensile and fatigue tests have been performed on traditional and SLM AISI 316L specimens by monitoring the temperature evolution with an infrared camera. The energy release of the material during the damage process seems to be strictly affected by the material internal microstructure. Failure analysis have been performed showing the

differences in the traditional and AM manufacturing process, giving an insight to understand and improve the quality of the AM production process.



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Role of surface finish on the fatigue behaviour of L-PBF IN718 using miniature specimen

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ABSTRACT

Additive manufacturing (AM) of metals, and in particular Laser Powder Bed Fusion (L-PBF), has been recognized as one of the most revolutionary technologies of the recent years. Many industrial sectors approach AM because of the possibility to fabricate extremely complex components in a reduced time-to-market and at a competitive cost. However, success in structural applications depends on specific knowhow about all the factors affecting the mechanical properties of components realized with this technology.
In the case of fatigue critical components, the effect of as-built surfaces, support removal and post fabrication surface finishing has to be investigated. Optimized part orientation in the build chamber may require local support structures that after removal leave peculiar surface features that need to be considered and studied for their detrimental effect on fatigue endurance. Different surface post-processing may lead to a uniform surface finish and acceptable fatigue performance.
This contribution is focused on the systematic investigation of the fatigue behavior of notched specimens manufactured using Inconel 718 powder in a L-PBF industrial system (EOS M400) then post processed with different surface finish techniques. A novel fatigue test methodology based on the use of prismatic miniature specimens loaded in cyclic bending was adopted for its versatility and to reduce material consumption and production costs.

4th Session

4. Properties and models of AM materials and metamaterials

2D triangular-like additively manufactured lattices: an experimental study

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ABSTRACT

Analogous to the lattice structure of a crystal, a lattice material is defined as a 2D or 3D spatially periodic structure that can be idealised as a network of slender beams or rods. Thanks to recent advances in additive manufacturing technologies, a wide variety of lattice materials can easily be fabricated. Such “architectured” materials may display a broad range of features like auxetic behaviour [1, 2], tunable elasticity [3, 4] and energy absorption [5-7], just to mention a few.

In the present work, three different designs of well-known 2D triangular lattice are considered. The unit cell constituting the first design is characterized by straight elements, while in the other two the elements possess a certain curvature. In addition to this purely geometrical approach, further preliminary studies are carried out in order to evaluate the influence of high stiffness gradients, obtained by having some elements or unit cells made by a harder material, on the mechanical behaviour of the lattice.

3D-printed specimens, made of both highly deformable or stiff polymers, are manufactured using the FDM technique, where the soft material is realized by thermoplastic polyurethane (TPU) and the hard one by acrylonitrile butadiene styrene (ABS). Compressive tests under different strain rates are performed on the finite-size specimens to evaluate their different elastic in-plane behaviour.

Acknowledgements

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Influence of infill topology on the flexural stiffness of FDM produced PLA

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ABSTRACT

Fused Deposition Modelling is one of the most widespread additive manufacturing technologies due to its relatively low cost and simplicity. Usually, printed parts have an internal structure that isn't produced with 100% material density. This strategy is adopted to save material and time thanks also to the fact that when a component is loaded, stress are concentrated on its skin rather than in the internal section. Nonetheless, infill structure can have different percentages and topology. Slicer software have different configurations that can be exploited: some are intended for functional parts while others are more indicated to prototypes only. Aim of this work is to compare the effect of different infill topologies, printed given constant settings and infill percentage, on the flexural resistance of produced material. Using three point bending test, flexural modulus as well as ultimate flexural stress are determined. MaCh3D, an innovative miniaturized universal testing machine, has been used for the entire experimental champaign.

Mechanical behaviour of soft membranes: simulation and possible AM biomimicking tissues

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ABSTRACT

Skin is the most extended organ in human body representing 16% of the total body weight with a surface extension up to 2 m^2. From a mechanical viewpoint, skin can be described by an hyperelastic membrane, particularly when computational modelling for in-silico testing of reconstructive surgery procedures is needed. These procedures often involve complex topological manipulations of the skin tissue in order to minimize post-operative scarring. In this work, the simulation of reconstructive surgery procedures is described by FE membrane models developed within the framework of finite strain elasticity (an hyperelastic incompressible model for skin is adopted). An algorithm is presented to generally describe complex topologies of cutting and removing of material, while suturing is enforced by suitable multi-point constraints along wound boundaries. The archetypal reconstructive surgery of the Z-plasty is here considered, where a rotational transposition of resulting triangular flaps is involved, leading to severe stress/strain localization and displacement discontinuities. The results are discussed in terms of key deformation parameters commonly used to guide surgical decisions during reconstructive procedures. Regarding the validation of the proposed model, 3D printed tissue phantoms can be used to replicate the surgical operations herein analysed. A novel hydrogel AM technique, capable to print polymeric hydrogels with embedded biological fibres, is suggested as a suitable tool to obtain artificial tissues resembling the microstructure observed in natural skin, which composition is characterised by a dispersion of collagen fibres.

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Additively Manufactured Triply Periodic Minimally Surface Structures for Biomechanical Application

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ABSTRACT

Three-dimensional printing also known as Additive Manufacturing has revolutionized the world of manufacturing of complex geometries with the minimum waste material. When combined with computational methods, AM can optimize the time, cost, and energy of production. Bioprinting is an attractive area of using 3D printing to generate biomimicking organs or artificial tissues. Mimicking the hosting cell heterogeneity is the main advantage of creating artificial tissues using AM. Bone tissues, like other complex tissues, can be therefore replicated by lattice structures. Unit-cell design based on a mathematical algorithm is one of the novel design methods that leads researchers to create Triply Periodic Minimal Surface (TPMS) lattice structures [1]. Even though they are difficult to produce with prevailing manufacturing processes, TPMS structures can be effortlessly produced using AM. Based on the specific mechanical behavior and biological applications of each scaffold, a combination of these structures, consisting of one or more lattice types, is efficient in term of biomechanics [2, 3]. Nevertheless, different cells cannot be arranged alongside one another without any consequence. In this vein, the transitional zone in multi morphological scaffolds, considering stress concentration, overall strength, and yield strength of the scaffold has been studied in this work. Furthermore, a challenge in the field of TPMS scaffolds is that their response under complex loading cannot be studied easily. Seldom can a specimen be designed with an appropriate fixture for the complex test. To predict scaffolds' behavior under complex mechanical loading, a method has been proposed based on the combination of micro-computed tomography and Finite Element Modeling (μCT-FEM).

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CFD-DEM approach towards a multi-track selective laser melting

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ABSTRACT

In selective laser melting process, the quality of the melted track and subsequently the quality of the solidified track is highly affected by the evolution of the melt pool. Accurate prediction of melt pool dynamics allows reliable assessment of the resulting physical characteristics of the final solid. Fully predictive simulations of AM processes will require linking melt pool models to other models, including those predicting the powder deposition and microstructure formation. On the other hand the powder bed characteristics including size distribution and packing density plays a determining role in the process. There are also different modes of heat and mass transfer between the particles, the melt and the ambient gas that will significantly influence the whole system.

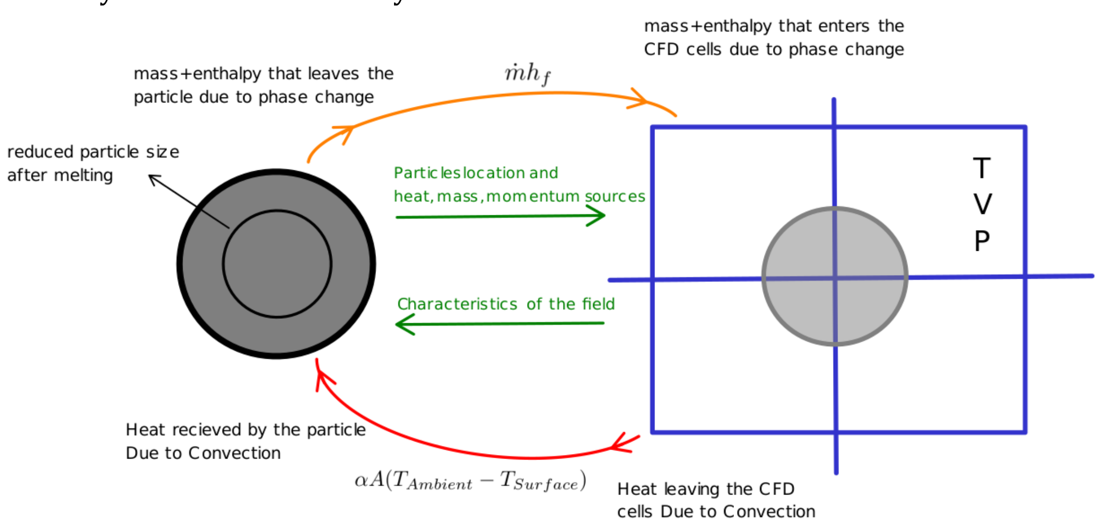

Figure 1. Schematic illustration of the CFD-DEM Coupling

In the present study a coupled CFD-DEM simulation framework is devised to model the powder bed fusion process. The Extended Discrete Element Method(XDEM)[1], an advanced numerical tool based on the discrete-continuous concept, is investigated to distinctly resolve the particles in the powder bed, featuring the powder deposition, powder distribution, and heat, mass, and momentum exchange with the melt pool.

The random packing of the powder bed is modeled by a DEM model. The DEM model is also responsible for modeling the dynamics and thermodynamics of powder particles which are modeled as distinctive 1-Dimensional entities. The particles receive radiative heat from the laser in the form of a Neumann Boundary condition of heat flux on the particle outer boundary. They have also conduction heat transfer among each other and convective heat transfer and mass transfer with the ambient gas and surrounding liquid (melt). These modes of transfer with the liquid are taken care of, by the coupling between the CFD and DEM models.

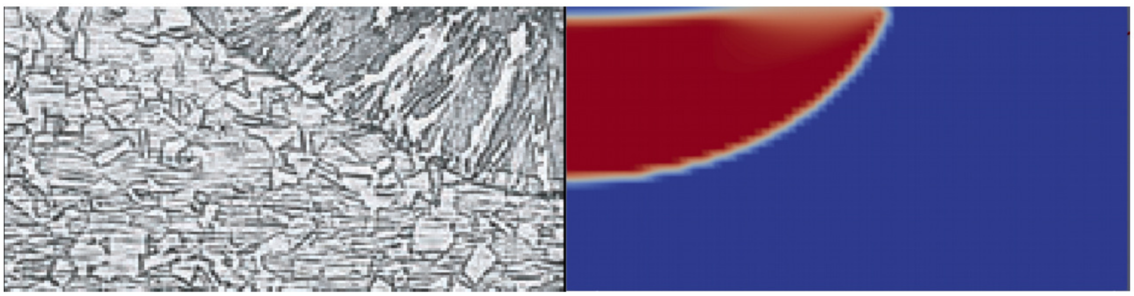

Figure 2. Comparison of the melt pool dimensions in experiment(left)[2] and simulation(right)

In the CFD model an incompressible multiphase solver is used to solve the heat,mass and momentum transports inside the ambient gas and liquid are solved. The solver is also modified and fitted to the additive manufacturing application, to take into consideration the effects of the Marangoni force and the laser radiation. The laser radiation in the CFD solver is modeled as a Neumann Boundary condition of surface heat flux at the liquid-gas interface. Due to the high temperature gradient from the laser spot outwards, high surface tension gradients are produced which lead to a flow inside the melt pool, known as Marangoni flow. This inner-flow is a deciding factor over the shape and size of and generally the evolution of the melt pool.

The simulation framework that is the result of this research will be able to model a multi-track laser melting and solidification of the tracks. The geometry and temperature distribution of the solidified track may be fed to a microstructure model to predict the microstructure and subsequently the mechanical behavior of the printed part.

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Design of cellular structures fabricated by the additive manufacturing method

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ABSTRACT

1. Introduction

The presented work concerns the issues related to the design of cell structures produced by incremental SLM (Selective Laser Melting) and SLS (Selective Laser Sintering) techniques. When choosing 3D printing instead of traditional manufacturing method (injection molding, CNC machining or casting), it is worth to consider optimization of spatial models in order to reduce their weight. One method of weight reduction is the adaptation of cellular structures in the designed part. Cellular structures, which enable innovative applications in many fields, are characterized by low density and mass, as well as high strength, stiffness, and thermal conductivity. The use of such structures leads to a high stiffness-to-weight ratio. In addition, mass savings result in lower manufacturing costs for additive manufacturing. Due to the potential associated with the realization of complex cellular structures by means of additive techniques, intensive work has been carried out on the development of software for cellular material design. This paper is mainly focused on nTopology software, presenting its capabilities and advantages. The aim of this work was to develop a configured workflows to design specimens for static tensile testing. Solutions were proposed for the following structures: strut - based, TPMS (Triple Periodic Minimal Surface), graded and Voronoja.

2. Designing cellular structures in nTopology software

The nTopology software is an engineering system that has been specifically developed for the advanced production of complex geometries. The use of the implicit modeling technique provides us with a much greater capability in terms of producing very complex geometries. In addition, a design methodology is available that allows you to control design variations using formulas, test or simulation results and other data. Furthermore, it is possible to create a configured, automated and reusable workflow. To export a designed element in the nTopology environment, an "implicit model" must be converted to a surface mesh. The nTopology software enables simple design of strut-based structures and TPMS (Triple Periodic Minimal Surface) structures. The application has predefined individual cells, while allowing to create any shape. Additionally, it is possible to change the cell orientation in space, cell size and relative density. As an example, Fig. 1 shows the various stages of designing a structure based on struts.

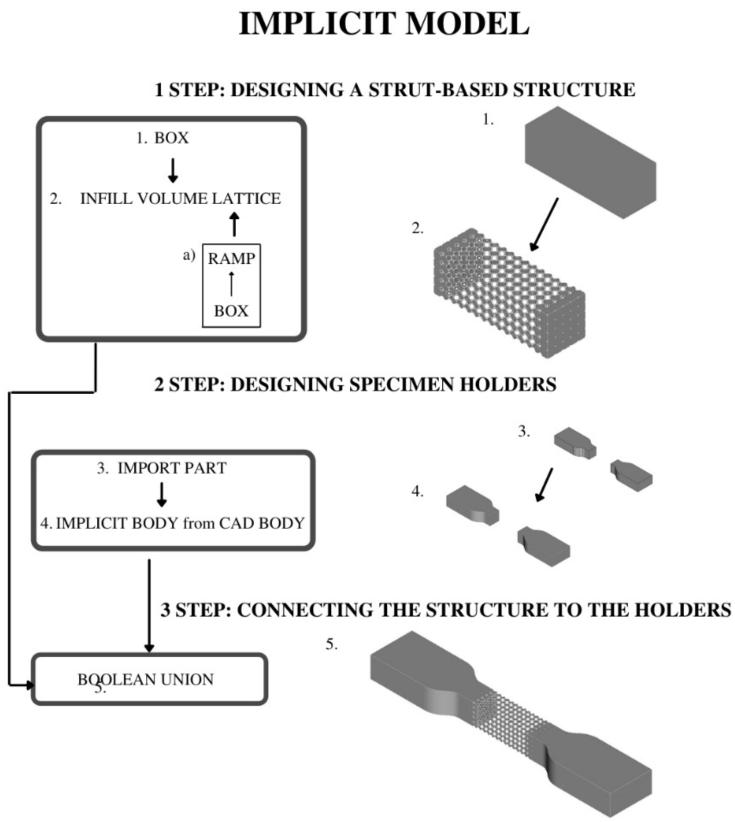

Fig. 1 Workflow for modeling strut – based specimens.

Figure 2 shows the specimens that were designed with the nTopology program using predefined workflows.

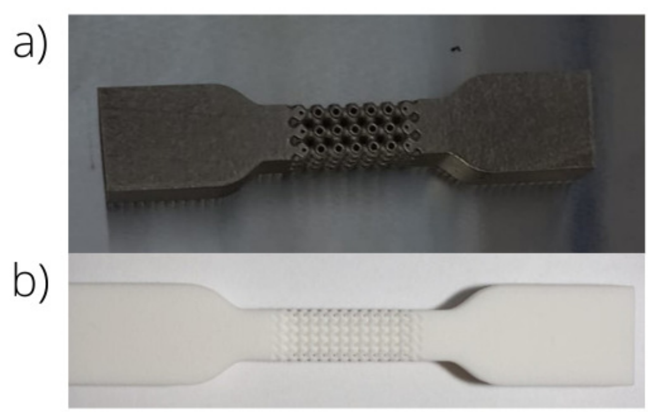

Fig. 2 Additively manufactured static tensile test specimens: a) TPMS Shell Schwarz structure manufactured by SLM technique, b) Kelvin cell strut structure manufactured by SLS technique.

Analysis of mechanical properties of bulk architectured materials

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ABSTRACT

Bulk architectured materials combine two or more materials ordered in specific geometrical patterns. Such structure allows obtaining properties combination not achievable by single material solution. The presented research is focused on 3D printed structures that combines two polymeric materials ordered in two patterns that are able to vary Poisson' ratio of the tested sample. The study combines tensile experiments with 3D FE simulations. The analysis shows the overall evolution of Poissons' ratio and also local distribution of strains.

5th Session

5. AM technologies: advancements & new experiences

Surface welding as an additive manufacturing technique to improve rail crack resistance

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ABSTRACT

It is known that surface welding with buffer layer is often in use because of its well-known ability to slow down crack growth, i.e. to improve crack resistance, [1]. The essence of this additive manufacturing technique is in melting of a filler metal using conventional welding processes (e.g. shielded metal arc welding) or more advanced ones (e.g. laser beam welding) to form couple of surface layers and thus to achieve the requested properties of a product itself, such as rail. To evaluate the effect of additive layers on crack resistance, total impact energy, as well as its components, crack initiation and propagation energies, are measured using Charpy instrumented pendulum, whereas fatigue threshold, Kth, and the crack growth rate da/dN, are evaluated using standard ASTM E647 procedure. It is shown that surface welding indeed improved crack resistance, even without the buffer layer, in the case of pearlitic steel typically used for rails.

Impact testing was performed at different testing temperatures, 20^{0}C, -20^{0}C and -40^{0}C, according to EN 10045-1, using Charpy V notched specimens, on the instrumented machine SCHENCK TREBEL 150 J. Results are presented in Table 3, as obtained for the base metal (BM) two samples taken from the heat-affected-zone (HAZ) and two samples taken from the weld metal (WM). One can see that the total energy of base metal is very low (5 J), due to very hard and very brittle cementite lamellae in pearlite microstructure, [2]. Total impact energy is a bit larger in HAZ and significantly larger in WM at all testing temperatures

Table 1. Total impact energy for BM, HAZ and WM

	Total impact energy, E_t, J		
	20^{0}C	-20^{0}C	-40^{0}C
base metal	5	3	3
sample 1-HAZ	12	11	10
sample 2-HAZ	11	10	9
sample 1- WM	29	23	17
sample 2- WM	34	14	11

Fatigue crack growth (FCG) tests had been performed on the CRACKTRONIC dynamic testing device, also using Charpy V notch specimens, only at room temperature, under the ratio R=0.1. Notch tip was positioned in the WM 3rd layer, so that crack initiated in WM and propagated into HAZ, providing evaluation of FCG rate, *da/dN*, and the stress intensity factor treshold, ΔK_{th}. Results for two samples with notch tip in HAZ are given in Table 2, in form

Paris law parameters C and m and ΔK_{th}. One can see that values of stress intensity factor threshold and crack growth rates correspond to initiation and propagation energies in impact testing.

Table 2. Parameters C, m, ΔK_{th} and FCG rate values for HAZ

Sample	ΔK_{th}, MPa $m^{1/2}$	Parameter C	Parameter m	Crack growth rate, da/dN, m/cycle, for ΔK=30 MPa$m^{1/2}$
1	9.5	$4.07 \cdot 10^{-13}$	3.79	$1{,}61 \cdot 10^{-07}$
2	8.9	$3.76 \cdot 10^{-13}$	3.93	$1.18 \cdot 10^{-06}$

Acknowledgements
This research is financially supported by EU H2020 project ''SIRAMM'', under grant agreement No. 857124.

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3D Digitalization and modelling of Cultural and Historical treasures of Montenegro

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ABSTRACT

The National Museum of Montenegro is the institution that preserves the largest number of cultural and historical assets of Montenegro and it is essential to create its digital archive with the help of 3D technologies. The possibility of applying 3D technologies as well as the way of solving problems and optimizing the whole process of digitalization of the cultural and historical heritage of Montenegro is analyzed in this paper through the given example. Digitalization of cultural heritage is currently very common in the world because it is a way to protect and preserve the cultural and historical heritage of a country. 3D scanning has a significant role in the process of digitalization, it is very efficient in collecting information about the subject in the form of digital format, which can later be further analyzed, changed, corrected, etc. This is especially important for objects of unknown dimensions and complex contours. The greatness of the importance of digitalization of cultural heritage is that like everything else, cultural and historical goods over time get old, which affects their appearance, i.e. their destruction may occur. Also, the influence of weather disasters or some other undesirable event is possible, which leads to the loss of the authentic appearance of the good. With the use of 3D technologies artifacts can be captured in high resolution, which allows the cultural history of Montenegro to be monitored, studied, disseminated, and understood. In this paper, CREAFORM Go! Scan 50 3D scanner will be used to digitize the bust of Njegos. The digital file can be saved in .stl format and later printed on a 3D printer.

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Center for Optical Measurements and Rapid Prototyping - Challenges in Additive Manufacturing

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ABSTRACT

The application of new materials in additive manufacturing opens new challenges that directly influence the development of new experimental setups and analysis of results. In the engineering and scientific practice of additive manufacturing, it often happens that standards for testing polymers and metals cannot be applied. This paper describes new methods that have been developed and used for the analysis of materials obtained using additive technologies. Also, the possibilities of application of equipment for additive manufacturing, equipment for determining mechanical properties, and control of dimensional stability within the Center for Optical Measurements and Laboratory for Rapid Prototyping on Faculty of Mechanical Engineering, University of Belgrade are presented. The experimental results obtained for tension, bending and compression of different polymeric materials are presented and future research directions are given.

New methods for CAD development of parts adapted to additive production technologies

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ABSTRACT

Recently it is used new methods for CAD development of parts adapted to additive production technologies. New methods are usually based on usage of lattice part structure. In this paper is presented usage of lattice tool in Creo Parametric 8 software package based on shape optimization for given part which is predicted to be manufactured by additive production technologies. Initial idea was to start with machine part which shape should be optimized for additive production. Based on generative design and using a lattice tool in given software package, initial CAD model was generated. Using these two methods for CAD model development it is possible to modelling the best designs which can be founded in nature. Based on FEA analysis it was conducted several iterations of CAD model in order to get maximal part rigidity. At final step was by using Creo Parametric 8 software package to conduct build direction optimization using built direction tool. At the and several parts was printed in order to make experiments to determine real stress and deformation state on produced parts.

Implementation of additive manufacturing at TechLab Tehnopolis

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ABSTRACT

Most important implementation of additive manufacturing is production of functional prototypes, which can be used at many industrial branches, medical sector, science and research purposes. In our 1-year experience we employed FDM printing technology for executing several hundred projects, using different thermoplastic materials such as: PLA, ABS, PET G, PC-ABS, CARBON and TPU. Additionaly, we employed BMD printing technology for manufacturing projects from 17-4 PH stainless steel.

This paper explains several key projects we have executed for innovators, students or costumers during the last year, by utilizing possibilities of 3D modelling, scanning and additive technologies. Our activities were focused on modeling, optimization, preparation and production of parts which will be assembled into the functional prototypes, presentation models or final parts. Printed parts had various geometries, dimensions and complexity, but at the end all of them were fabricated and assembled successfully. Parts and prototypes are now being tested in order to get information about parts matching, material wearing and overall performance.

KEYWORDS

Additive manufacturing, 3D modelling, 3D scanning, FDM technology, BMD technology,

Challenges of 3D printing implementation in Civil Engineering

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ABSTRACT

3D printing is probably the most often used additive manufacturing technology. Among innovations in the science and technology the world had experienced in the XXI century, many relevant solutions have emerged. Stil some believe that 3D printing might have the "hurricane" impact globally [1]. Recent, the development of 3D printing has been very significant in the domain of various production technologies and industries. The production of parts in this way is very flexible since completely different geometrical models on one device can be made.

Applications and implementations of 3D printing science and in engineering can be numerous. Although it is applicable in many industries, it still embeds several difficulties in the field of construction and civil engineering. Key challenges in this field lay in innovative materials and new procedures which have to be studied, developed and applied prior to the wider application of this process [2]. Different materials can be used in 3D printing of buildings: the most often used is concrete, however clay is used too, reinforced concrete or biomaterials, either environmentally safe or recycled ones. Using 3D printing in Civil Engineering as well as in building mechanical parts or products, reduces waste of material [1], [2].

Different objects and constructions can be 3D printed: houses; multi-storey buildings; bridges [1] - [3]; entire communities [4], [5]; either on Earth or simulation of habitats aimed to be built on other planets [4], [6]. As stated on ICON's web site [4], which is one of the leading enterprises in this industry, 3D printing is "shifting the paradigm of homebuilding". Shapes that can be built vary. Structures having circular base were built initially, then houses having rounded edges and now houses having sharp edges or free-forms can be built. There are two ways 3D printing is used in building: printing the chunks of construction in factory, that are to be assembled on the site; or 3D printing of the whole object, near or at the building site.

Building using 3D printer on the building site can reduce use of traffic and transportation and decrease the CO_2 footprint as well. Building of wind power plants can benefit from 3D printing [2]. Blades for the fans of wind power plant can be 3D printed. Onshore wind towers can be regarded as less complicated structures, from the structural engineer point of view they could be 3D printed as well [2].

Some types of installation systems such as plumbing can be 3D printed simultaneously, as integral part of the walls. 3D printing can help in improving tools for analysis and sensor [1]. To improve roads, bridges, railways, and other construction designs, fiber-optic sensors can be exploited [1], [7]. These sensors may be costly to install in the structures or not compatible with the construction materials used [1]. Simple 3D printed packaging for these sensors has been developed that is simple to mount and suitable for almost all construction materials [1]. In railways 3D printing is esspecialy interesting in maintenance (preventive and corrective), i.e. for 3D printing of obsolete spare parts. The principal advantages and disadvantages of the 3D printing in the construction sector are further listed in [8].

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Prototyping of clamping mandrel for pipe welding by method FSW

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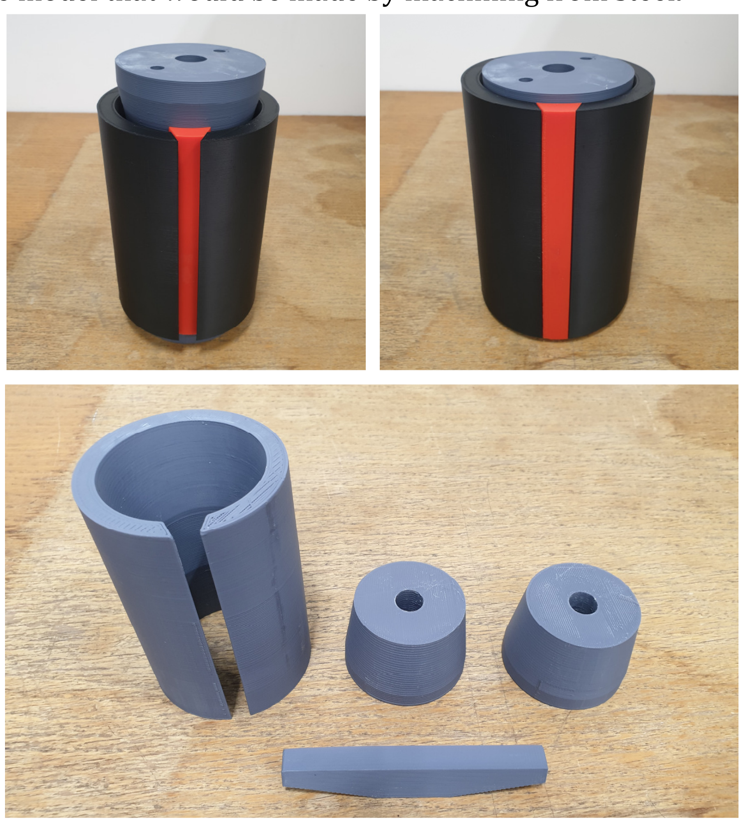
ABSTRACT

This paper presents a model of clamp device that is being developed for the purpose of welding pipes using the Friction Stir Welding (FSW) method. A detailed approach to the development of this prototype and its fabrication using Fused Deposition Modeling (FDM) printers is presented. As this accessory consists of several components between which sliding movement is performed, a special challenge is the necessary low coefficient of friction between the manufactured components. The paper describes the procedure for improving the properties of the obtained surfaces, by using ABS material and smoothing it with acetone vapour. CAE analysis of this model was also performed, and the obtained values were compared with the model that would be made by machining from steel.



3D metal printing - Development and innovation

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ABSTRACT

3D printing of metal is more complex and expensive than printing other types of materials. Pure metals in powder form are most often used for printing, but also their alloys. The following materials are considered: stainless steels, alloys of aluminum, chromium, nickel, cobalt, etc. This is how metal elements are created that have a geometry that is impossible to make with traditional methods. The most widely used 3D metal printing technology is Direct Metal Laser Sintering (DMLS) or Selective Laser Melting (SLM), followed by Binder Jetting and Metal Extrusion. This paper presents the development of 3D metal printing, with an emphasis on innovation. As so far, all metal 3D printers have used extremely expensive and dangerous to health atomized metal powder as a raw material, this required that the operator be maximally protected and trained to work. A printer has appeared on the market, which uses metal wire as a raw material, which is a clean, safe and cheap metal raw material. What makes this printer special is the technology that allows you to print two metals / materials in a row with very fast wire changes. The material change is automatic and takes only a few seconds. In this way, the risk of contamination of parts, which often occurs with powder fusion technology when changing the production material, is minimized. Even with this technology, post-processing is required on parts that require high tolerances and surface quality.

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3D printing applications in civil engineering

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ABSTRACT

3D printing is one of additive manufacturing technologies. Applications and implementations of 3D printing can be numerous. Initially 3D printing was envisioned as a technique to make scaled models, or to produce objects that are not easily manufactured or formed using classical manufacturing technologies (sometimes referred to as subtractive manufacturing) or machining. This way also was 3D printing exploited in civil engineering and architecture in design of constructions and buildings.

Over the past decade significant advance has been made in 3D printing applications in Civil engineering [1]. 3D printing is "shifting the paradigm of homebuilding" as stated on web site [2]. Building with 3D concrete printers seems to bring great promises [3]: freedom of shape, personalized designs, faster construction, and more sustainability. This technology had made process of building much faster and cheaper. Building using 3D printing had inspired variety of initiatives launched in this area in recent time [3]. For the past five years, companies were competing to make 3D printed houses having more rooms, having multi-storey buildings, or concurrent building of many houses, within shorter time frames [1] - [6].

Buildings made using 3D printing can be more robust and resistant to earthquakes [1], or to harsh temperatures, either extremely low or extremely high. Densely populated countries, like China and India, promote projects with 3D printed houses, which are economically more affordable than traditionally built houses. 3D printing had made possible building houses resembling sculptures [1] or objects with intricately designed facades. Buildings and houses are not the only civil engineering projects that are being made using 3D printing. Several bridges were 3D printed as well, e.g.-in Netherlands [7].

Nevertheless, there are some chalanges in 3D printing of concrete structures, arising from the nature of this material itself [3]. Additional challenges exist regarding use of concrete that are not inherent to 3D printing with other materials [3], [8]. Freshly 3D printed concrete is still soft, which may cause walls to buckle, sag or fall flat during printing [3]. Curing of the concrete also has to be not too quickly nor to slow. If it is too fast, the 3D printed layers will

not bond and cracks will occur [3]. In addition, for each printable shape the interdependence of curing, bonding and the increase in forces as the structure grows during the 3D printing process, is different [3]. This new technology draws broad attention in the scientific community, resulting in extensive studies of structural behaviour [9], [3]. Some theoretical studies have been conducted also at the Faculty of Civil Engineering of the University of Belgrade, which will be followed by the practical realisation in close future.

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Production park Torpedo - how to become the main center of additive technology in Croatia

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ABSTRACT

We opened Production park Torpedo in December 2020. to expand the system of existing entrepreneurial incubators in the City of Rijeka and to increase their quality and offer of services. Also, to increase the number of newly established companies and startups and their survival rate and to improve the competitiveness of local, regional and national SMEs, providing high-quality services for its users, based on additive technologies.

We did reconstruction and conversion of the former 'Hall 14' of old torpedo factory into the Technology park Torpedo – a technological/educational incubator for entrepreneurs, aiming specifically to the innovative companies in the production sector.
We purchased highly sophisticated equipment – industrial 3D scanner and industrial 3D printers (polymers, metal, sand), as well as the corresponding software systems, which enable the SMEs enhancement of their services and results. Also, we are doing the transfer of knowledge and skills through new educational programs.

Experimental AM drawing tool

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ABSTRACT

Global economy shift from mass production of products to personalized production challenges traditional manufacturing processes. Requirement for shorter prototype development times led to development of highly customizable forming processes such as incremental sheet forming [1]. Available tooling processes require either a large infrastructure or high tooling costs in order to achieve manufacturing flexibility [2,3].
One of the technologies that allows production of vide variety of products is rubber pad forming (RPF). By replacing one of the tool sides with rubber pad it allows faster and more affordable tooling production, but still requires die traditionally produced out of metal. Solid metal die can be produced on milling machine, which leads to high tooling cost and lead-time.
To shorten the lead-time and make toolmaking more affordable additive manufacturing (AM) processes may be used. Fused deposition modelling (FDM) as manufacturing process is well suited for tool making for cold deformation of sheet metal.
Additive manufacturing allows creation of both tool sides, eliminating the need for elastomer used in RPF and allowing the creation of more complex tooling.
FDM manufacturing process is also well suited as it provides wide variety of the production materials and new material blends are still under research [4].
In the forming tools application, key properties of used material are:

1) Stiffness – determines final part accuracy,
2) Strength – limits the loading force on the forming tool,
3) Brittleness - increases the risk of tool snapping [5].

Experimental part of the research was performed on forming tools produced out of 3 different polymer materials: ABS, PLA and PEI. All materials were printed using FDM technology, on printer with enclosed build chamber with the infill of 90%.
Tools were used for forming of 1,5 mm aluminium sheet (Al 99,5) using 30 ton hydraulic press. In order to determine the force needed for deformation preliminary pulls were used. The force of 250 kN was sufficient for complete geometrical definition of the part. 10 deformation cycles were performed with each tool made at 250 kN force setting.
Tool wear was monitored optically and after completion of all deformation cycles, tools were measured with optical scanner GOM Atos 300. ABS material preformed the worst with visible layer tear after 10 deformation cycles (picture 1). Rest of the tools (PLA and PEI) showed no significant visual defect other than rounding of the sharp edges. After 10 deformation cycles measurement with optical scanner was performed in order to detect maximal deformations per material. Deviations from initial form in range from 0,1 mm on PEI to 0,42 mm on ABS part were measured.

Fig 1 Filleting of the edges after number of deformation cycles

From tested materials ABS performed the worse of all. Better results in terms of tool wear resistance can be achieved by using PLA or PEI materials. When comparing those two materials PLA stands out as much easier to manufacture and overall, more affordable material. Although PLA is well suited for most applications on higher temperature and more demanding geometries PEI could provide better wear resistance.

The experiment confirms the feasibility of using form tools manufactured by using AM. In modern production, where "time is money" the demand for fast tooling prototyping could be solved with FDM manufacturing. In addition, the demand for great level of flexibility and customer-specific variants could be met with usage of AM tools as they minimize lead-time and provide cost efficient solution for small series tool production.

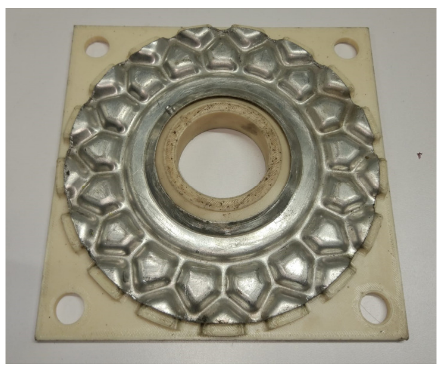

Fig 2 PEI tool with deformed part after trimming

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