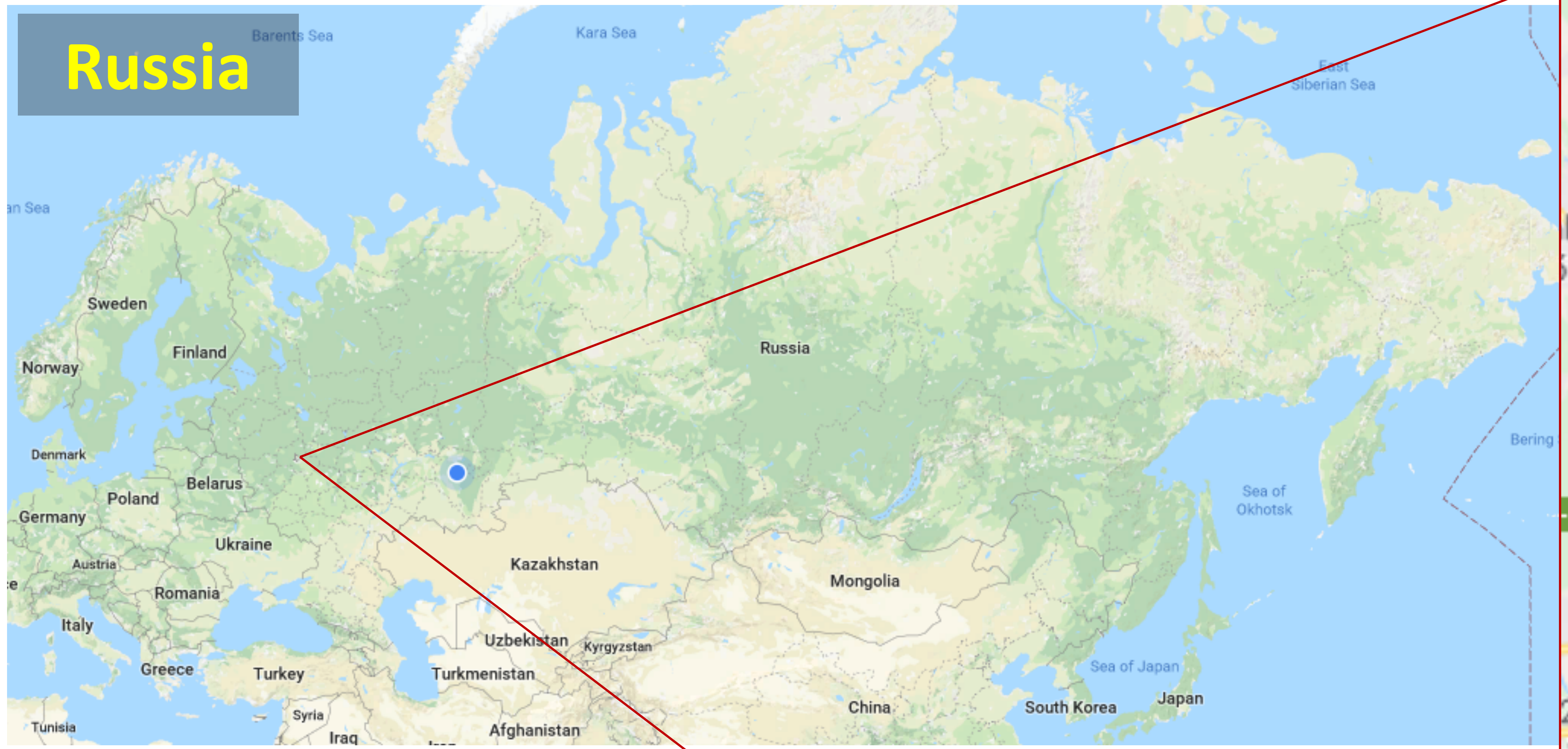
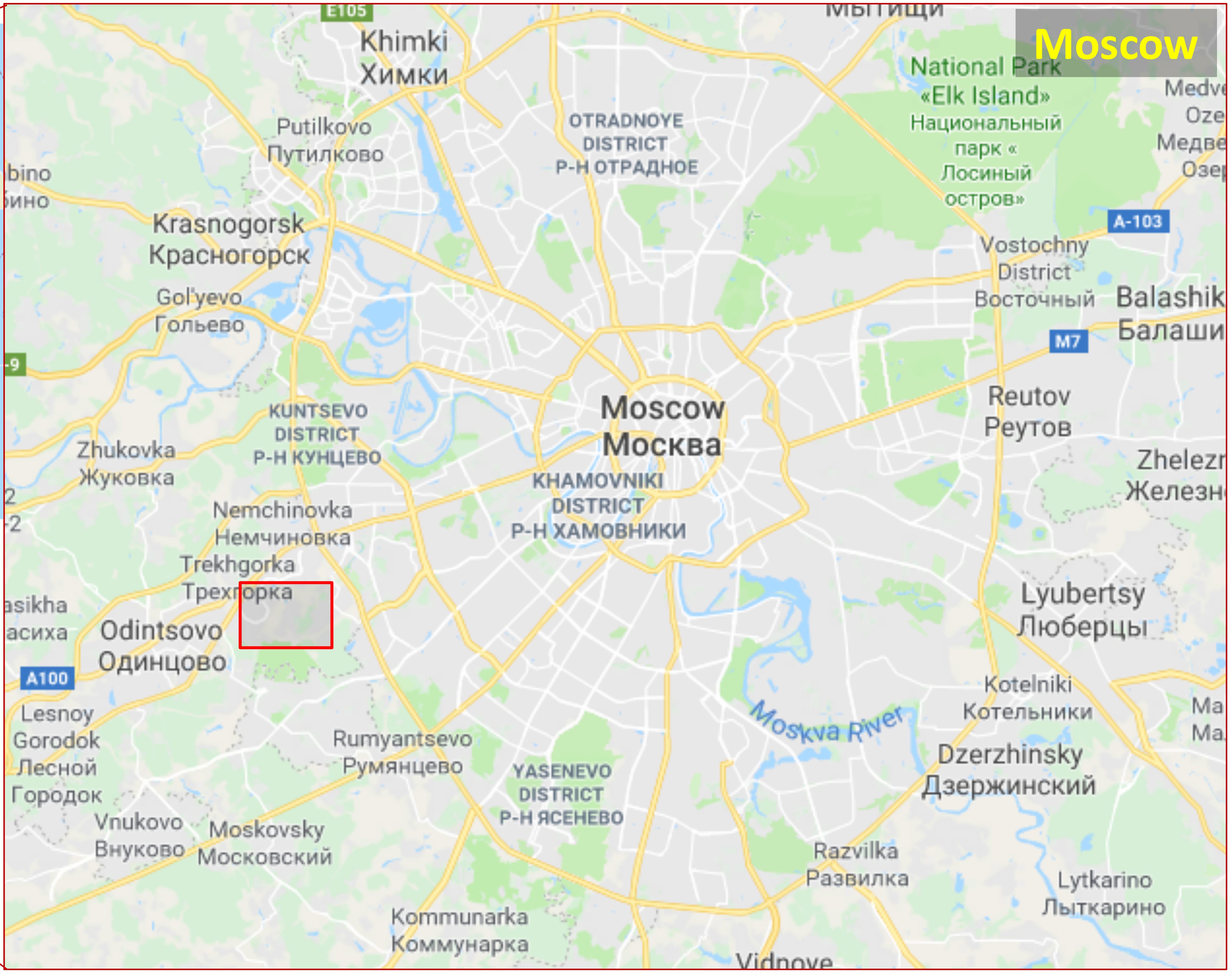
Technological Concepts of 3D Printing: How to make the technology better.

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)
that conducts basic and applied research aimed at development and implementation of
new design and manufacturing concepts for materials and structures
with enhanced lifecycle, widely demanded in various industries.

Skoltech Location

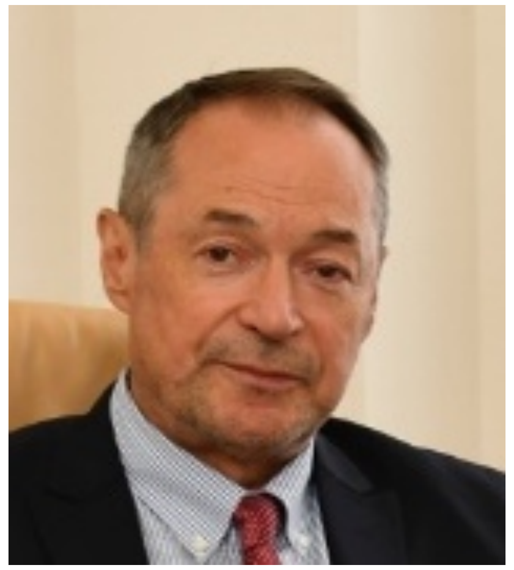




Campus of Skolkovo Innovation Center


NEW CAMPUS

Center for Design, Manufacturing & 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.**

To be opened in the new Campus

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
- Powder-bed Fusion
- Selective Laser Melting
- Stereolithography
- Direct Energy Deposition

Laboratory: Information Technologies for Advanced Manufacturing

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 nano-structural 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.

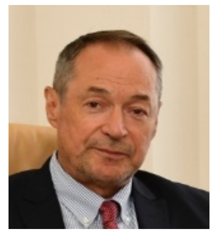
Laboratory: Thermal Spray and Functional Coating

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 advanced sensorics to industrial manufacturing lines. Optimization of production process in automotive, aviation, marine, heavy instrument industry

Center for Design, Manufacturing & Materials



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Kirill Niaza

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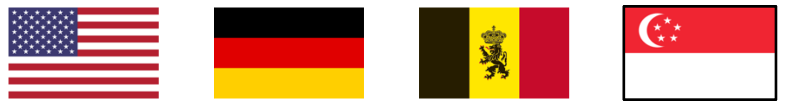
Klim Karelin
Alexander Akhmedov

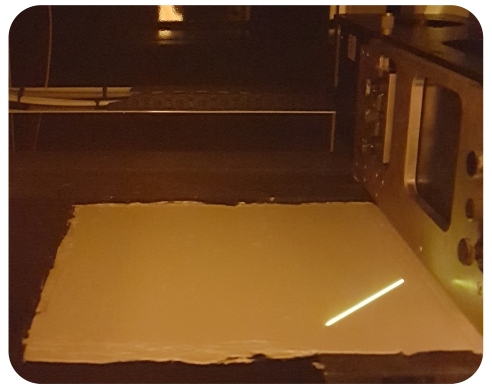
International Collaboration of CDMM:



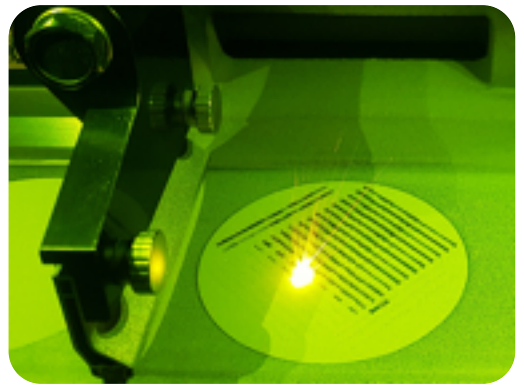
- **USA**: University of Dayton
- **USA**: University of Maryland
- **USA**: New Mexico State University
- **Germany**: Technical University of Munich
- **Germany**: University of Göttingen
- **Belgium**: KU Leuven
- **Singapore**: Nanyang Technological University

Total ~ 40 employees and PhD students

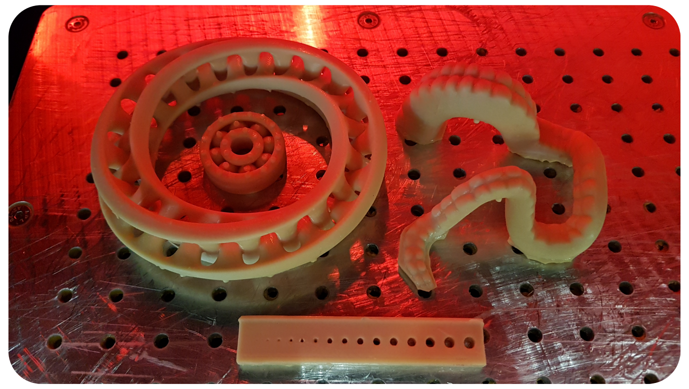
3D Printing Technology @ CDMM



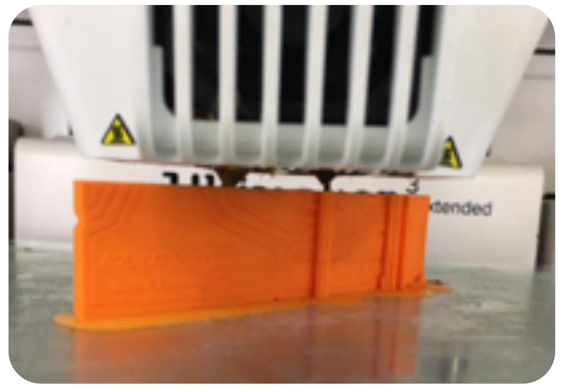
Stereolithography
(SLA)



Selective Laser Melting
(SLM)

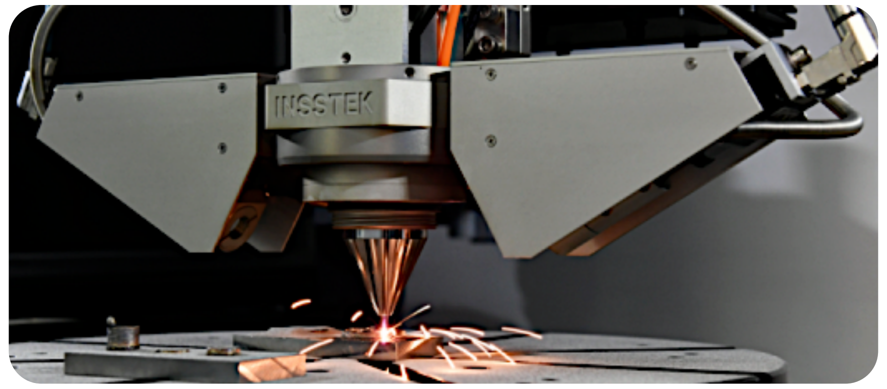


Digital Light Processing
(DLP)



Fused Deposition Modeling
(FDM)

Binder Jetting
(BJ)



Direct Energy Deposition
(DED)

The Largest 3D Printers @ CDMM

3D Metals

Direct Energy Deposition

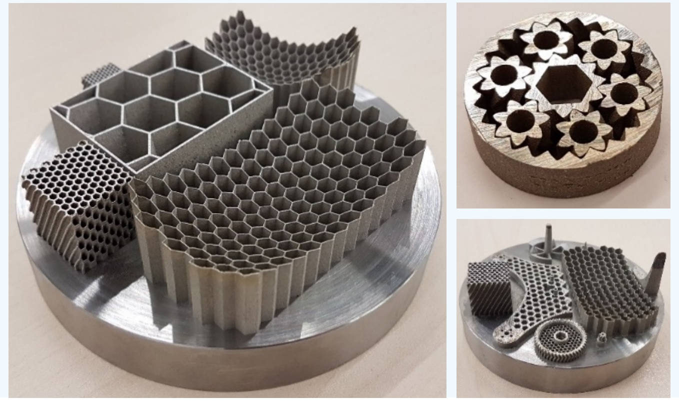
Direct energy deposition technology is used to print large-scale parts from steels, copper, aluminum, titanium, nickel and other alloys.

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

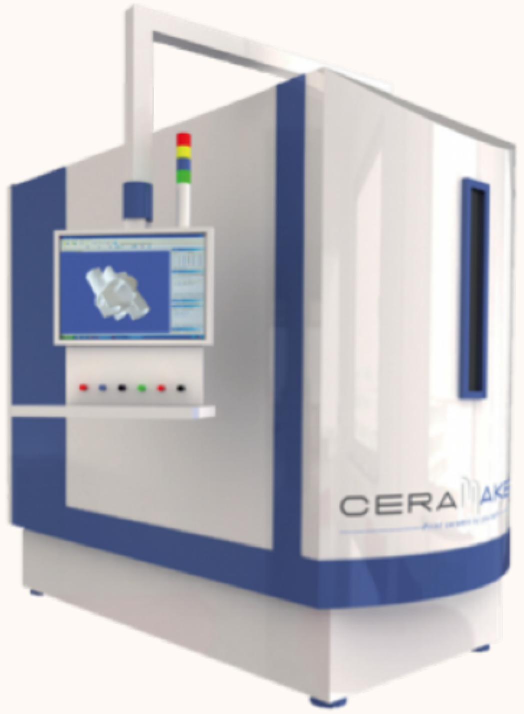
Selective Laser Melting

Laser metal 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.



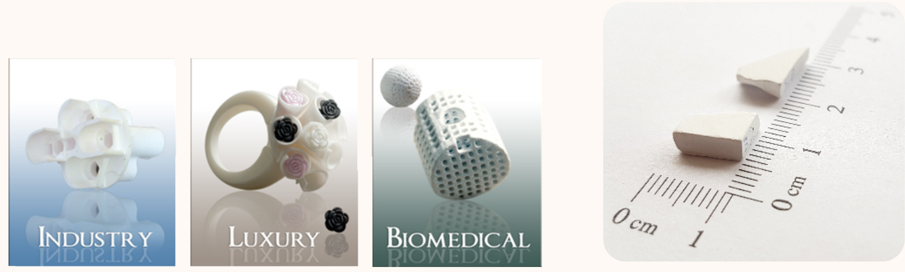
3D Ceramics



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).

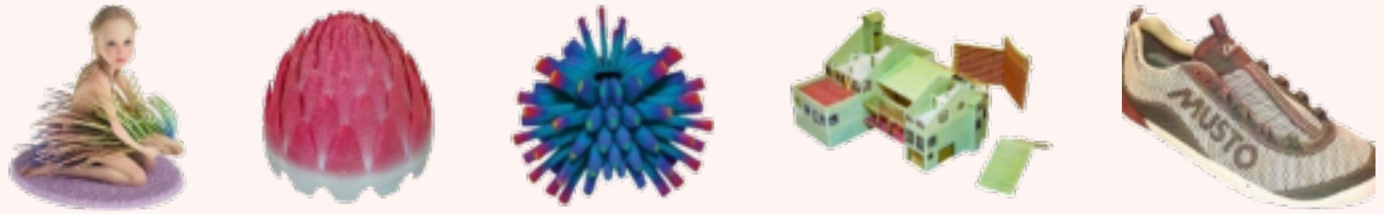


3D Plastics

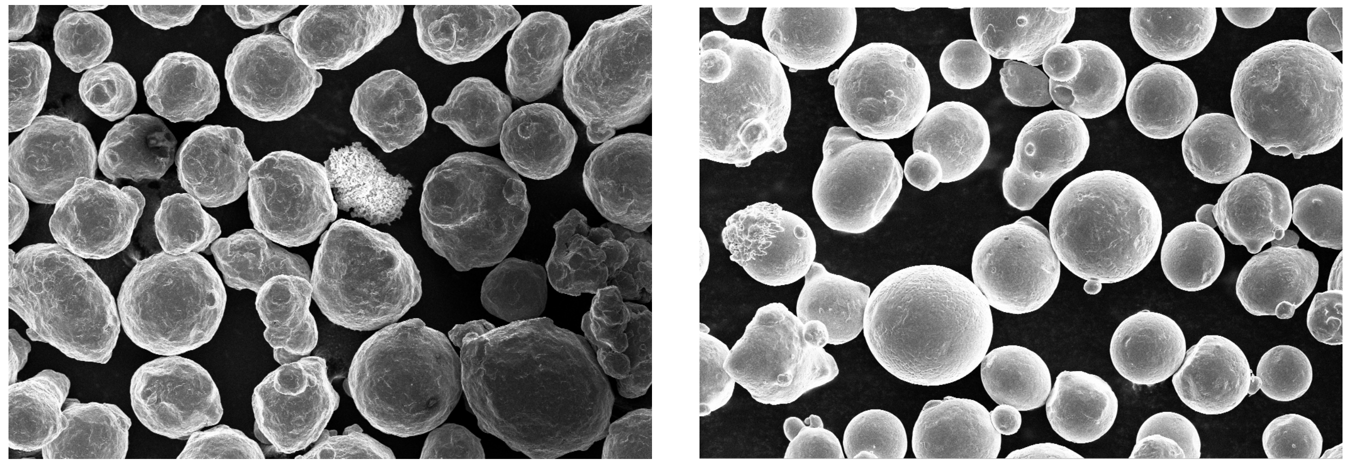
Binder Jetting

ColorJet 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

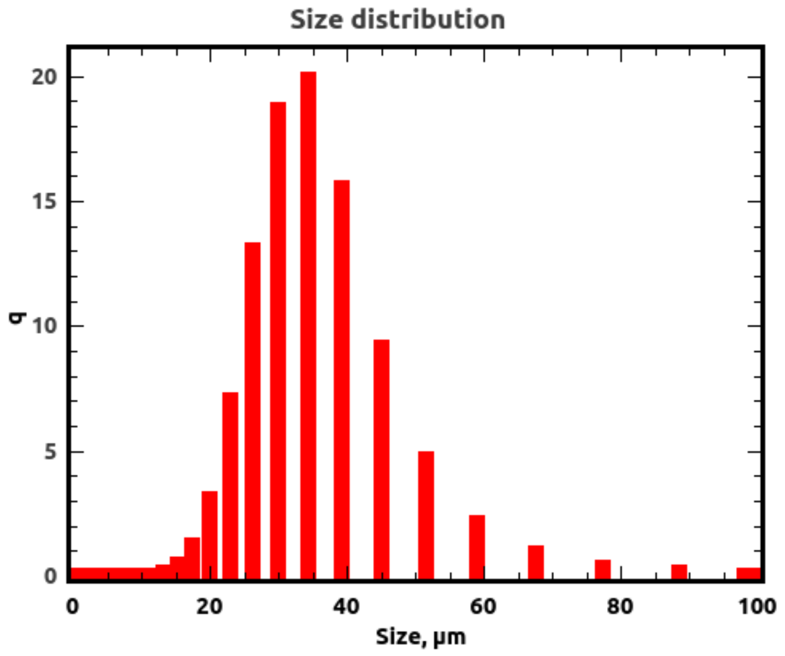


3D Metal Printing



Typical morphology of stainless steel particles for 3D printing

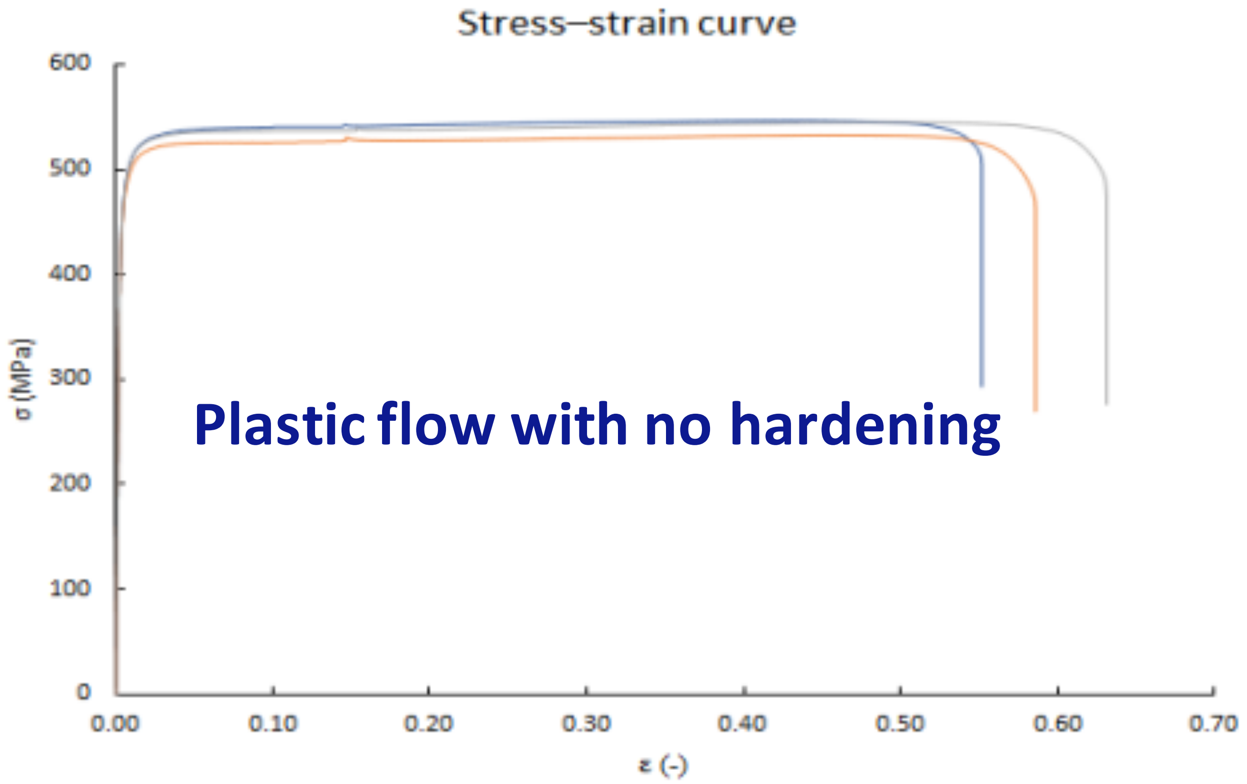
Selective Laser Melting and **Direct Energy Deposition** technologies help to transfer metal powder into objects of complex geometry



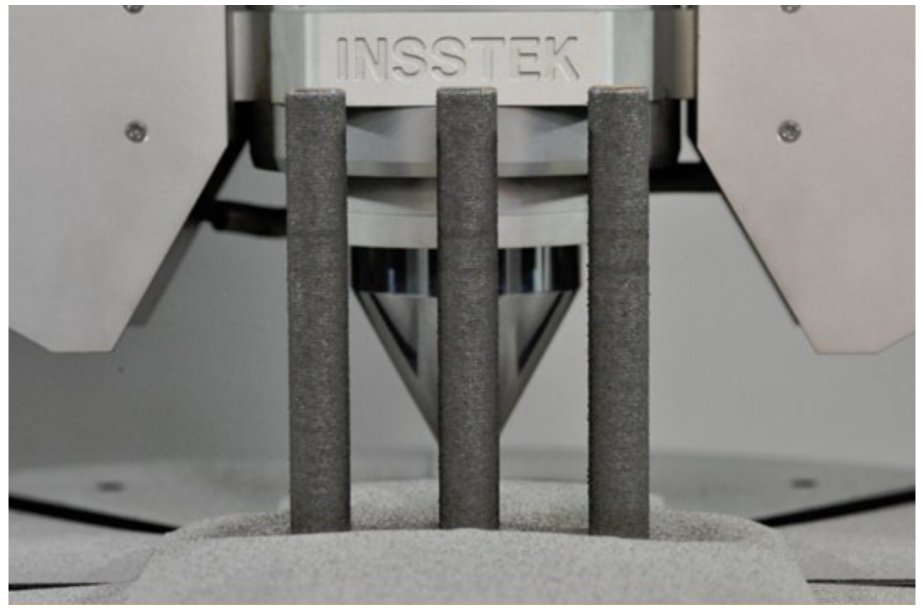
Distribution of particle size

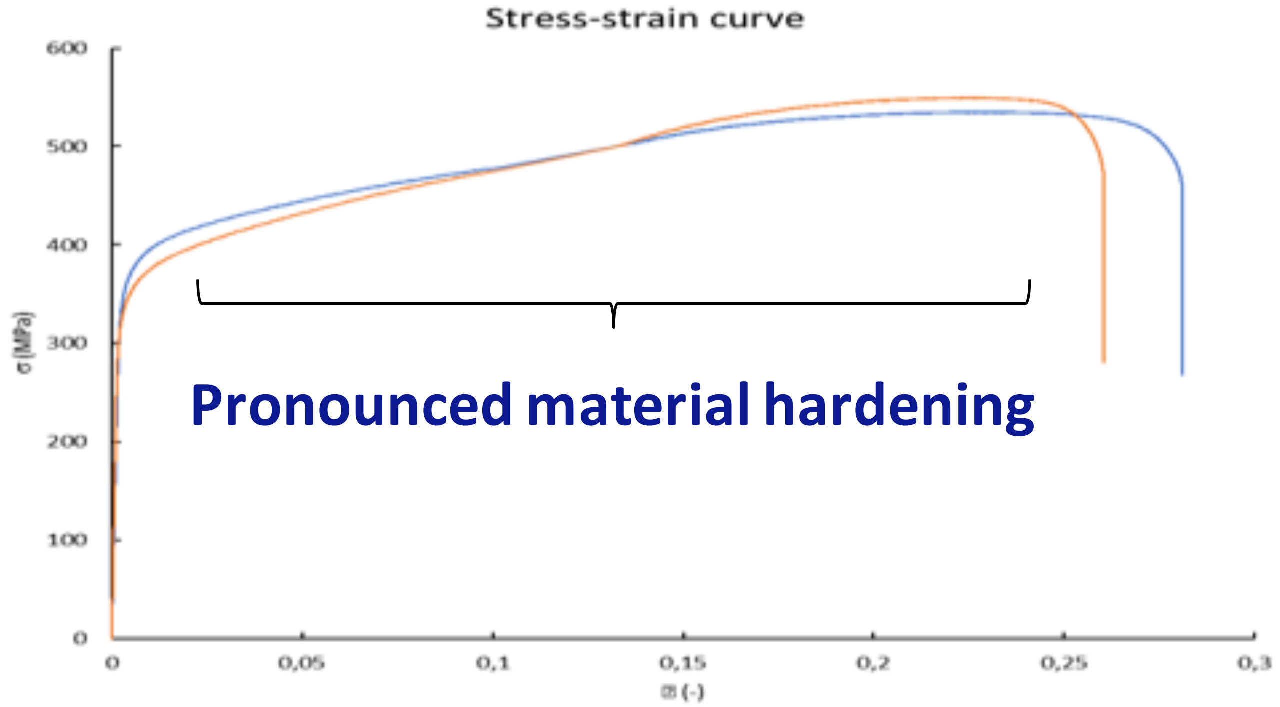
3D Printed Metals: Material Mechanical Testing

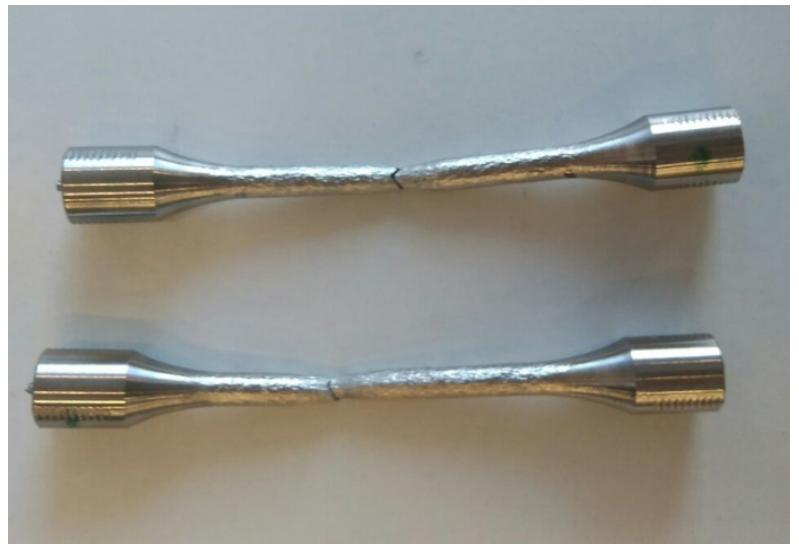
Selective Laser Melting



Direct Energy Deposition





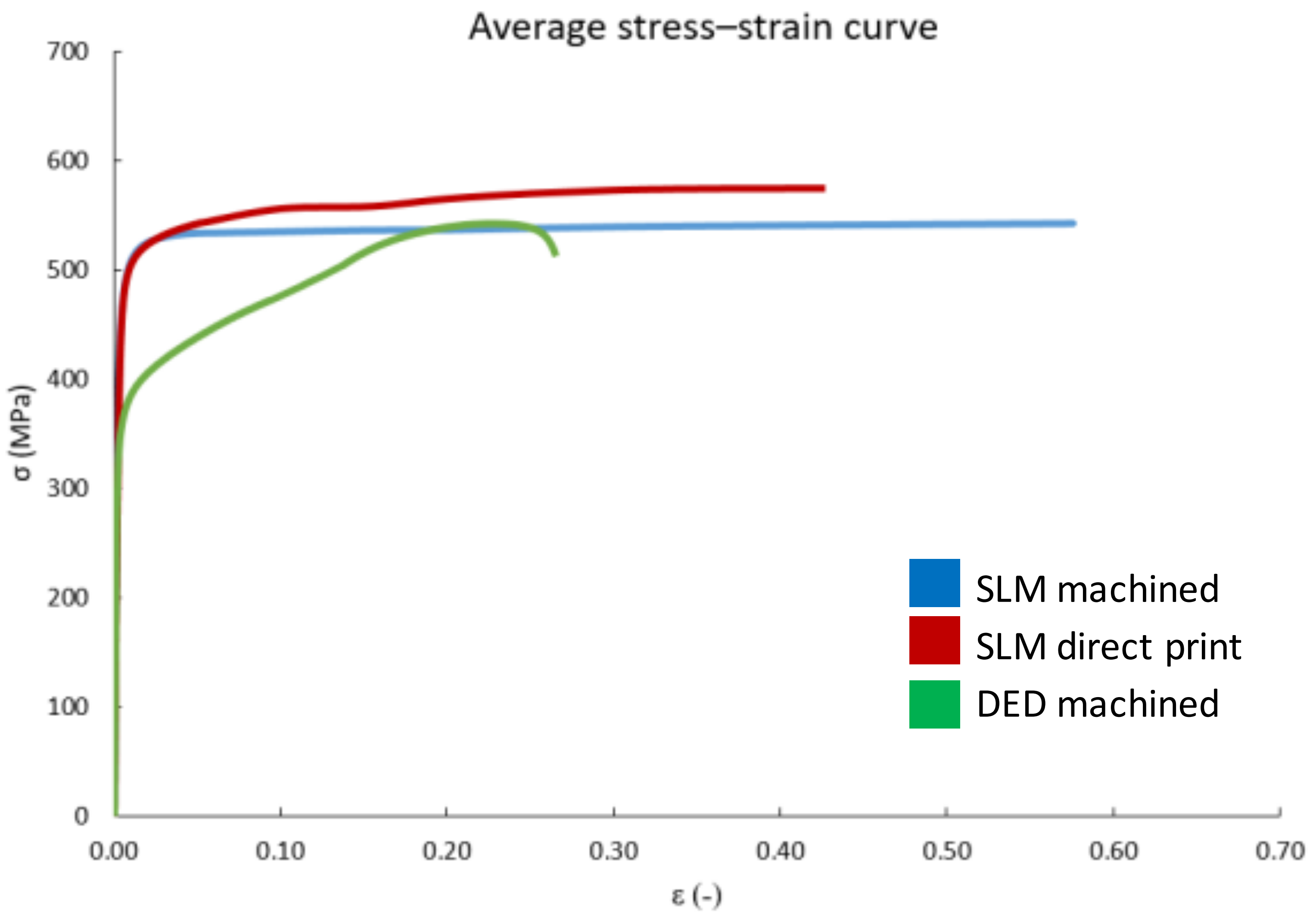


3D Printed Metals: Post-Processing Effects

SLM directly printed samples

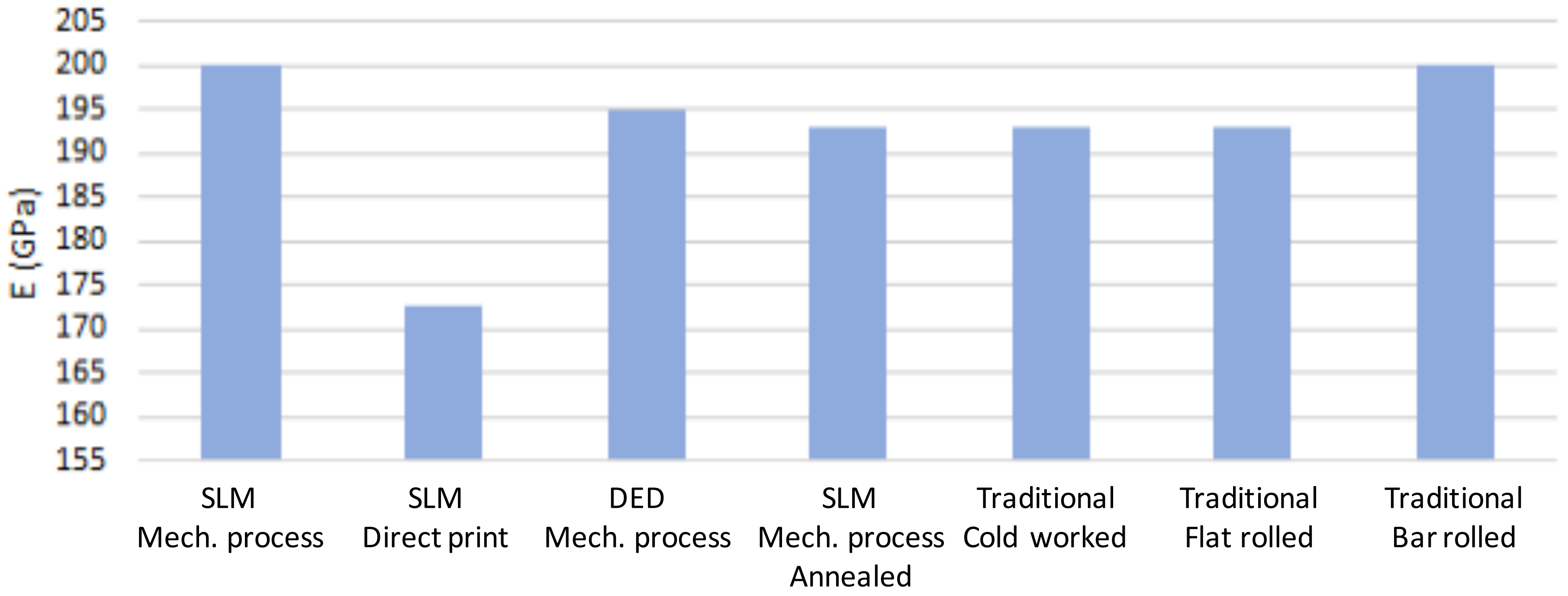
1) 3D printed stainless steel samples demonstrate mechanical properties on par with those of traditional materials, while offering wide range of possibilities for geometrical complexity of parts and components

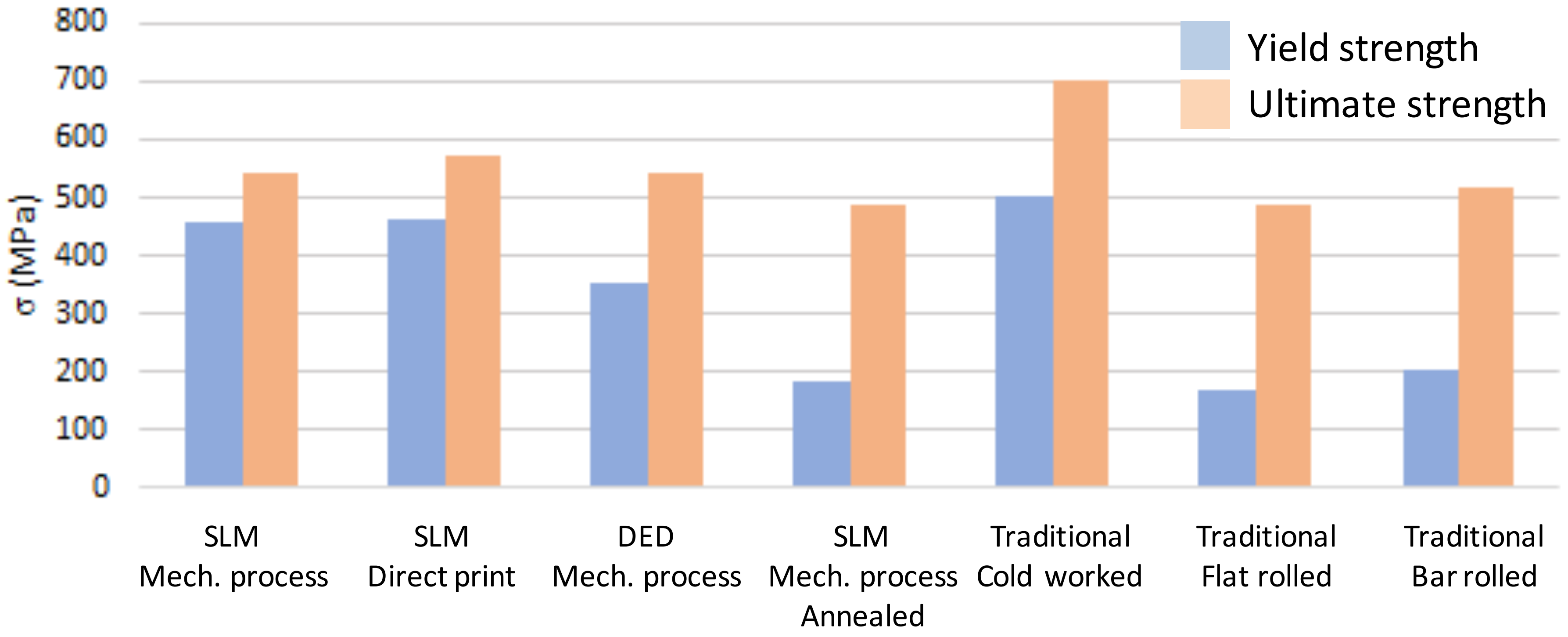
	3D printed	Traditional
Yield strength	Higher	Lower, Except cold worked
Ultimate strength	Comparable	Comparable
Young modulus	Comparable, except SLM w/o post processing	Comparable
Elongation at failure	Higher	Lower



2) Technology comparison

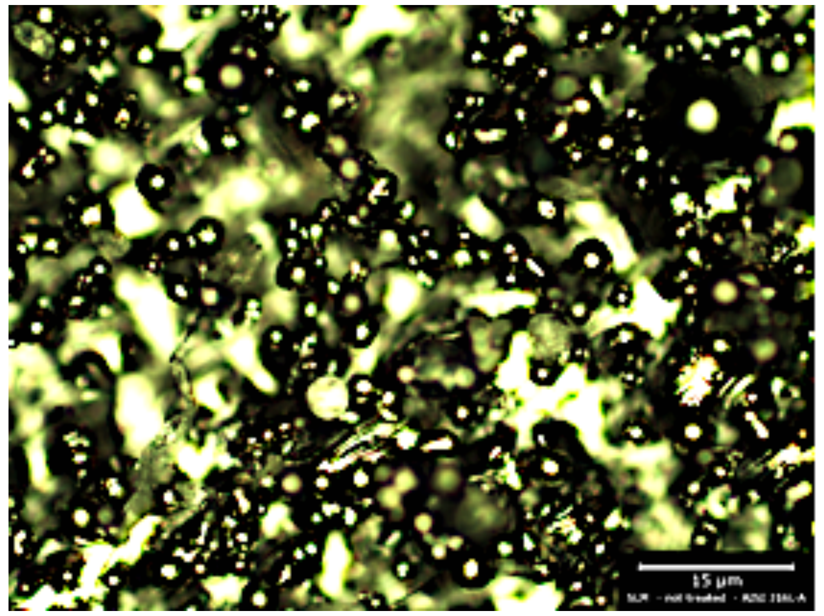
- SLM provides slightly higher mechanical strength than DED
- Mechanical post-processing has minimal effect on SLM samples
- Lower E for SLM direct print, is possibly due to differences in heat fluxes during 3D printing, which affect grain structure and orientation

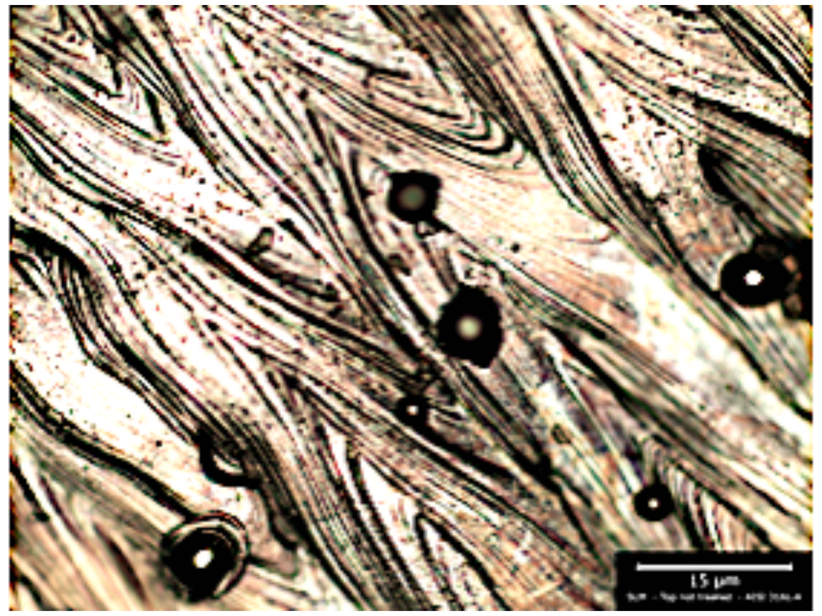


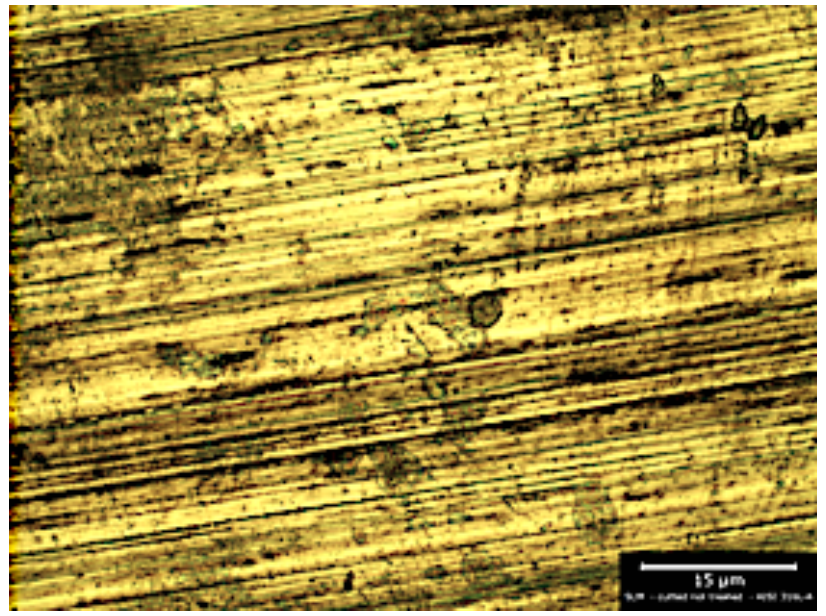


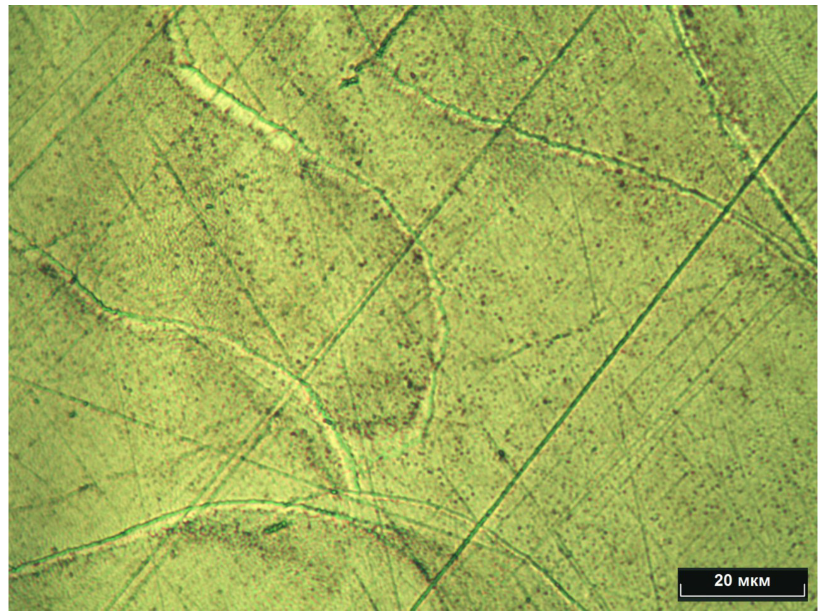
3D Printed Metals: Microstructure Comparison

Selective Laser Melting









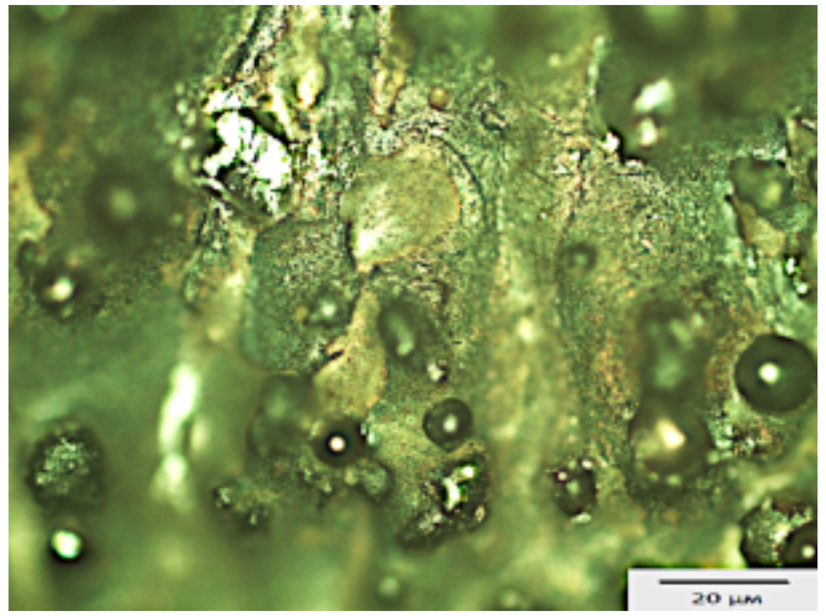
Sample side surface (X-Z direction)

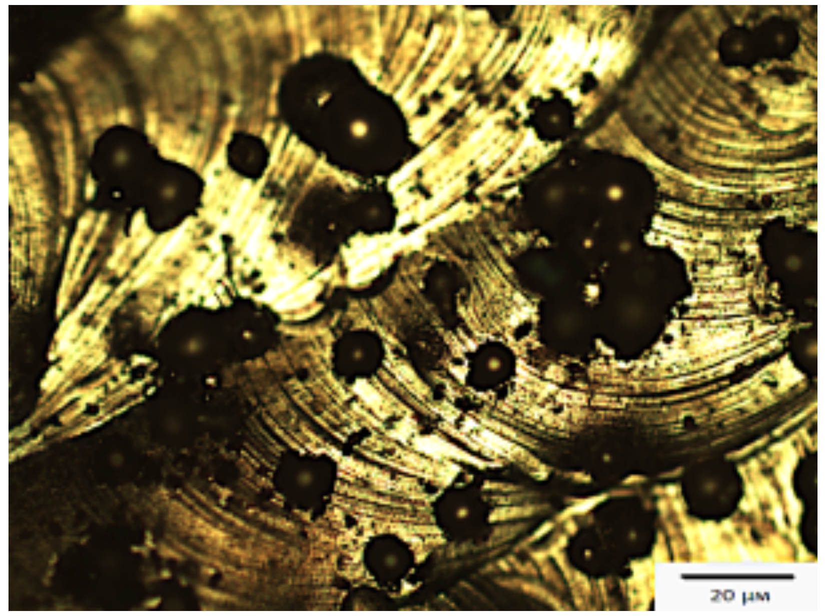
Sample top surface (X-Y direction)

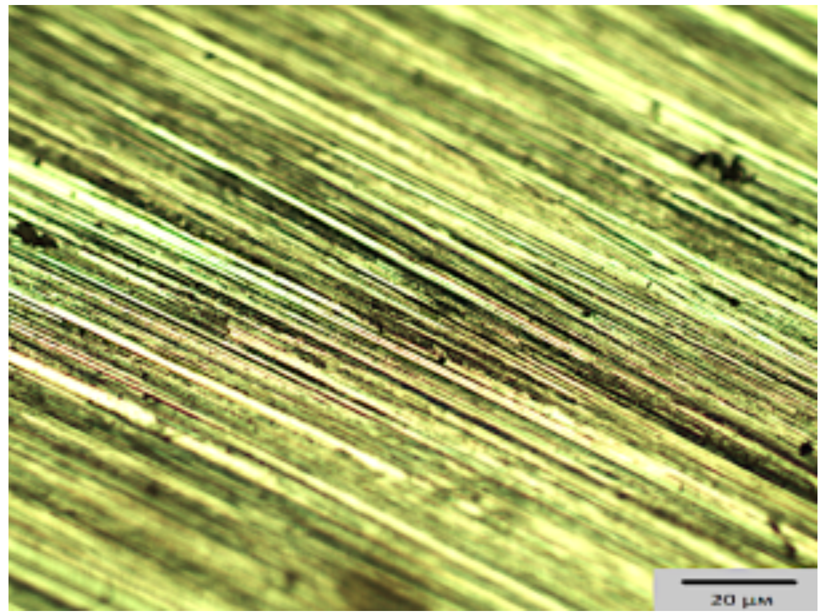
Cut surface from a middle of a sample

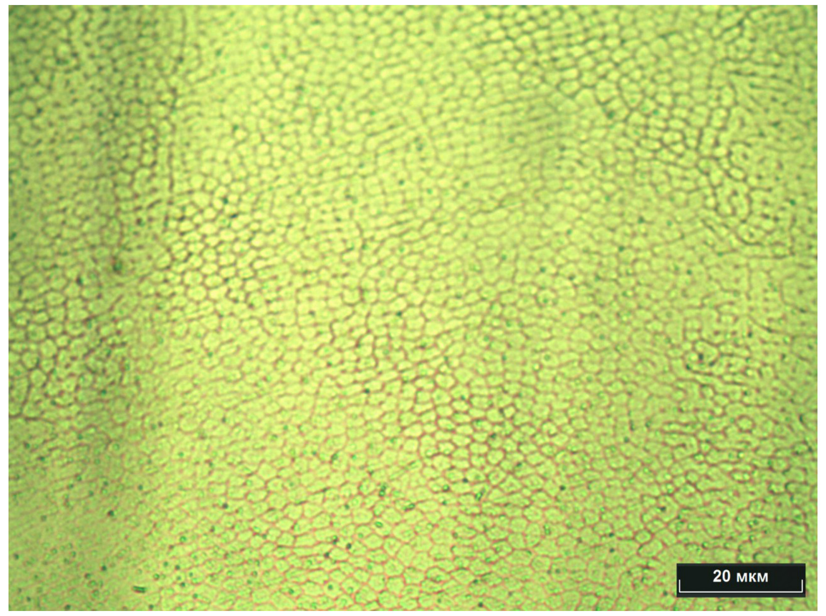
Grain structure

Direct Energy Deposition

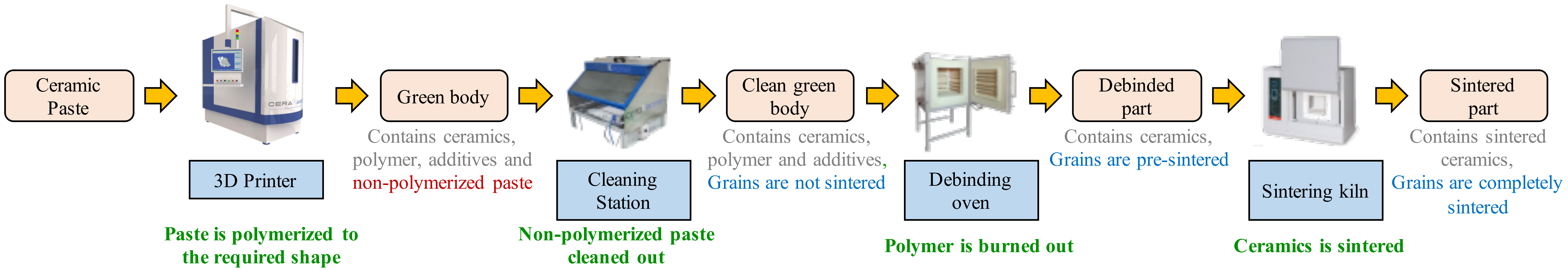






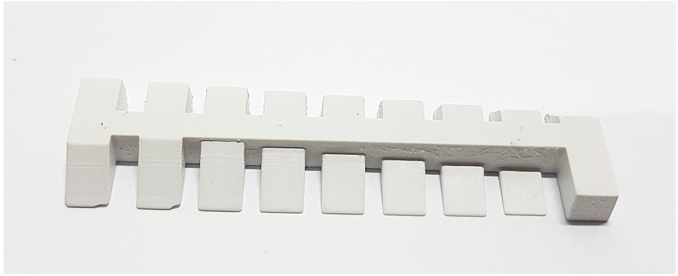


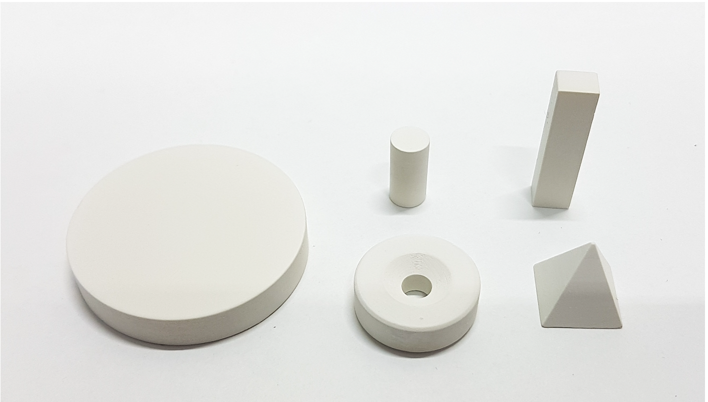
Stereolithography

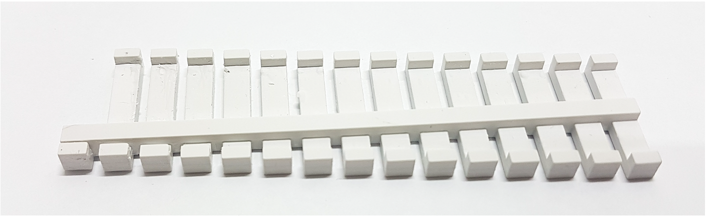


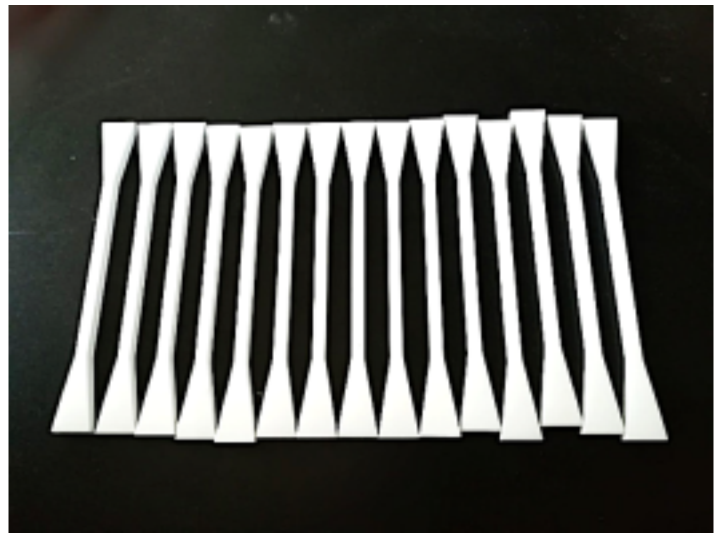
Room for improvement **(Synonyms: Opportunities for further enhancement, areas for further development)**

- Samples are too fragile, a special handling is needed during mechanical testing
- Due to the action of surface tension and substrate adhesion processes during printing, the printed structure tends to curl
  - Even slightly curled parts lead to incorrect stress distribution in ASTM-based samples, during mechanical testing
  - A base-layer having a special configuration is used to counteract this effect
  - A numerical simulator of physical processes during printing is on demand
- Non uniform parts contraction during debinding and sintering
  - A numerical model of debinding and sintering processes are needed
- Novel materials are needed
- Limitations of the debinding procedure – maximum wall thickness is within millimeters
- A special sintering process is required to sinter hybrid metal-ceramics materials, due to the difference in CTE of the constituents



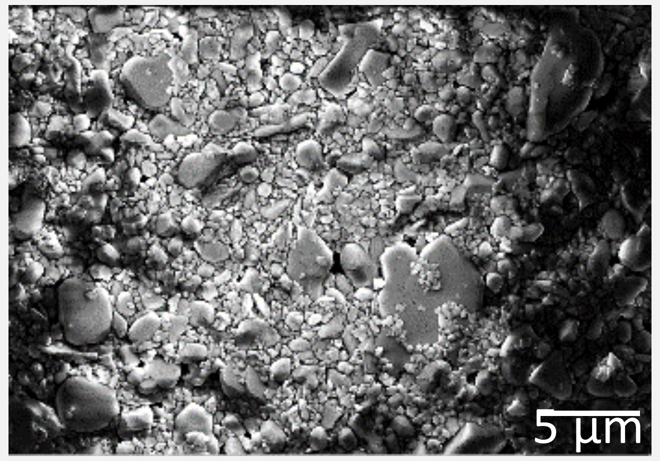




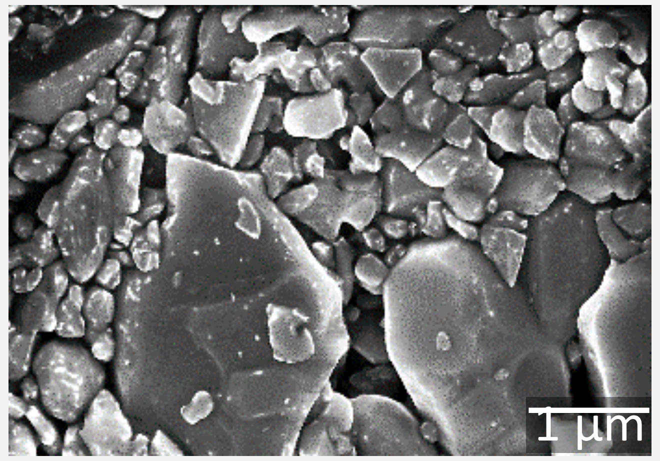


Stereolithography: Material Microstructure

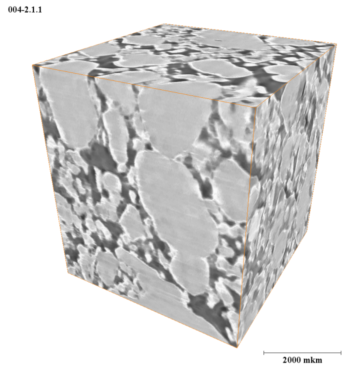
Ceramic Feedstock → Greenbody → Brownbody → Sintered object



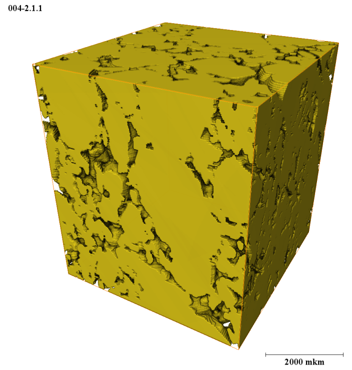
Al_2O_3 Microparticles



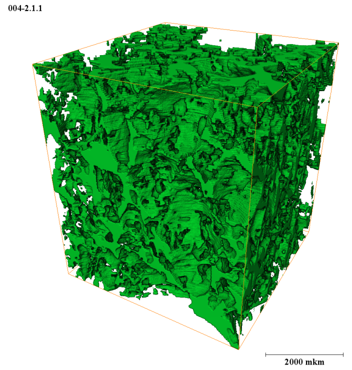
Al_2O_3 Nanoparticles



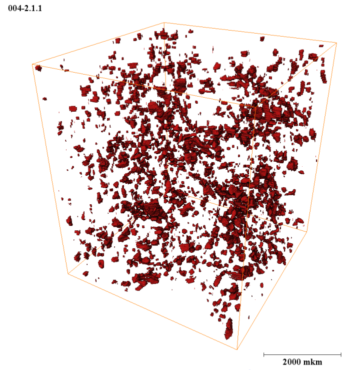
3D Grayscale Model



Ceramics Particles

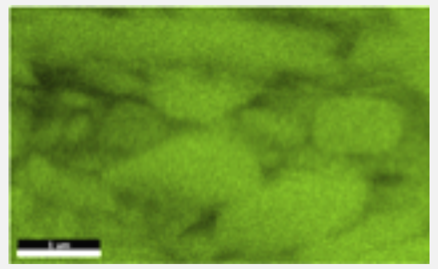


Polymer Interfill

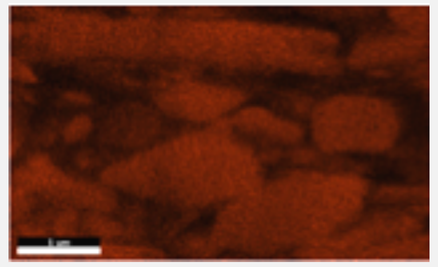


Pores in Polymer

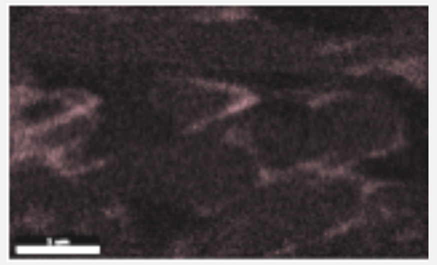
Distribution of chemical elements in a debinded samples of Al_2O_3



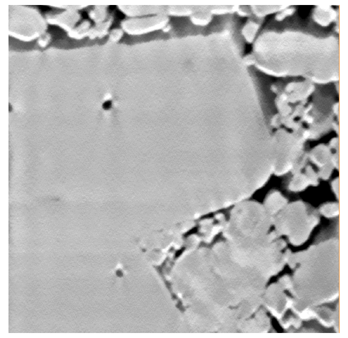
EDS: Aluminum

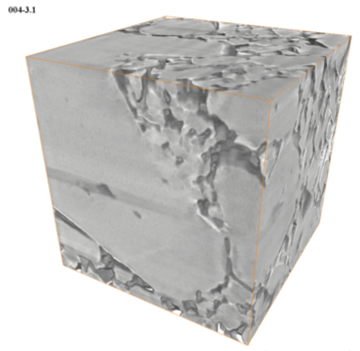


EDS: Oxygen

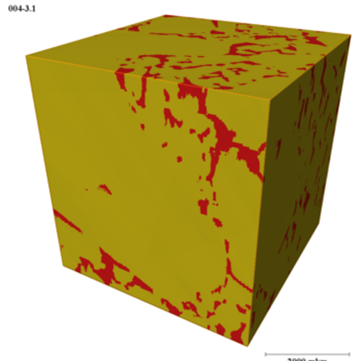


EDS: Carbon

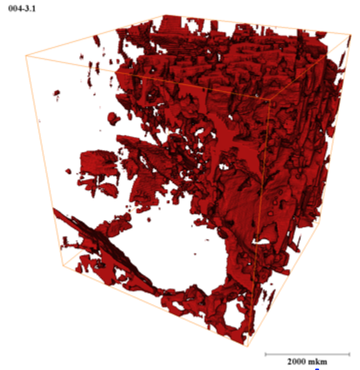




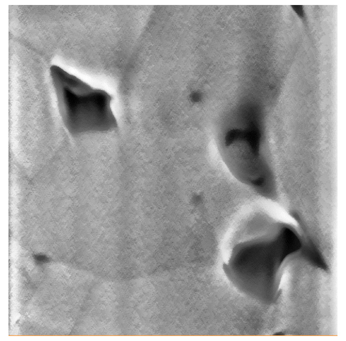
3D Grayscale Model

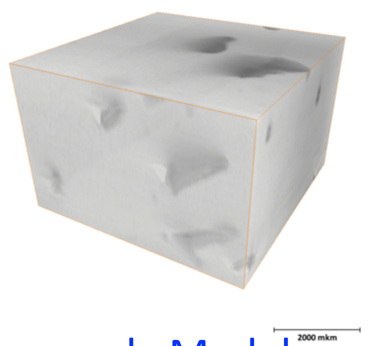


Ceramics Particles



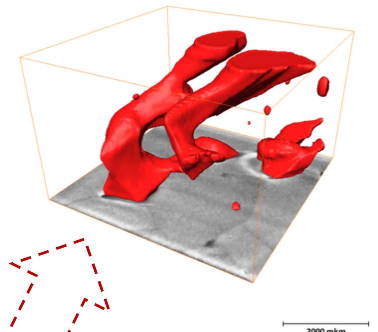
Pores in Brownbody





3D Grayscale Model

Ceramics Grains



Pores in Sintered object

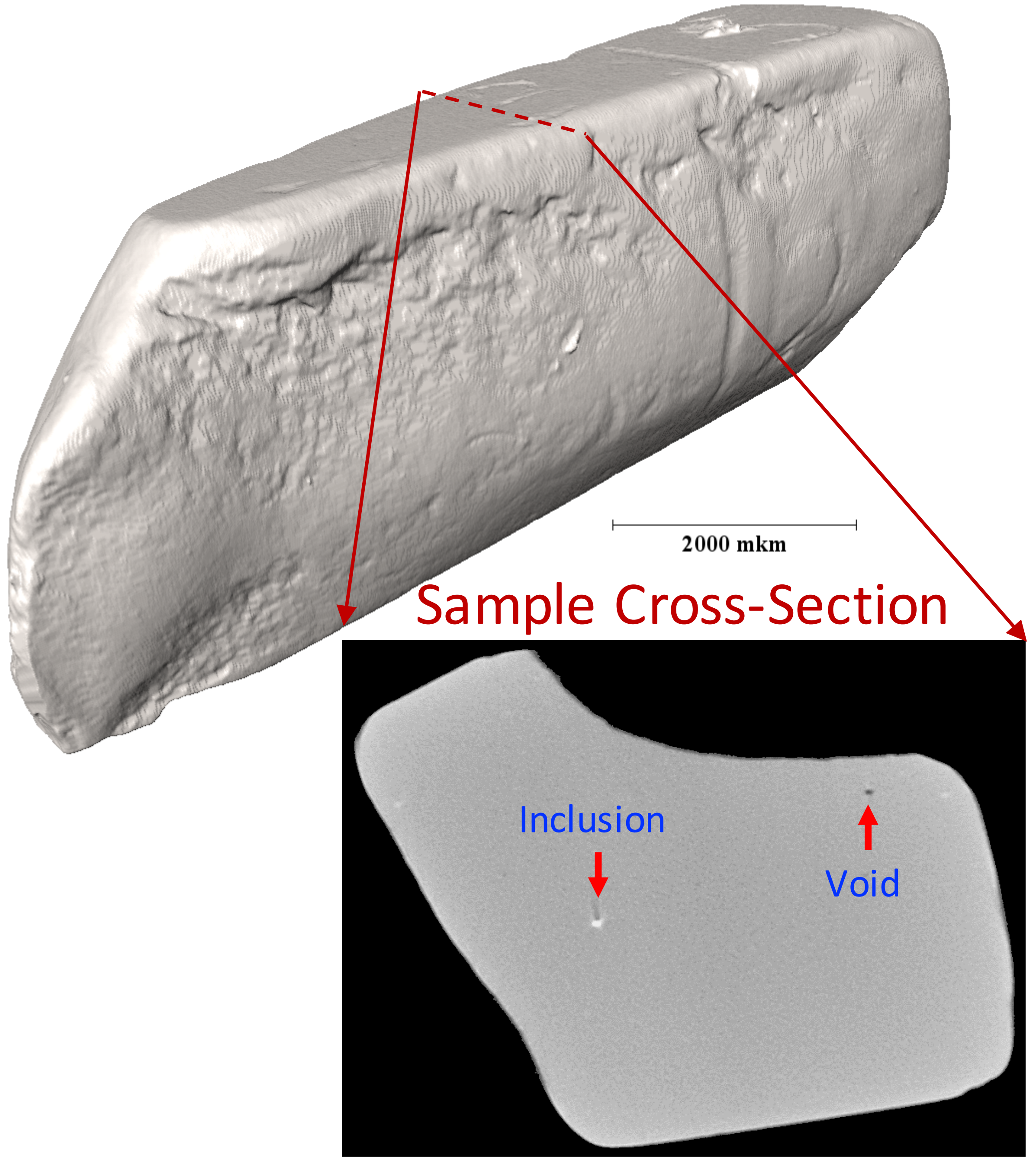
The FIB/SEM-based microstructural 3D images of the Sintered Object reveal the existence of large roundish voids, despite the strict following of the manufacturer's suggested optimized procedure for the feedstock especially developed for the utilized 3D printer.

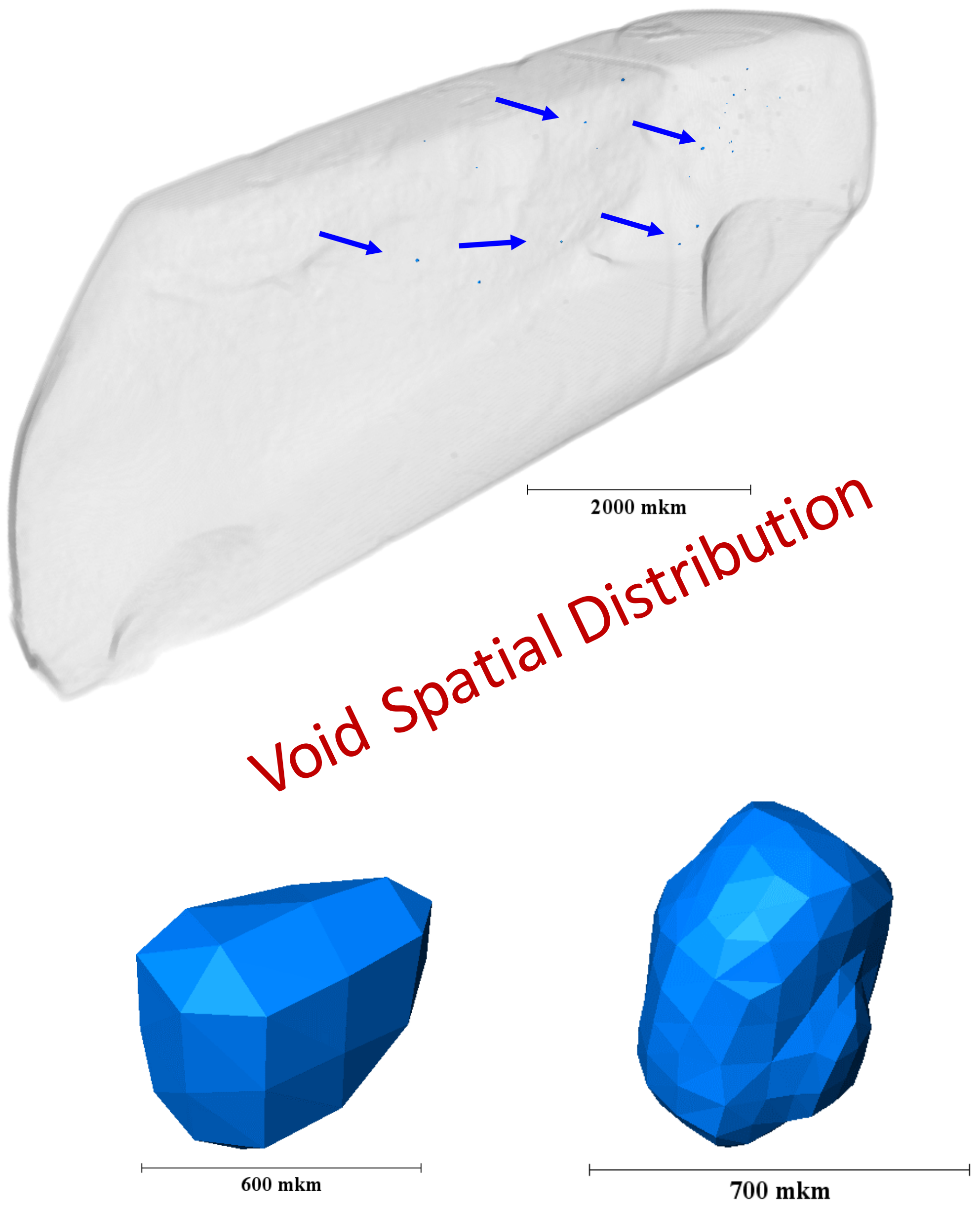
Why the Coarsening process takes place where the Densification process is expected? Why it happens at some spots only?

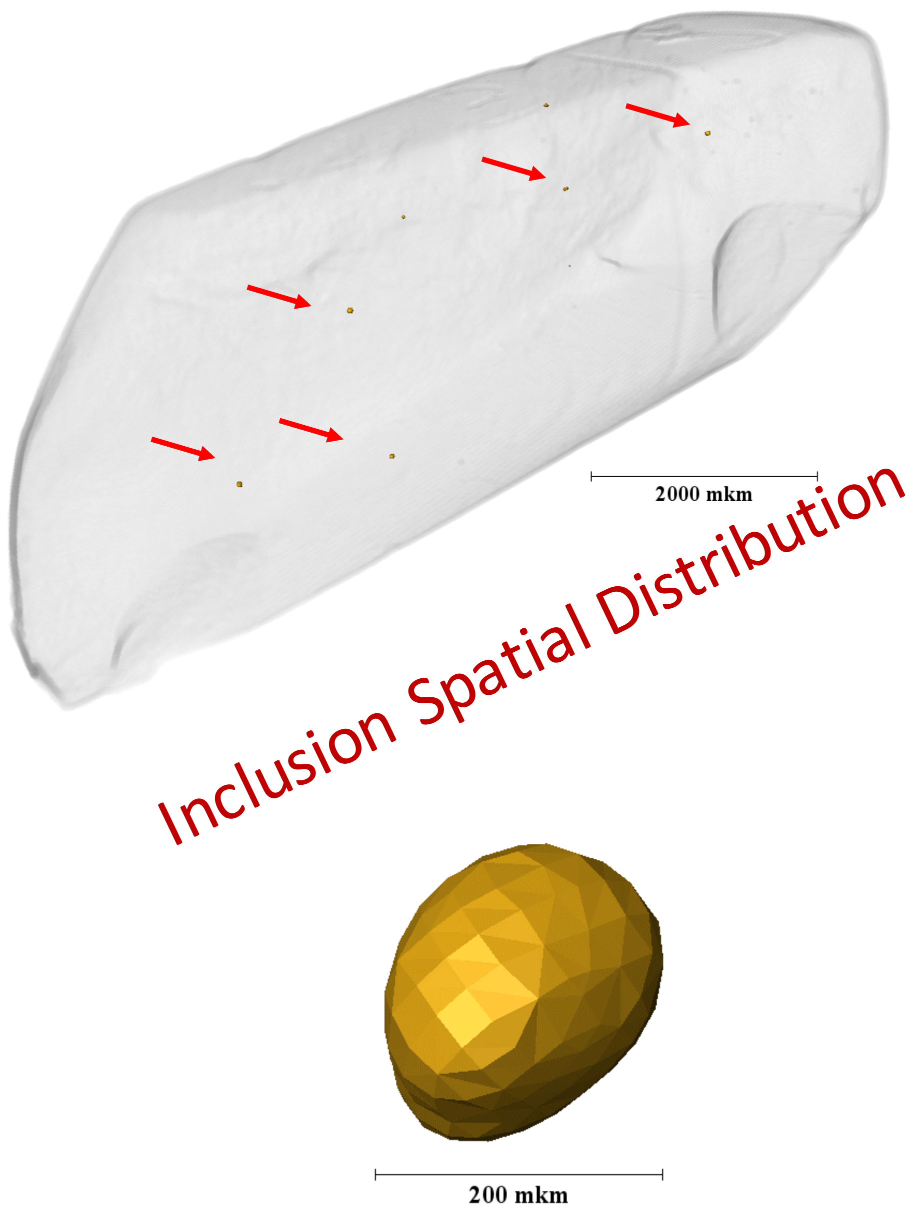
Stereolithography: Material Characterization

Microstructural material characterization at large scale allows assessment of a large volume of material with the cost of reduced resolution.
The shown CT model is in centimeter range, the scanning resolution reached 5 µm/voxel

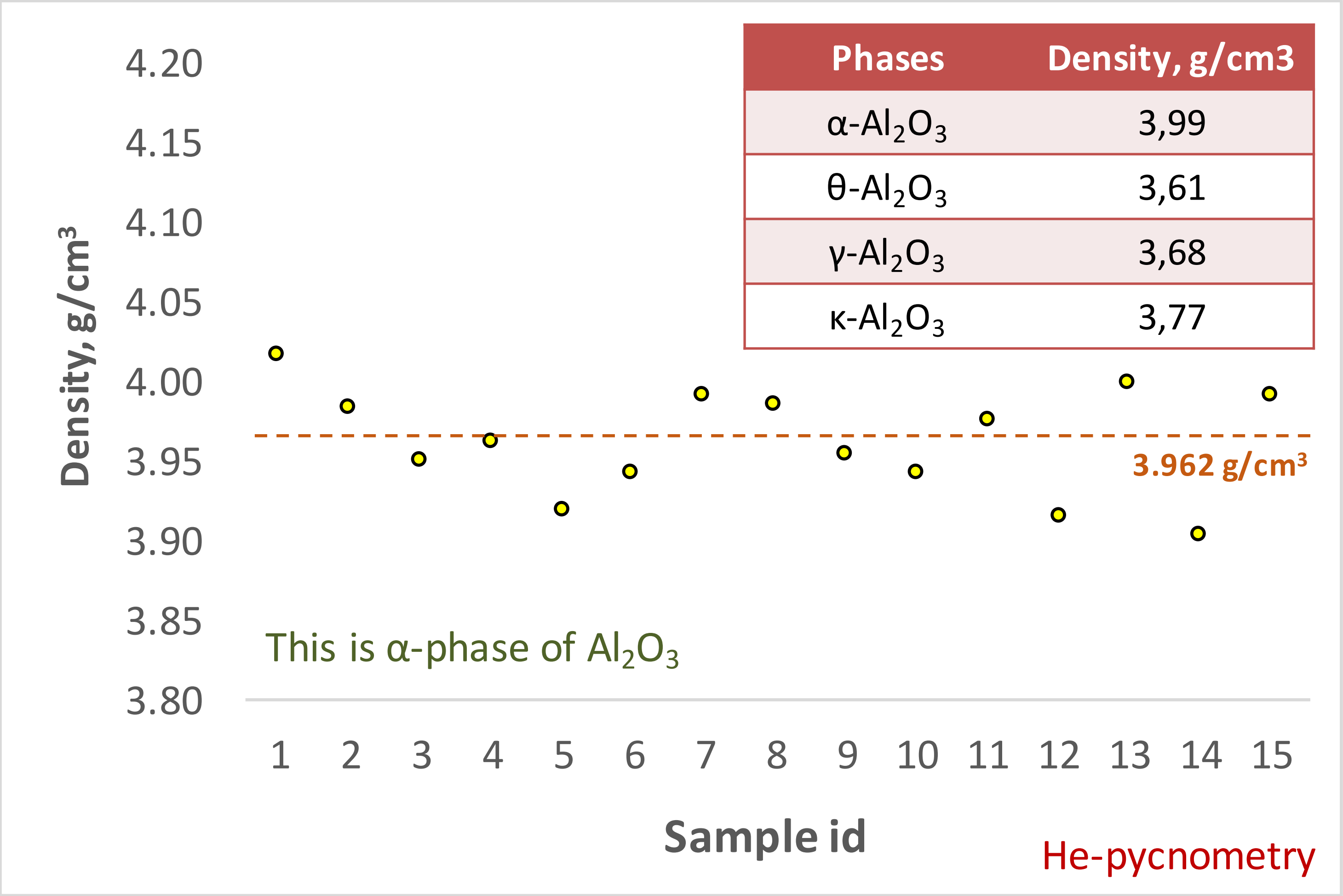
The completely sintered ceramic material, additively manufactured in accordance with the optimized procedure, contains a number of large pores and a few dense inclusions. What is the nature of the voids and the dense inclusions? What physical process is responsible for their origin?



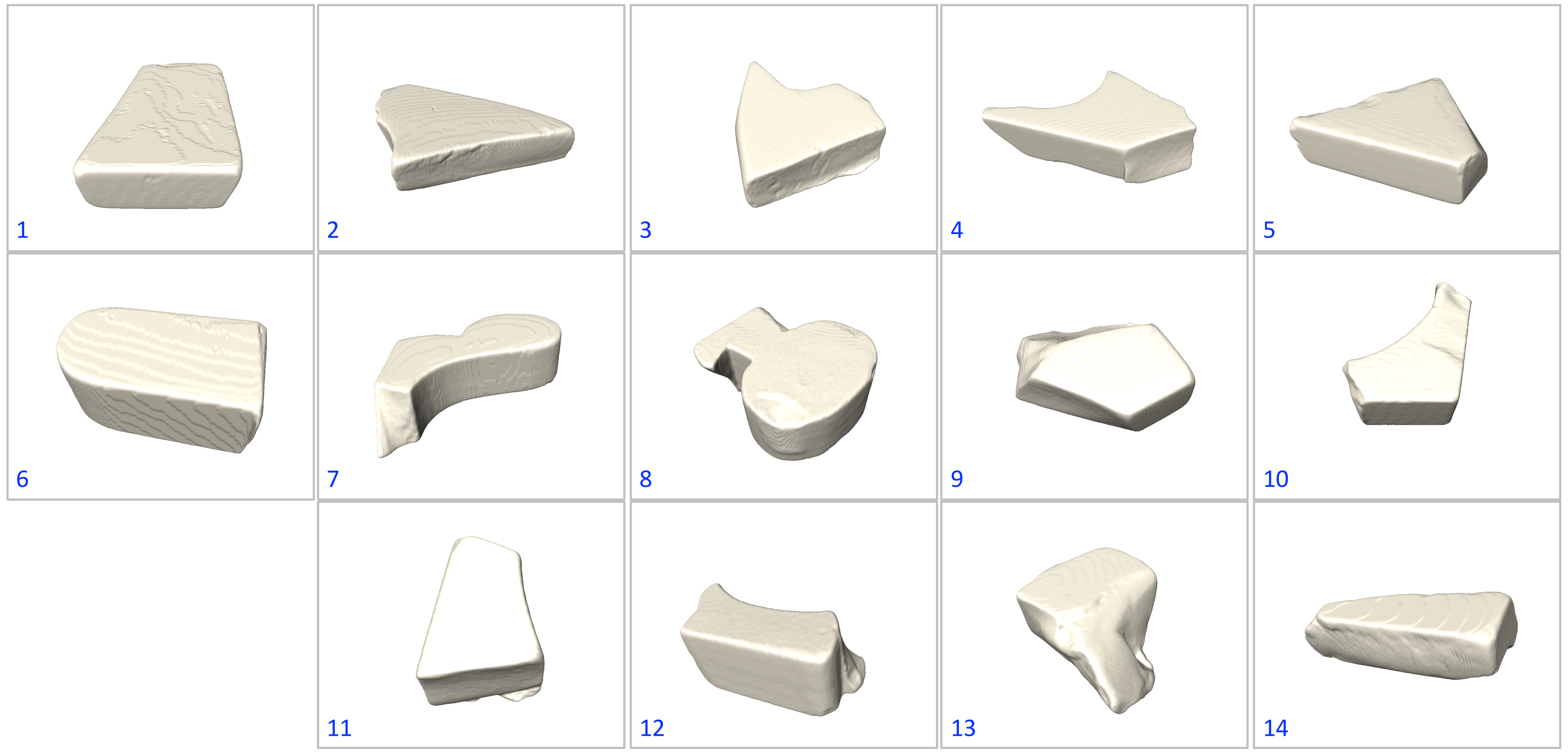


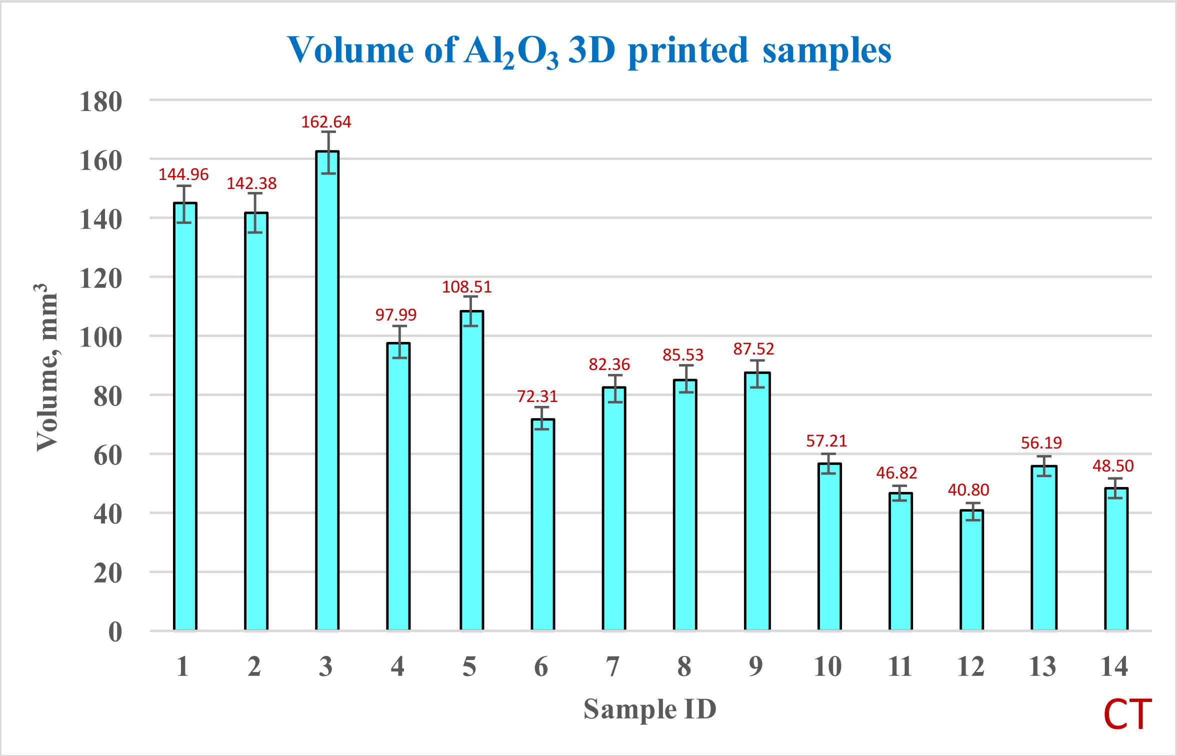


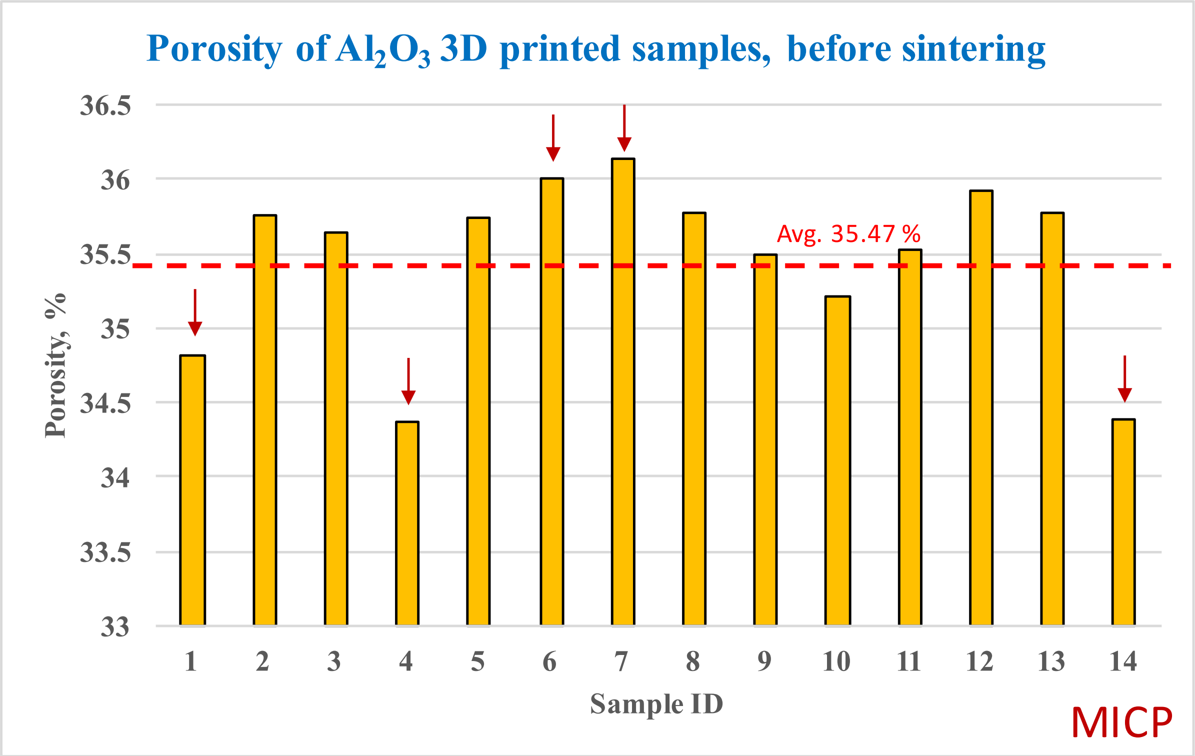
Stereolithography: Material Characterization

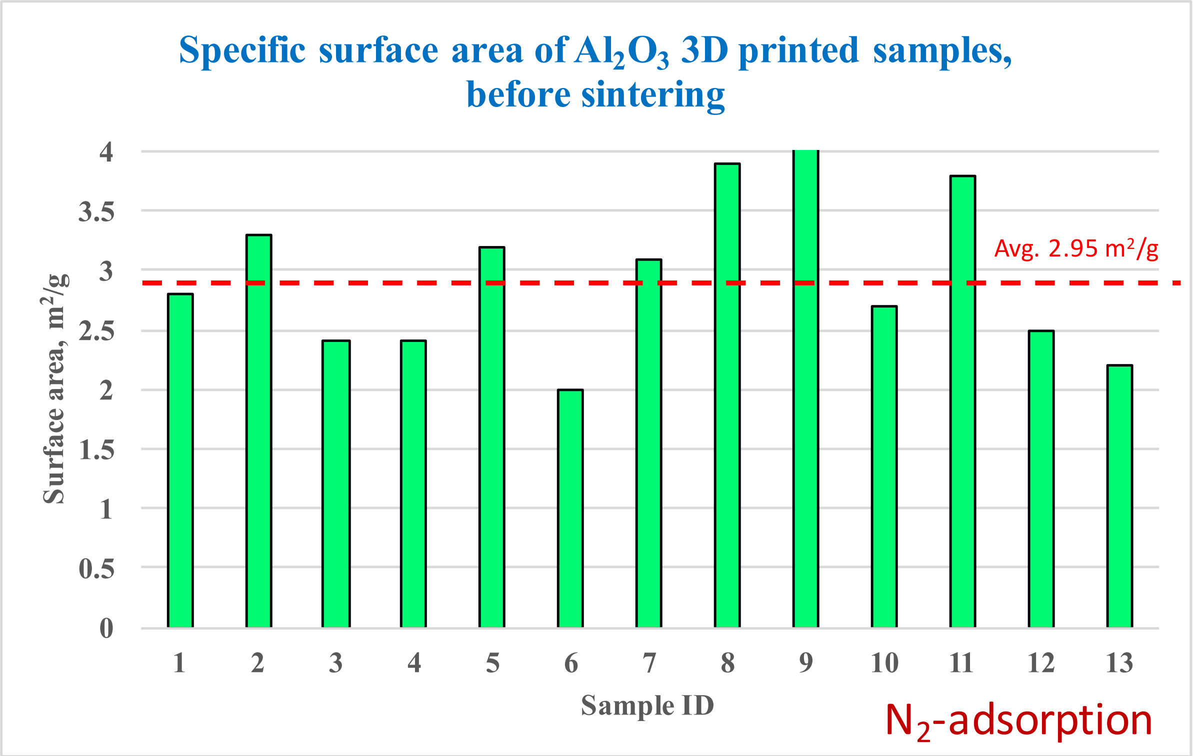


Phases	Density, g/cm3
α-Al_2O_3	3,99
θ-Al_2O_3	3,61
γ-Al_2O_3	3,68
κ-Al_2O_3	3,77

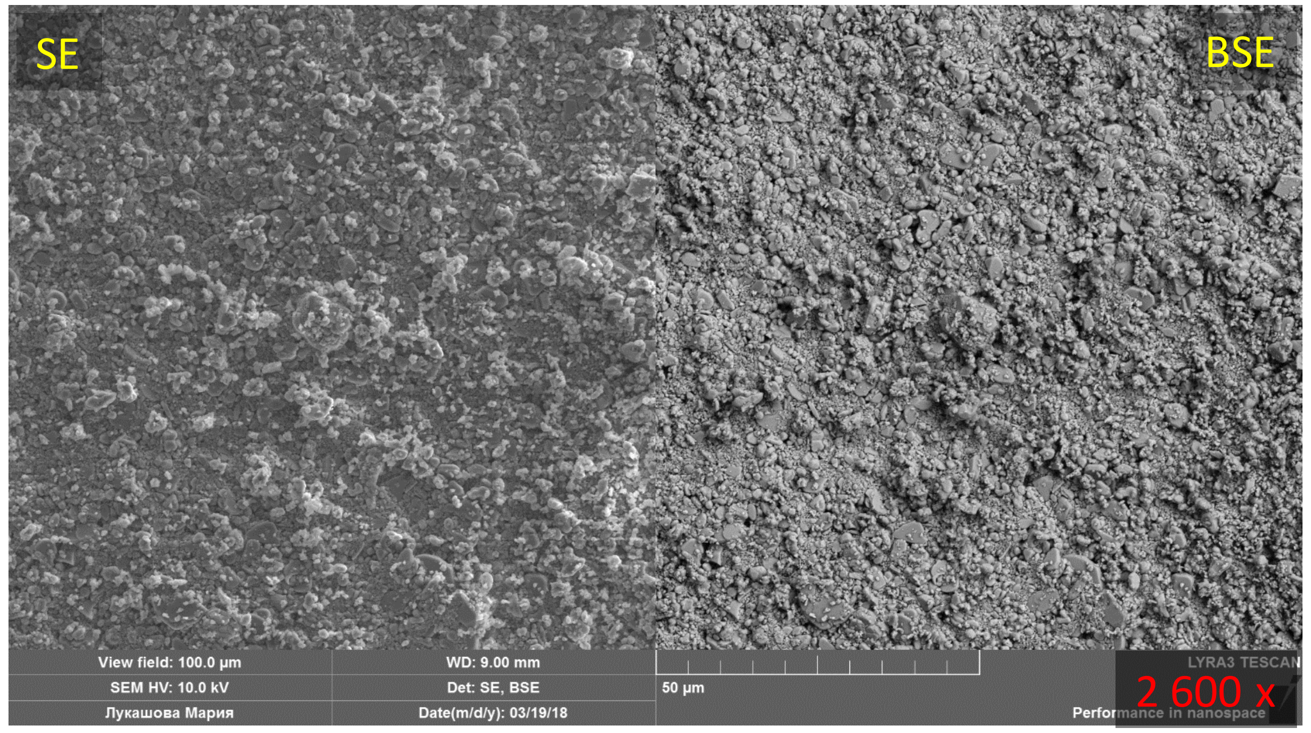


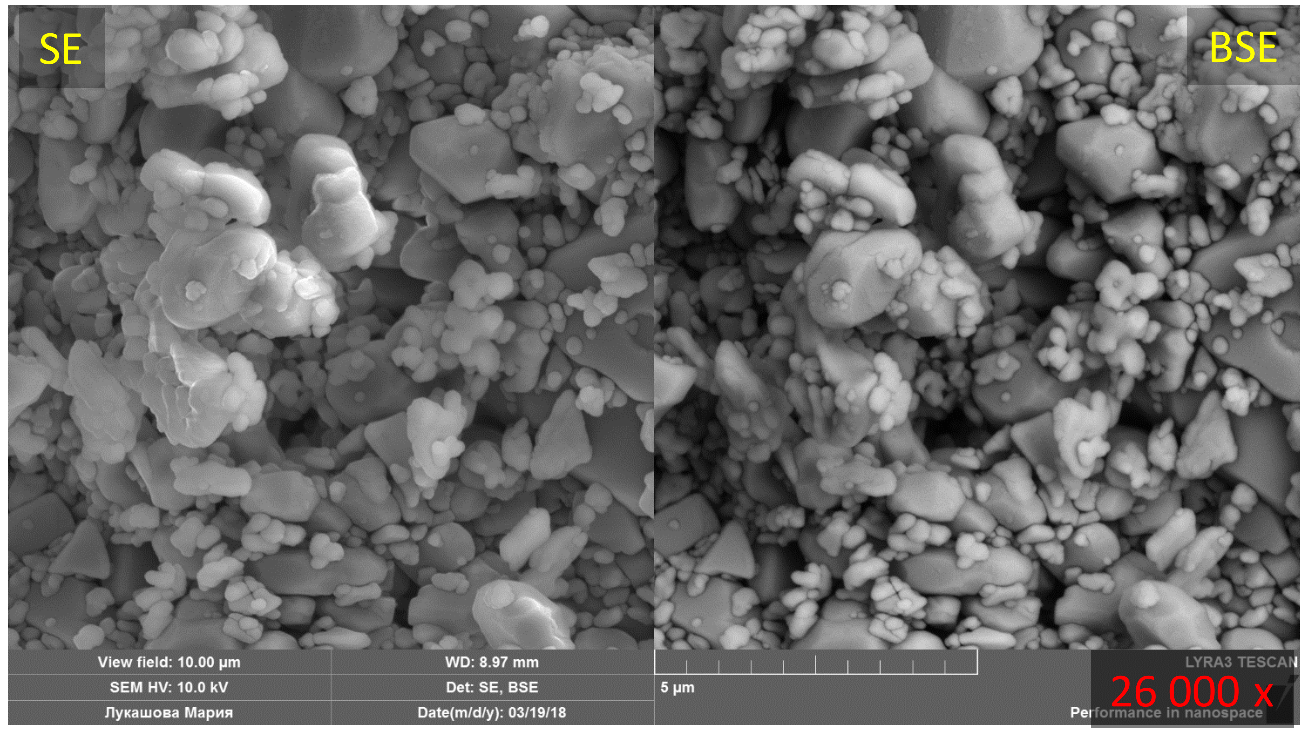




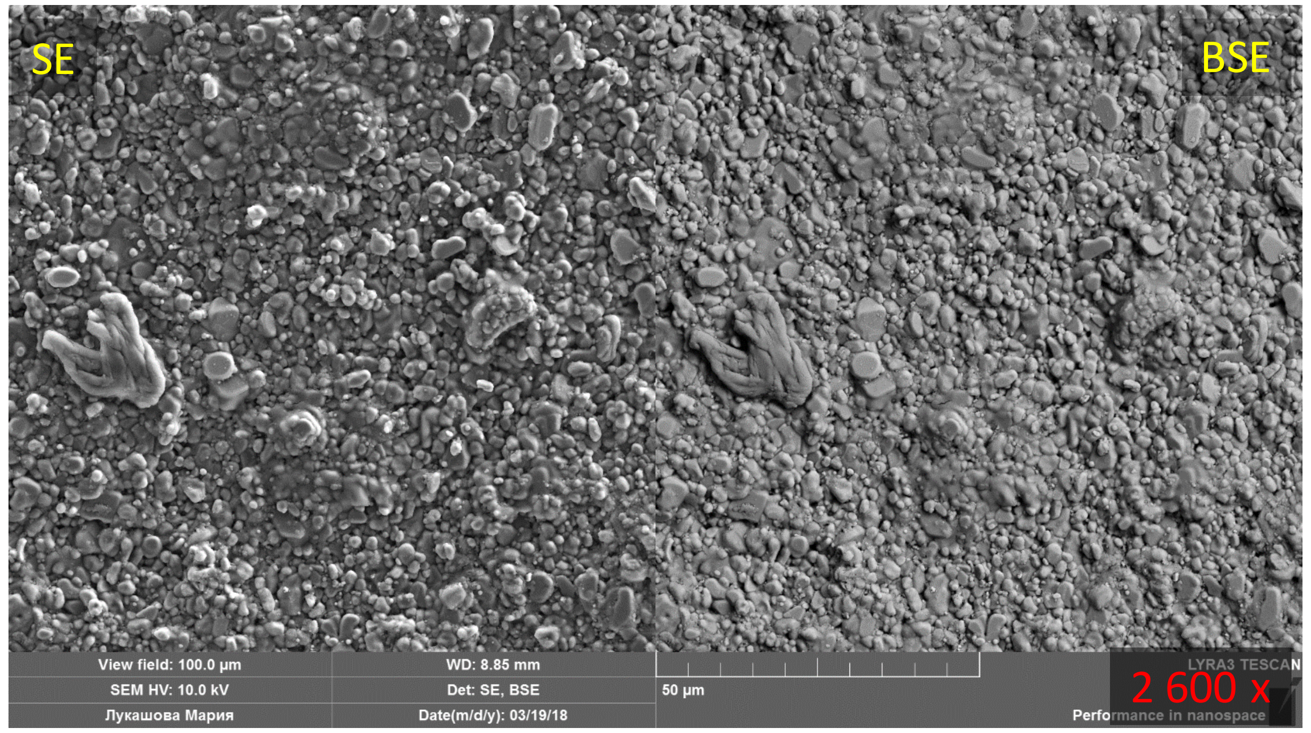


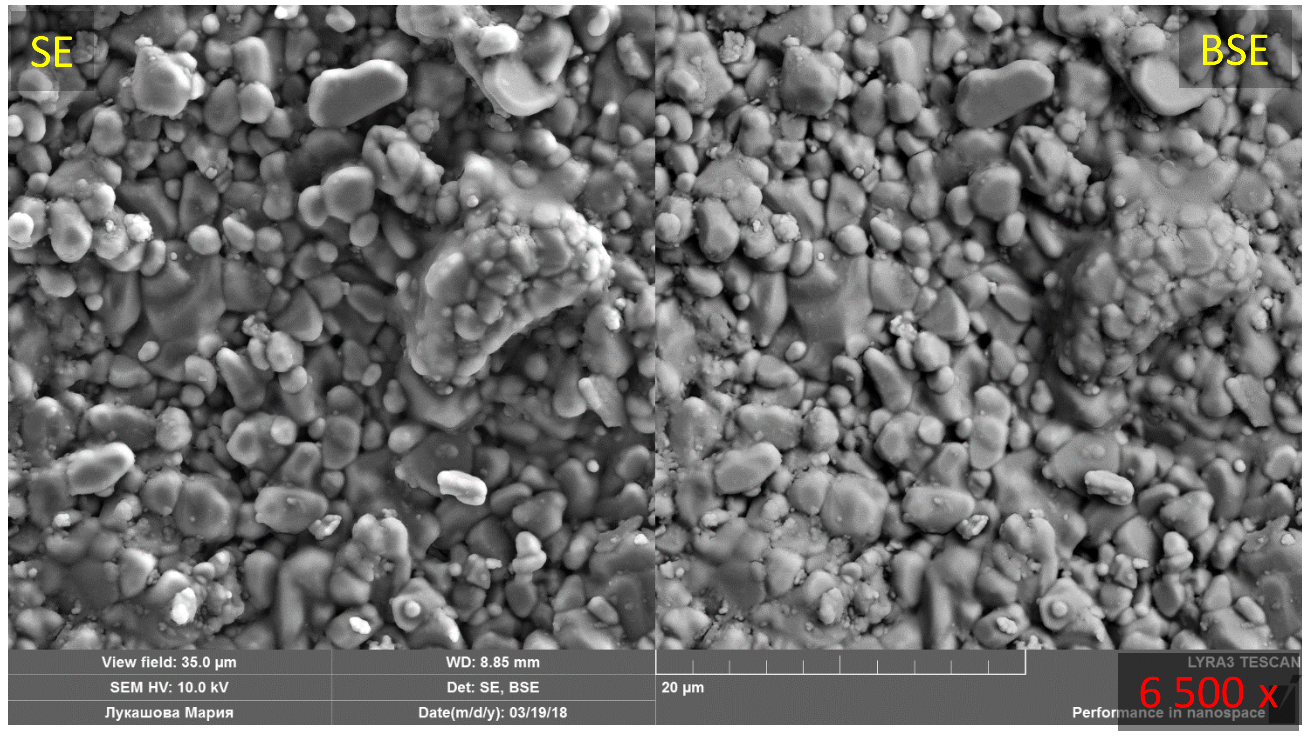
Stereolithography: Material Characterization



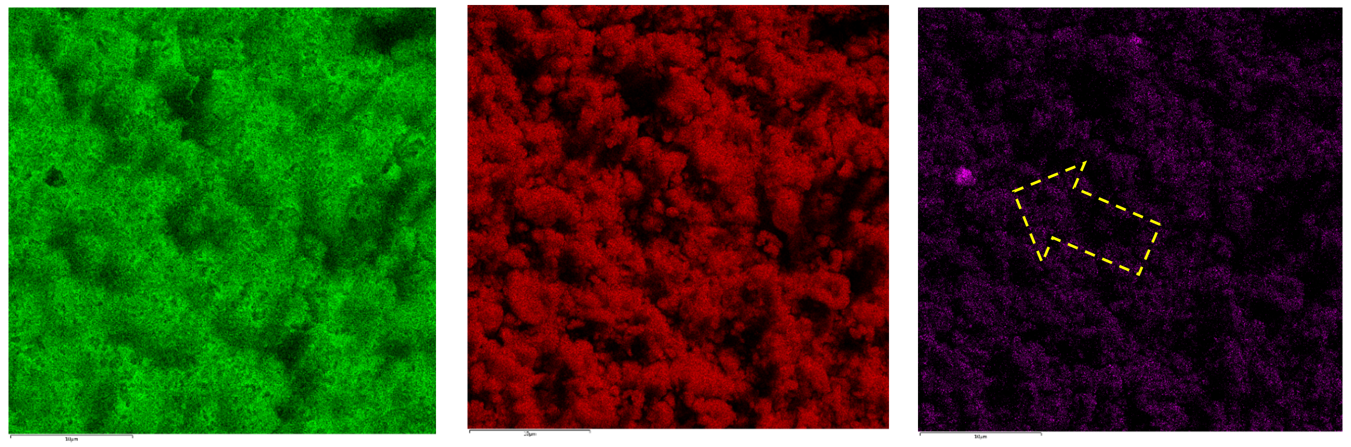


SEM image of a debinded sample surface



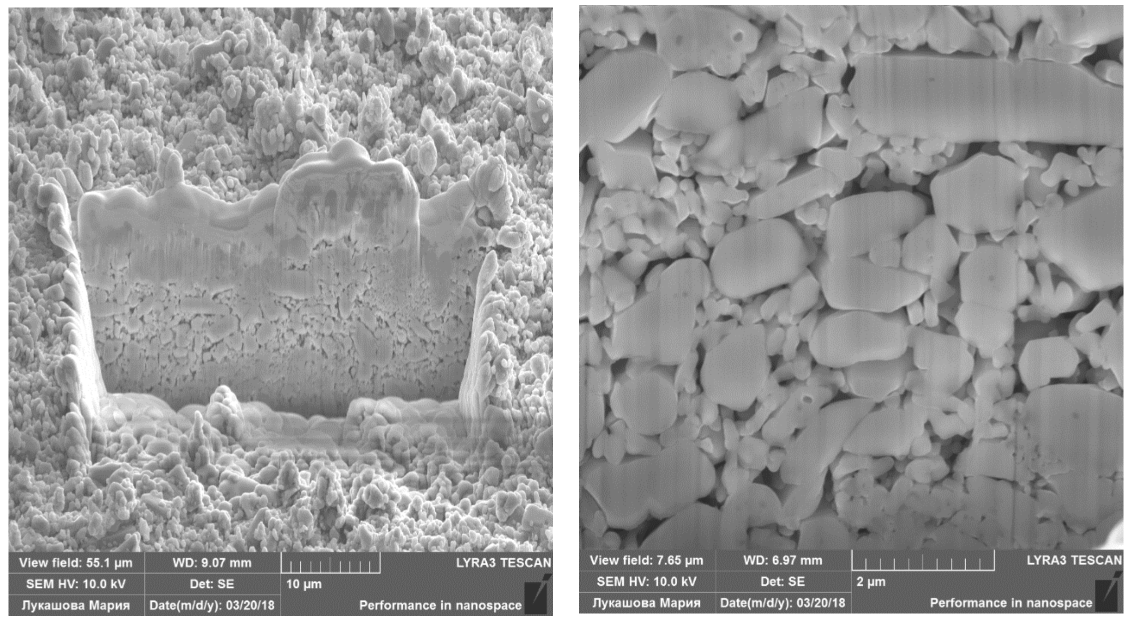


SEM image of a sintered sample surface



Aluminum Oxygen Carbon

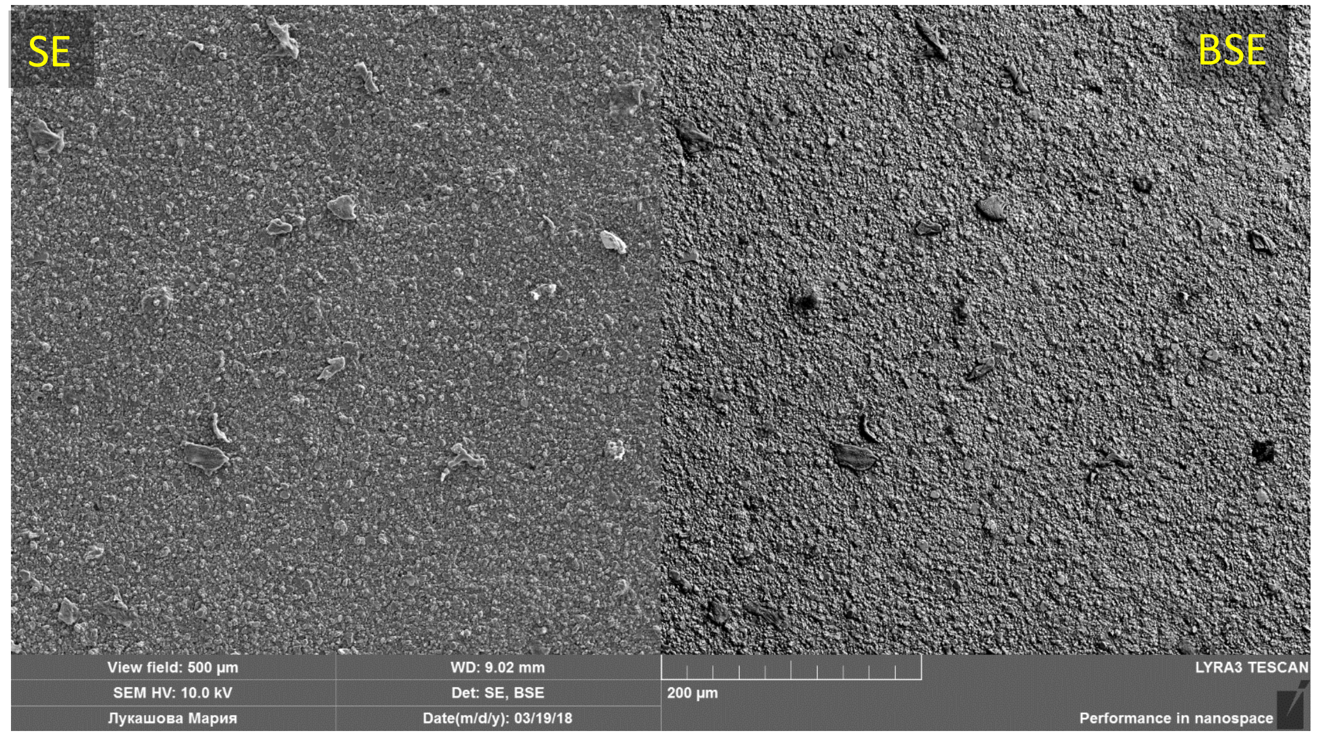
EDS images of a sintered sample
There are inclusions of carbon in the structure.
Was the debinding efficient?



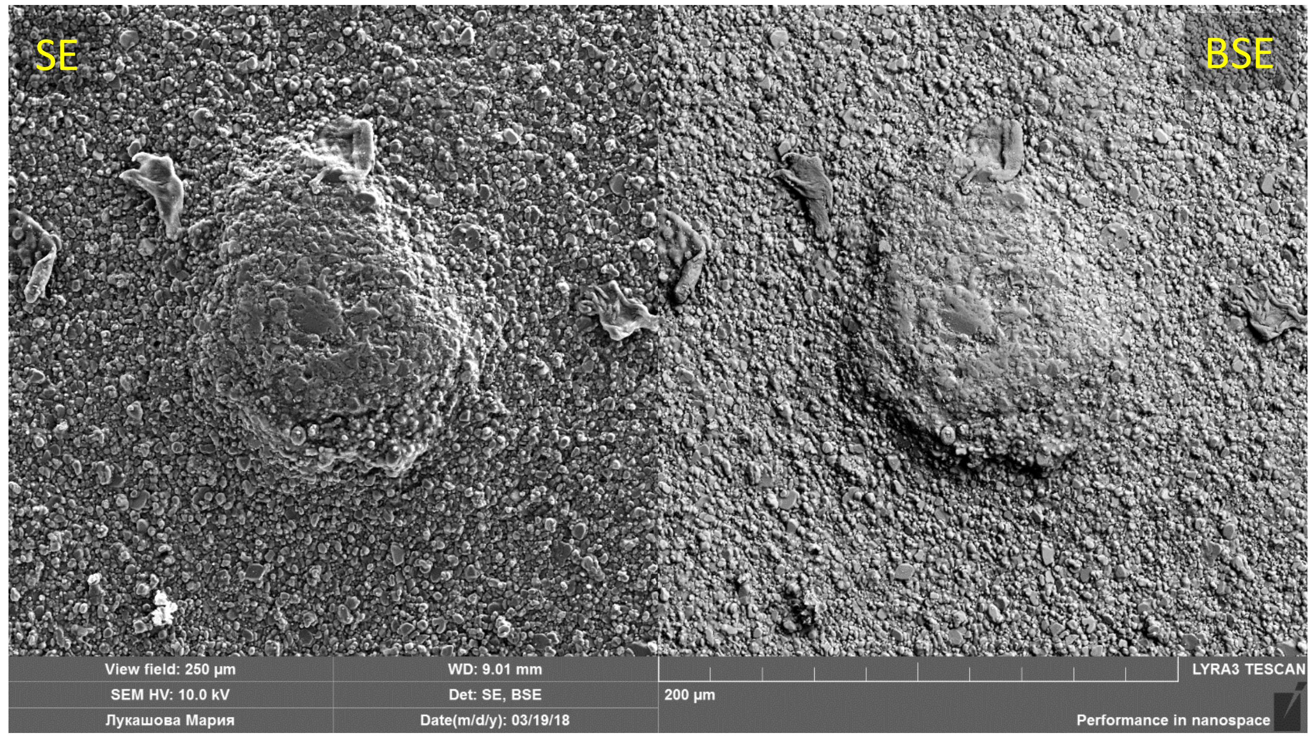
Debinded material "under the surface" structure, revealed with FIB

In terms of the surface structure, the debinded and sintered samples appear not much different.
2D SEM characterization is not sufficient – a 3D "under the surface" structure is of great interest

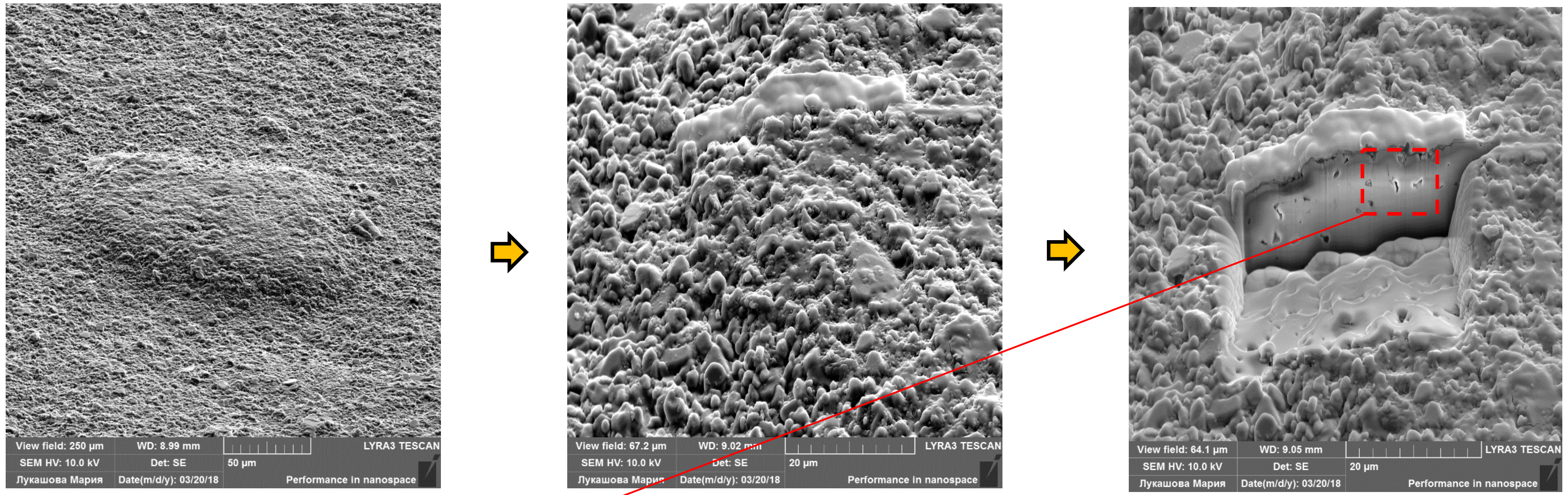
Stereolithography: Microstructural irregularities, Carbon inclusions

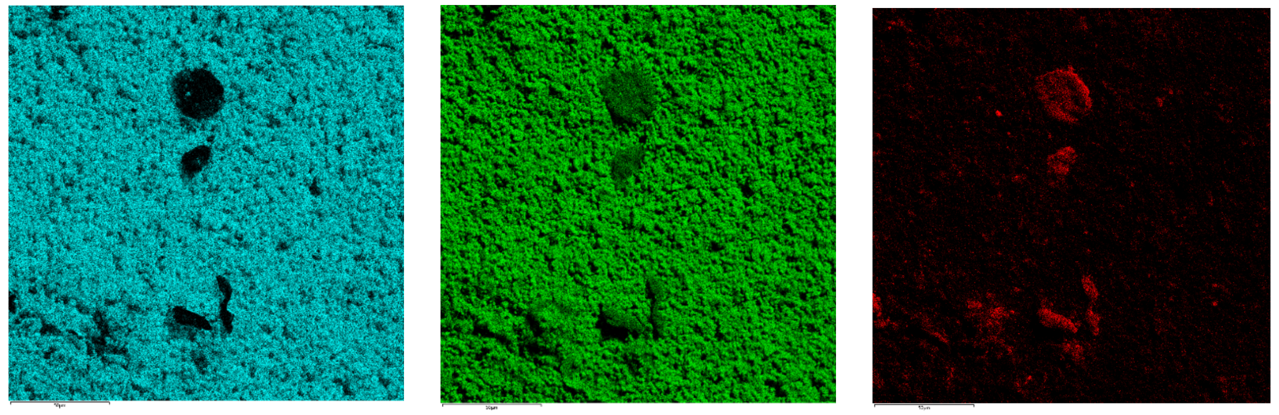


"Flakes" at the surface of the sintered sample.



Convexities at the surface of the sintered sample.





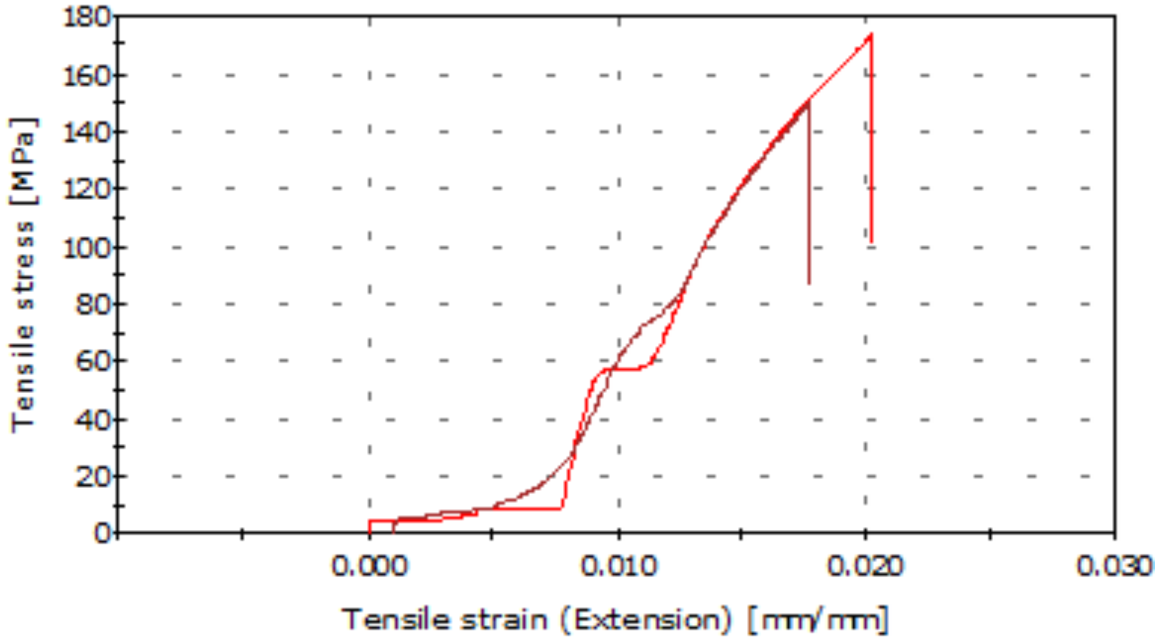
Aluminum Oxygen Carbon

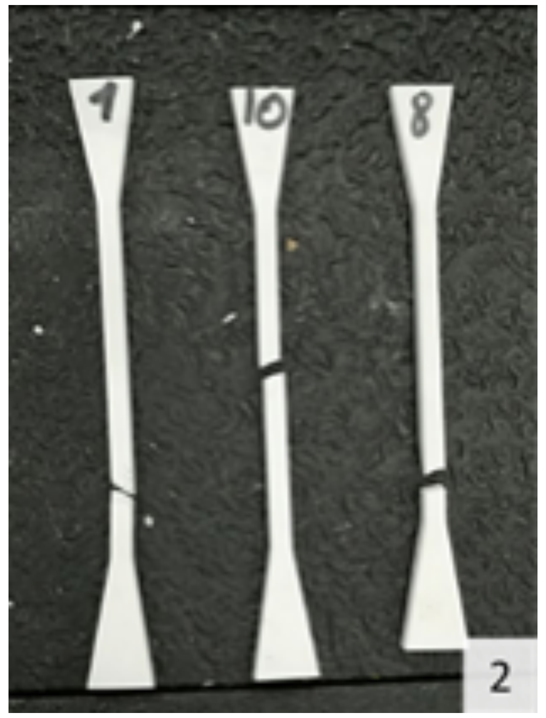
Carbon inclusions form flake-like structures in the sintered Al2O3 material, they appear despite following the manufacturer's suggested optimized manufacturing procedure.

An advanced numerical simulator of ceramics sintering process is on demand, to account for multiple physical peculiarities and to pre-engineer material's microstructure.

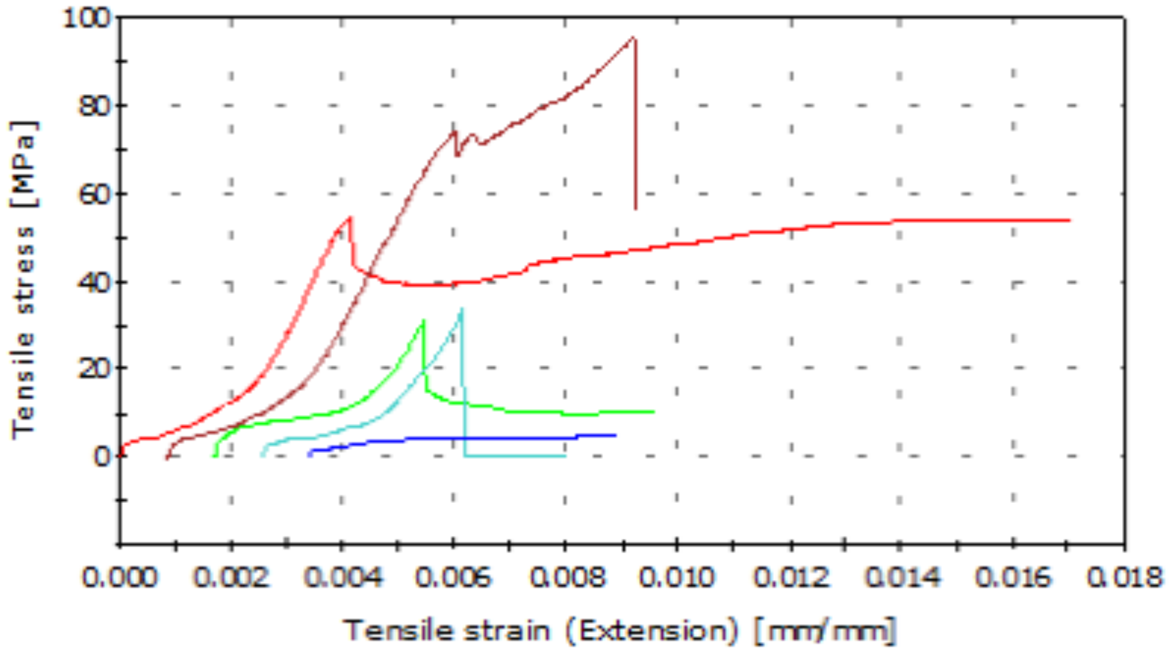
Stereolithography: Material Mechanical Testing

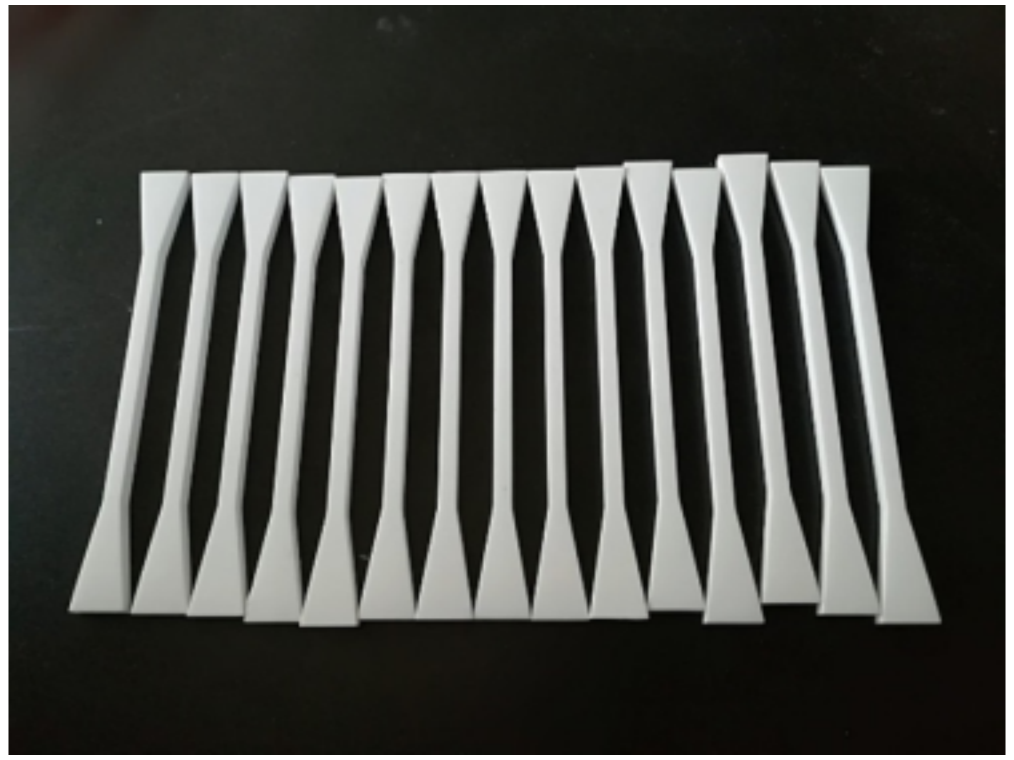
Successful tests





Testing Failure





Mechanical testing often fails for ceramic samples, because even light deviation of the sample from the straight shape converts Tensile test into Bending test, while sample is being clamped to the testing device

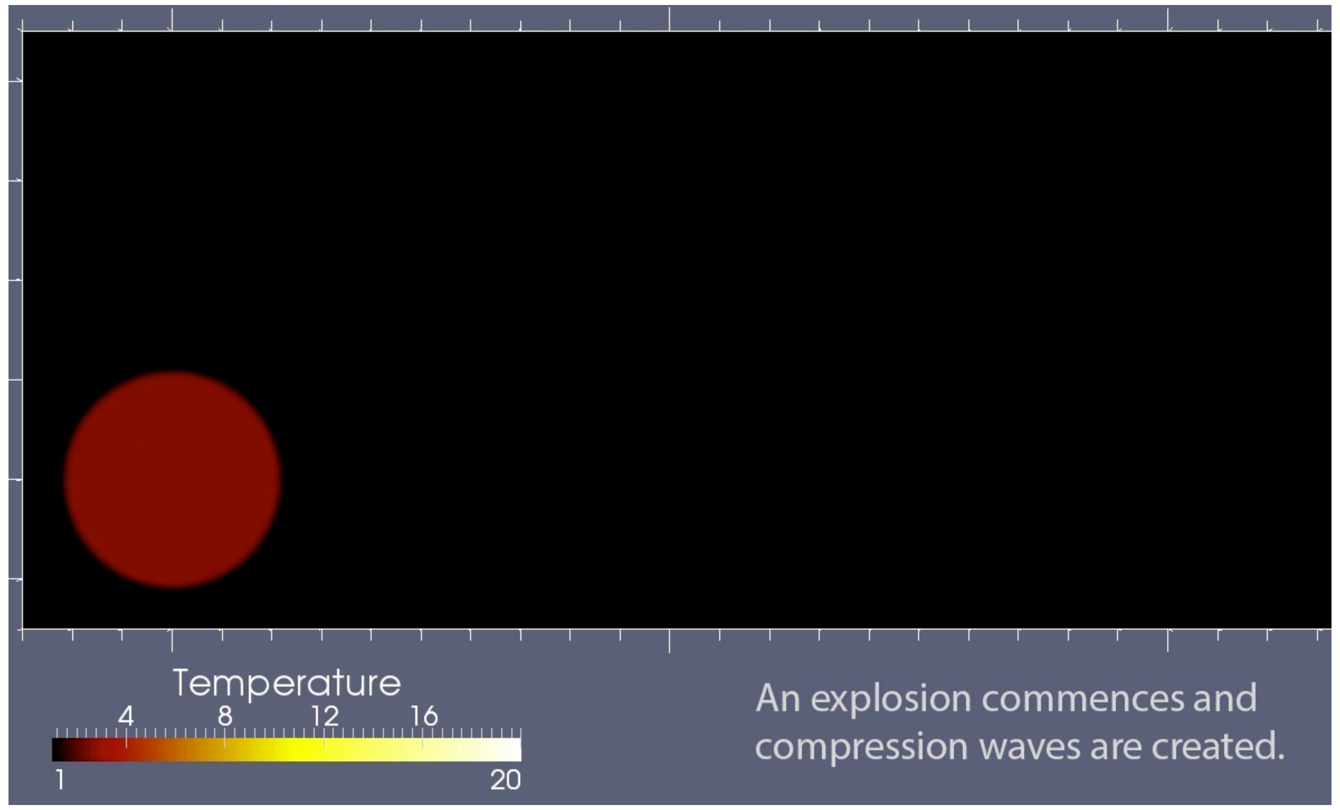
Physics of the printing process needs to be studied in detail to determine correlations between the action of surface tension and substrate adhesion, which are the primary sources of parts curling during 3D printing

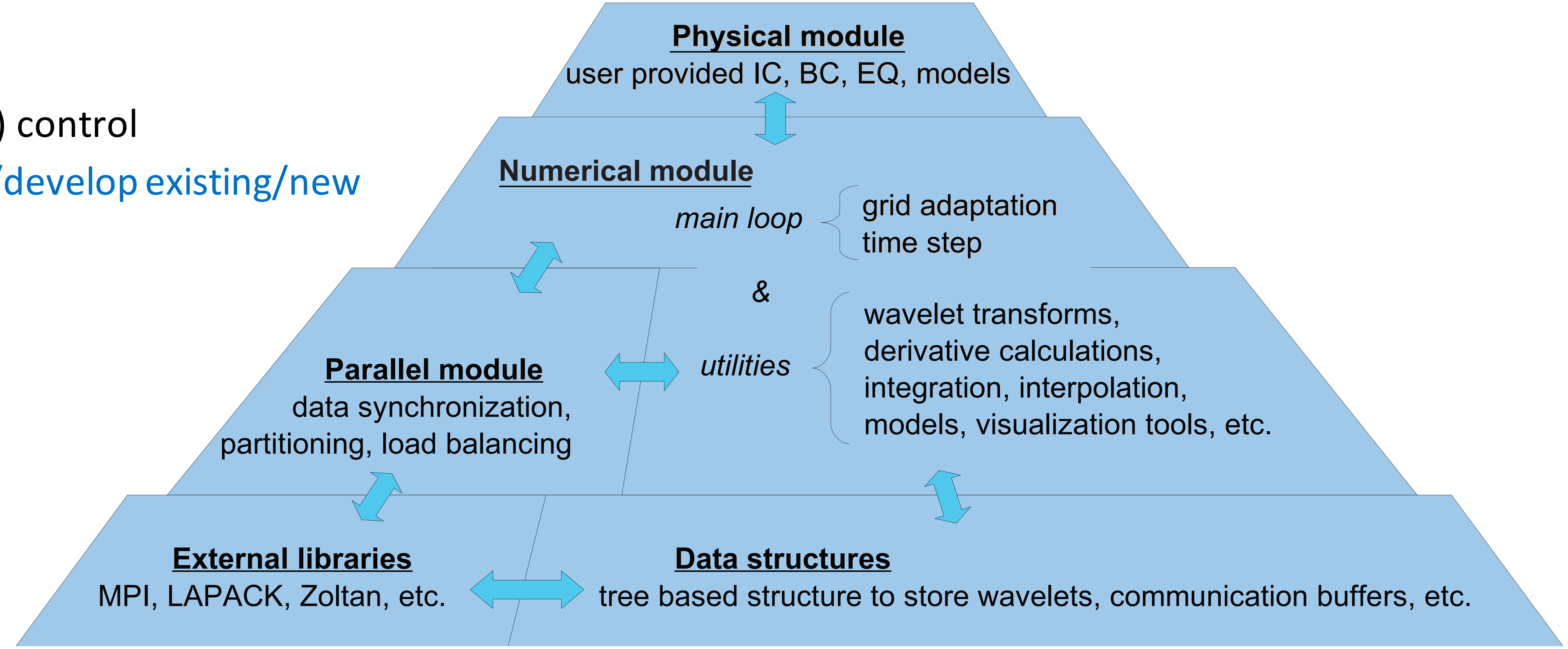
Modeling of Multiscale Phenomena for Additive Manufacturing

Development of robust, computationally efficient, predictive modeling and simulation tools with fully integrated and automated:

1. massively parallel CFD code
2. wavelet multi-resolution
3. space-time mesh adaptation
4. mesh generation from auto CAD
5. dynamic model-form selection/adaptation,
6. active error control
7. mesh quality control
8. model fidelity (physical complexity) control

that can be used to understand/improve/develop existing/new advanced manufacturing technologies.





Adaptive Wavelet Environment for in Silico Universal Multiscale Modeling (AWESUMM)

Multiscale Modeling and Simulation of Selective Laser Melting (SLM)

Additive manufacturing process:

1. Powder is deposited by layers
2. Powder grains are melted by high-power laser beam
3. Part is build slice by slice

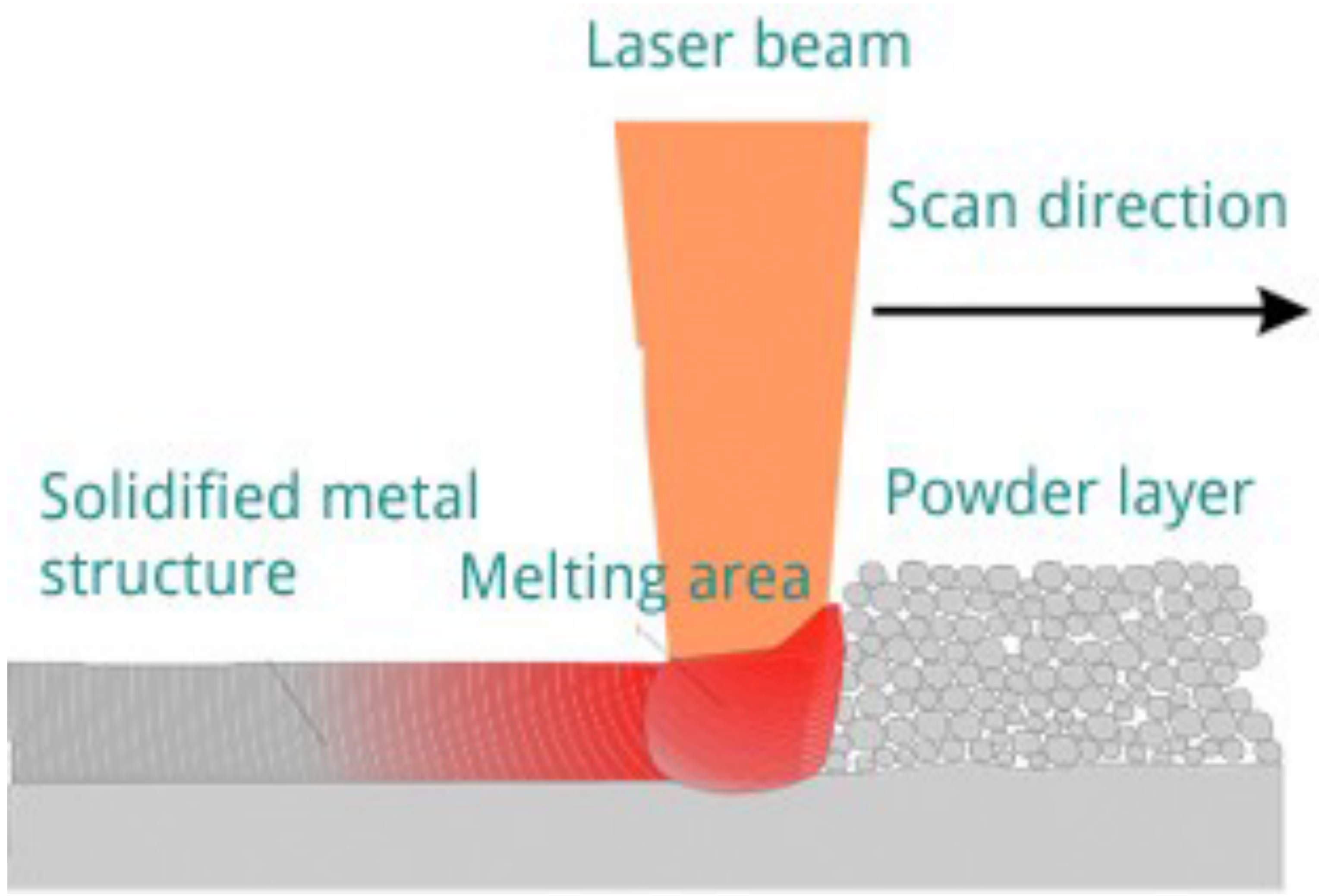


Image source: http://iq-evolution.com/en/slm-centrum/selective-laser-melting-ii

Limitations and Challenges of SLM:

1. Limited to selective materials
2. Improve the mechanical characteristics of parts manufactured by SLM
   - anisotropic static and fatigue behavior
   - impact strength
   - compression strength
   - fracture toughness
3. Optimize SLM process to
   - minimize needed support structures and finishing operations
   - increase productivity
4. Improve reproducibility and reliability

Predictive and efficient simulations tools are *required!*

Multiscale Modeling and Simulation of Selective Laser Melting (SLM)

Physical processes to be modelled:

1. Melting, solidification, and melt dynamics including surface tension
2. Evaporation, condensation, and vapor dynamics
3. Heat conduction
4. Laser beam reflection and absorption
5. Effect of surfactants
6. Prediction of microstructure of solidified material

Complexity of SLM physics:

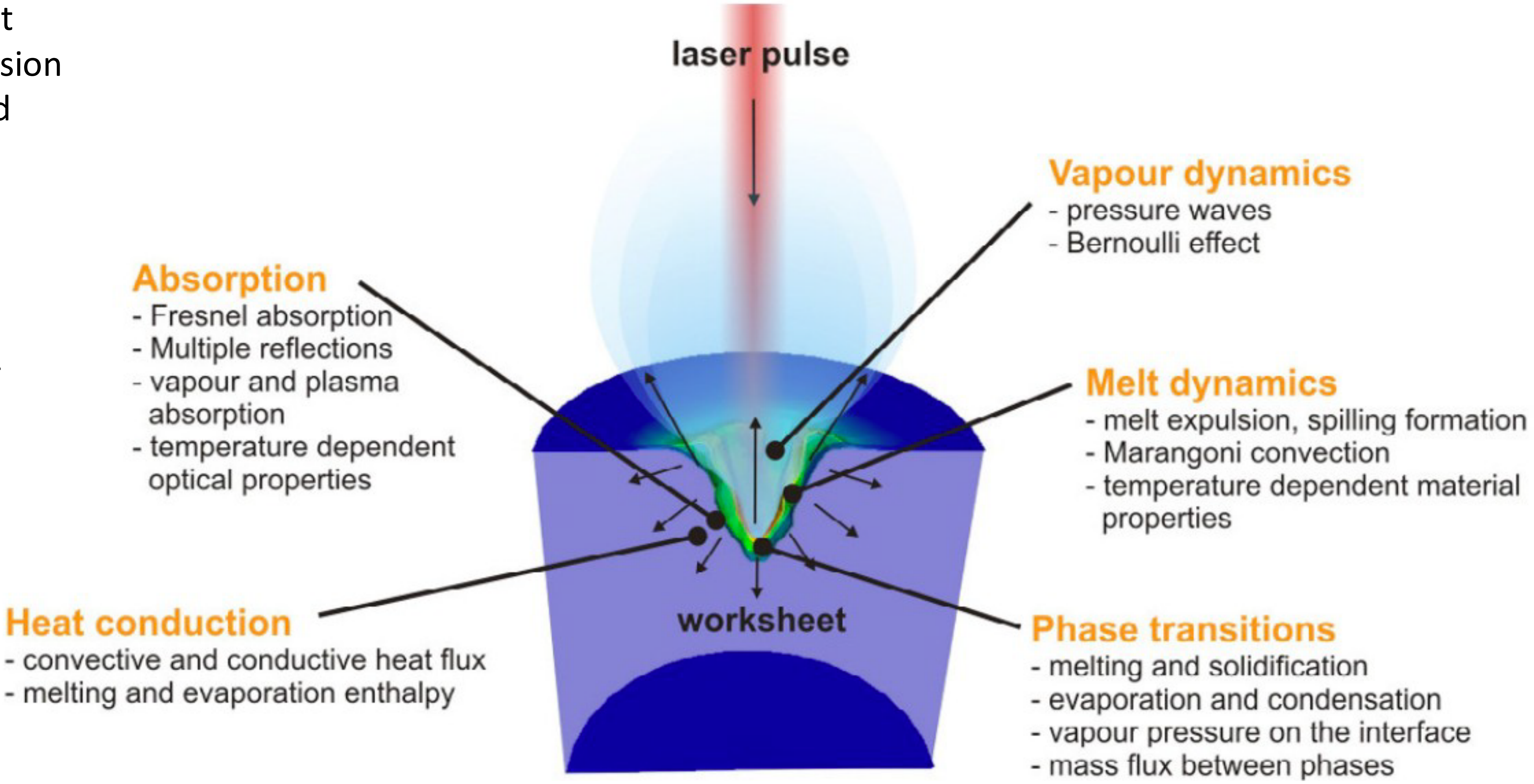


Image source: Andreas Otto and Michael Schmidt. Towards a universal numerical simulation model for laser material processing. Physics Procedia, 5:35–46, 2010.

Geometric Modeling for AM

Problems with Using Additive Manufacturing

- Absence of the “3D Print” button
- Necessity of specialist knowledge: from 3D modeling to the printing process details
- The process includes up to 5 stages: (1) modeling, (2) saving/conversion to a special file, (3) validation, (4) healing, (5) loading and parameter tuning
- 3D models are often non-printable – often simply “garbage”
- No universal protocol covering capabilities of modern printers:
multi-material printing and multi-level microstructures with extremely high resolution

Lack of Universal Protocol

No universal protocol covering capabilities of modern printers:

- multi-material printing
- multi-level microstructures with extremely high resolution

Modeling system for geometry, nested microstructures and multiple materials

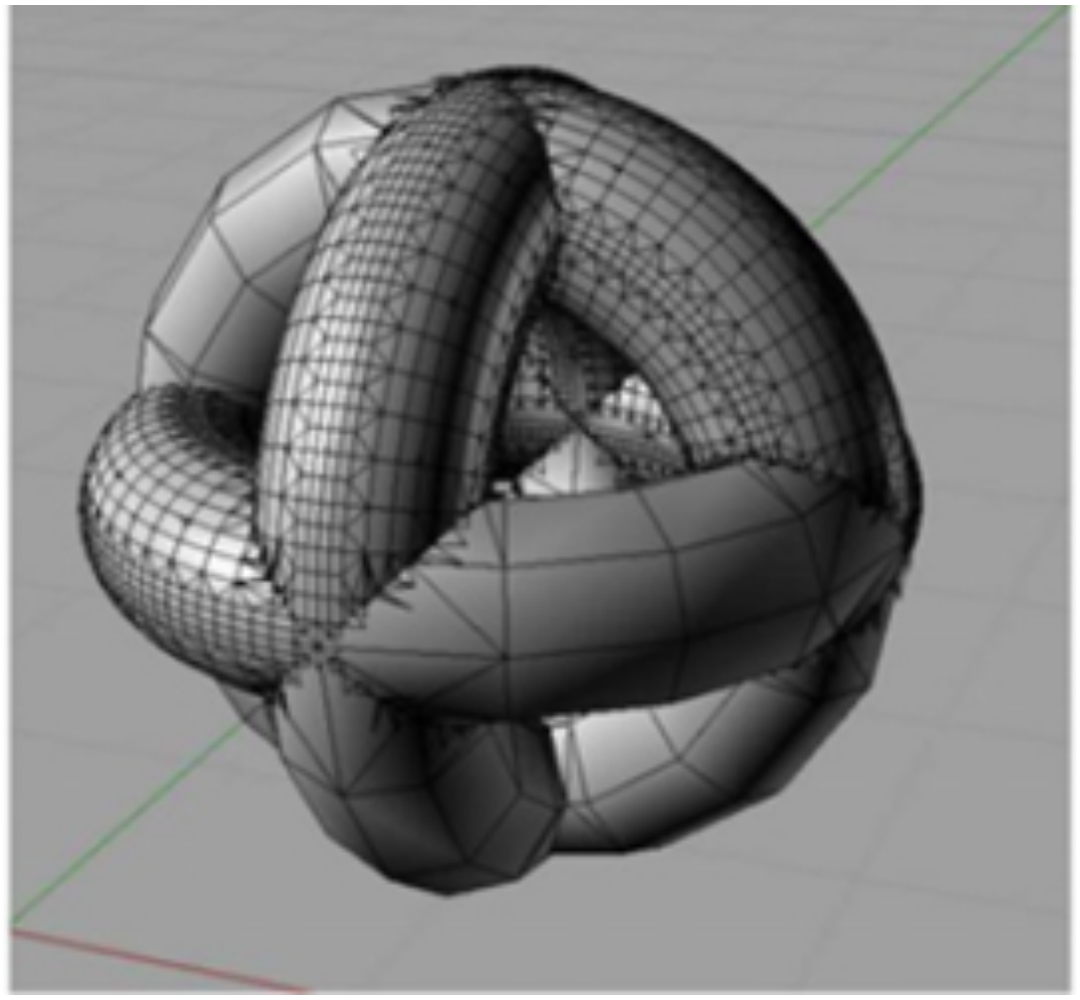
NO PROTOCOL

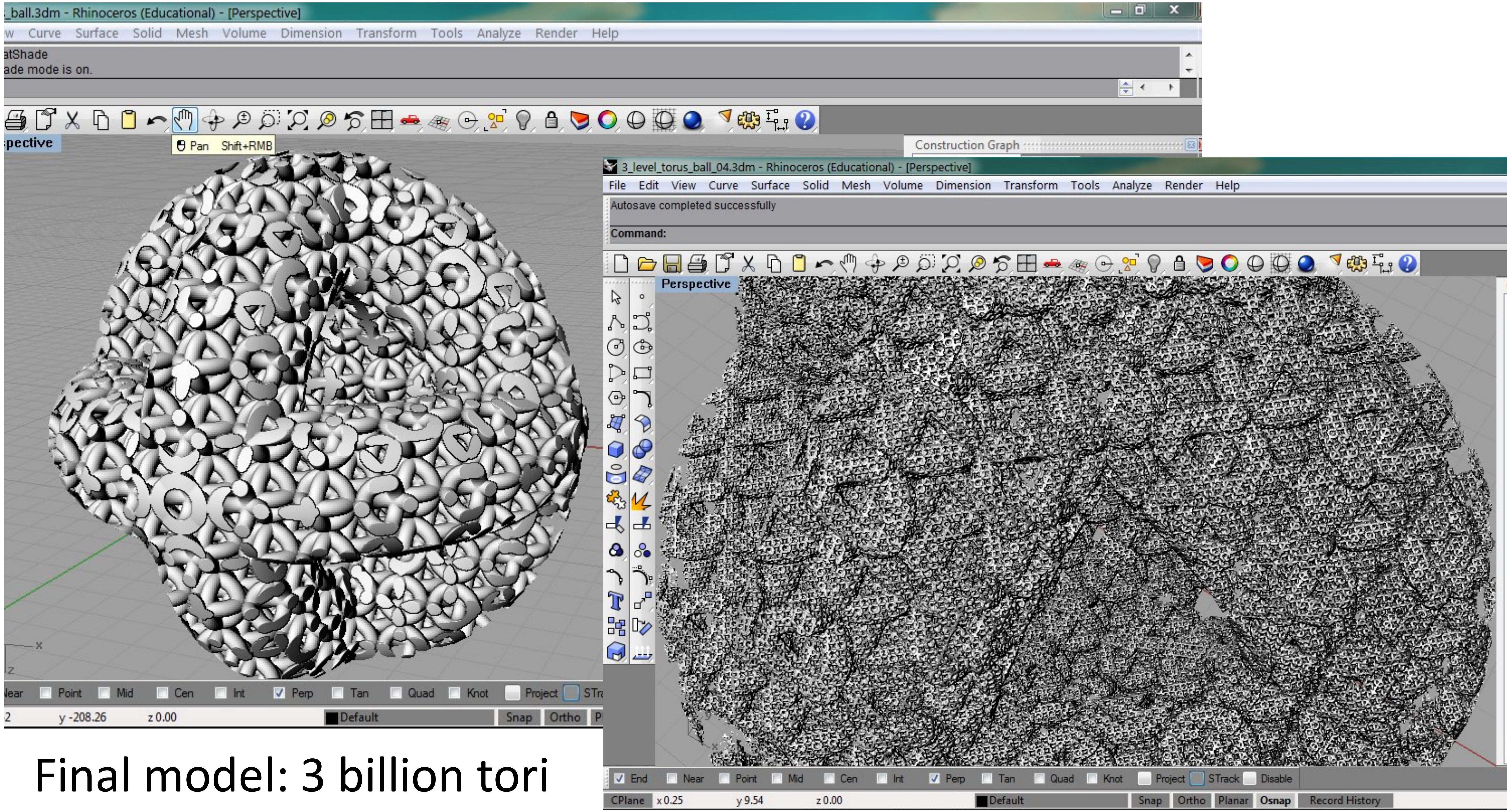
3D printer with high resolution and multiple materials

Image by Objet

Multi-Level Nested Microstructures

We need to achieve microstructure details 2-3 orders of magnitude smaller than the object size

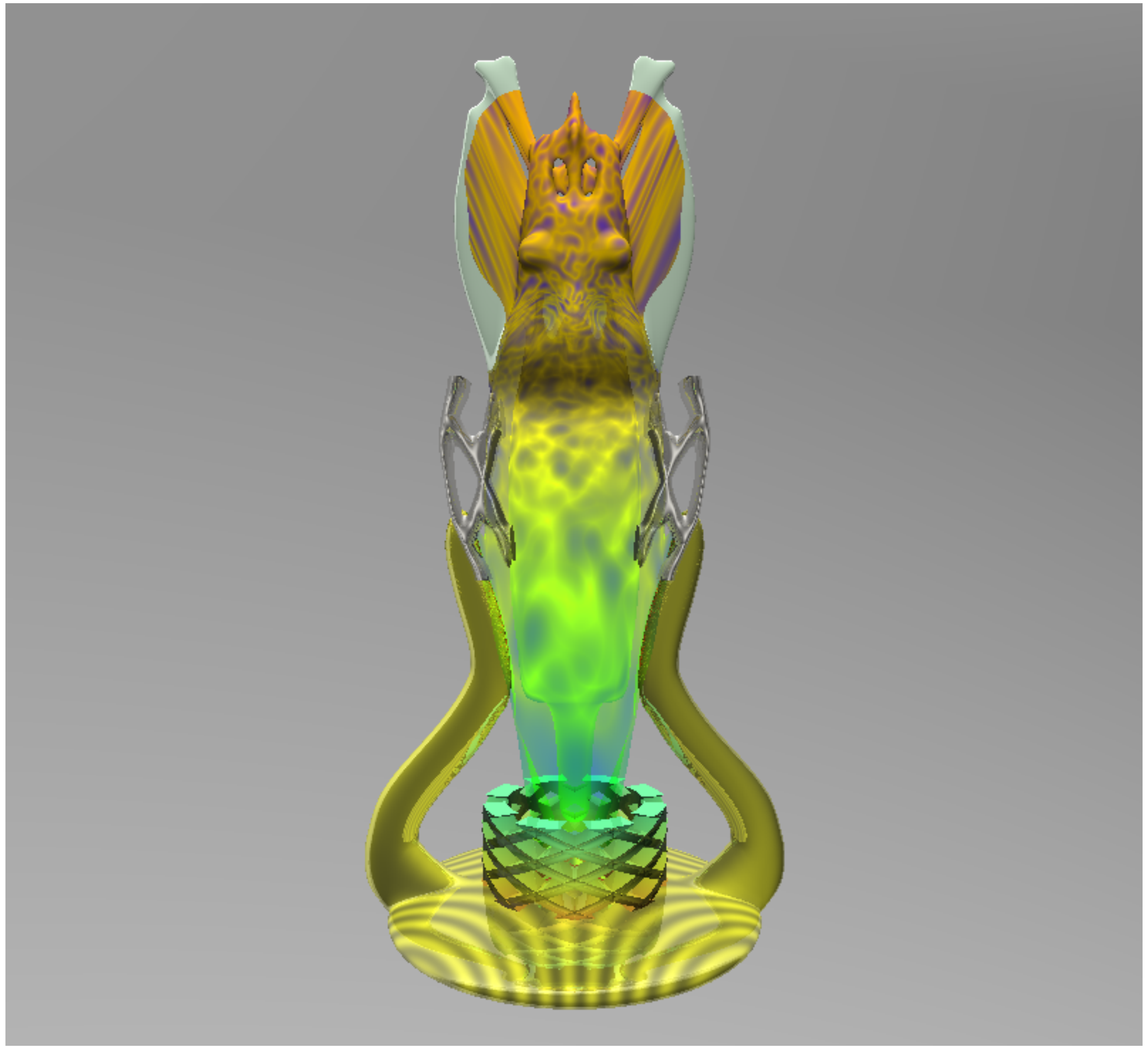




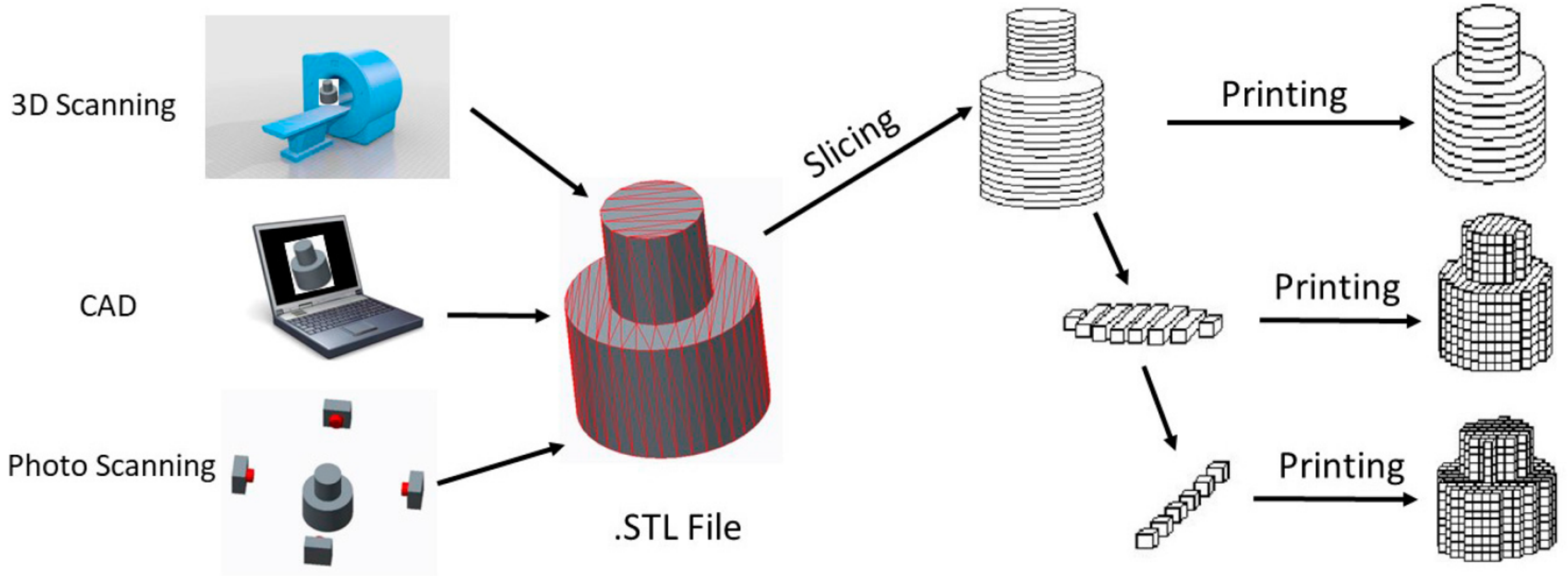
Final model: 3 billion tori

Volumetric Distribution of Multiple Materials

This is a color glass vase, but it can be metal, plastics and even mixture of bio-materials



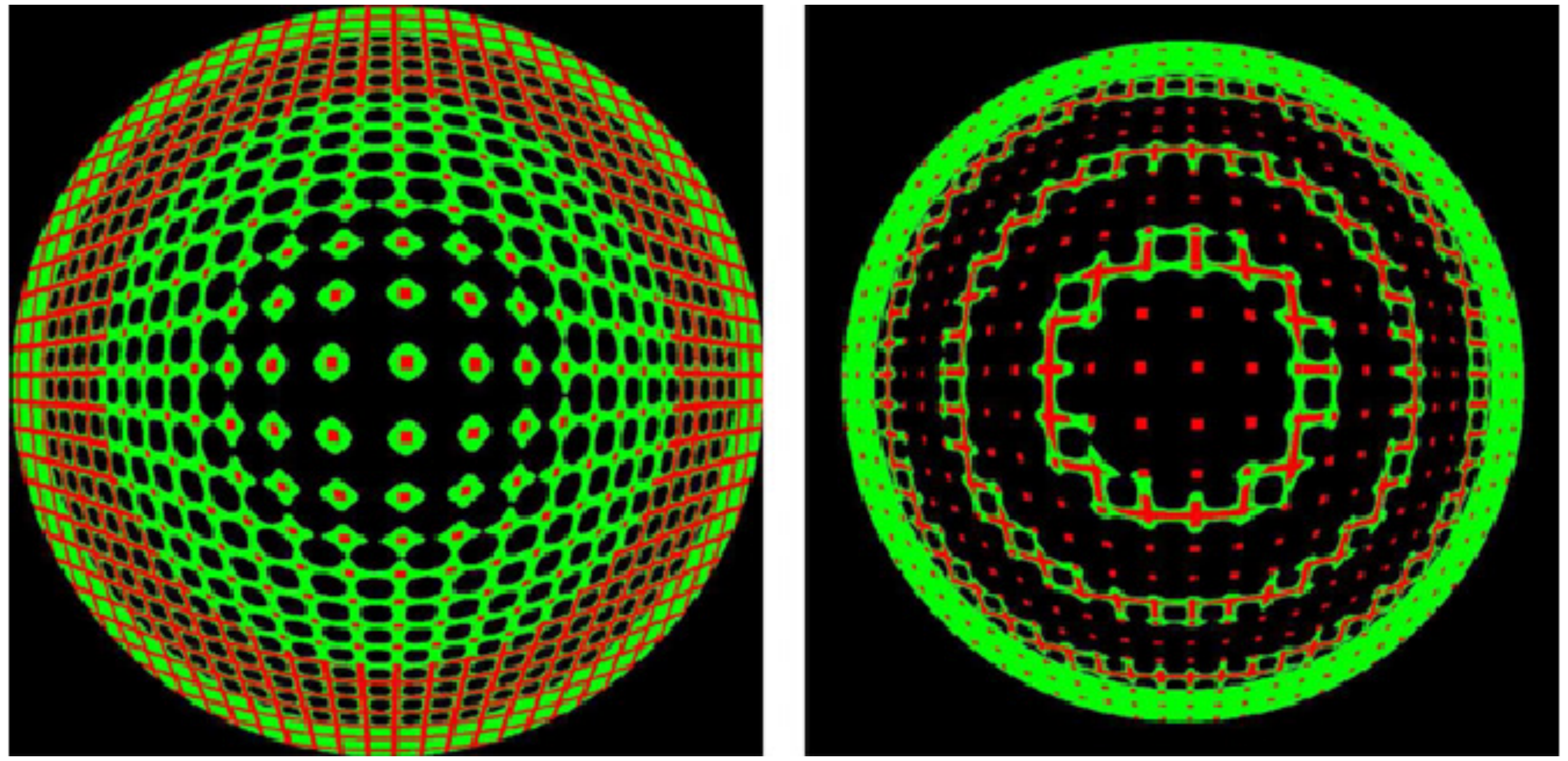
Direct Fabrication without Poor Intermediate Formats



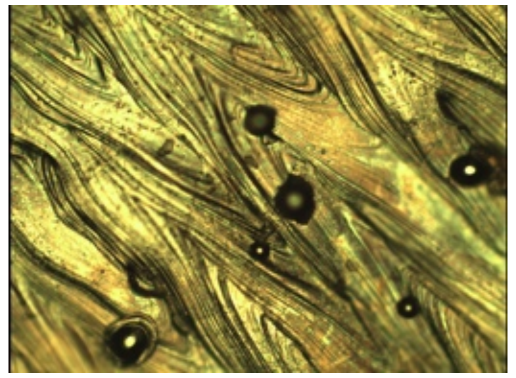
Current geometry presentation is a usually faulty triangle "soup" (STL file)

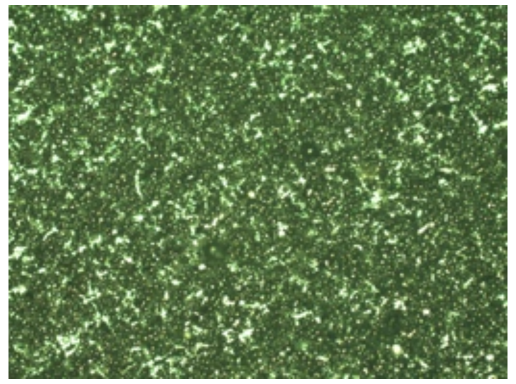
Alternative protocols for 3D printing:

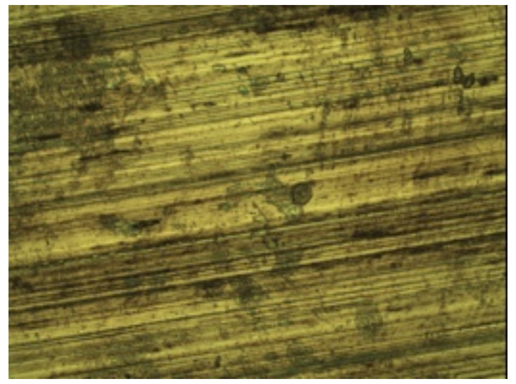
- Vector slice protocol (no info about material, just a slice contour)
- Raster-slice protocol (multi-material)
- Machine command protocol (e.g., g-code)



Color raster slices with two materials



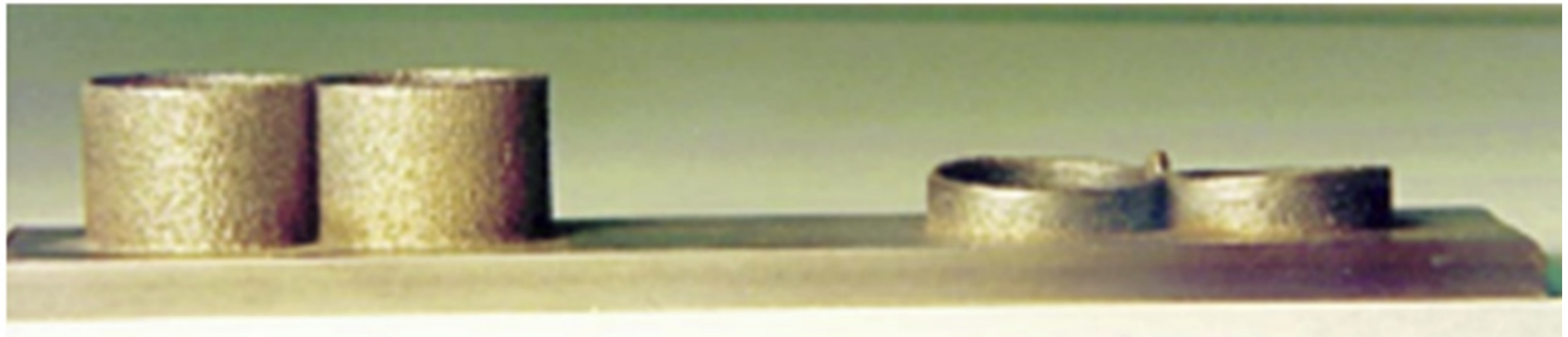




Образовательные курсы

Аддитивные Технологии:

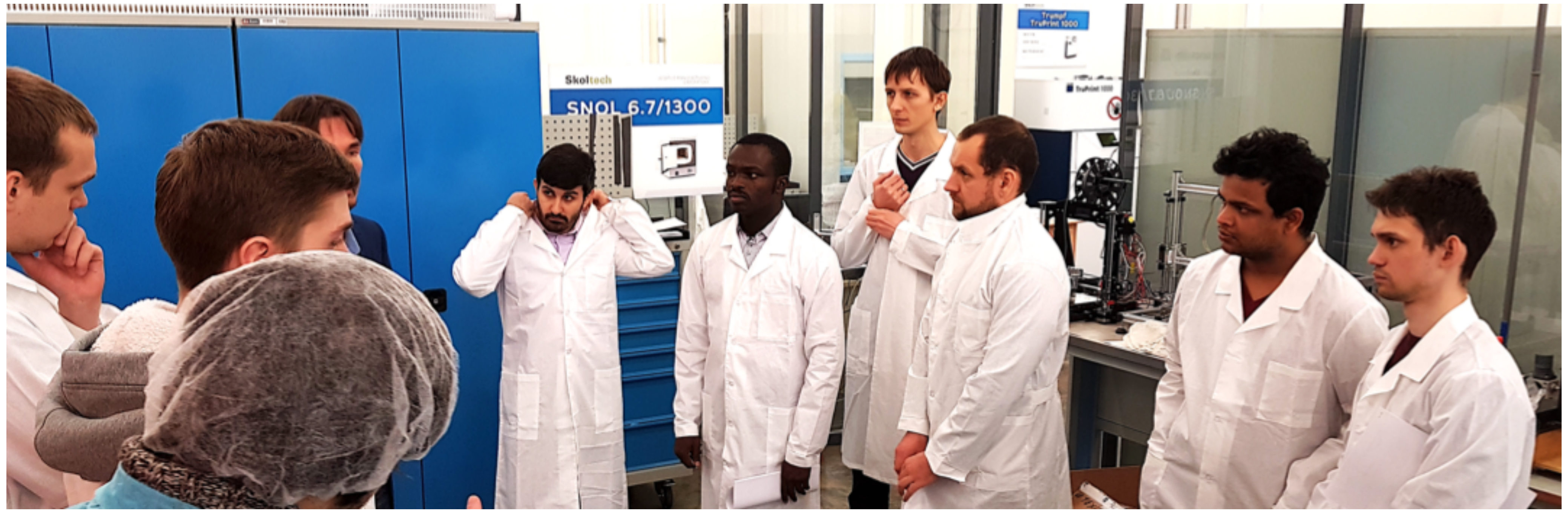
- Прямая 3D печать металлами
- Послойная 3D печать металлами
- 3D печать керамикой
- 3D печать пластиками



Цель и аудитория курсов

Обучить сотрудников индустриальных компаний передовым навыкам работы с 3D принтерами

Курс рассчитан на инженеров-конструкторов, инженеров-расчетчиков и инженеров-технологов, менеджеров и руководителей предприятий, производящих или использующих изделия из полимерных, металлических и керамических материалов, с текущим или предстоящим использованием аддитивных технологий.



Продолжительность: 1 неделя, 40 часов

Количество слушателей в каждом курсе: 5 человек

Место проведения: Сколковский институт науки и технологий (г. Москва, улица Нобеля, д. 3)

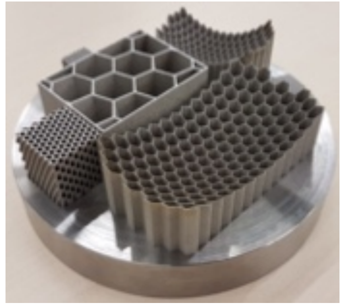
Описание курсов

Курсы посвящены технологиям производства изделий с использованием 3D принтеров по металлу, керамике, пластику. Данные курсы позволят понять основные принципы проектирования моделей, печати изделий, а также технологии пост обработки, и анализа.

Во время лекционных занятий обсуждаются следующие темы и вопросы:

Введение в технологии аддитивного производства

Технологии 3D печати пластиками



Технологии послойной 3D печати металлами

Технологии прямой 3D печати металлами

Технологии 3D печати керамикой

Методы испытаний и анализа изделий, изготовленных методом 3D печати

Практические занятия

- Основная часть курсов посвящена практическим занятиям, во время которых слушатели при поддержке инструкторов и с использованием методических указаний, изготавливают изделия по предложенным четырем технологиям аддитивного производства: 3D печать пластиками, послойная 3D печать металлами, прямая 3D печать металлами, 3D печать керамикой.
- В начале практических занятий проводится подготовка 3D принтеров к работе, включающая юстировку устройств, загрузку материалов, выставление рабочих режимов
- В процессе выполнения технологических лабораторных работ изготавливаются образцы для последующей постобработки и проведения механических испытаний.
- После окончания печатных работ, проводится базовое обслуживание 3D принтеров

Результаты курса

В результате проведения образовательных курсов сотрудники индустриальных компаний получат **знания и практический опыт** по следующим направлениям:

1. Технологии компьютерного моделирования изделий для печати на разных типах 3D принтеров.
2. Технологии и особенности печати на 3D принтерах
   - полимерных
   - металлических
   - керамических
3. Методы постобработки изделий полученных технологиями аддитивного производства.
4. Проведение испытаний образцов и изделий, полученных методами аддитивного производства.

Основные характеристики курса

Место проведения программы:
Сколковский институт науки и технологий
(г. Москва, улица Нобеля, д. 3)

Трудоемкость программы:
Продолжительность 1 неделя, 40 часов
В рамках программы:

- 8 часов лекций
- 24 часа лабораторных работ.
- Самостоятельная работа с 3D принтером

Аттестационные процедуры по курсу:

Очная работа в течение курса

Финальная презентация (4 часа)

Количество слушателей:
5 человек на каждый курс

Научная команда и преподаватели курса

Станислав Евлашин

**Лектор,
старший научный
сотрудник, PhD**

Занимается технологией металлической печати, а также изучением свойств полученных материалов. Обладает большим опытом (более 10 лет) в области материаловедения, а также получении и исследовании новых материалов, в том числе и композитных. Автор более 25 научных публикаций, 3 патентов, результаты исследований не один раз освещались в отечественных и международных новостных средствах.

Святослав Чугунов

**Лектор,
старший научный
сотрудник, PhD**

Занимается технологией керамической аддитивной печати, исследованием микроструктурных и микро-механических свойств, материалов, изучением влияния структуры пустотного пространства на гидродинамические и фильтрационные характеристики материалов. Имеет обширный (более 10 лет) опыт работы с научно-исследовательским оборудованием. Принимал участие в успешных индустриальных и научно-исследовательских проектах в России и США.

Александр Сафонов

**Лектор,
ведущий научный
сотрудник, к.т.н.**

Занимается методами математического моделирования технологических процессов, прочностным анализом, топологической оптимизацией конструкций, обладает обширным опытом работы (более 15 лет) в индустрии композиционных материалов, участвовал в ряде успешных научно-исследовательских проектов для компаний НПП «АпАТэК», ФГУП ЦАГИ, ПАО «ОАК»,
АО «АэроКомпозит»,
АО «Уралвагонзавод»,
АО «Уралкриомаш» и др.

Иван Сергеичев

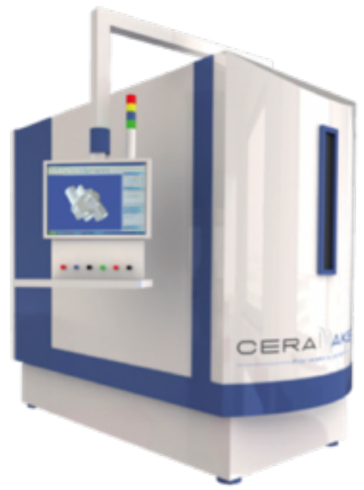
**Лектор,
ведущий научный
сотрудник, к.ф.-м.н.**

Занимается исследованием влияния технологических параметров на физико-механические свойства и структурные характеристики полимерных композиционных и аддитивных материалов, численным моделированием деформации материалов. Опыт работы в индустрии композиционных материалов - более 15 лет; участие и техническое руководство в ряде успешных научно-исследовательских проектов.

Оборудование

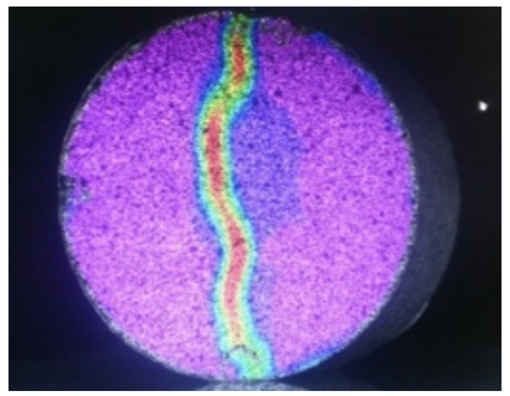
Технологическое оборудование

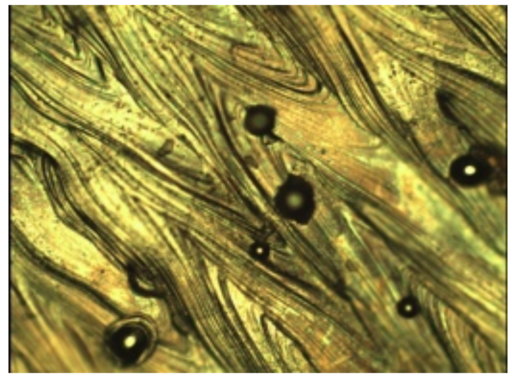
- Полимерные принтеры Hercules и 3D systems ProJet 4500
- Металлический принтер Trumpf TruPrint 1000
- Металлический принтер Insstek MX-1000
- Керамический принтер 3DCERAM Ceramaker 900
- Станция очистки образцов CeraKleaner
- Высокотемпературные печи Kittec CLL15 и ThermConcept HTL 20/17
- Отрезной станок Struers Accutom 100

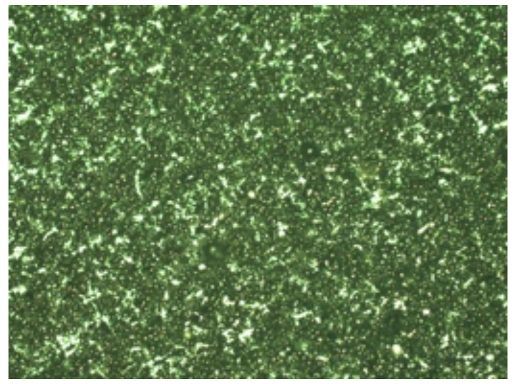


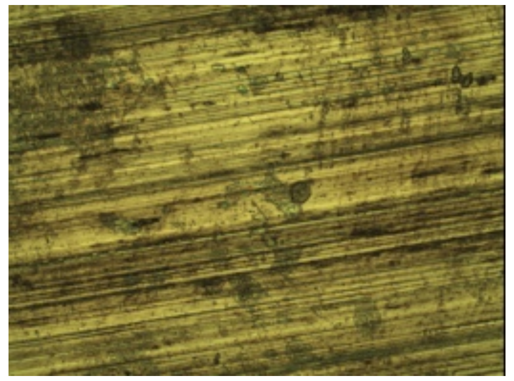

Испытательное оборудование

- Универсальные испытательные машины INSTRON 5969, INSTRON 5985;
- Система анализа деформированного состояния Vic3D;
- Машина для усталостных испытаний SHIMADZU USF-2000
- Машина для испытаний в условиях низких/высоких (-150 - +300 C) температур INSTRON 8801







Для связи с нами:

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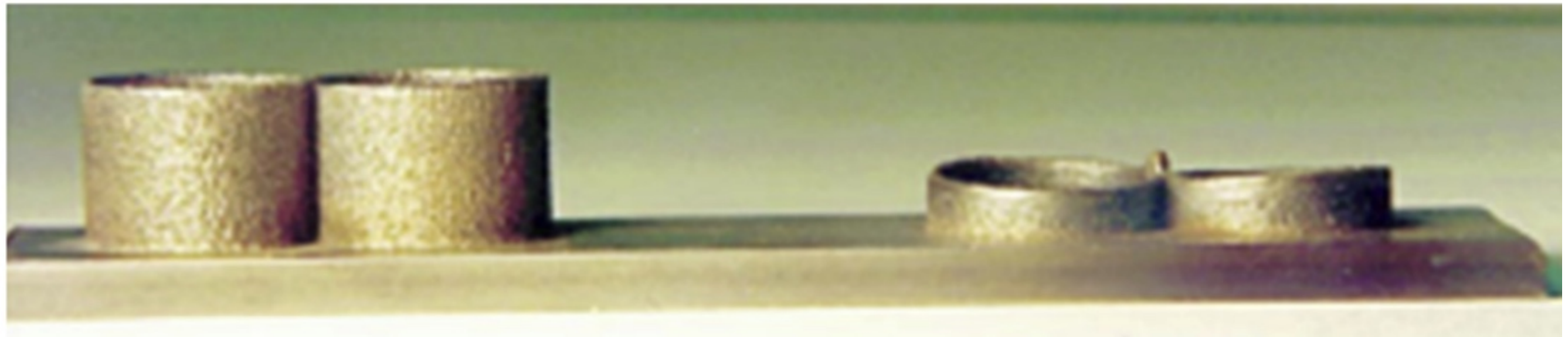
industry@skoltech.ru



Thank you!