Part 2: Additive Manufacturing Lab

(Daily works and Researches)

Igor Vladimirovich Shishkovsky

Associate Professor, office E-B5-2015

Chief of Additive Manufacturing Laboratory

Center for Design, Manufacturing and Materials

Skolkovo Institute of Science and Technology (Skoltech)

Part 1: Daily Works and Researches

- *Additive Manufacturing Lab : People and Equipment*
- *Teaching Activity in AML*
- *Research Projects*
- *MSc and PhD students researches*

CENTER FOR DESIGN, MANUFACTURING, AND MATERIALS

Director
Prof. Iskander Akhatov

Skoltech **Center for Design, Manufacturing and Materials** (**CDMM**) was established in March 2015 as a Center of Research, Education and Innovation (CREI) of Skoltech that conducts basic and applied research aimed at development and implementation of **new simulation-driven design and manufacturing paradigms for advanced materials, structures, and engineering systems with enhanced lifecycle, mechanical and physical characteristics demanded in high-tech industries**.

Laboratory: Composite Materials and Structures

Composite materials manufacturing:
- Vacuum Infusion
- Pultrusion
- Filament Winding
- Pressing

Matrix: thermo & thermoplasts
Reinforcement: glass and carbon fibers, micro- and nano-fillers

Laboratory: Additive Manufacturing

3D printing:
- *Plastics*
- *Metals*
- *Ceramics*

Additive technologies:
- Selective Laser Melting
- Stereolithography based Ceramics
- Direct Energy Deposition
- FDM
- DLP
- Binder Jetting

Laboratory: Cyber Physical Systems

Product Lifecycle Management technologies for design, manufacturing support, and product state tracking during the exploitation phase. Building product's digital twins. Running full-blown product testing in numerical form. Product design optimization, version control.

Laboratory: Micro- and Nano-Mechanics

Study of fundamental physical processes responsible for micro- and nanostructure properties of materials. Special experimental methods of material testing at micro- and nano-scale.

Laboratory: Mechanical Testing and Material Characterization

Certified laboratory for testing materials' mechanical properties. Characterization of materials' thermal response, acoustic response, rheology, thermal decomposition kinetics.

Laboratory: Thermal Spray and Functional Coating

Development of new technology and optimization of existing technology for creation of functional coatings with Thermal Spray, Cold Spray, HVOF, Hot and Cold Plasma-based coating methods. This area of technological applications is on extremely high demand in industry.

Laboratory: Industrial Robotics

Development of automated industrial systems for production of complex parts and components. Introduction of IoT and advanced sensorics to industrial manufacturing lines. Optimization of production process in automotive, aviation, marine, heavy instrument industry

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Additive Manufacturing Laboratory (AML),

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was establish in 2017 .

Igor Shishkovsky, Chief of AML,
Associate Professor
PhD in Solid State Physics from P.N. Lebedev Physics Institute of Russian Academy Of Sciences (RAS), Dr. Sci. in Chemical Physics, including Physics of Combustion, from the Institute of Structural Macrokinetics and Material Science of the RAS, Russia

Stanislav Evlashin,
Leading Researcher, Ph.D. in Physics Electronics,
from Moscow State University named Lomonosov, Russia

Svyatoslav Chugunov,
Senior Researcher, Ph.D. in Mechanical Engineering,
from North Dakota State University, USA

Engineers:

- *Andrey Dyakov (senior engineer)*
- *Denis Firsov (engineer – Trumph, FDM)*
- *Oleg Dubinin (engineer – InssTek, DLP)*
- *Andrey Tikhonov (engineer - Ceramaker)*
- *Vladimir Popov (engineer, DLP)*
- *Alexandr Filimonov (intern)*

Collaborators in industry and academia:

- Polema (Tula, RF),
- RusAT (ROSATOM Co., RF),
- MMK Metiz,
- Oerlikon,
- Gazprom Neft Co., RF.

ACADEMIA:

- Technical University of Munich (Germany),
- Aachen (Germany)
- Bundesanstalt für Materialforschung und prüfung /BAM/, (Germany)
- MIT (USA),
- Leven Univer. (Belgium),
- ENISE (France),
- Karlstad Univer. (Sweden).

Our PhD & Msc students:

- Daniil Panov (PhD1)
- Stanislav Chernyshihin (PhD2)
- Julia Kuzmonova (PhD2)
- Konstantin Makarenko (PhD2)
- Maxim Isachenkov (PhD2)
- Oleg Volgin (PhD3)
- Zamila Isabaeva (Msc2)
- Igor Pchelintsev (Msc2)

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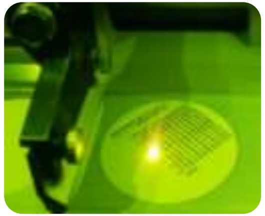
3D PRINTING TECHNOLOGY @ CDMM

Stereolithography
(SLA)



Selective Laser Melting
(SLM)

Digital Light Processing
(DLP)

Fused Deposition Modeling
(FDM)

Binder Jetting
(BJ)

Direct Energy Deposition
(DED)

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THE LARGEST 3D PRINTERS @ CDMM

3D Metalls

Direct Energy Deposition

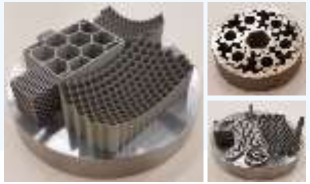
Direct energy deposition technology is used to print large-scale parts from steels, copper, aluminum, titanium, nickel and other alloys.

- Fabrication of parts and components for aviation, automotive, medical and space industries;
- Repair of damaged and worn out parts.

Powder Bed Fusion (Selective Laser Melting)

Laser metal powder fusion technology is used to fabricate various parts from alloys such as stainless steel 316L-A and Ti64-A.

- Fabrication of parts and components for aviation, automotive, medical and space industries;
- Repair of damaged and worn out parts.



3D Ceramics

Stereolithography

Stereolithographic 3D printing with zirconia, alumina, hydroxyapatite, and others.

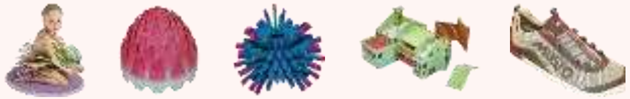
- Medical implants (artificial joints, bone replacements, bone support);
- Electronics components (antenna arrays, filters, resonators, dielectric elements).

3D Plastics

Binder Jetting

Color-Jet 3D Printing technology is employed to utilize a core material and a color binder to fabricate full-color high-quality semi-rigid parts.

- Rapid modeling and functional prototyping for real-use products
- Architectural modeling, fashion design and a wide range of consumer products



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Materials and 3D samples characterization and certification

Возможность привлечения широкого спектра оборудования для задач обучения

SAM 301
Акустический микроскоп

Axio Scope.A1
Оптический микроскоп

ElectroPuls E3000
ElectroPuls ™ E3000 - это самая современная электродинамическая испытательная машина, разработанная для динамического и статического тестирования механических свойств широкого спектра материалов и компонентов

INSTRON 5985
Испытательная машина, которая позволяет проводить исследования материалов на растяжение, сжатие, сдвиг, изгиб. Машина используется для испытания высокопрочных металлов и сплавов, аэрокосмических и автомобильных конструкций

CSM-Трибометр

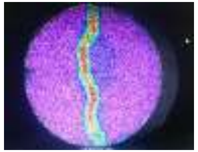
Lectropol 5- Электрополировка

CEAST 9340
Система ударного механического воздействия с энергией удара 0.3 - 405 Дж. Машина позволяет проводить механические испытания поведения материалов при ударных воздействиях, оценивать прочность материала

INSTRON 8801
Система усталостного тестирования материалов и их компонентов, в режиме многоцикловых и низкоцикловых испытаний, термомеханических испытаний на усталость и механику разрушения. Оснащена тепловой камерой -150 ... 300 С

Пробоподготовка Tech Press 2 и Met Prep 3

Accutom 100- Прецизионная резка



VIC-3D
Vic-3D - это система для бесконтактного высокоточного измерения формы, перемещений и деформаций поверхности изделия в трех измерениях

Shimadzu USF-2000
Ультразвуковая испытательная машина для усталостных испытаний с гига-цикловой нагрузкой

Более 50 возможных стандартных тестов в соответствии с: ASTM/ISO,ГОСТ

MSc Education Courses by Additive Manufacturing in Skoltech

- Fundamentals of Additive Manufacturing - MA06243
- *Material Selection & Design (As. Prof. Salimon A.)*
- *Geometrical Modelling (Prof. Pasko A.)*
- *Introduction to Product Lifecycle Management (PLM) – (Prof. Uzhinsky I.)*
- *Additive Manufacturing Training Courses for Industry*
- 3D Bioprinting: Processes, Materials and Applications - MA03354

Course MA06243 –
Fundamentals of Additive Technologies

Summary of Lecture Topics:

- ❖ Week 1: Generalized AM Process Chain
- ❖ Week 1: AM with liquid phase
- ❖ Week 2: Powder based AM
- ❖ Week 3: Solid phase AM
- ❖ Week 4: Hybrid technologies of AM

Summary of Laboratory Topics:

- ➢ ***Plastics:*** *Binder Jetting Technology (BJM), Fused Deposition Modelling (FDM), Digital Light Processing (DLP)*
- ➢ ***Metals:*** *Powder Bed Fusion* (PBF, Trumpf TruPrint 1000)
- ➢ ***Ceramics:*** *Stereo- Lithography* (3DCeram Ceramaker 900)
- ➢ ***Metals:*** *Direct Energy Deposition* (DED, InssTek MX 1000)
- ➢ ***Mechanical Testing of AM materials:*** (INSTRON 5985)

Course MA03354 –
3D Bio-printing: Processes, Materials and Applications

Summary of Lecture Topics:

- *Introduction in 3D bioprinting*
- *Main processes and materials of 3D bioprinting*
- *3D fabrication process route*
- *Testing for 3D parts. Application of 3D bioprinting*

Summary of Laboratory Topics:

Project 1	Topological and biomimetic design
Project 2	Experimental project on production of bio-scaffolds on Liquid Crystal Pro
Project 3	Experimental project on production of bio-implants on Picasso Ultimaker
Project 4	Experimental project on Mechanical Testing of AM samples during laboratory class
Final project	Review of results by the1-4 projects. Essay of `1500 words on the design of biomaterial by a student choice to check the understanding of Topics 1 and 4.

Ongoing Academia and Industrial projects in AML:

- **Oerlikon – Skoltech (CDMM) project :**
  - Stereolithography based ceramics (Dr. S. Chugunov)
  - Selective laser meting of Metal-Matrix Composites (Dr. S. Evlashin)
  - Numerical multi-scale modeling of the SLM processes (Prof. A. Kasimov)
  - AMLab SLM setup for data collection and process diagnostics (Prof. I. Shishkovsky)

Project leader in CDMM (Skoltech) - Prof. Akhatov I.S.

- The **Russian Foundation of Basic Researches** (RFBR) has awarded support from 2021 until 2022 to our project No 20-51-56011 – "*Topological design and selective laser melting of porous nitinol implants and scaffolds for medical applications*".

Project leader in CDMM (Skoltech) – ***Shishkovsky I.V.***

- The ***Russian Science Foundation*** has awarded support from 2020 until 2022 to our Project No 2020-19-00780 "*The novel manufacturing approach to production of highly efficient lead-free textured piezo-ceramic materials using additive manufacturing technologies*"

Project leader in CDMM (Skoltech) – Shishkovsky I.V.

- The ***State Corporation RosAtom*** (VNIEF, Sarov) has funded from 2019 until 2021 the Project in frame works of own the Unified Industry Thematic Plan ЕОТП-МТ-097 "*3D Virtual Printer – Digital twins*".

Project leader in CDMM (Skoltech) – Shishkovsky I.V.

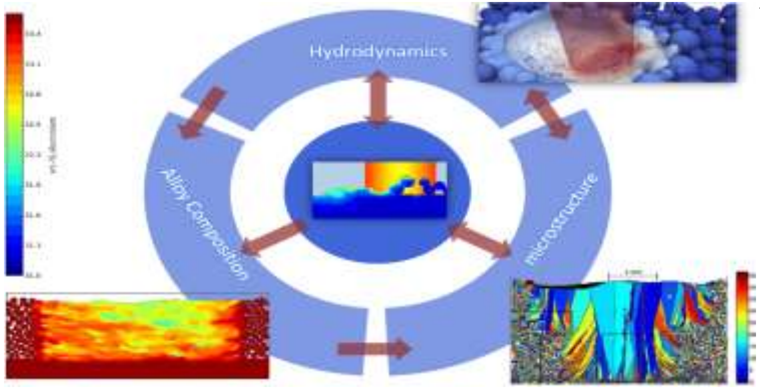
Additive process diagnostics in CDMM (Skoltech)

The principal advantage of the proposed CDMM Laboratory Setup from well-known industrial SLS/SLM equipment will be ability in the laboratory configuration:

1. To STOP the synthesis process at any stage in order to change the technical process parameters on the fly, for example
   - *add (or remove) powders,*
   - *mix disparate materials (the so-called “multi-material approach”, which is only planned in foreign installations),*
   - *change the composition of the protective gas mixture,*
   - *enable (disable) the processing zone heating (cooling!?)*
2. To carry out the process temperature diagnostics (thermocouple measurement over the powder volume, pyrometer measurements from the surface);
3. 3D scanning system *with “flat-top” shape beam*
4. To determine the deviation of the layer shape from the CAD model;
5. To evaluate the microelement composition of the surface layer (diagnostics by induction-coupled plasma spectroscopy)
6. To evaluate stresses and deformations (from the surface by the laser speckle holography; or by volume via ultrasonic diagnostics).
7. ….*(input into the chamber of an additional energy source, evaluation of the phase composition and transformation during 3D part fabrication, etc.)*

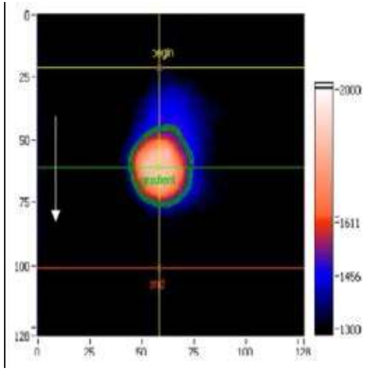
Project 4:
Data Collection & Process Diagnostics

Types of sensors needed:
- High resolution cameras
- Melt-pool sensing
- Temperature sensors
- Humidity/moisture, O_2 sensors
- Gas flow
- US vibration / diagnostics
- Some method to look inside the powder-bed
- Stress cracking detection

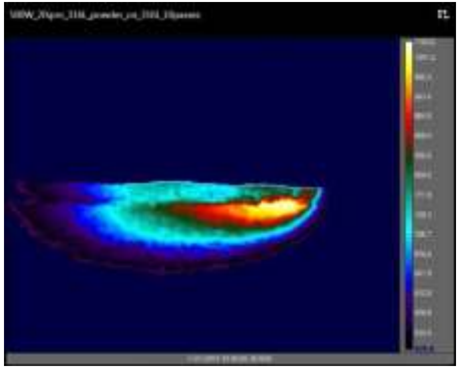


In-Situ Monitoring:

✓Photodiodes to see variation in melt pool size with geometry
✓High-speed imaging of the melt pool (10+ KHz)
✓Close-loop control interface monitoring module integrated with laser signals
✓Ultrasound (porosity & cracking detection in a ‘noisy’ environment)
✓Infrared / pyrometer (thermography of a large area with localized hot zones a challenge)
✓Quantitative multi-elemental (2D) analysis by means of laser induced breakdown spectroscopy (LIBS)



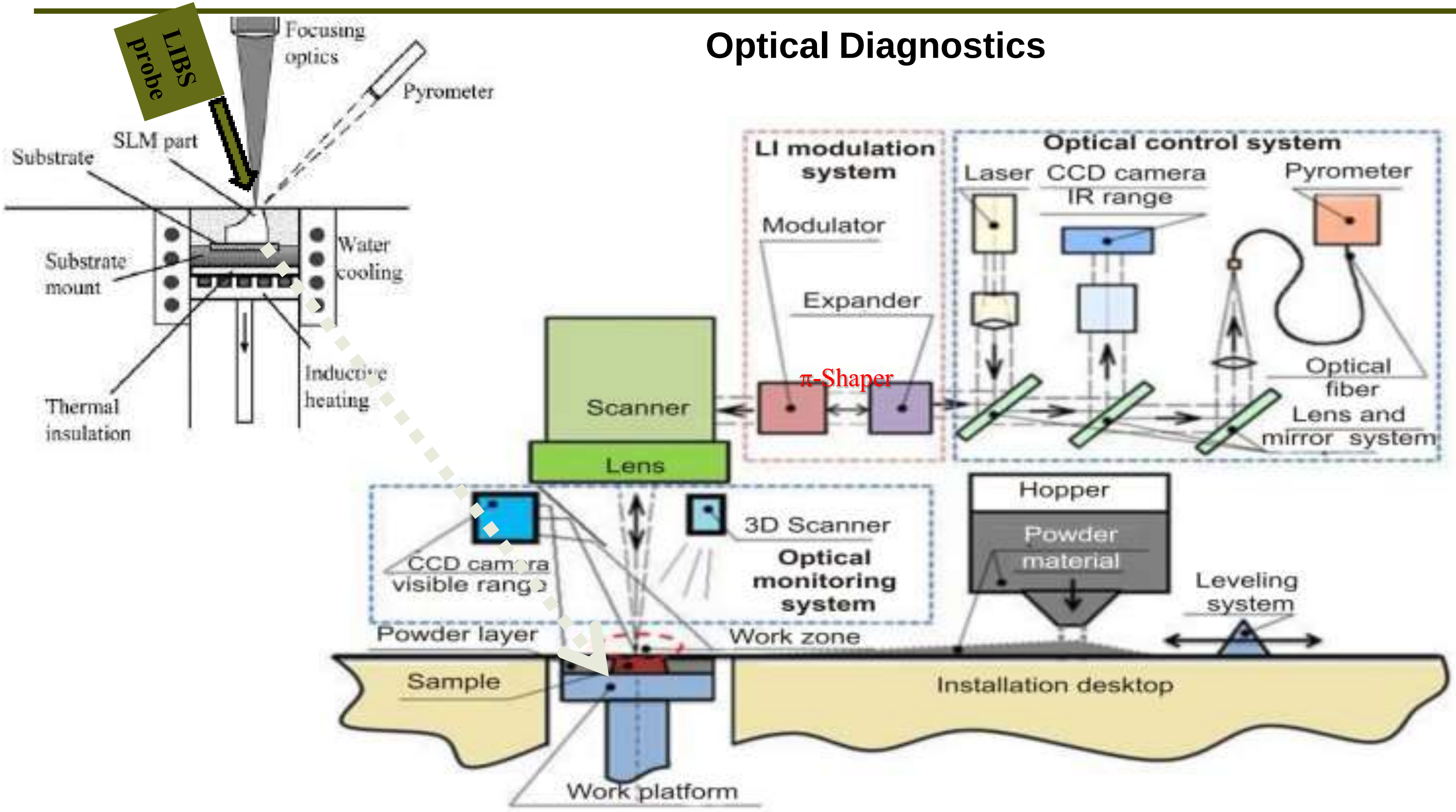
Thermal image of top view



Thermal image of side view

Data Collection & Process Diagnostics

Optical Diagnostics



PhD & Msc students at AML:

I. Daniil Panov (PhD-1) – Thesis title '*Numerical and experimental investigation of the laser structuring processes based on the remelting of the metallic surface*' (Skoltech –Aachen, Germany)

II. **Stanislav Chernishihin** (PhD-2) – Thesis title '*Topological design and selective laser melting of porous nitinol implants and scaffolds for medical applications*'

III. **Konstantin Makarenko** (PhD-2) – Thesis title *'Fabrication of functionally-graded structures and tools via Direct Energy Deposition'*

IV. **Maxim Isachenkov** (PhD-2) – Thesis title *'SLA based Lunar regolith ceramics fabrication and their applications'*

V. **Yulia Kuzminova** (PhD-2) – Thesis title *'Microstructure and mechanical properties of high and medium-entropy alloys after powder bed fusion process' (Skoltech –Karlsbad Univer., Sweden)*

VI. **Oleg Volgin** *(PhD-3) – Thesis ttile 'Theoretical and numerical modeling of shape memory effect in polymers suitable for 4D p* rinting'

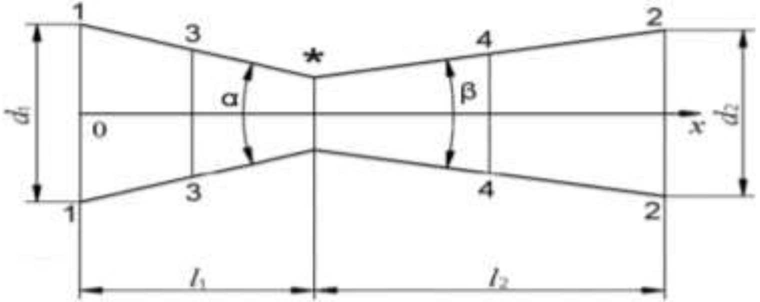
VII. *Zhamila Isabaeva* (Msc-2) – Thesis title '*Experimental study of the shape memory effect in 3D polymer parts fabricated by the FDM method'*

VIII. *Igor Pchelintsev (Msc-2) - Thesis title 'Production of complex hierarchical structures by laser stereolithography (SLA) for improving performance of SOFC fuel cells'.* (Skoltech – MIT, USA)

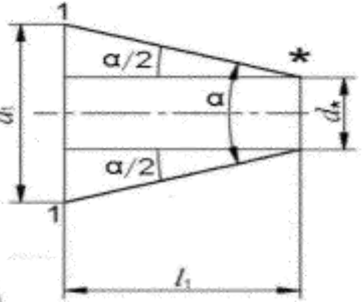
Konstantin Makarenko (PhD2)

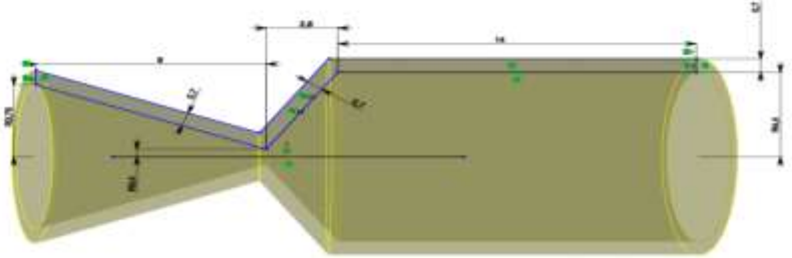
Direct Energy Deposition of the Functionally Graded Materials

Design of the rocket engine components for DED

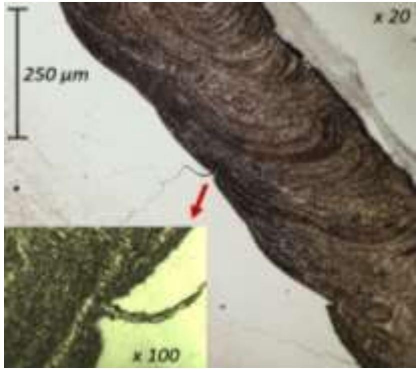


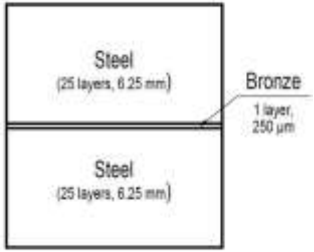
De Laval nozzle of the electrothermal jet engine

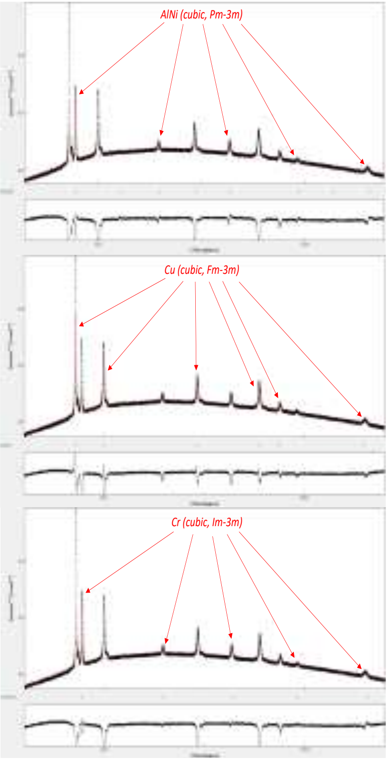


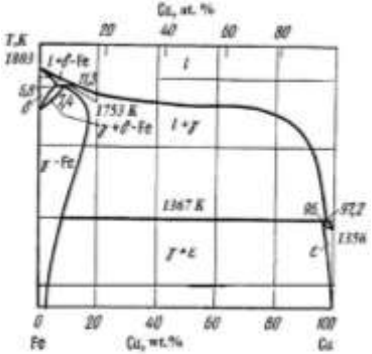


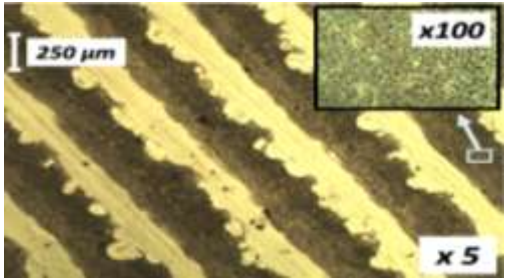
The OM, SEM structure and XRD researches of the FGM

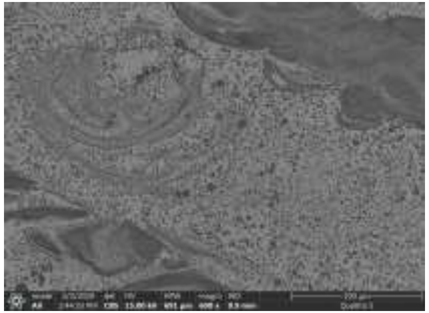


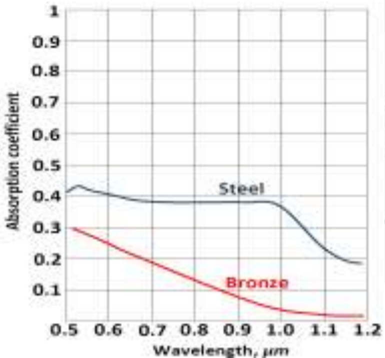












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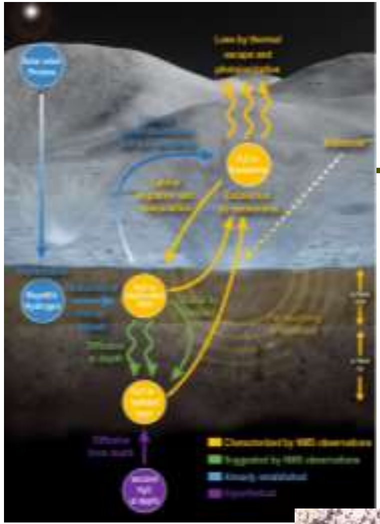
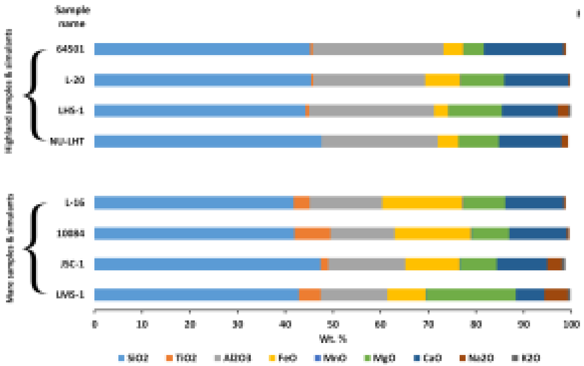
Maxim Isachenkov (PhD2) –
SLA lunar ceramics fabrication and their applications

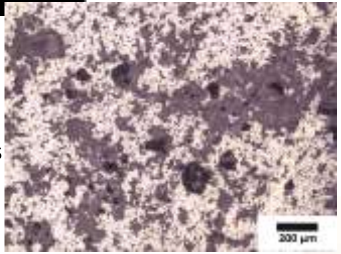


What is Lunar Regolith!?

Lunar regolith (LR) is an upper layer of space-weathered lunar soil, which mineral composition is somewhat similar to earthern volcanic areas



-NASA's JPL ATHLETE as mobile ISRU platform (2010)-Deutsches Zentrum für Luft- und Raumfahrt (DLR) + LIQUIFER Systems Group experiments in 2017



- Politecnico di Milano, Italy 2018

- Loughborough & Birmingem universities, UK, 2018

-CAS's Key Laboratory of Space Manufacturing Technology, 2019

- SLA produced spare parts by Austrian Lithoz for ESA's URBAN project, 2018

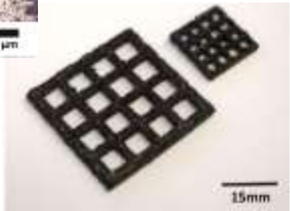
-ESA space research center + Monolite ltd., Alta spa., 2018

- JPL Caltech 2018

Selective Solar Light Sintering

-NASA's JPL ATHLETE as mobile ISRU platform (2010)!?

Selective Microwave Sintering



Selective Laser Melting

Stereolithography

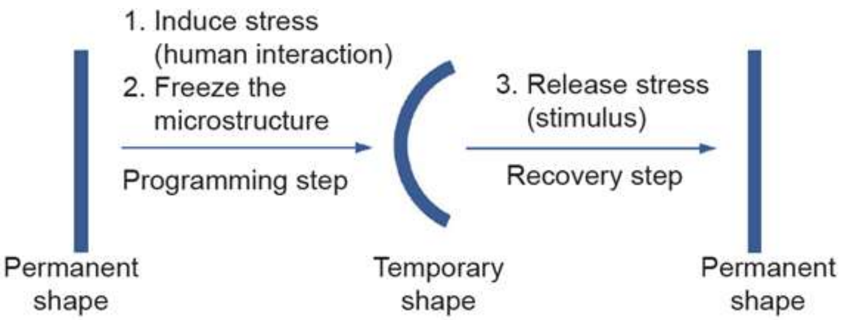
Binder jetting

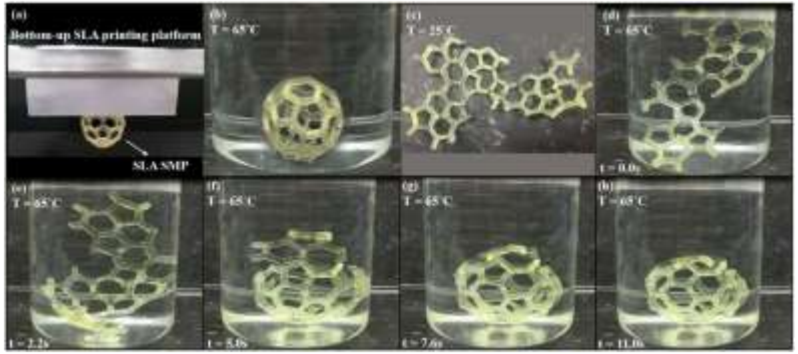
Ink jetting

Current examples of 3D printing with lunar regolith

Oleg Volgin (PhD-3) – *Theoretical and numerical modeling of shape memory effect in polymers suitable for 4D printing*

- Shape memory materials have the inherent capacity to fix a **temporary** shape and recover their **permanent** structure under suitable **energy source** (external stimulus)
- 4D printing = 3D printing + time-dependency
- By using additive manufacturing, more complex devices and parts can be produced
- The need for human interaction, sensors, and batteries could be partly or fully eliminated



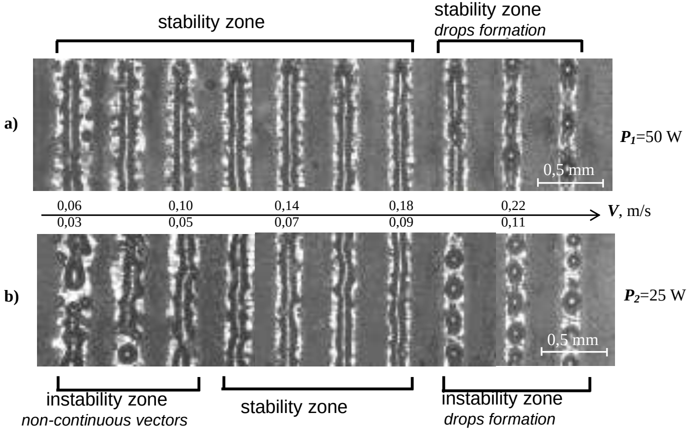


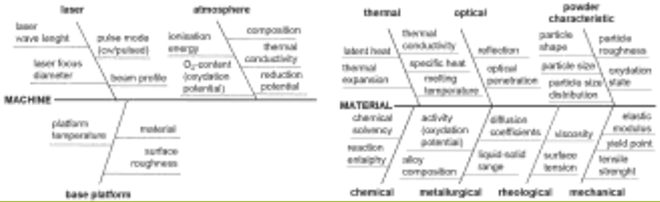
<u>MSc Project 1:</u> Comparative parameterization and microstructural feature's optimization of 3D parts from Powder ??? alloy, produced by laser PBF & DED methods of additive manufacturing.

Advisor: Prof. Igor Shishkovsky, (CDMM) Skoltech, Office: 2015-E-B5. Email: i.shishkovsky@skoltech.ru.

Background:

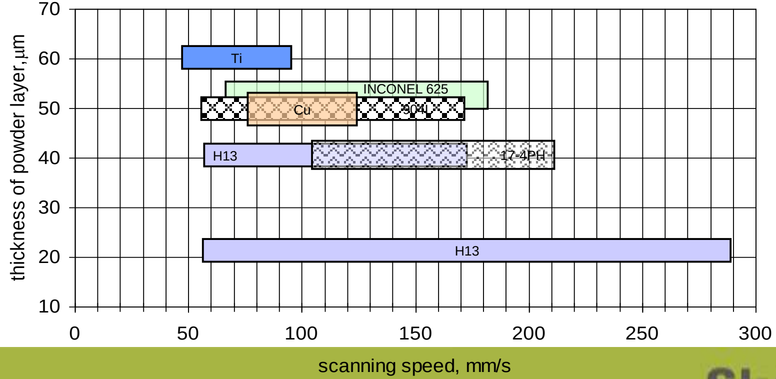
In spite of the fast growth of laser-based powder additive manufacturing processes as a part of everyday industrial practice, achieving consistent production is hampered by the scarce repeatability of performance that is often encountered across different additive manufacturing (AM) machines. In addition, the development of novel feedstock materials, which is fundamental to the future growth of AM, is limited by the absence of established methodologies for their successful exploitation. This dissertation will be devoted to develops a structured procedure with a complete test plan, which defines step-by-step the standardized actions that should be taken to characterize and to optimize the processing parameters and scanning strategy in powder bed fusion (PBF) and direct energy deposition (DED) of new alloy grades.





Synopsis:

We need experimental and statistically treated results of optimization of laser processing regimes and characterization of the microstructure and mechanical properties of new grades of powder alloys for the AM of the PBF and the DED methods. Master Students will develop a holistic comparative methodology, which take into account consideration all the laser/material interactions in different local geometries of the build, and suggests, for each possible interaction, a specific geometry for test specimens, standard energy parameters to be analyzed through a design of experiment, and measurable key performance indicators. The proposed procedure, therefore, represents a sound and robust aid to the development of novel alloy grades for the PBF and the DED and to the definition of the most appropriate processing conditions for them in comparison, independent of the specific AM machine applied.



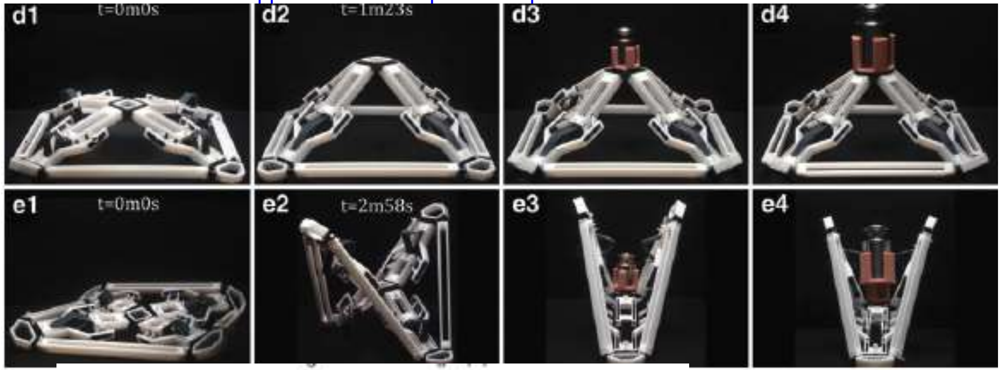
MSc Project 2: Experimental study of the shape memory effect (or magnetic nanoparticles behavior) in 3D polymer parts fabricated by the AM (SLM, FDM, DLP etc).

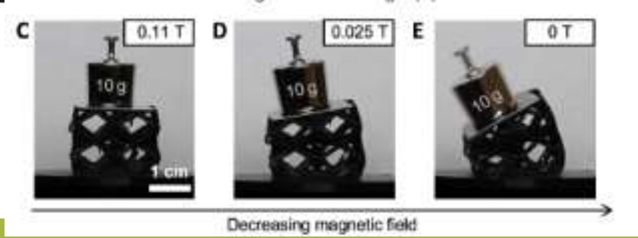
Advisor: Prof. Igor Shishkovsky, (CDMM) Skoltech, Office: 2015-E-B5. Email: i.shishkovsky@skoltech.ru.

Background:

An increasing number of active structures are designed and fabricated in a newly innovative field of four-dimensional (4D) printing. The 4D printing uses properties of 3D printing materials to achieve design shape change under environmental forces.

The shape memory effect (SME) of polymers is adopted in this research as the activation material. Shape memory polymers (SMPs) possess the advantages of large elastic deformations, low energy consumption for shape programming, low cost and density, potential biocompatibility, biodegradability, and excellent manufacturability. While the SME is observed with most thermosets, it is not feasible for traditional fabrication methods to produce complex functional parts. In this study, we will exploit the fused deposition modelling (FDM) technology to fabricate complex designs of different stiffness and glass transition temperatures. FDM works on an “additive” principle by laying down material in layers; a plastic filament or metal wire is unwound from a coil and supplies material to produce a part.





Synopsis:

We need experimental and statistically treated results of the thermo-mechanical properties for the 3D printed SMPs in the region between the glass and melt temperatures. These data will be combined with macro- and microstructural estimates.

3D printed material orientation under isothermal conditions (at temperatures below the melting temperature) is realized by using a tensile testing machine, Instron series, equipped with a temperature chamber. Each specimen will fix into the machine grips and subjected to a constant displacement-rate tensile test run. Viscous elastic-plastic behavior of material must show character hysteresis loop. A dynamic mechanical analysis (DMA) of the SMP will be performed. Master Students will develop simulation methods in ABAQUS environment to describing a temperature field distribution, a degree of crystallinity, a residual stress-strain state, prediction of mechanical properties of the material with the SME after FDM fabrication.

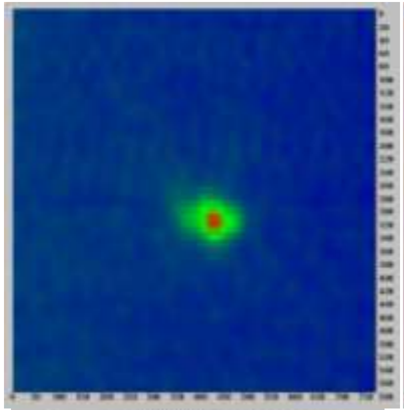
4D printing !

MSc Project 3: Thermographic Measurements during Laser Powder Bed Fusion Process

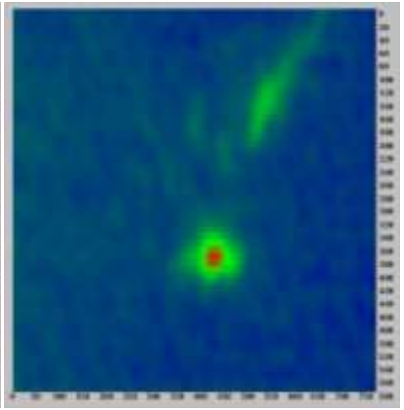
Advisor: Prof. Igor Shishkovsky, (CDMM) Skoltech, Office: 2015-E-B5. Email: i.shishkovsky@skoltech.ru.

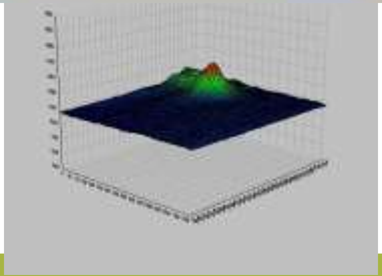
Background:
Measurement of the high-temperature melt pool region in the laser powder bed fusion (LPBF) process is a primary focus of researchers to further understand the dynamic physics of the heating, melting, adhesion, and cooling which define this commercially popular additive manufacturing process. To convert a measured camera signal into a true temperature, the surface emissivity must be known. There are multiple methods for measuring emissivity and details several methods for calculating emissivity measurement uncertainty.

Surface heat distribution



Particle fly-off





Temperature fields in the zone of laser action during melting of powder.
Field of view is 2x1.5mm.
The size of the melting zone is 100µm.

Synopsis:
We need to provide calibrated, well-characterized temperature data to support simulation and modelling research, and to acquire high-speed, high-fidelity observations and measurements to support the development of in-situ monitoring and feedback control.
Master student will detail the design, execution, and results of high speed, high magnification in-situ thermographic measurements focusing on the melt pool region of the LPBF process. Knowing the approximate size of different isotherms around the melt pool will help determine the required magnification, and heating/cooling rates determine the required frame rate and integration time to temporally resolve these phenomena. Further work will relate these thermographic results to process finite element simulation of temperature distribution and improvement of in-situ sensing and control methodologies.

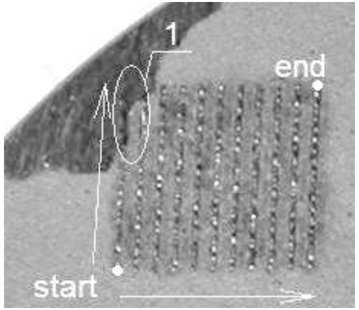
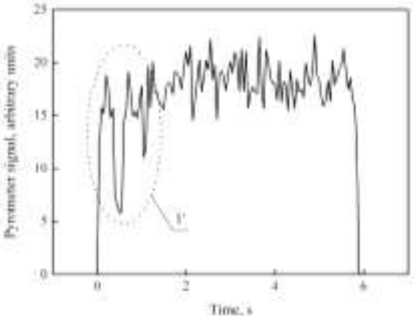


Photo of a 50µm thick powder layer with irregularity of the powder thickness at the end of the two first tracks



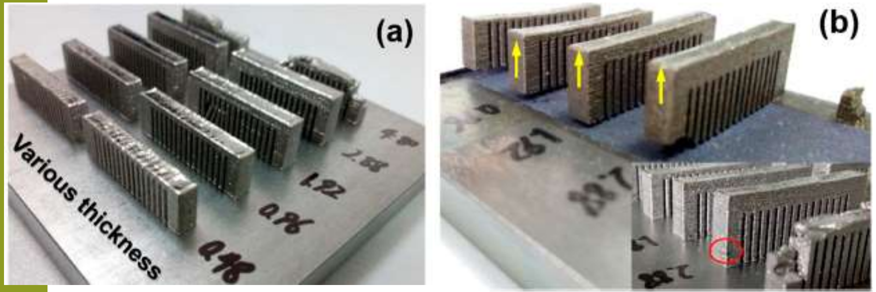
Evolution of the pyrometer signal with the zoom at the zone of irregularity in the powder layer.

MSc Project 4: Experimental and numerical modelling of mechanical properties in topological structures after the SLM process.

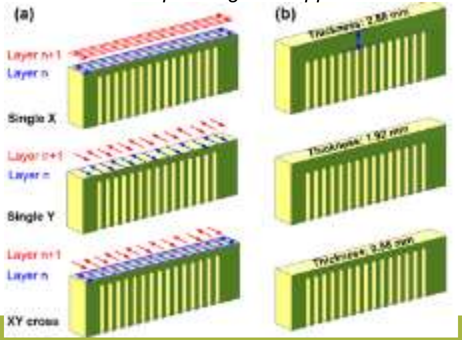
Advisor: Prof. Igor Shishkovsky, (CDMM) Skoltech, Office: 2015-E-B5. Email: i.shishkovsky@skoltech.ru.

Background:

During the SLM process, high heating and cooling rates generally cause inhomogeneous thermal distribution, induce heterogeneous thermal expansions and contractions, and inevitably result in serious thermal and residual stresses. Experimental methods to characterize residual stress in 3D printed specimens could be very complicated. The curvature method measures the deflection or curvature of a cantilever part caused by residual stresses, reflecting thermal stresses within layers. Therefore, this method is more suitable for 3D printed components, because SLM is based on the melting of successive layers, and the variation of processing parameters (such as scanning strategy, layer thickness, preheating, etc.) has a significant effect on residual stresses.



(a) 3D printed Zr-based cantilevers with various bar thicknesses and (b) spreading of cantilevers after separating the support.

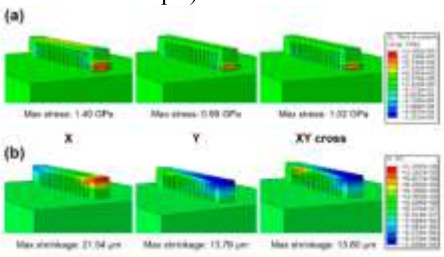


Schematic diagram of different (a) laser scanning strategies and (b) bar thicknesses.

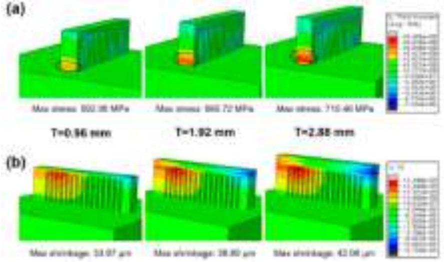
Synopsis:

We need experimental SLM fabrication of the cantilever structure on a substrate which will later be designed and evaluated into ABAQUS the FEM model. At the two ends of the cantilever arms, the additional supporting body must adapt to stand deformation. The bars will print with different scanning strategies, like X, Y and XY cross scanning strategies (scanning direction of 90^0 alternated among layers). The other group of cantilever specimens will be creating with the same XY cross scanning strategy, but for various bar thicknesses. To detect this difference, the comb-shaped supports were cut off from the substrate, and the cantilever bent towards the Z direction (building direction) due to the residual stress release. To probe the possible methods to release residual stress, low-temperature annealing as a relatively economical method will be considered.

A thermal-mechanical coupled analysis model consisting of a cantilever and substrate will be developed by ABAQUS software. The moving direction and velocity of the heat flux will be controlled by a subroutine, and elements will be activated step by step sequentially as the heat flux moved ("birth and death" technique).



(a) Residual stress field and (b) longitudinal shrinkage under different laser scanning strategies.



(a) Residual stress field and (b) longitudinal shrinkage of three typical bar thicknesses under the XY cross scanning strategy.

Questions !

Igor Vladimirovich Shishkovsky
Associate Professor, office E-B5-2015, i.shishkovsky@skoltech.ru
Chief of Additive Manufacturing Laboratory
Center for Design, Manufacturing and Materials
Skolkovo Institute of Science and Technology (Skoltech)