Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

stam™

先进增材制造技术及耐磨涂层

殷 硕

机械加工及生物医学学院
都柏林圣三一大学
Trinity College Dublin, the University of Dublin
https://www.tcd.ie/mecheng/staff/yins/

2022.07.06 - 武汉大学水资源与水电工程科学国家重点实验室学术交流汇报

Introduction to Trinity College Dublin

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Trinity Additive Manufacturing Lab

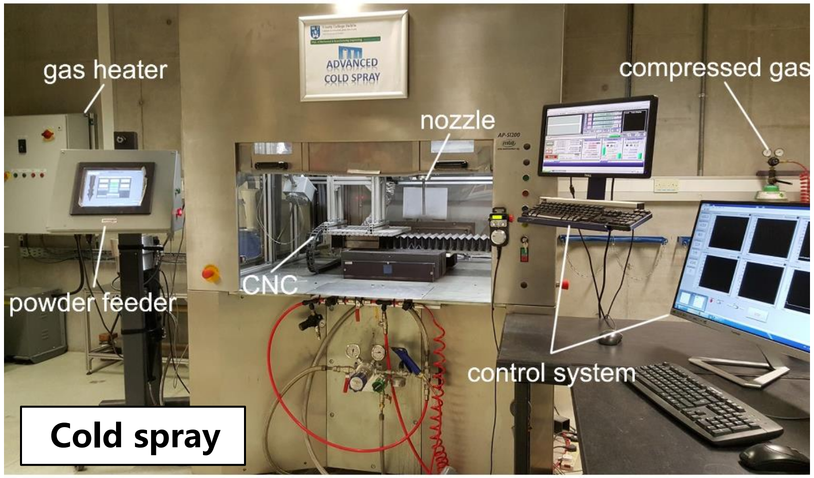
Lab Resources

- We are a **young** research lab, established in **2019**
- We have **1** Cold Spray, **2** SLM, **1** DLP, 1 DIW printers
- We print **polymers**, **metals**, **ceramics**, and **composites**
- We have **2** Postdoc, **9** PhDs, **1** visiting PhD now
- We published more than **150** papers and **1** book
- We have a total research fund of over **3.0 M euro**

DLP Lithoz

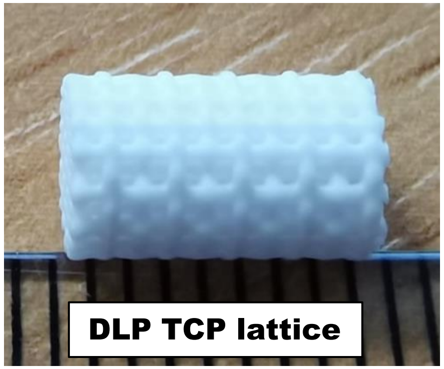
SLM Realizer 50

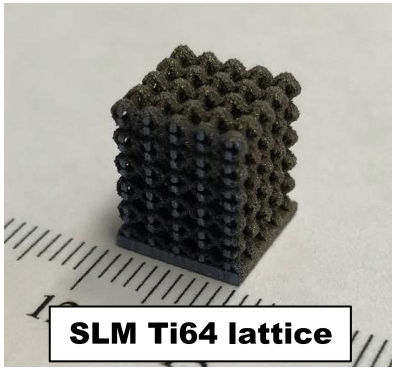
SLM 3D system

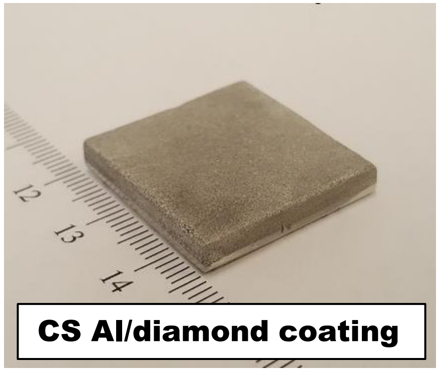


Cold spray

Lab Research

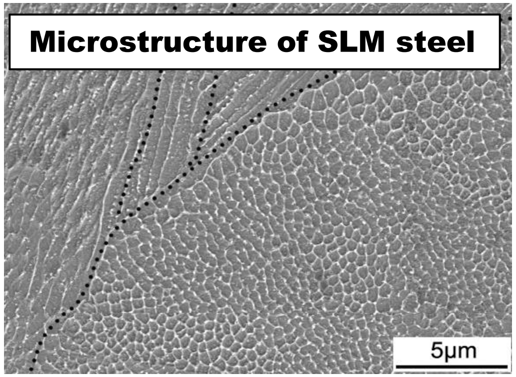


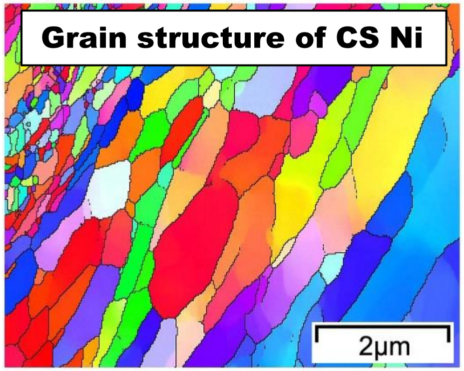


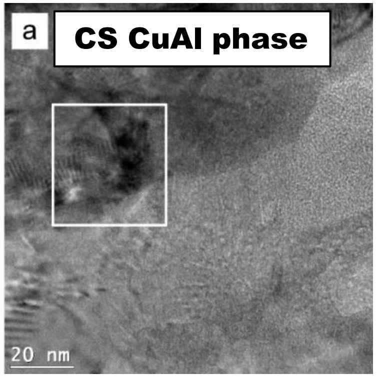


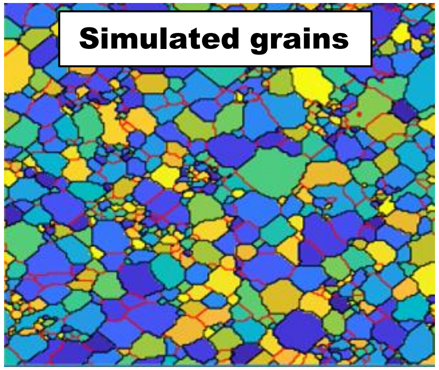
Research Topics

- ✓ **Metal Printing：CSAM、SLM、DIW**
- ✓ **Ceramic Printing：Digital Light Processing (DLP)**
- ✓ **Process Imaging：PIV、digital holography**
- ✓ **Simulation：CFD、FEA、Monte Carlo**

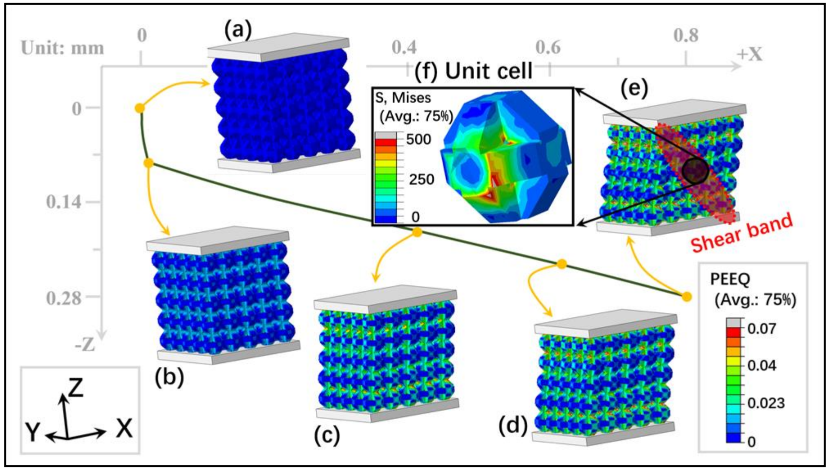




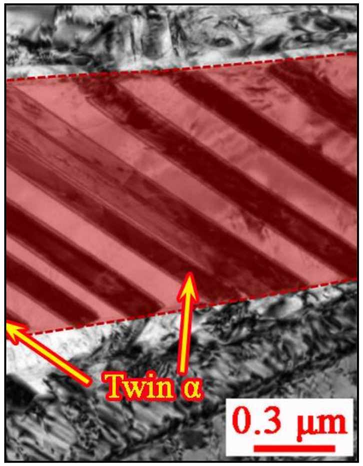




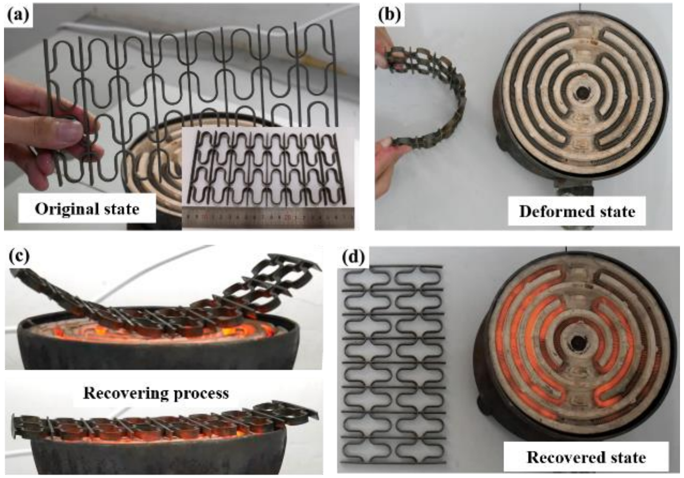
Selected Research



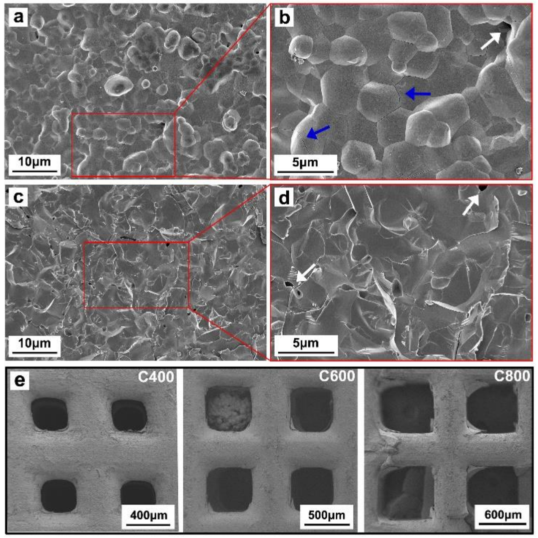
FEA simulation



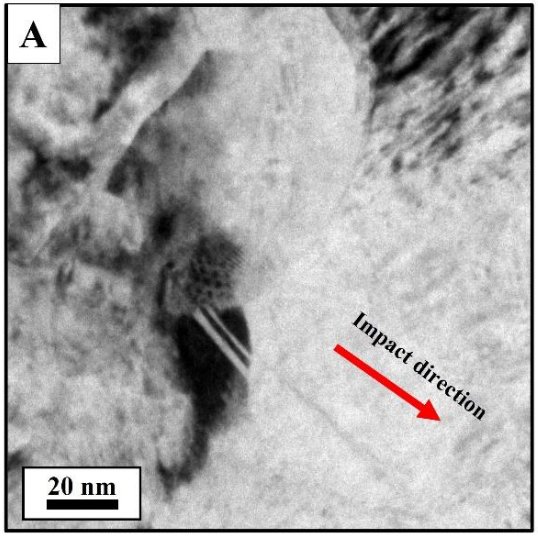
SLM Ti64



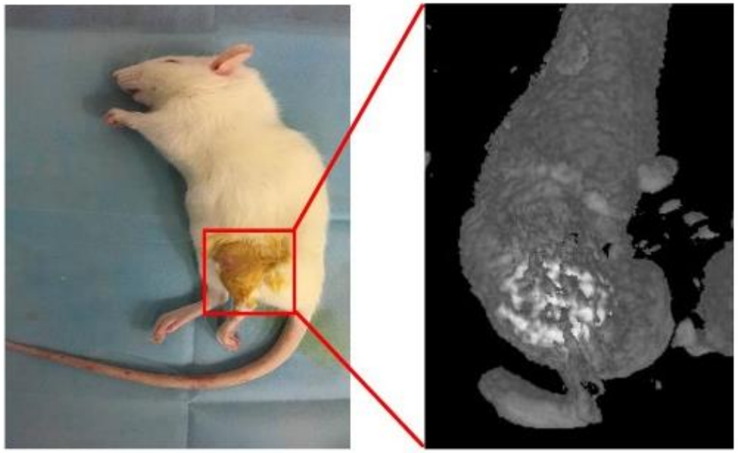
SLM shape memory Ni-Ti alloys



Microstructure of DLP TCD



CS FeCoNiCrMn HEA



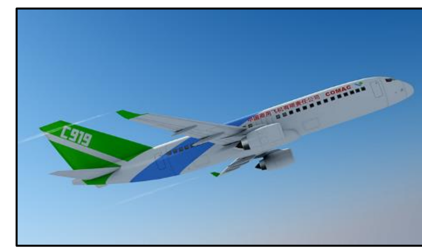
In vivo test of SLM Ti64 scaffolds

Research Background

Research Background

Additive Manufacturing is an evolutionary technology and represents the future.

Biomedical



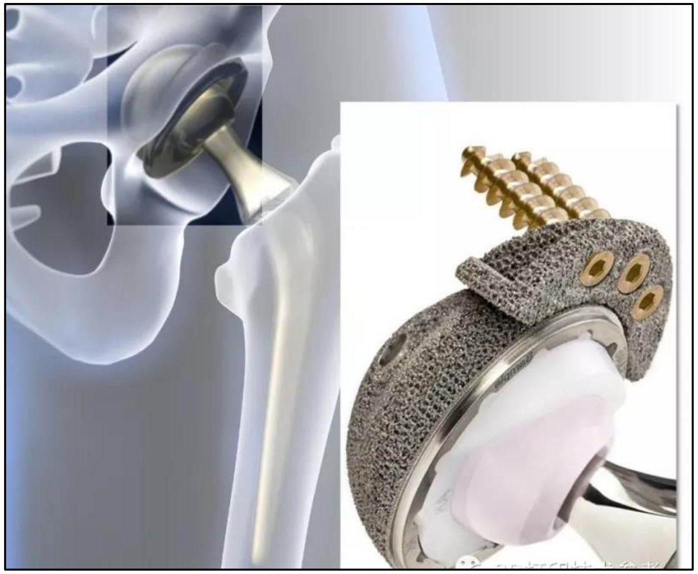
Aviation

Military

Digital, customization, design freedom, complex parts

Research Background

- **Layer-by-layer "fusion-solidification"**
- **Near-net-shape components with complex structure**
- **Digital, customization, high design freedom, small batch**



Key sectors: aviation, aerospace, bio-medical, nuclear

Research Background

Additive Manufacturing: process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as CNC milling.

Subtractive manufacturing

VS

Additive manufacturing

ADDITIVE MANUFACTURING (AM) or 3D PRINTING

"I GUESS THE TWO DEFINITIONS ARE VALID"

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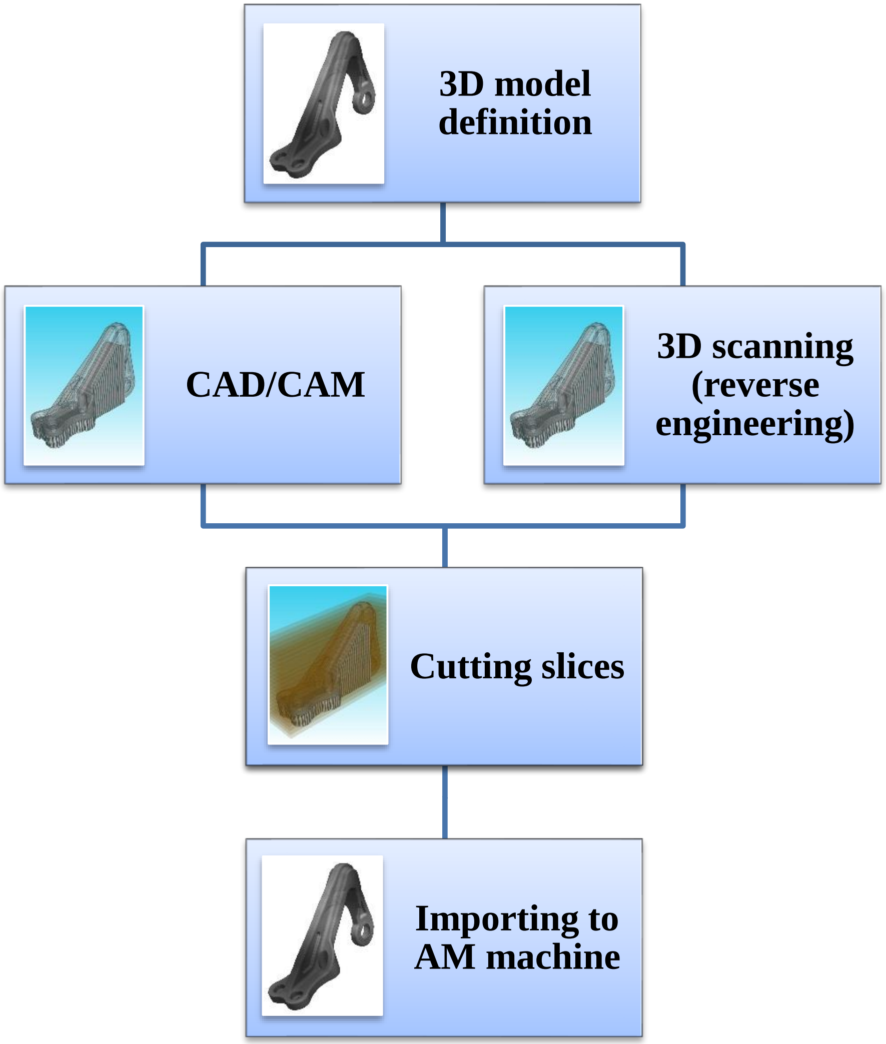
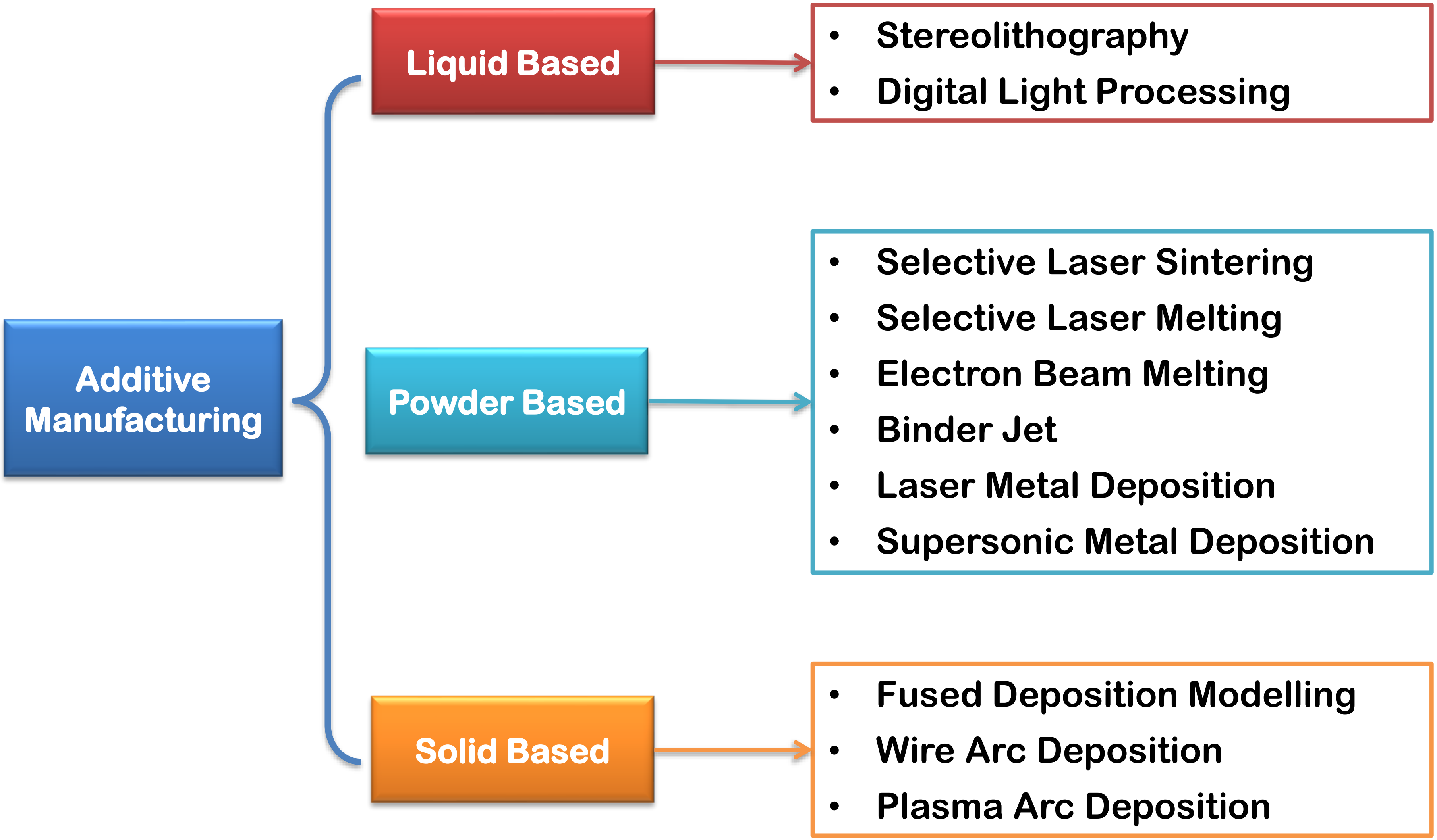
Manufacturing Principles

Mmanufacturing process



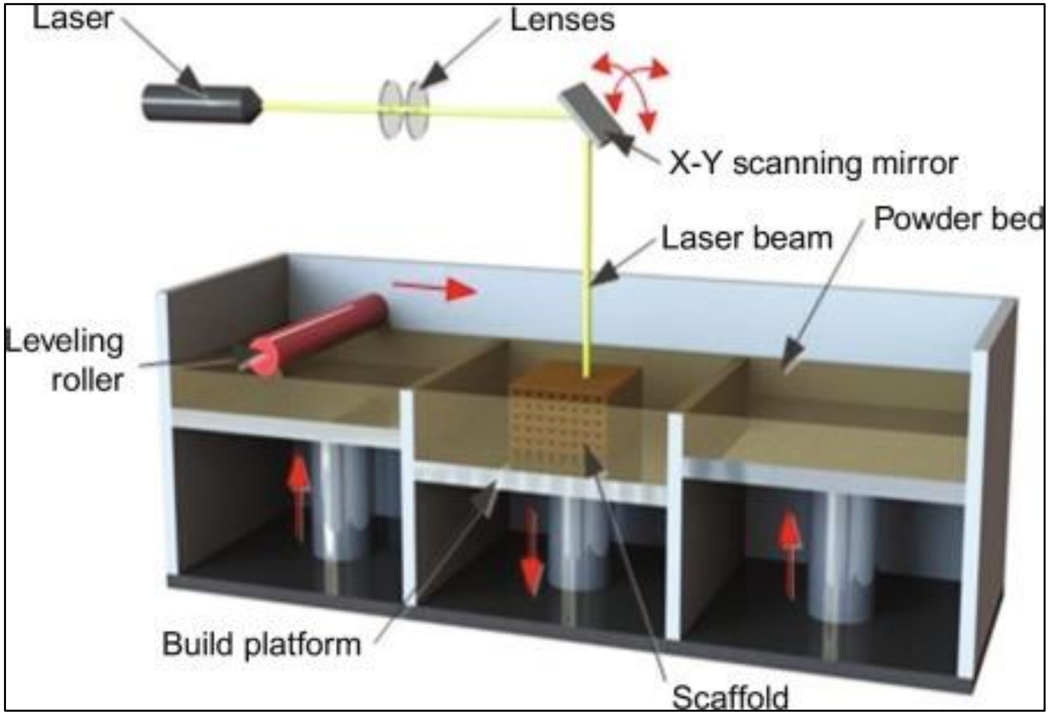
- CAD/CAM
- Reverse engineering (collect data from real object through 3D scanning and then input into CAD/CAM software)
- Cutting slices in CAD/CAM or special AM pre-processing software
- Exporting 3D printable .STL file
- Inputting .STL file into AM machine for executing
- Defining scanning parameters in on the AM machine control panel

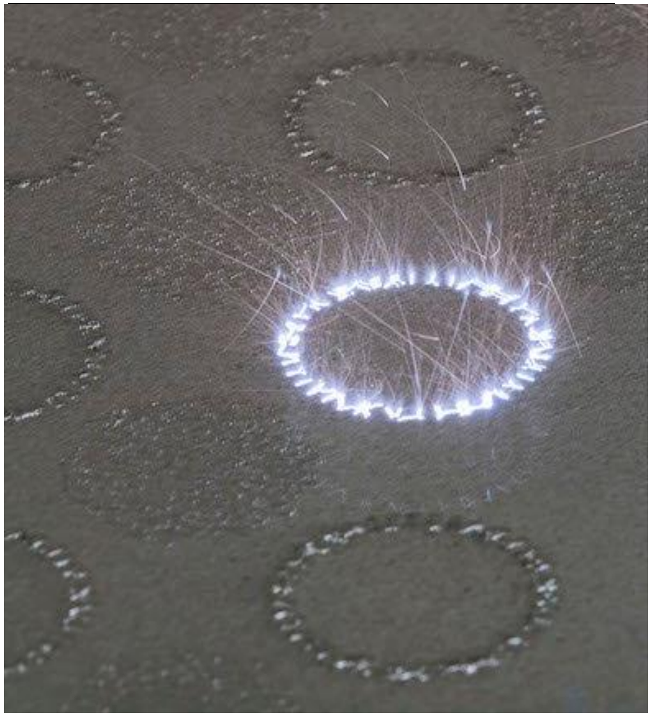
Additive Manufacturing Classification



Selective Laser Melting/Sintering (SLM/SLS)

- **SLM**: SLM uses high-power laser to melt and solidify metallic powders in a powder bed layer by layer based on a pre-defined CAD model.
- **Printing procedure**: CAD model buildup → slicing → laser parameter setup → import file to printer → print.
- **Key components**: laser, scanner system, platform, spreader, powder bed





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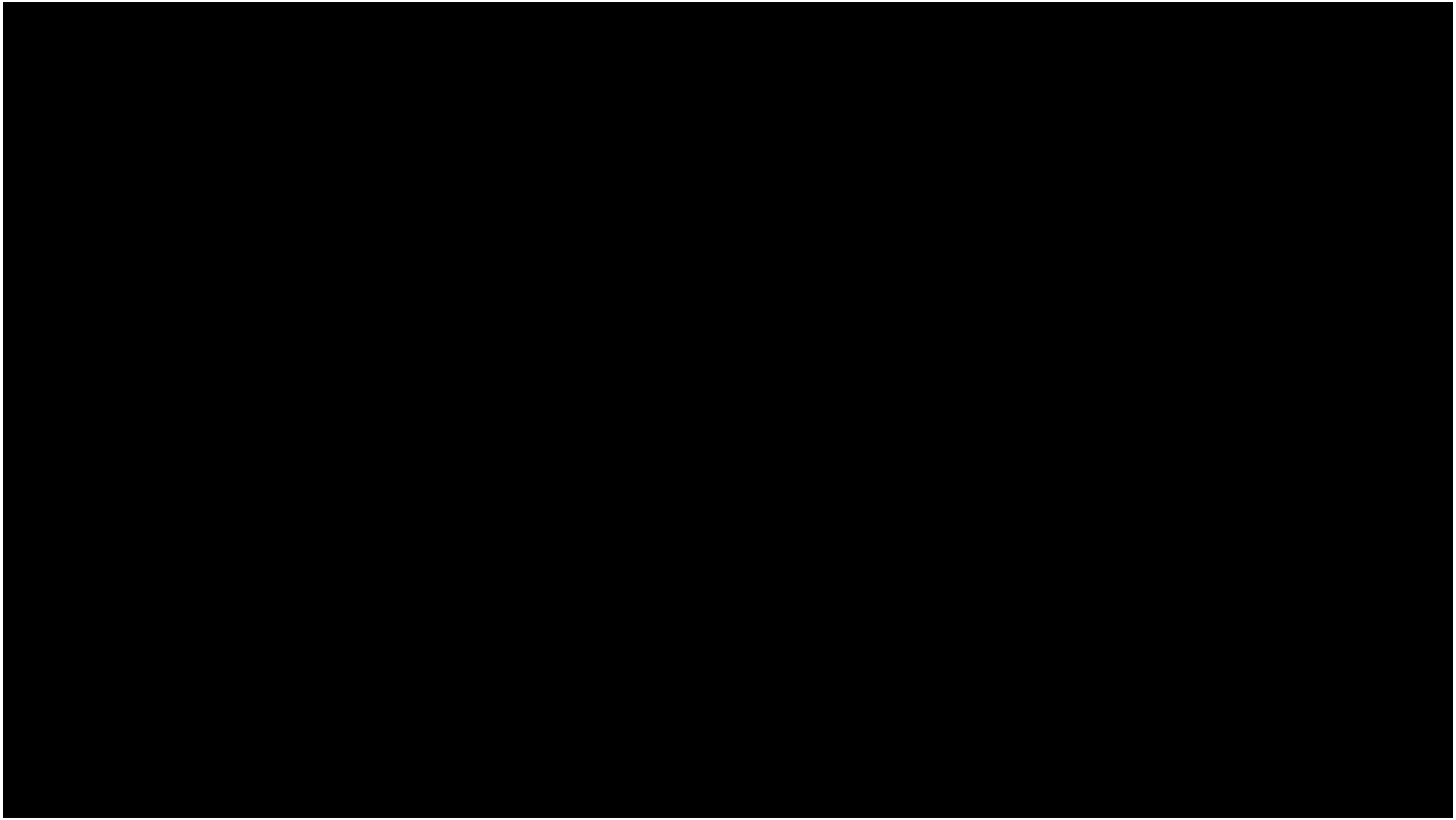
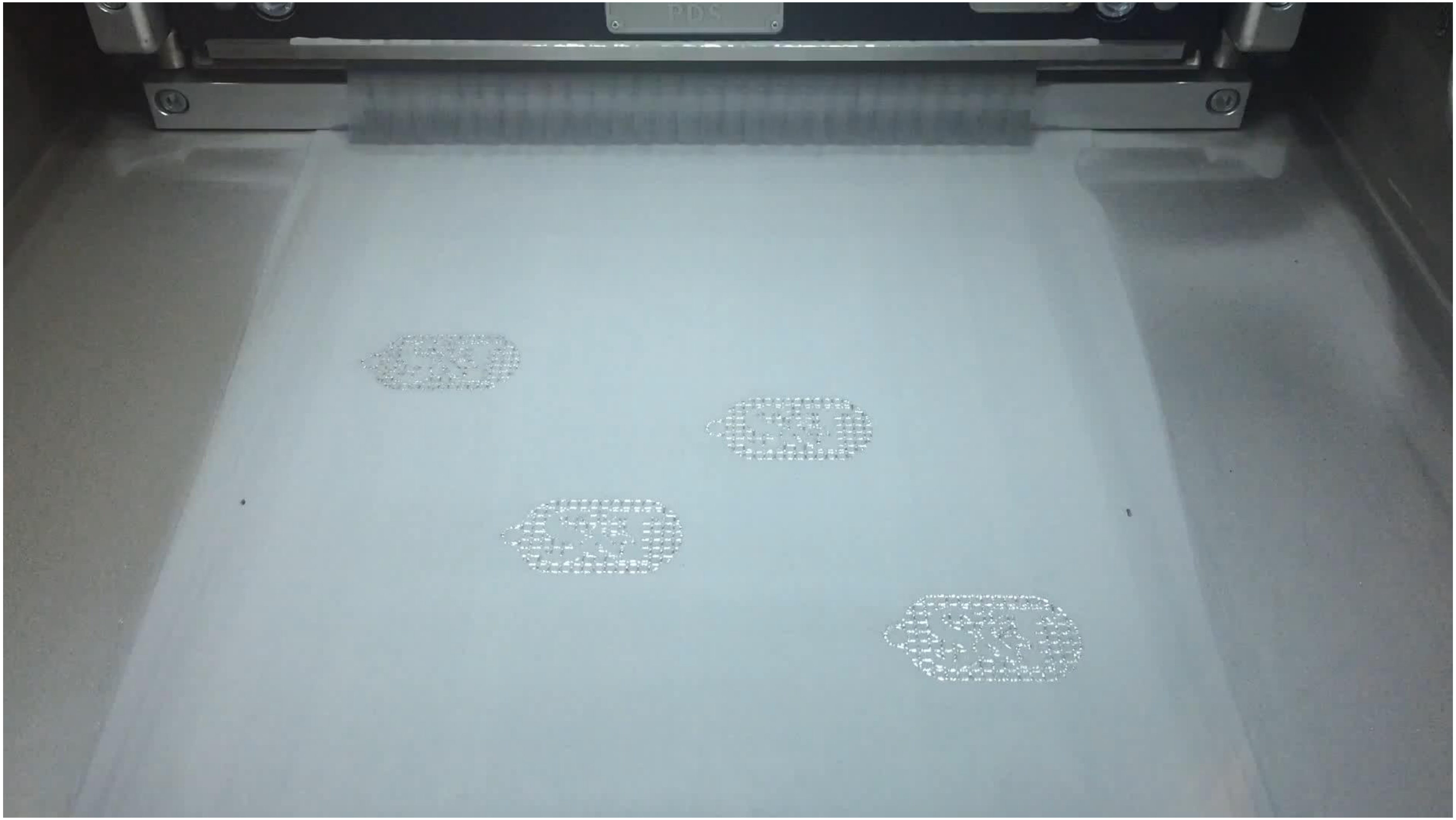
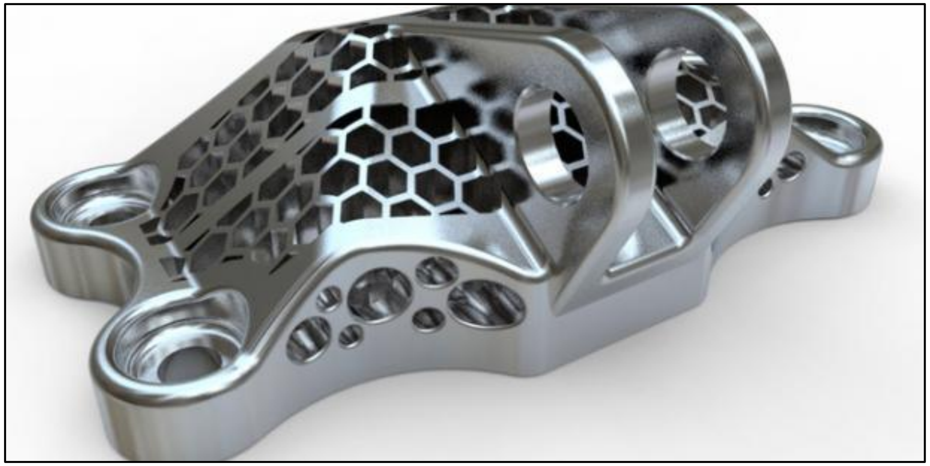


Selective Laser Melting/Sintering (SLM/SLS)



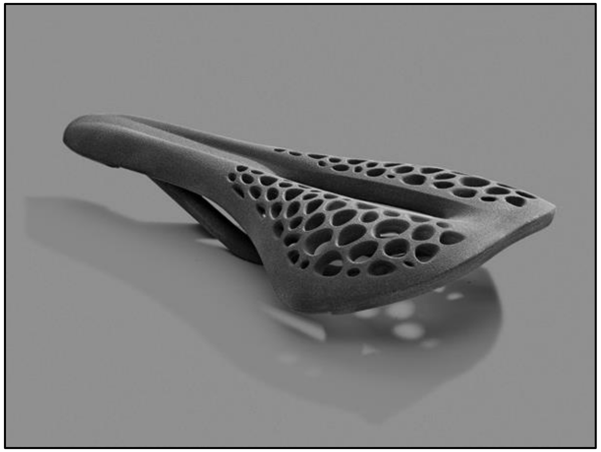
Selective Laser Melting/Sintering (SLM/SLS)



Commercial airplanes can have up to 700 seat belt buckles. A standard buckle weight is around 155g in Steel. With SLM and Ti alloys, the buckles' weight can be reduced to 68g. If all the conventional buckles are replaced by the SLM light-weight buckles, during the entire serving lifetime, an A380 can save fuels of 3,300,000 L and reduce CO_2 emission of 0.74Mt.

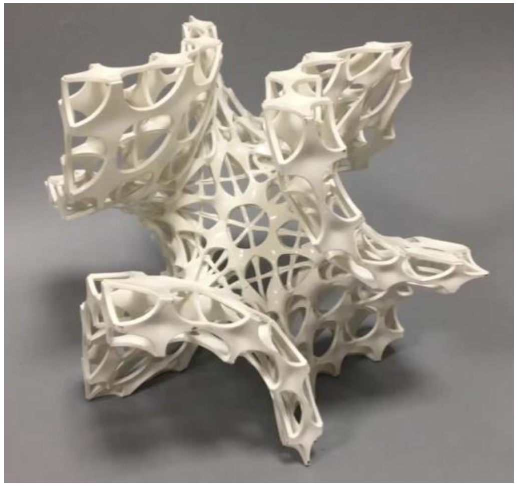
Light-weight parts

Selective Laser Melting/Sintering (SLM/SLS)

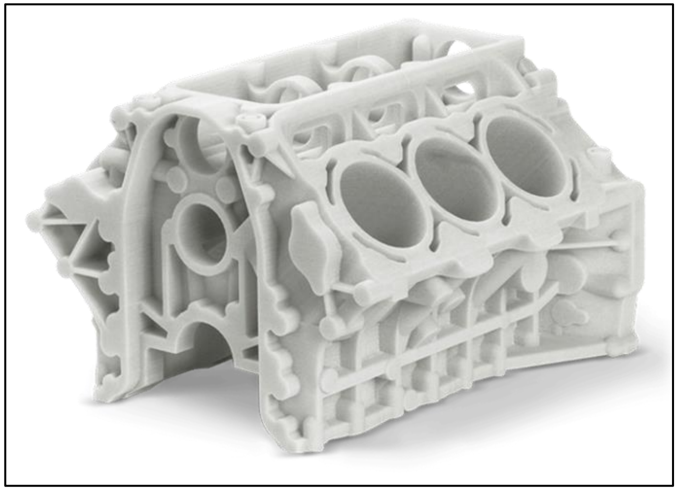



Light-weight design

Practical parts

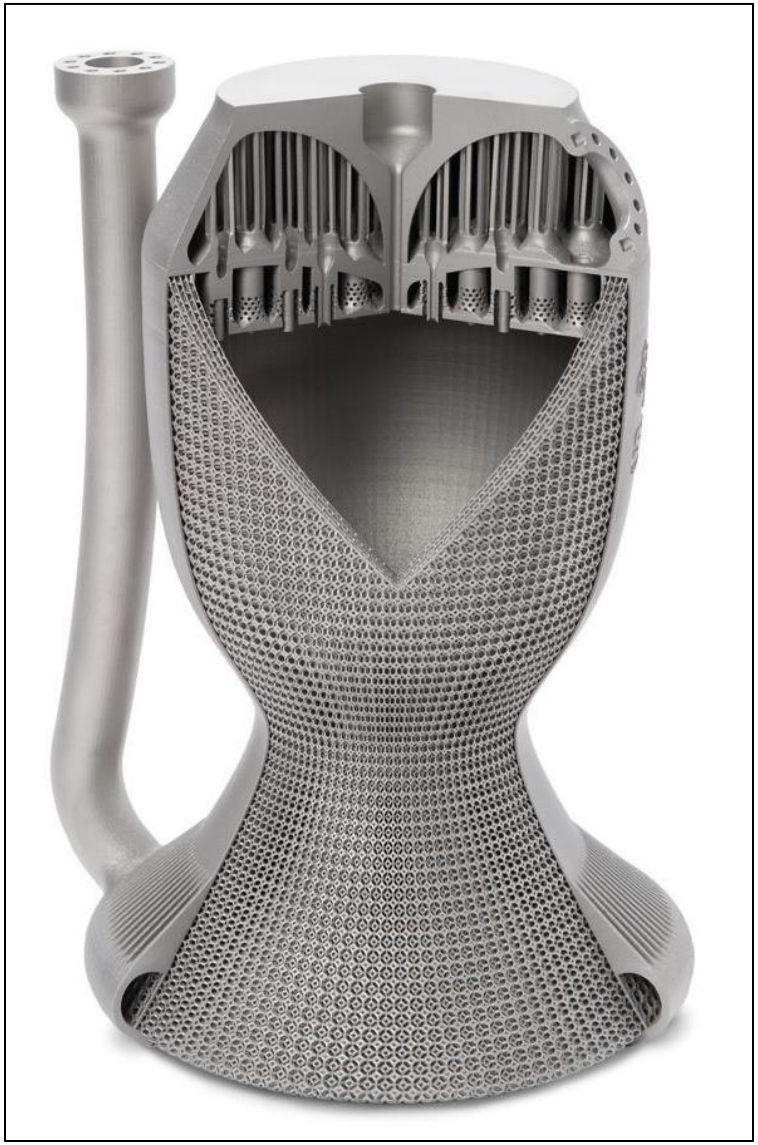



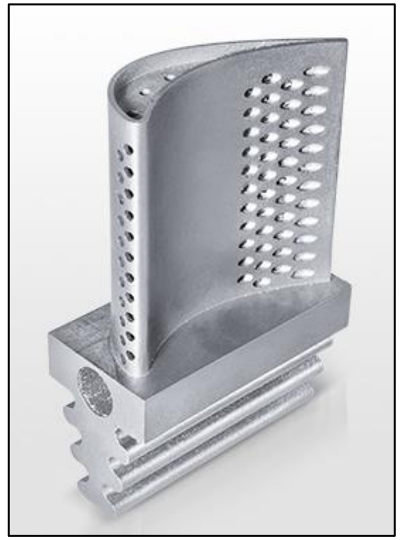
Arts and Crafts



Prototype / Demo

Selective Laser Melting/Sintering (SLM/SLS)



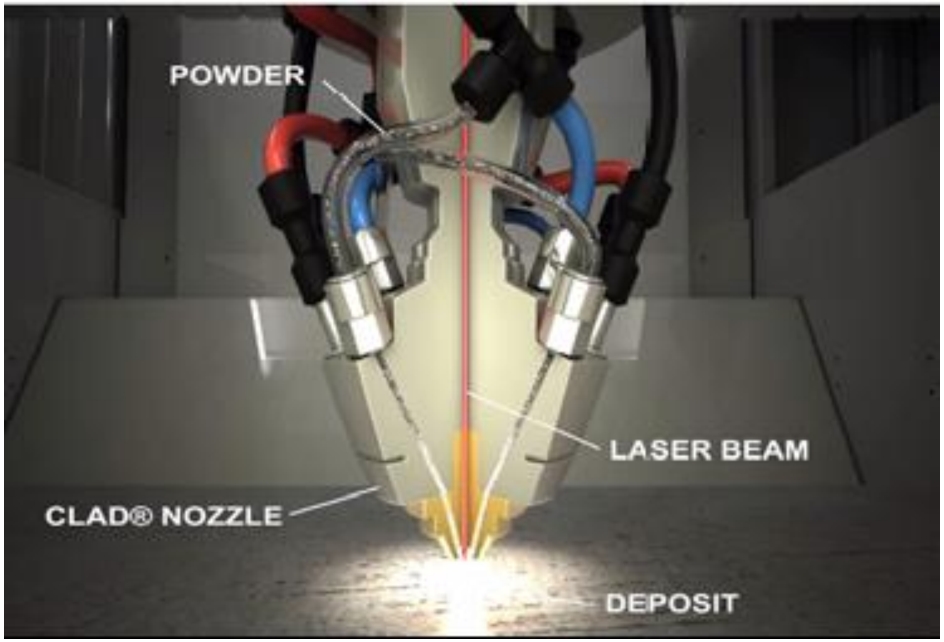


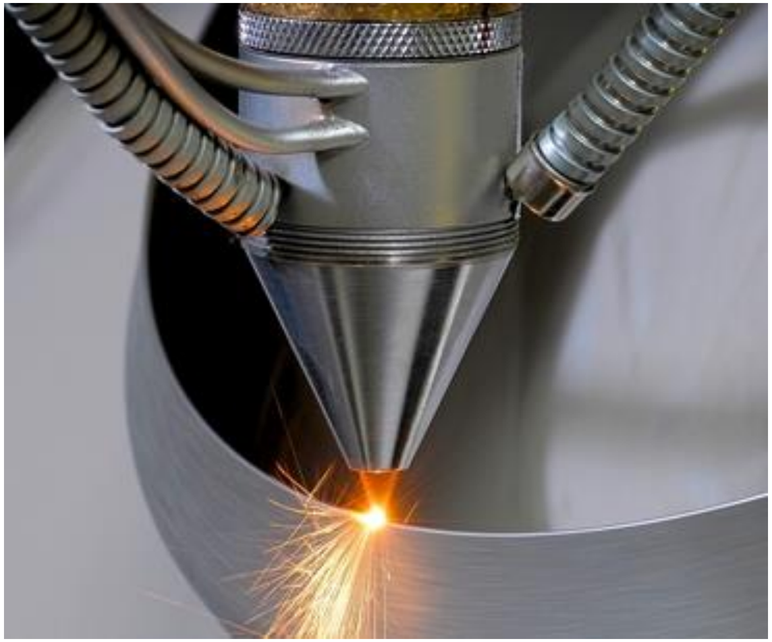
Complex parts

Selective Laser Melting/Sintering (SLM/SLS)

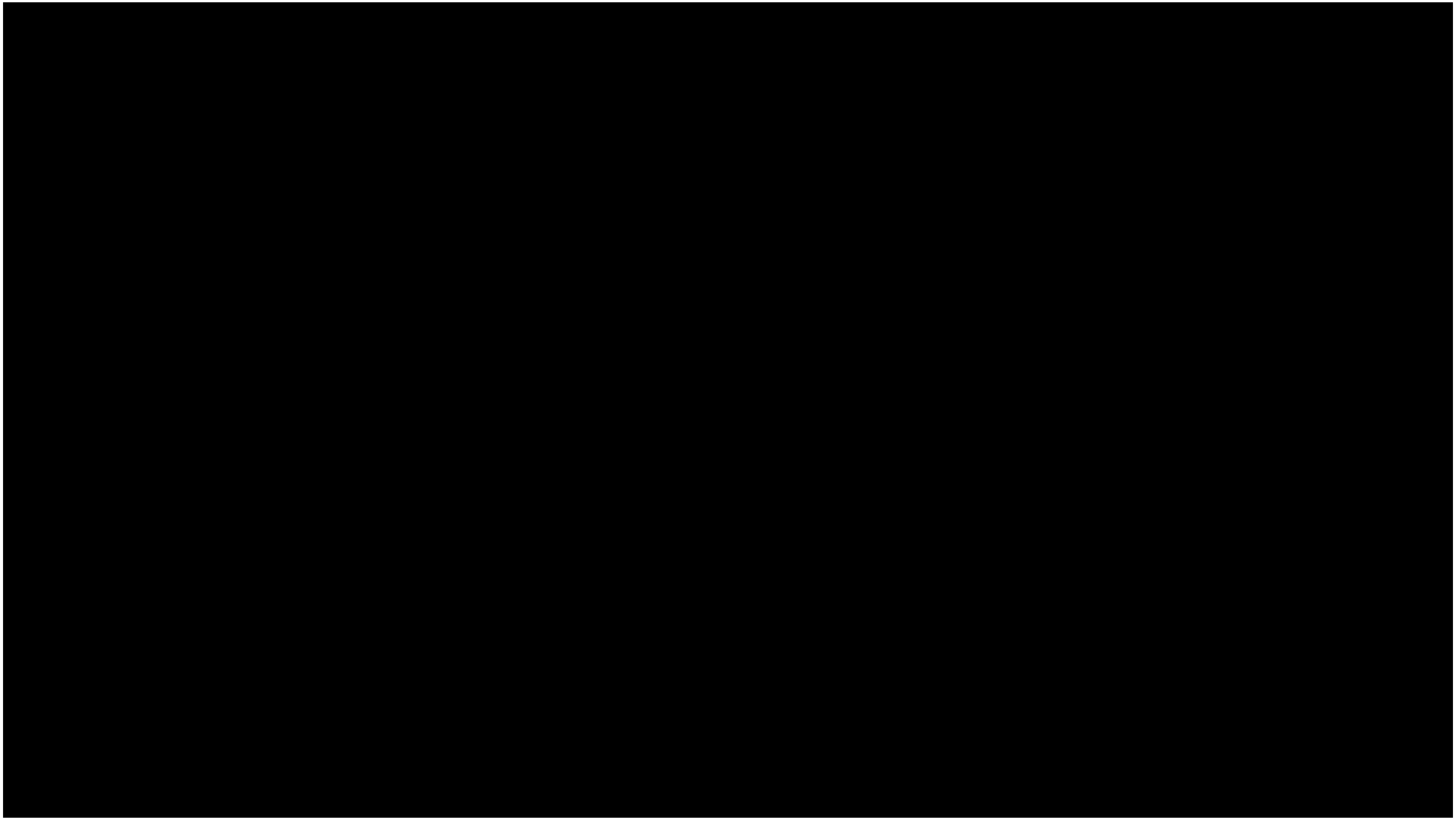
Laser Metal Deposition (LMD)

- **LMD**: a nozzle moves in multiple directions and deposits metal powder layer by layer based on CAD model. The powder material is melted immediately upon deposition and solidifies to form a special shape.
- **Printing procedure**: CAD model buildup → slicing (layer thickness) → laser and powder flow parameter setup → import file to printer → print
- **Key components**: nozzle, laser beam, powder feeding system

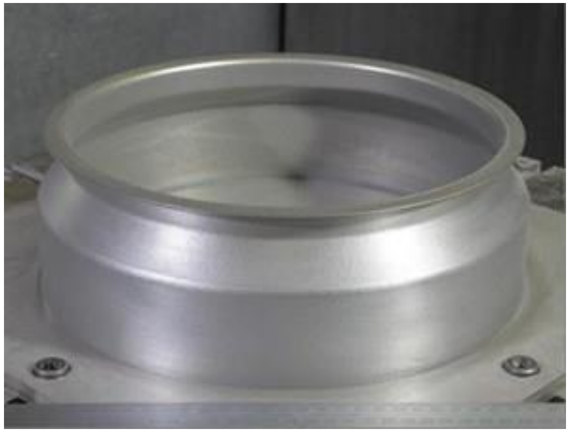
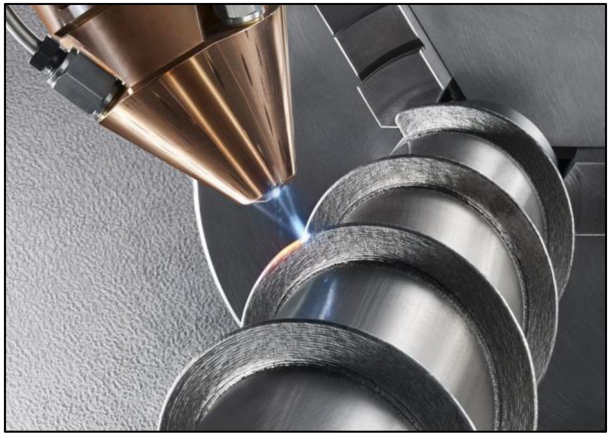




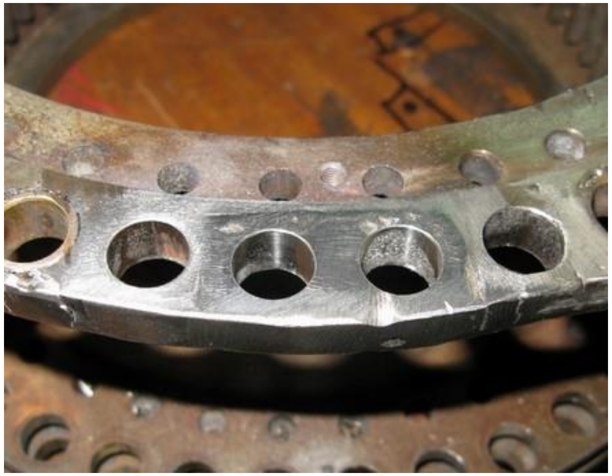
Laser Metal Deposition (LMD)



Laser Metal Deposition (LMD)

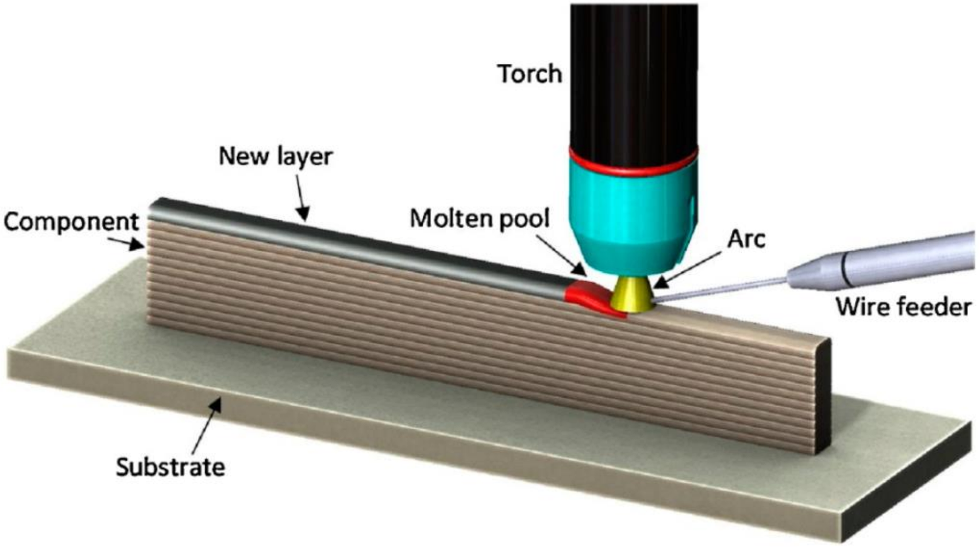
Thin-wall structured components

Structure restoration and modification

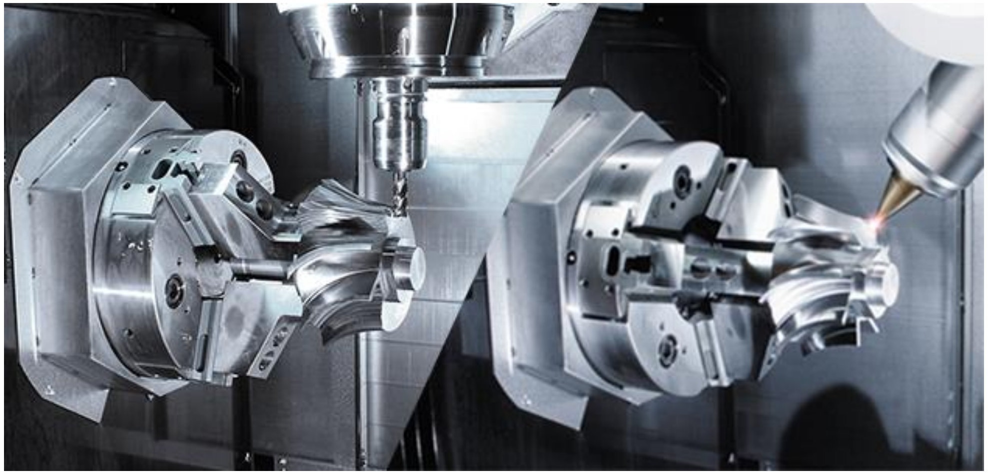
Wire Arc Deposition (WAD)

- **WAD**: WAD is developed based on conventional wire welding processes. Metal wires are melted and deposited by high-temperature electric (or plasma) arc layer by layer to form a specific shape.
- **Characteristics**: low cost, fast production, low precision, less automation
- **Key components**: welding power source, torches and wire feeding system



Wire Arc Deposition (WAD)

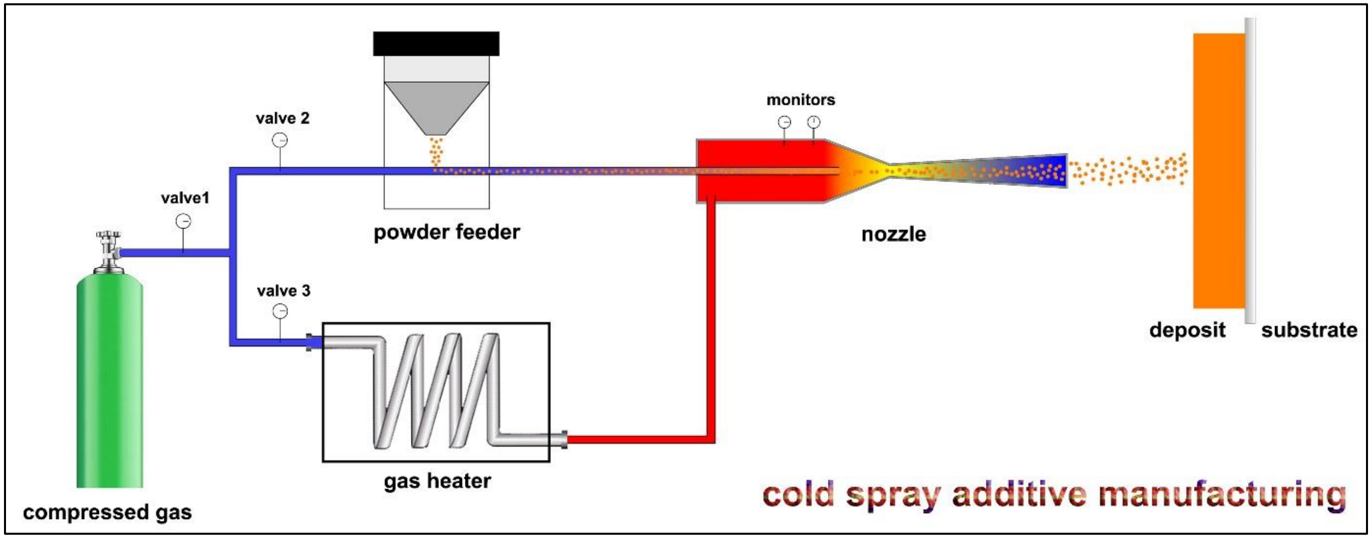
Wire Arc Deposition (WAD)

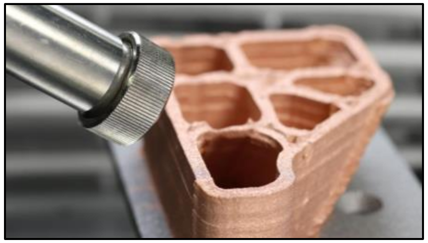


我国第一台3D打印冲击式水轮机转轮 （哈电集团）

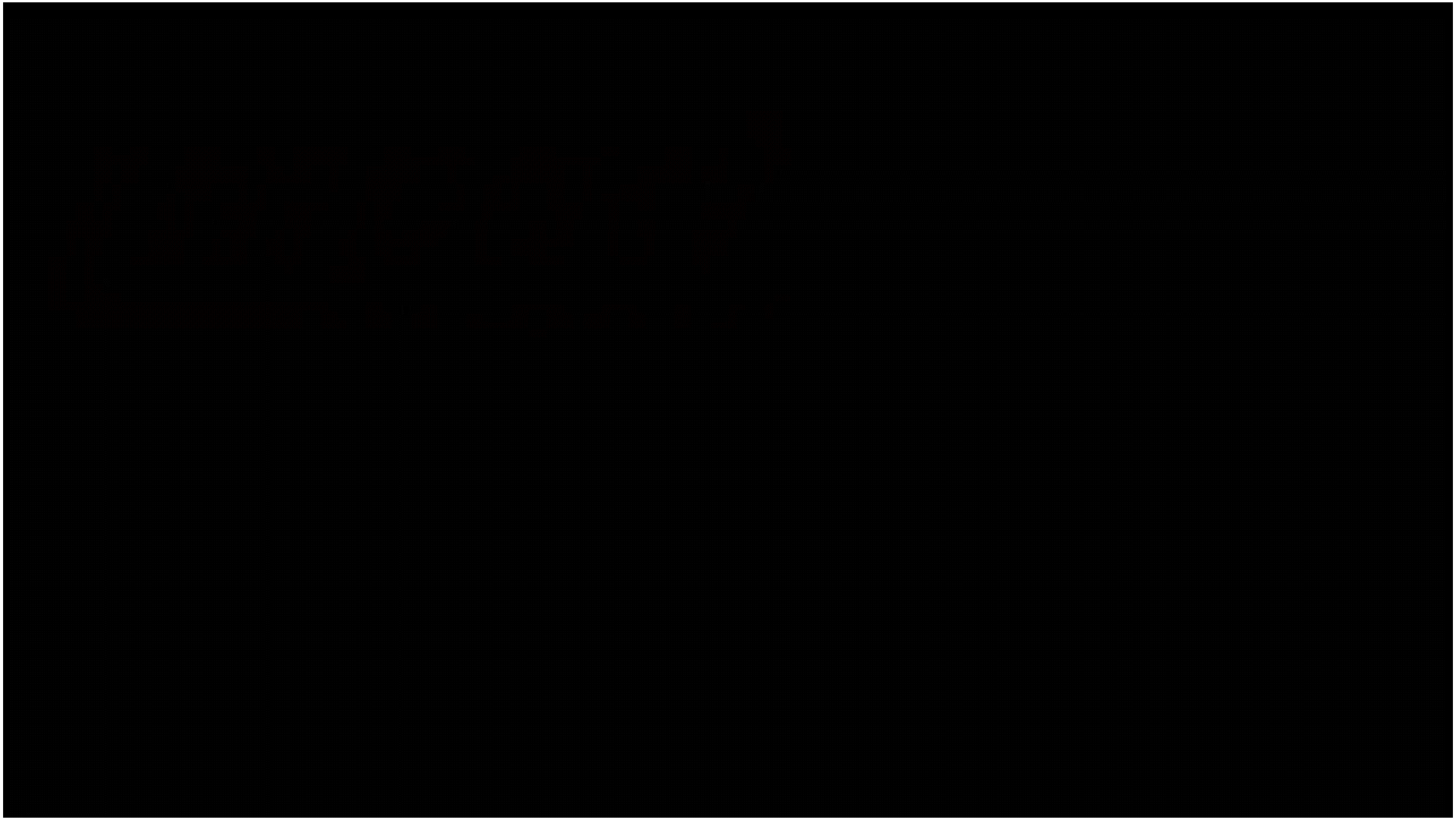
Supersonic Cold Spray Deposition

- **CSD**: a nozzle moves in multiple directions and deposits metal powder layer by layer based on CFD model. The deposition is achieved through solid-state plastic deformation upon impact to form a special shape.
- **Printing procedure**: CAD model buildup → slicing (layer thickness) → gas and powder flow parameter setup → import file to printer → print
- **Key components**: nozzle, compressed gas (air, nitrogen, helium), powder feeding system, gas heater

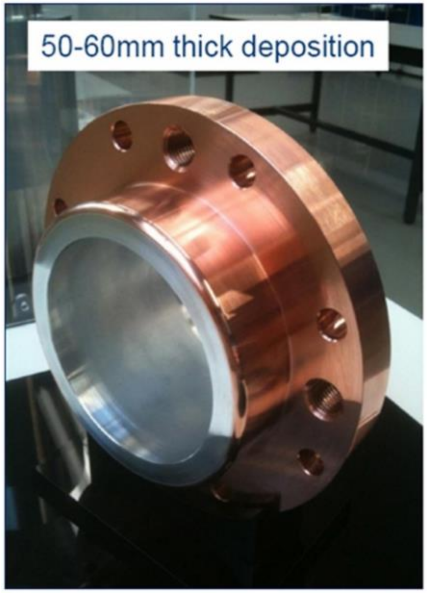


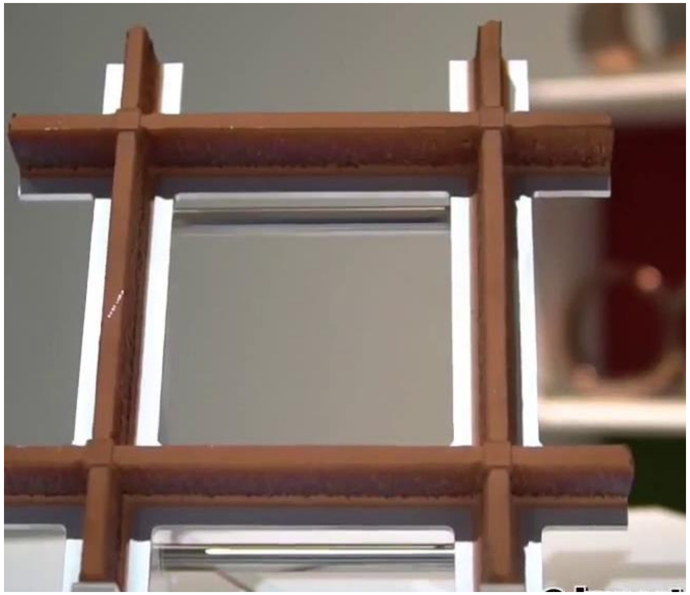


Supersonic Cold Spray Deposition



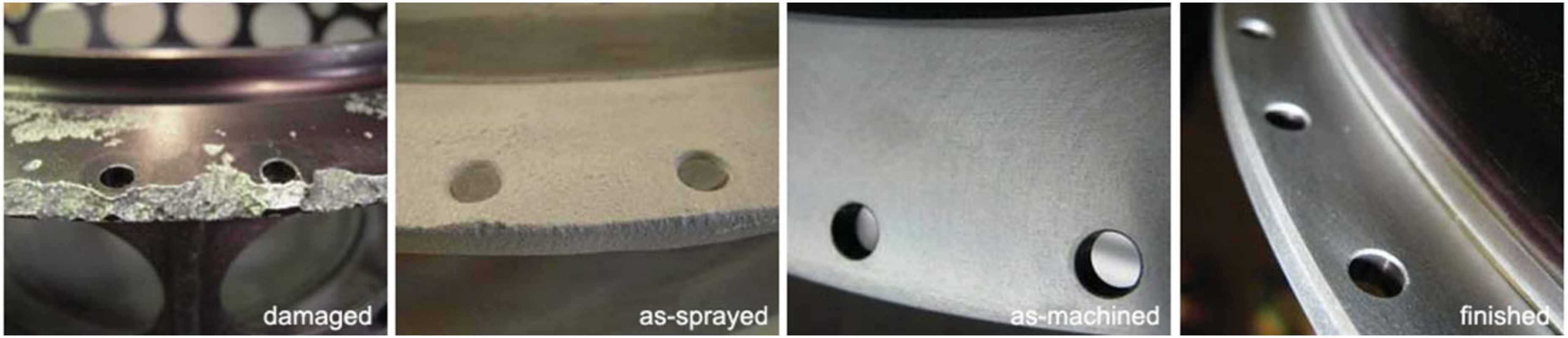
Supersonic Cold Spray Deposition





Cylindrical and thin-wall structures

LMD	CSD
Thermal energy	Kinetic energy
Melting	Solid
Slow	Fast
Higher mechanical properties	Lower mechanical properties

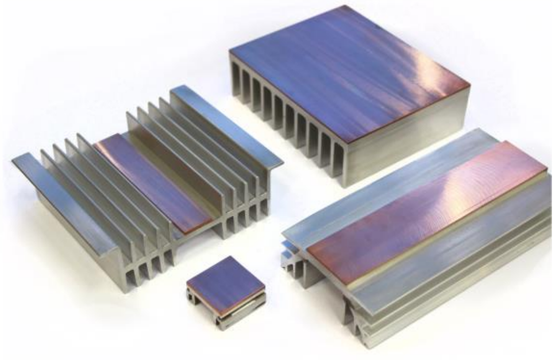


Structure restoration and modification

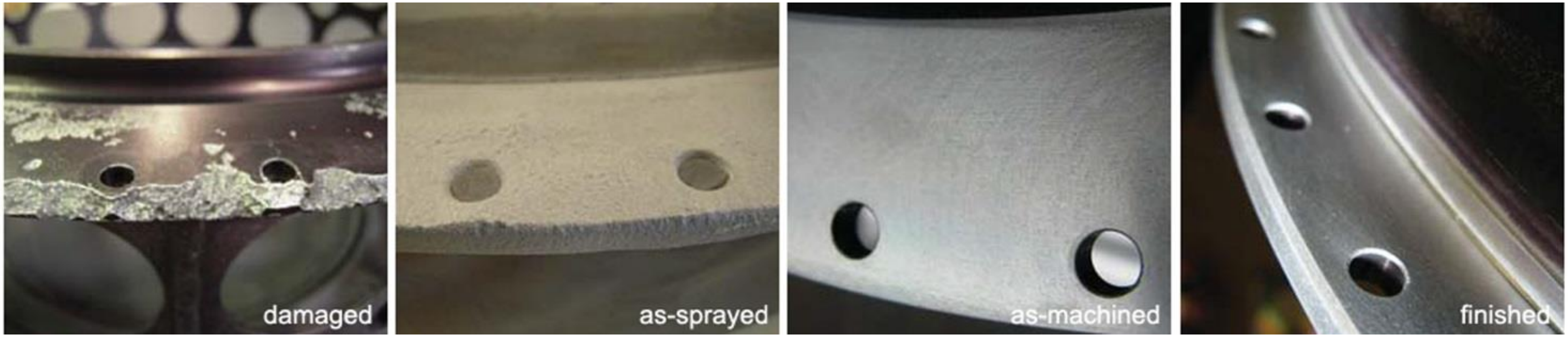
Supersonic Cold Spray Deposition

Sputter targets

Free-stand parts



Coatings



Repair (aircraft)

CSAM in the US Army

FRC	Nomenclature	Part Number	Replacement Cost*	Quantity Recovered to Date	Costs Avoided**
Southwest	F/A-18A/B/C/D AMAD Gearbox Housing (PTS Axis)	42312-231	$31,593.00	11	$318,648
Southwest	F/A-18A/B/C/D/E/F APG-73 Radar Rack Assembly	5099984	$193,510.00	20	$3,690,200
Southwest	F/A-18E/F/G AMAD Main Housing (Hydraulic Pad)	764035B	$168,573.00	10	$1,672,730
Southwest	F/A-18E/F AMAD Main Housing (Internal Gear Damage)	764035B	$168,573.00	4	$666,292
Southwest	F/A-18E/F Brake Carrier	2612020	$8,057.00	65	$347,165
Southwest	F/A-18E/F/G AMAD Hydraulic Gear Shaft	764123	$1,485.92	42	$9,492
Southwest	F/A-18A/B/C/D Outboard Wheel Bolt Spot Face	2606302-1	$7,664.67	0	$ -
East	H-1 Combining Gearbox		$756,000.00	12	$9,072,000
			Totals:		**$15,776,527**

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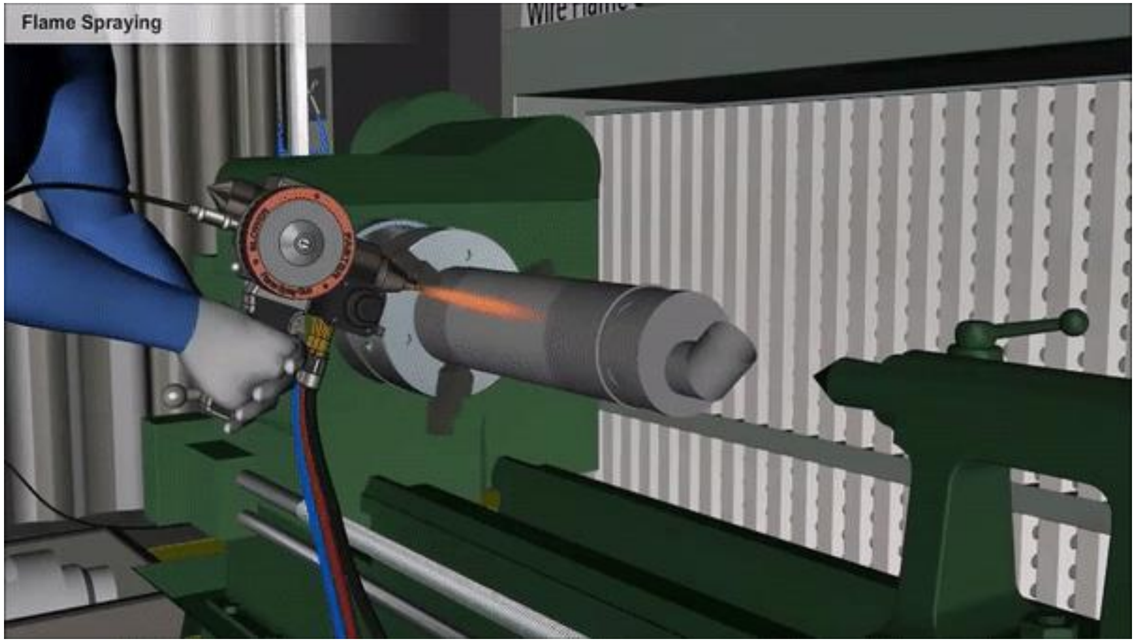
Wear-resistance Coating Technologies

Thermal Spraying

Thermal Spraying: molten or semi-molten feedstock are sprayed onto a substrate, where they solidify and adhere to the surface

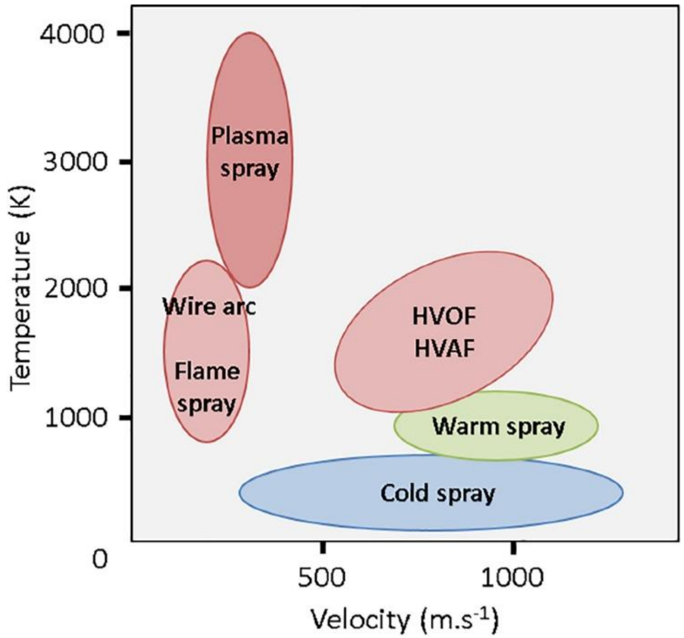
- **Feedstock form:**
  - ✓ Powder (mostly) and wire
- **Sources for melting feedstock:**
  - ✓ Oxyfuel flame (oxygen, air and fuel gases), electric arc, plasma arc
- **Coating materials:**
  - ✓ Metals and alloys
  - ✓ Ceramics
  - ✓ Cermet composites
- **Substrates:**
  - ✓ Metals and alloys,
  - ✓ Ceramics
  - ✓ Glass

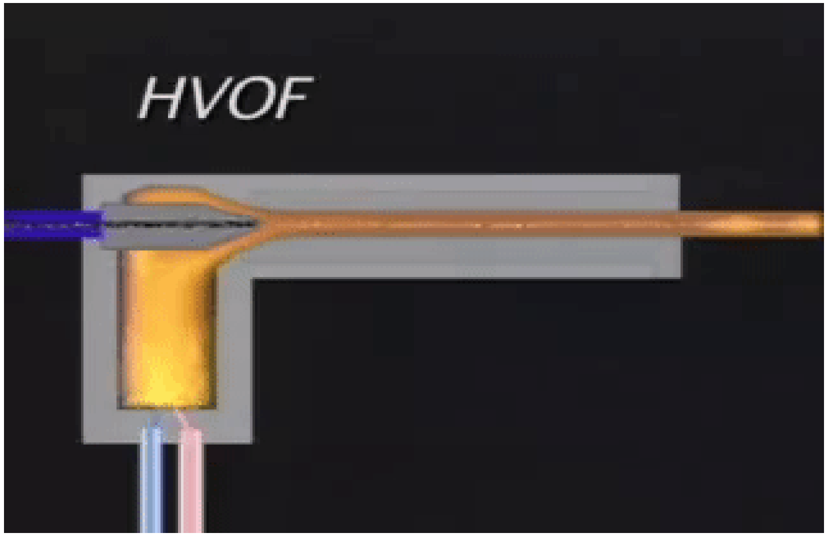


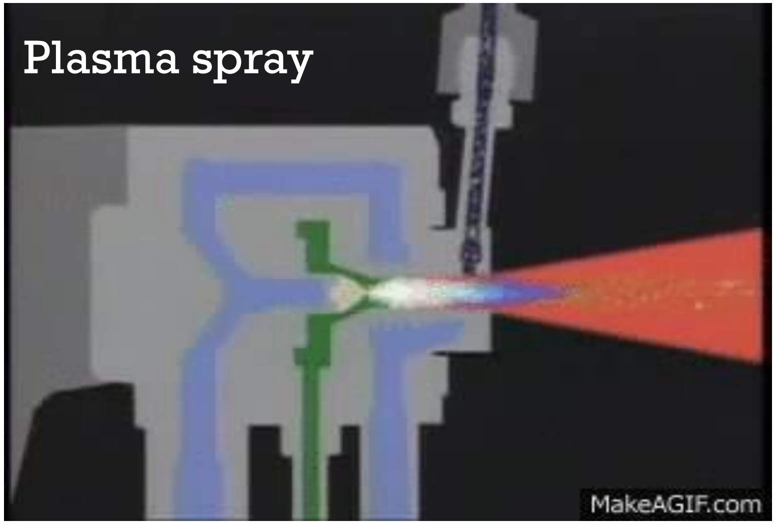
Thermal Spraying

Thermal spraying processes

- **Plasma spraying**
- **Wire arc spraying**
- **High velocity oxygen fuel (HVOF) spraying**
- **High velocity air fuel (HVAF) spraying**
- **Warm spraying/cold spray**



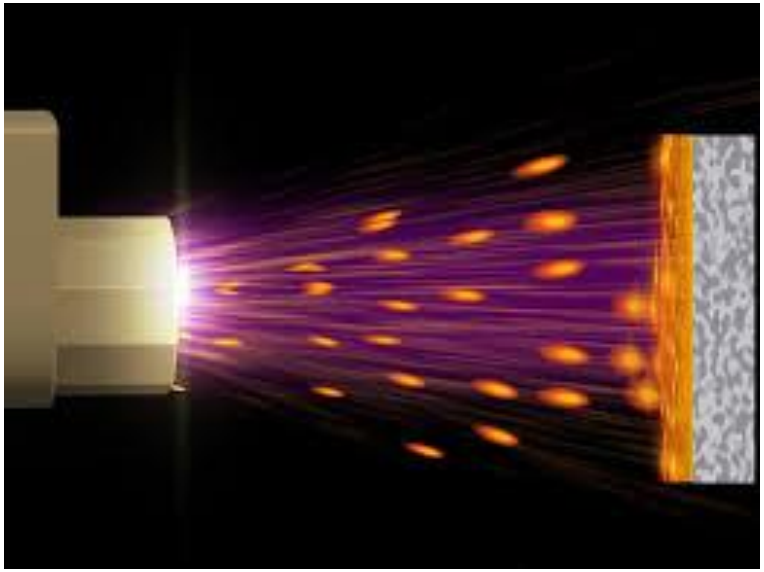




Thermal Spraying

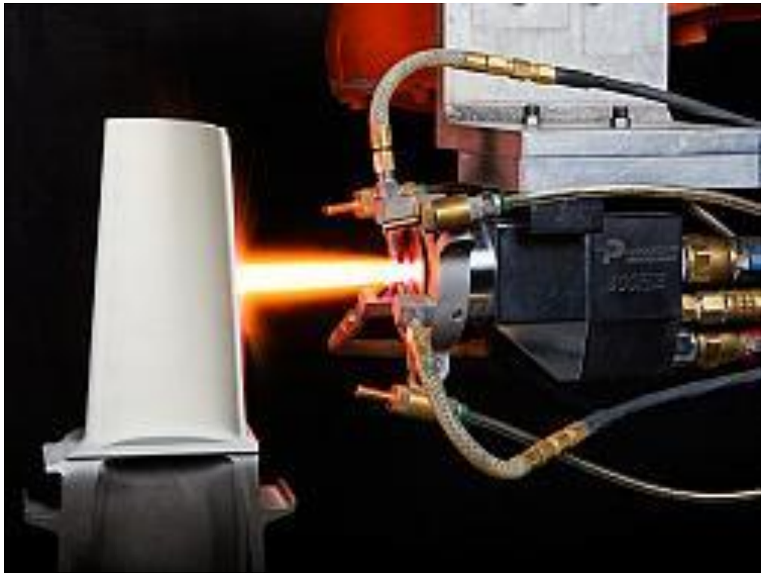
Advantages

- High adhesion and cohesion
- Various coating and substrate materials
- High efficiency and deposition rate
- Thicknesses: 0.05 to 2.5 mm
- Wide applications



Applications

- Wear and corrosion resistance
- Thermal barrier coating
- Thermal conductive coating
- Electrical conductive coating
- Damaged component repair.



Thermal Spraying

Vapor Deposition

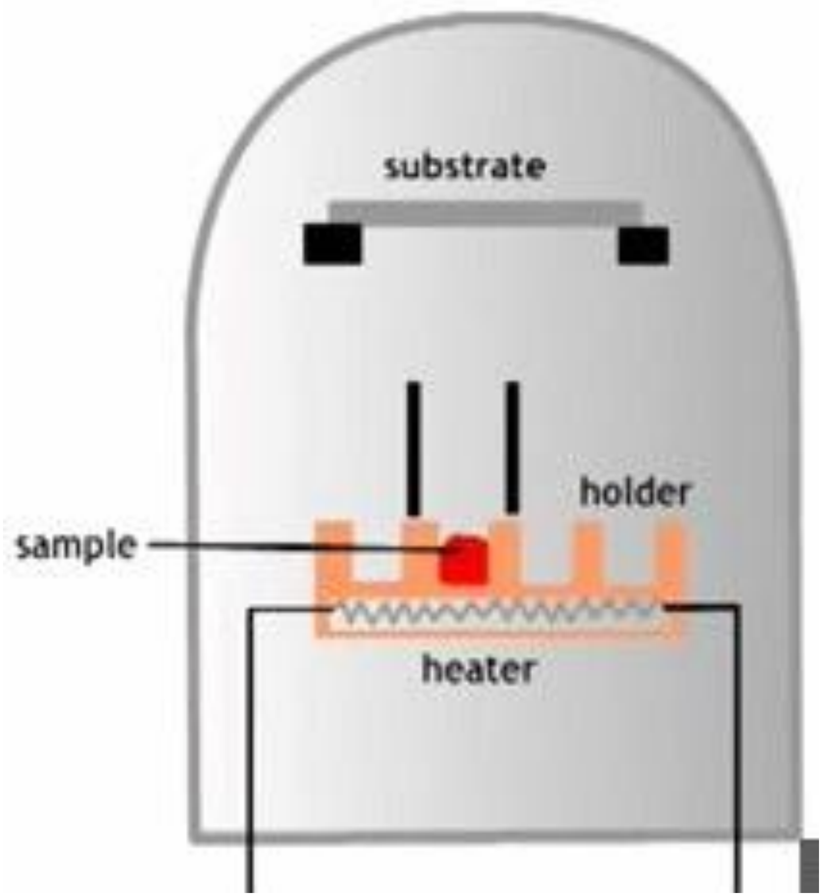
Vaper Deposition: form a coating through vapor condensing on a substrate or chemical reaction of a vaper with a substrate surface.

Vaper deposition processes

- **Physical Vapor Deposition (PVD):** gas (vapor) physically deposit on substrate surface
- **Chemical Vapor Deposition (CVD):** gas (vapor) chemically react with substrate materials to form coatings

Physical Vapor Deposition

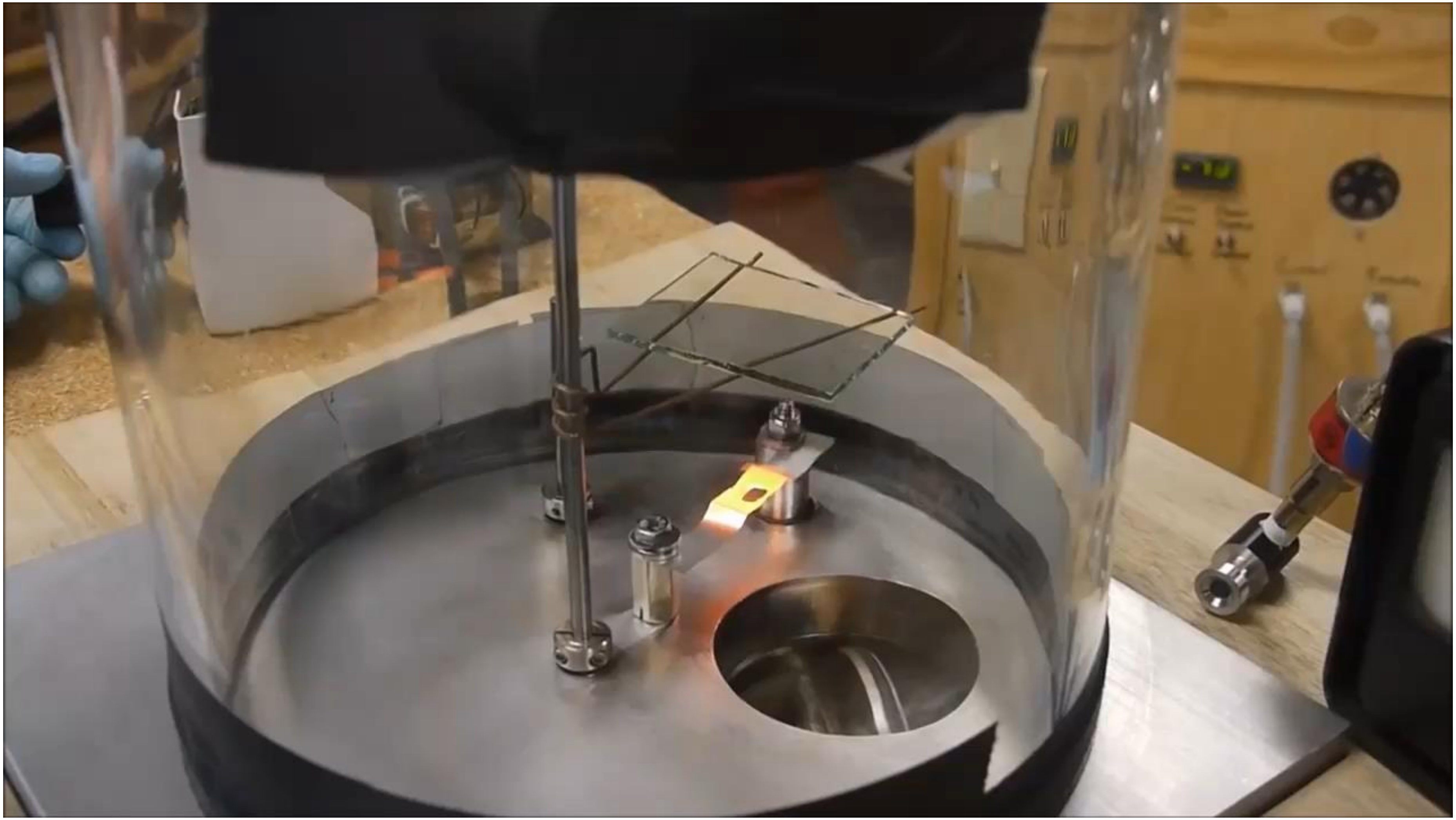
Vacuum Evaporation: deposit pure metals onto a substrate by first transforming them from solid to vapour state in a vacuum and then letting them condense on the 'cold' substrate surface.



General deposition steps

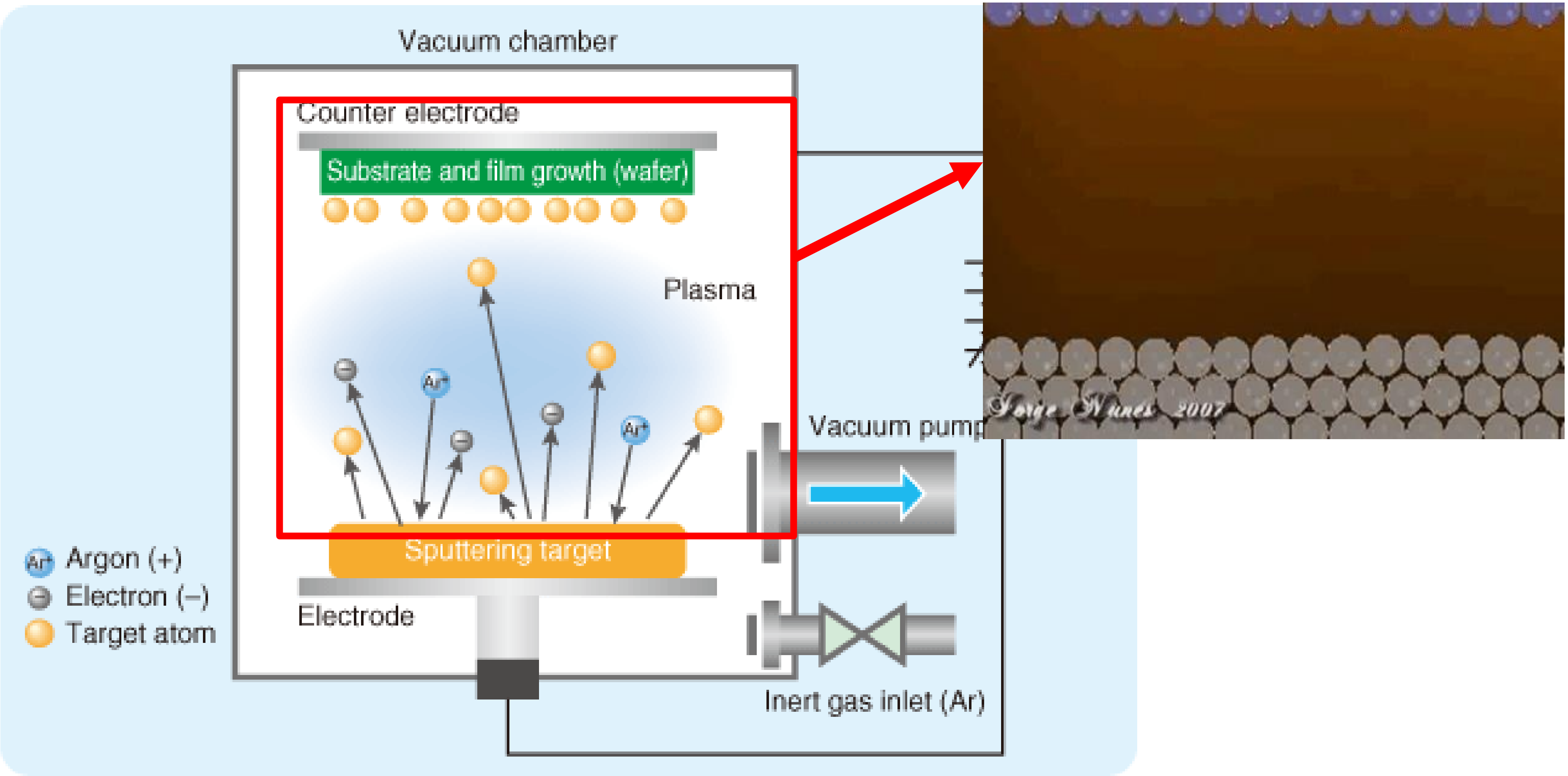
- ✓ **Vacuum the chamber**
- ✓ **Create coating vapour**
- ✓ **Vapour transports to the substrate**
- ✓ **Vapour condenses on the substrate surface**

Physical Vapor Deposition

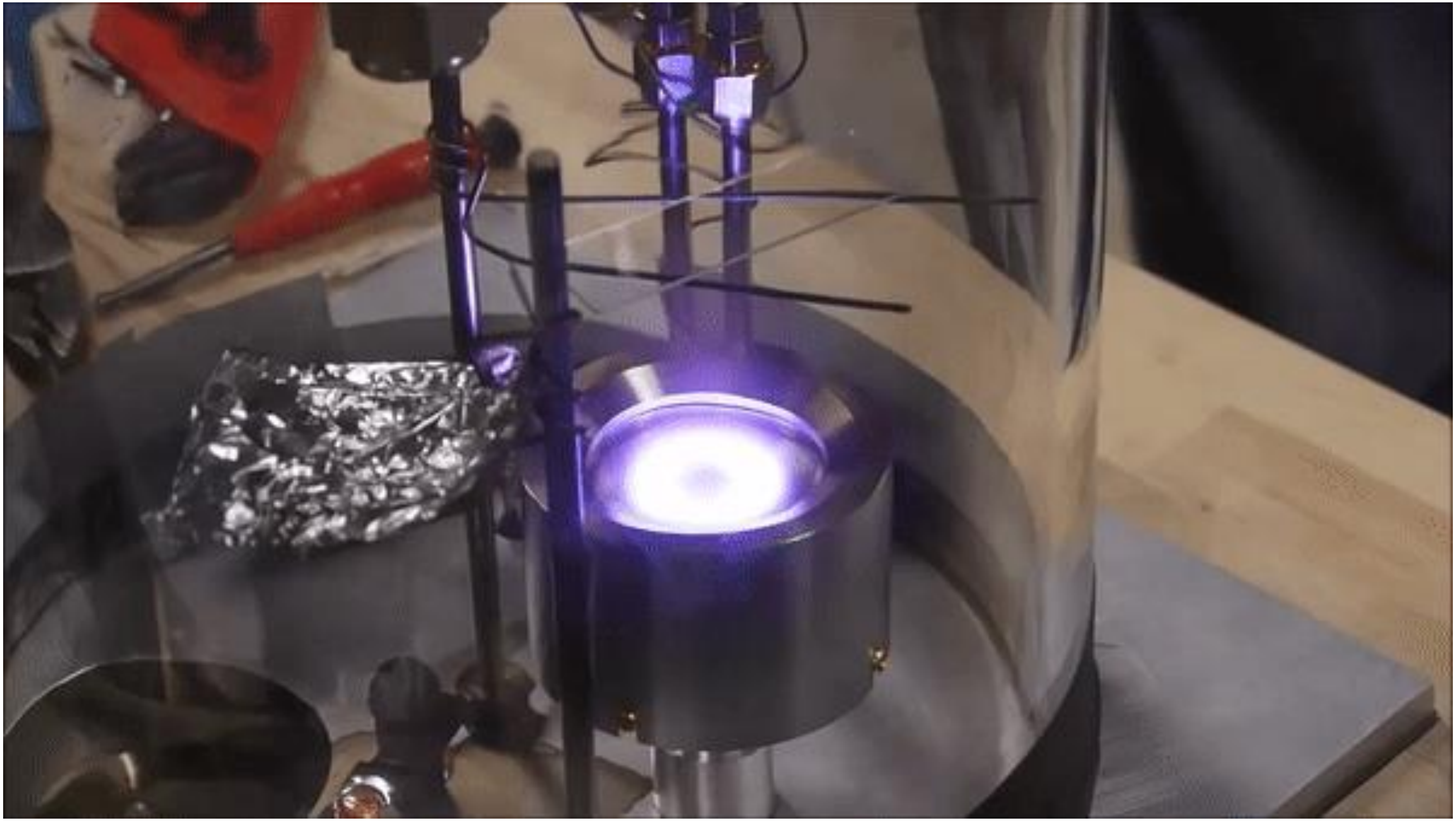


Physical Vapor Deposition

Sputtering deposition: the source material (sputter) is bombarded by energized argon ions (in plasma state), causing atoms to escape from the surface of the sources material, and then be deposited onto a substrate to form a thin film coating.



Physical Vapor Deposition



Physical Vapor Deposition

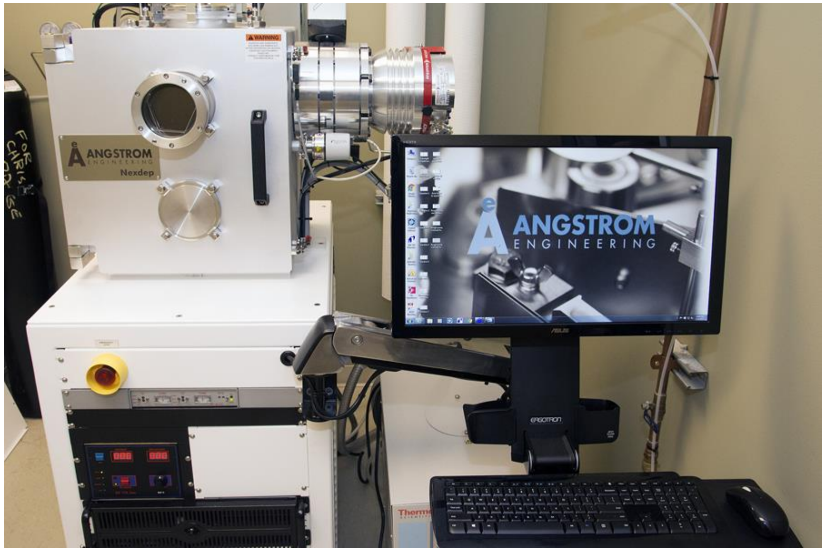
- Applicable for nearly all materials: metals, ceramics, polymers
- High cost
- Substrate is usually heated for better adhesion
- Applications: low-emissivity glass, solar cell, anti-reflection glass

Physical Vapor Deposition

Applications of PVD coatings:

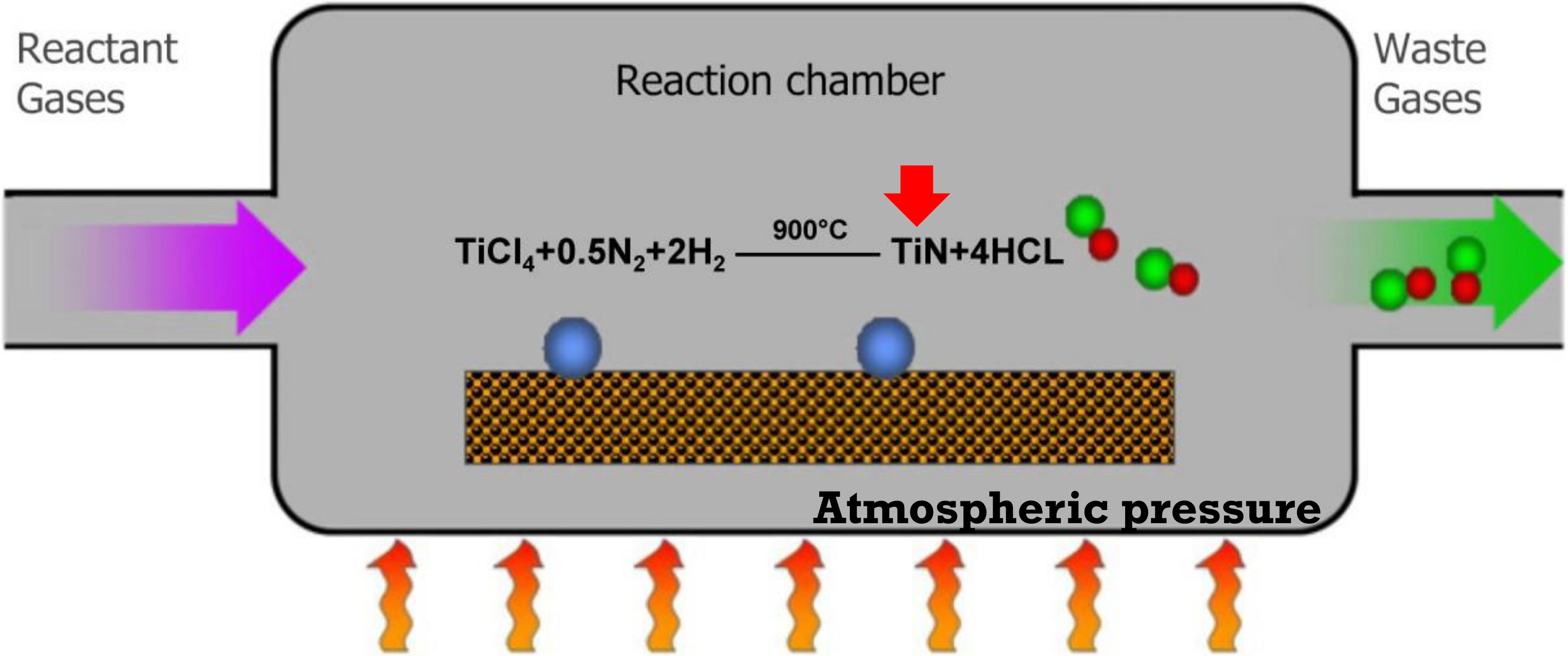
- ✓ Decorative coatings
- ✓ Low emission glasses for solar cell
- ✓ Ant-reflection coating onto optical lenses
- ✓ Conductive coating in circuits
- ✓ Titanium nitride (TiN) onto cutting tool for wear resistance

Physical Vapor Deposition



Chemical Vapor Deposition

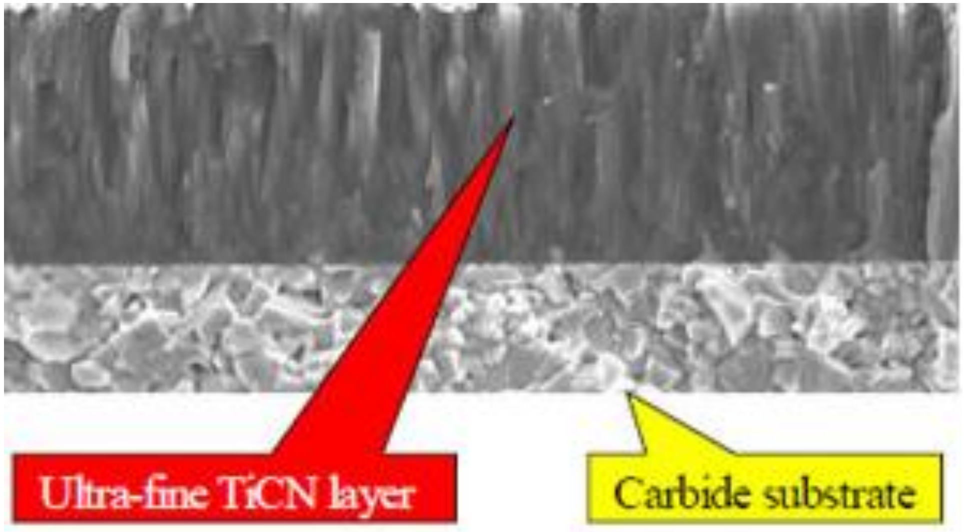
CVD working principle



Chemical Vapor Deposition

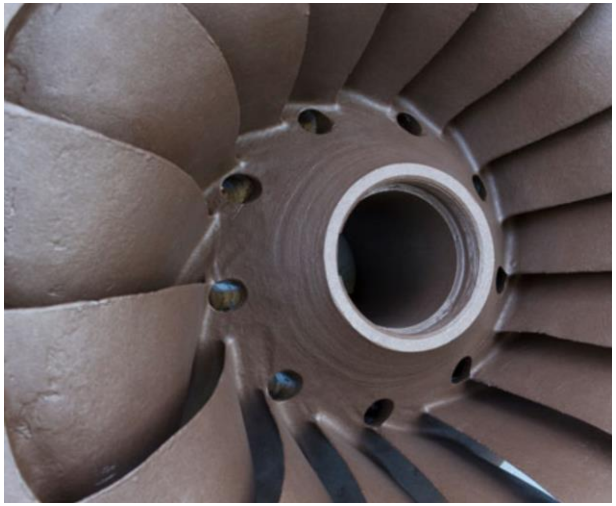
Applications:

- Solar cells
- Refractory metals on jet engine turbine blades
- Resistance to wear, corrosion, erosion



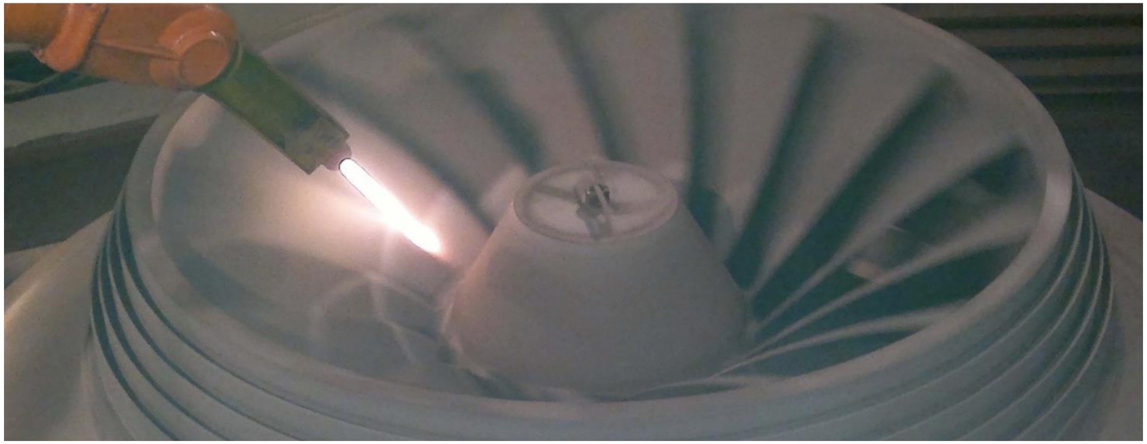
Wear-resistance Coating Research in Trinity

水轮机叶片的冲蚀及热喷涂涂层

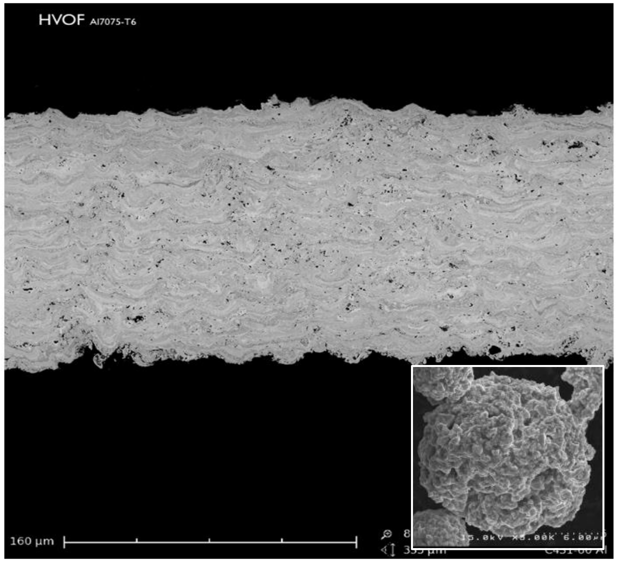


受到冲蚀破坏后的水轮机部件

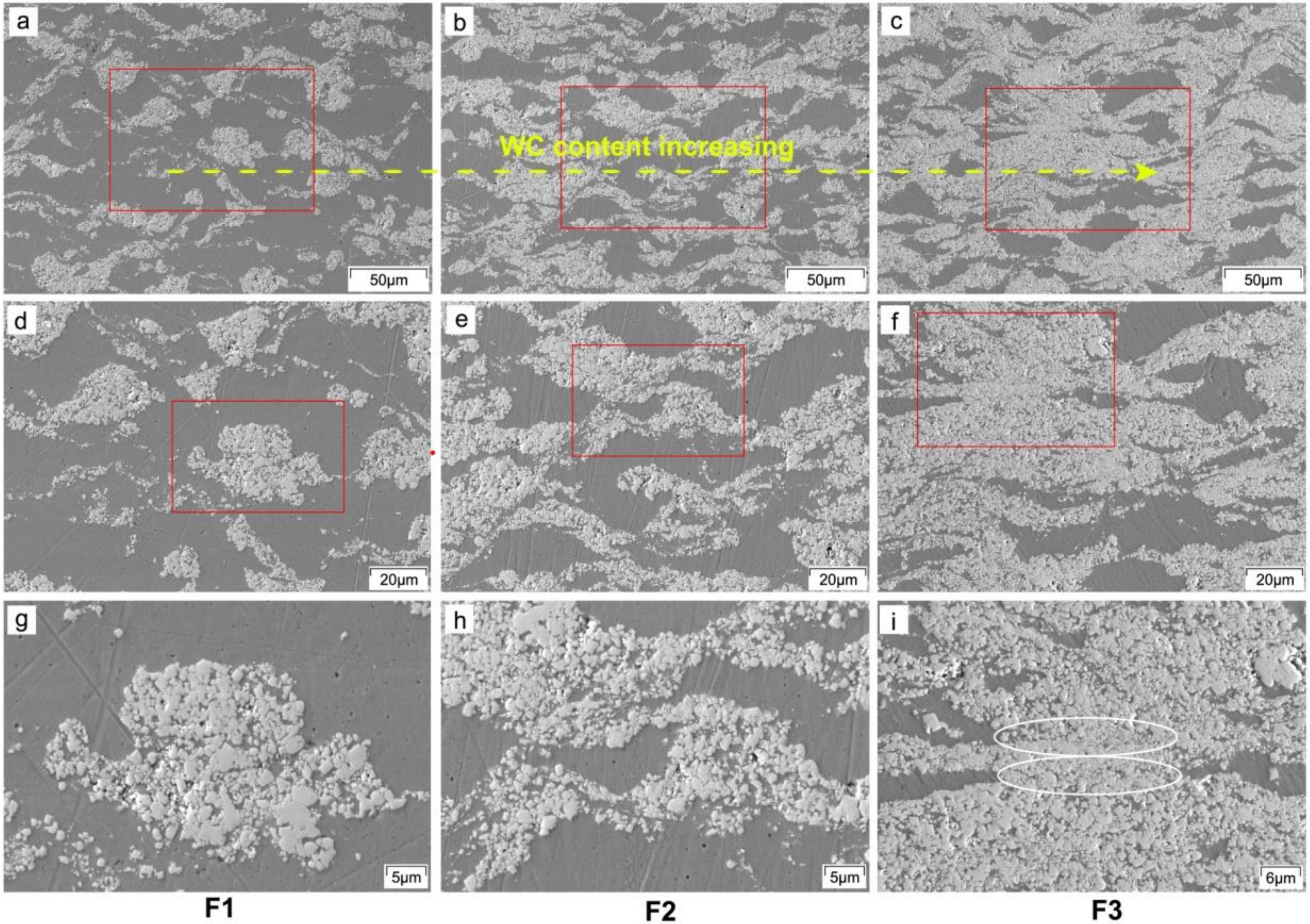
- ✓ 造成破坏的主要原因是颗粒冲蚀以及气蚀。
- ✓ 水轮机叶片及部件耐磨涂层通常为WC-Co涂层
- ✓ 通常采用热喷涂，如超音速火焰喷涂，电弧喷涂等



热喷涂涂层

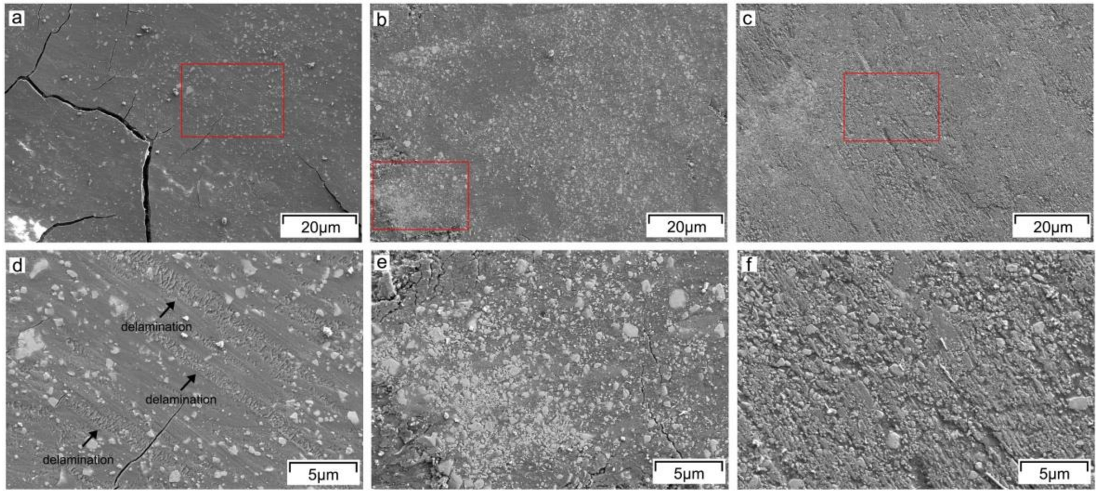


冷喷涂Ni-WC-Co金属基复合材料耐磨涂层



冷喷涂Ni-WC-Co复合耐磨涂层

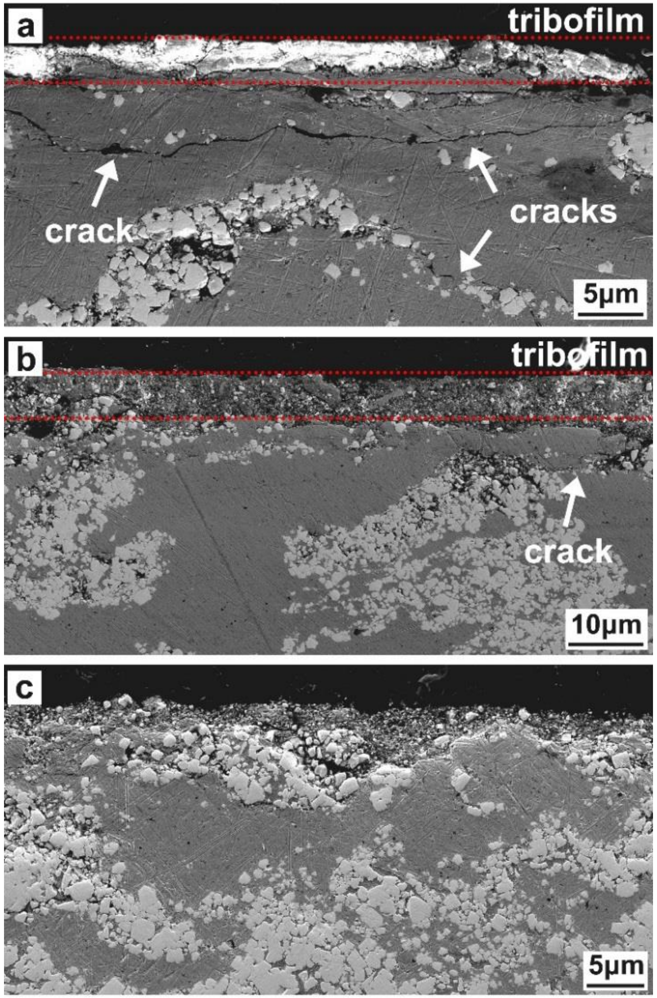
冷喷涂Ni-WC-Co金属基复合材料耐磨涂层



磨损试验后的涂层表面照片

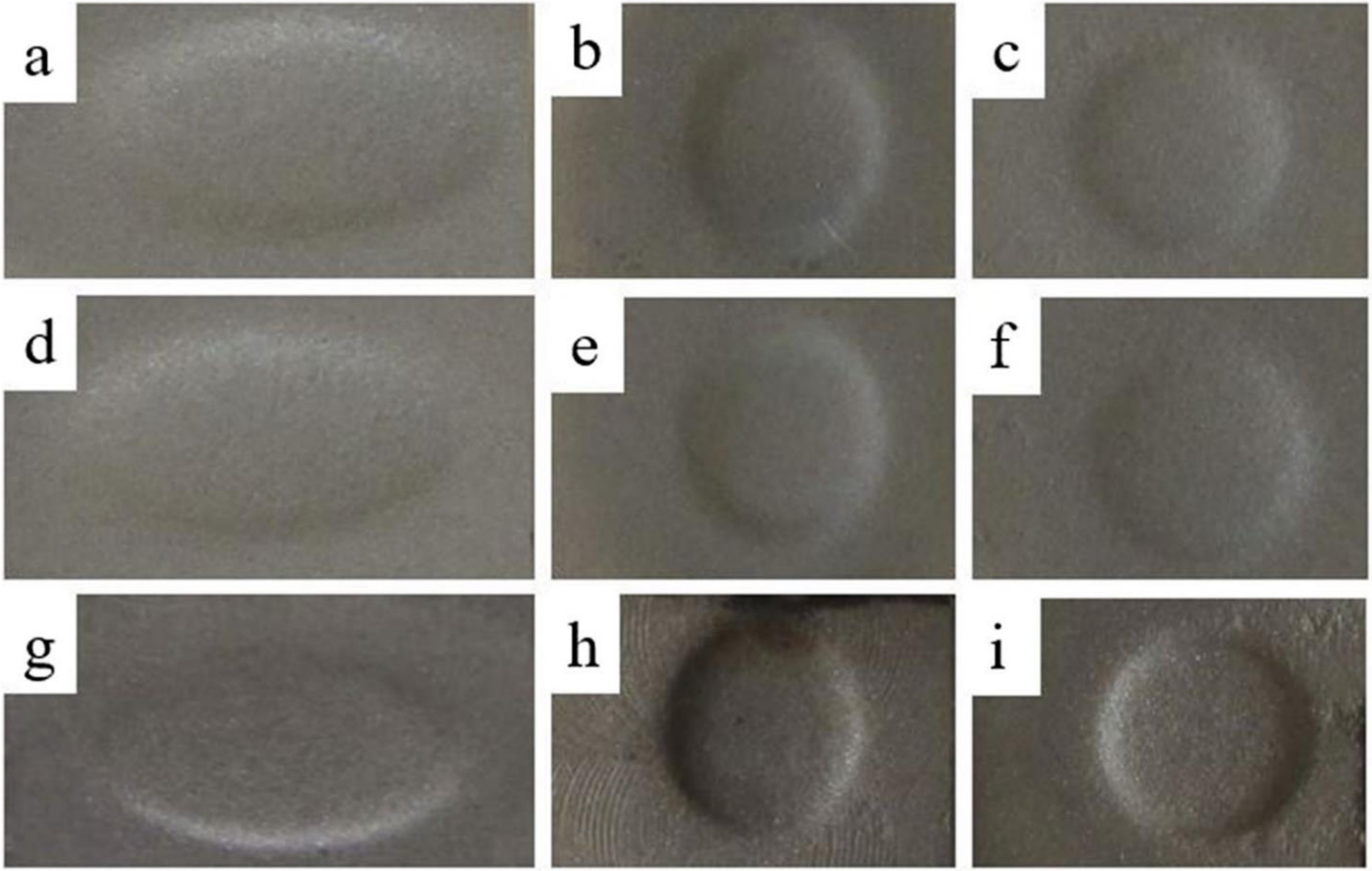
Coating	Coating wear rates [mm^3/N·m]
F1	12.263±3.028e^{-6}
F2	7.575±1.921e^{-6}
F3	3.382±1.020e^{-6}

涂层的磨损率



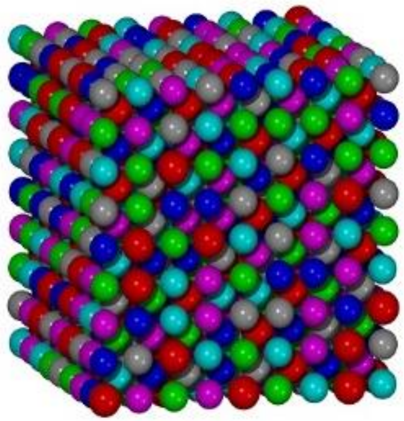
磨损试验后的涂层界面照片

冷喷涂Ni-WC-Co金属基复合材料耐磨涂层



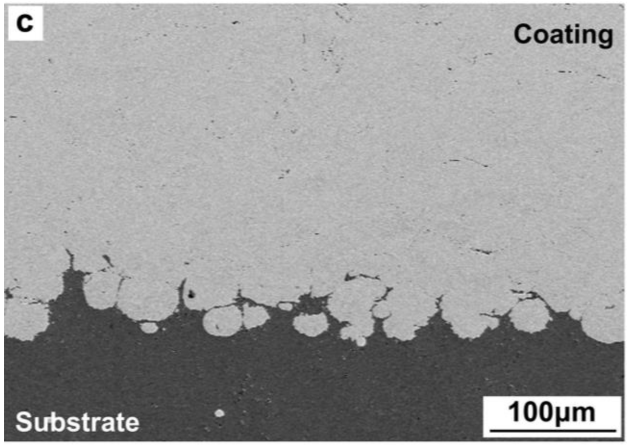
冷喷涂Ni-WC-Co复合耐磨涂层的冲蚀实验结果

冷喷涂高熵合金耐磨涂层

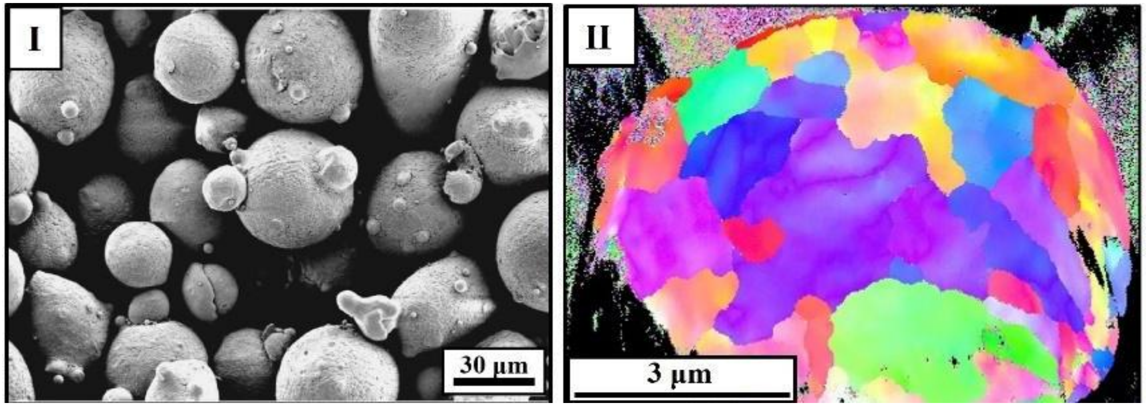


- High strength
- Wear resistance
- Corrosion resistance
- Oxidation resistance

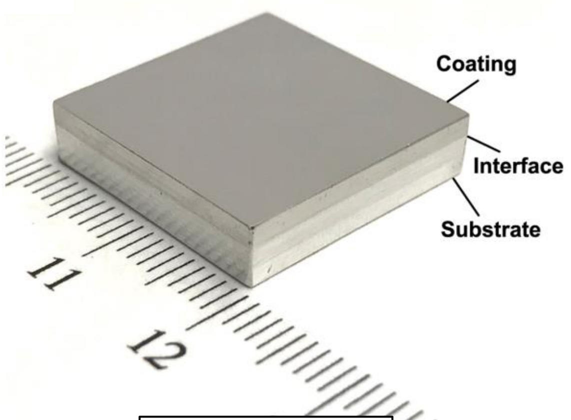
High entropy alloys



Cross-section

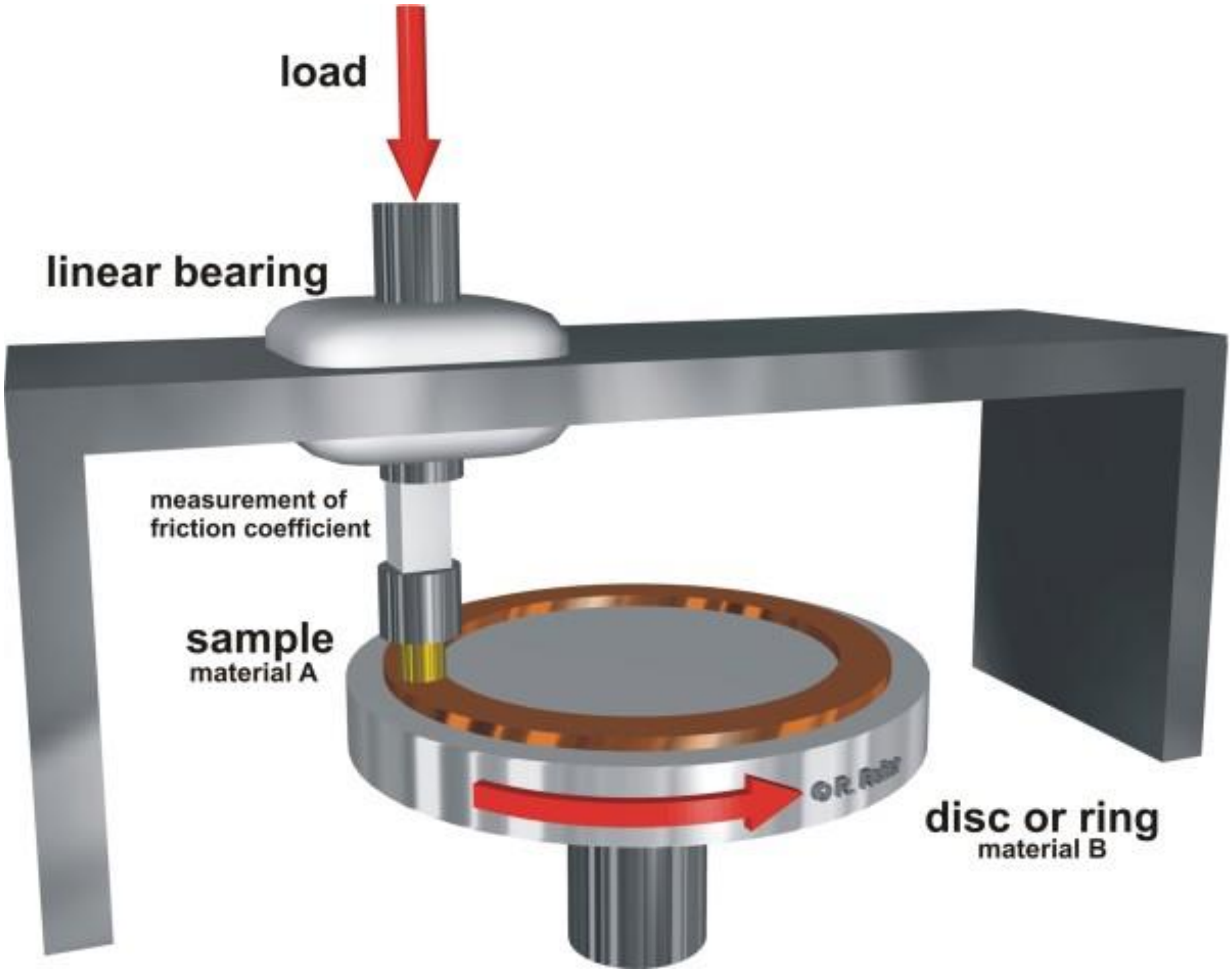


FeCoNiCrMn HEA powders



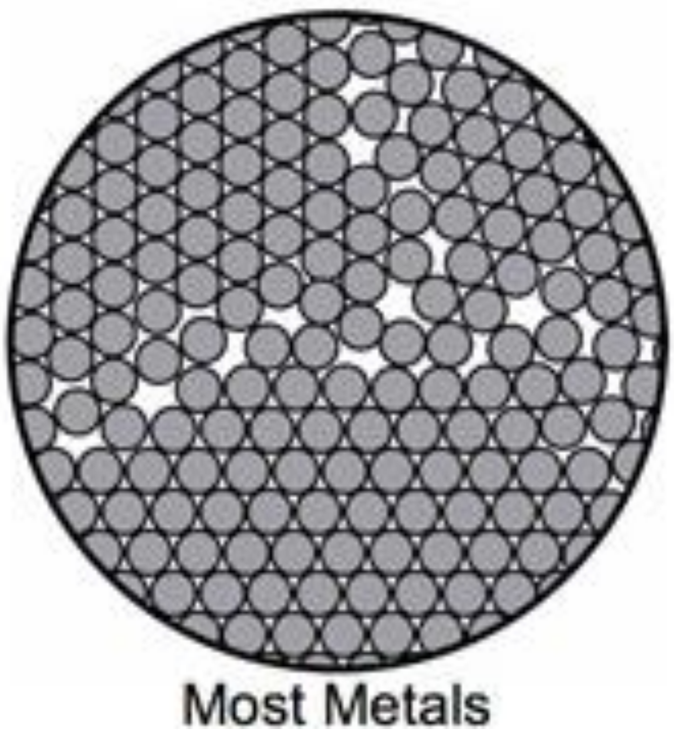
HEA sample

冷喷涂高熵合金耐磨涂层

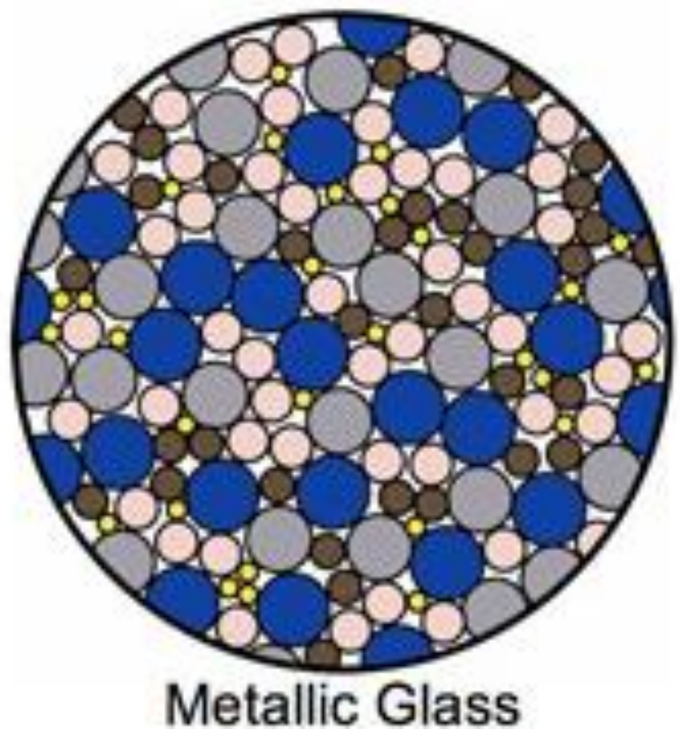


涂层耐磨性测试试验机

冷喷涂非晶合金耐磨涂层

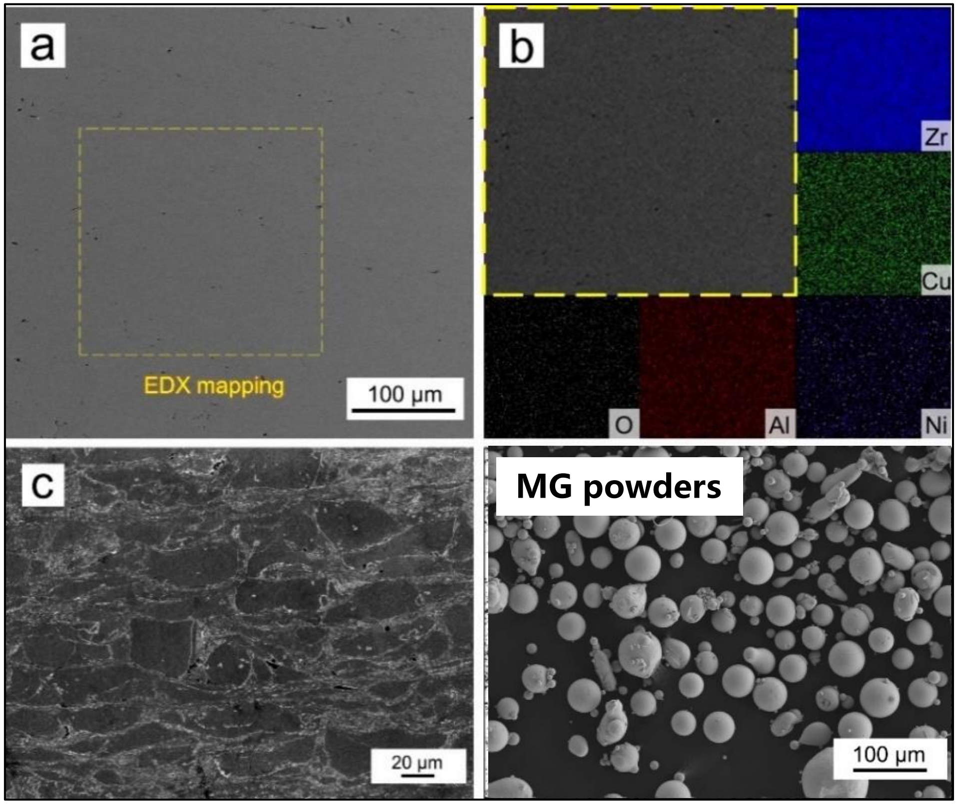


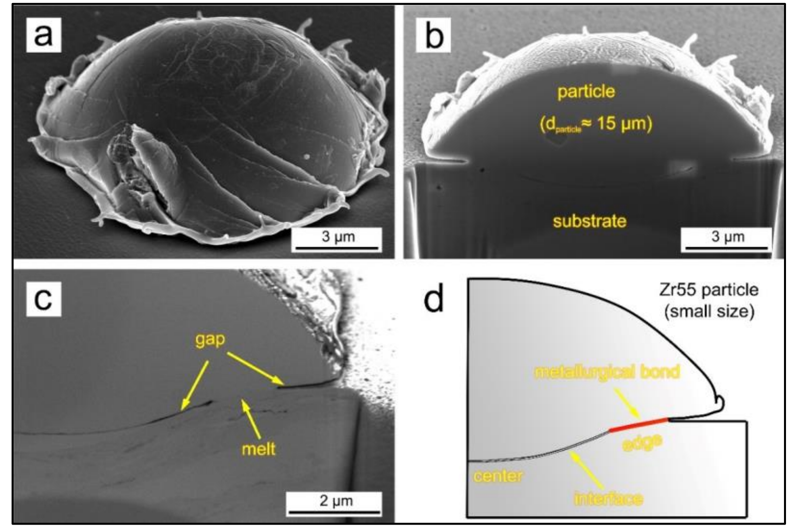
- Polycrystalline grains of varying shapes and sizes
- Grain boundaries represent week spots



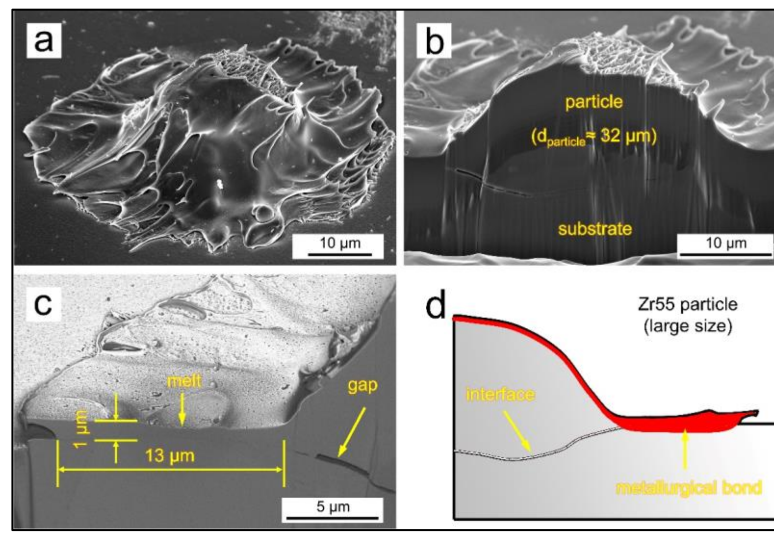
- Cooled faster than atoms can rearrange into a crystal
- High strength and hardness
- High corrosion resistance
- High electrical resistance
- Excellent magnetic properties

冷喷涂非晶合金耐磨涂层





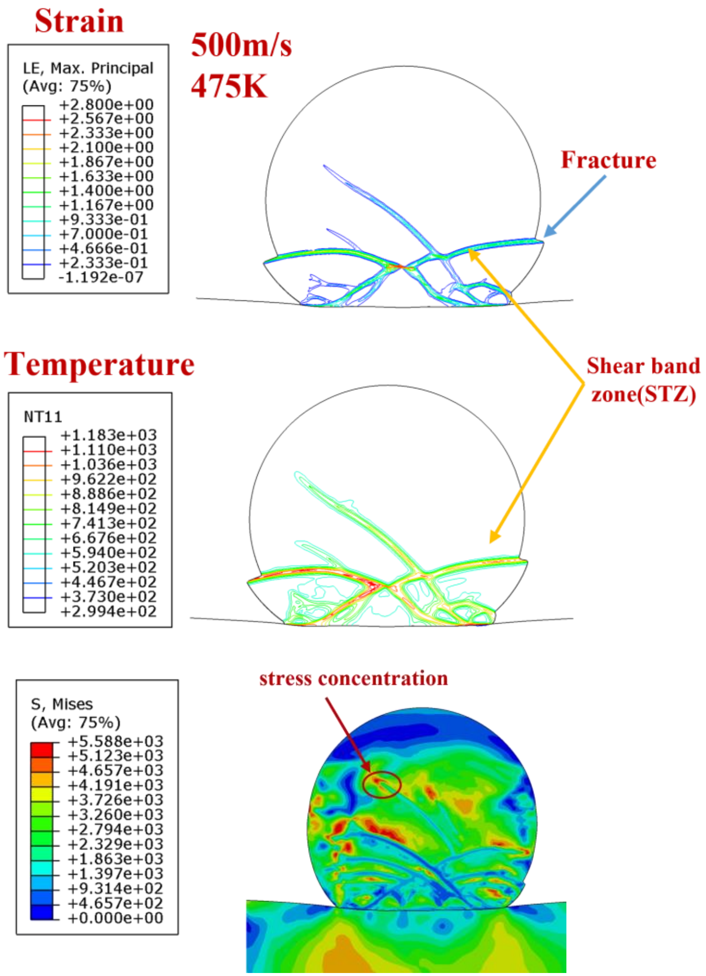
Mechanism I

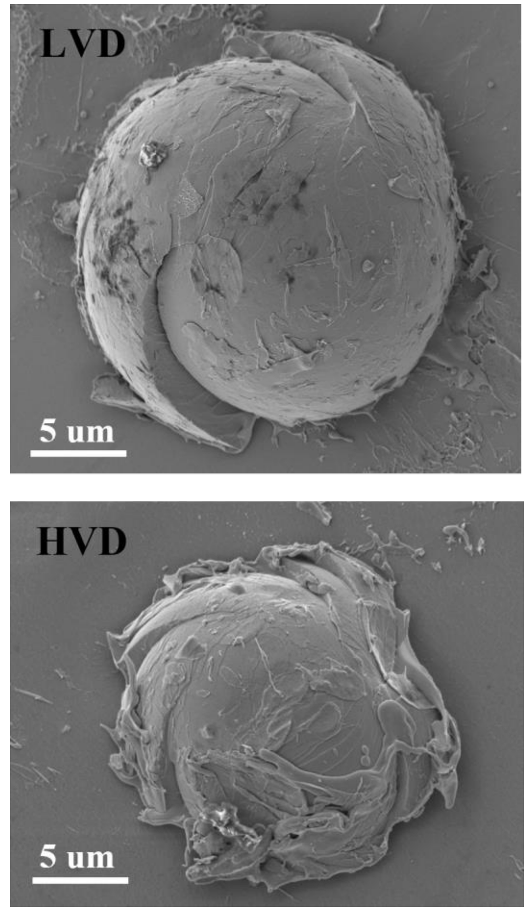


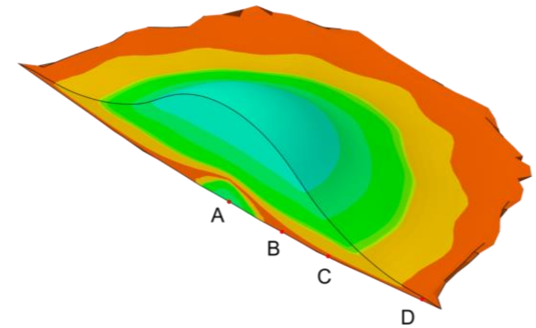
Mechanism II

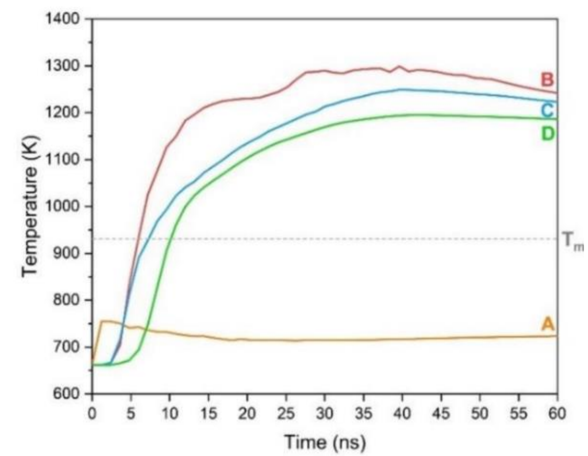
- **Zr55**
- **Density：99.70 %**
- **Microstructure and mechanism**

冷喷涂非晶合金耐磨涂层



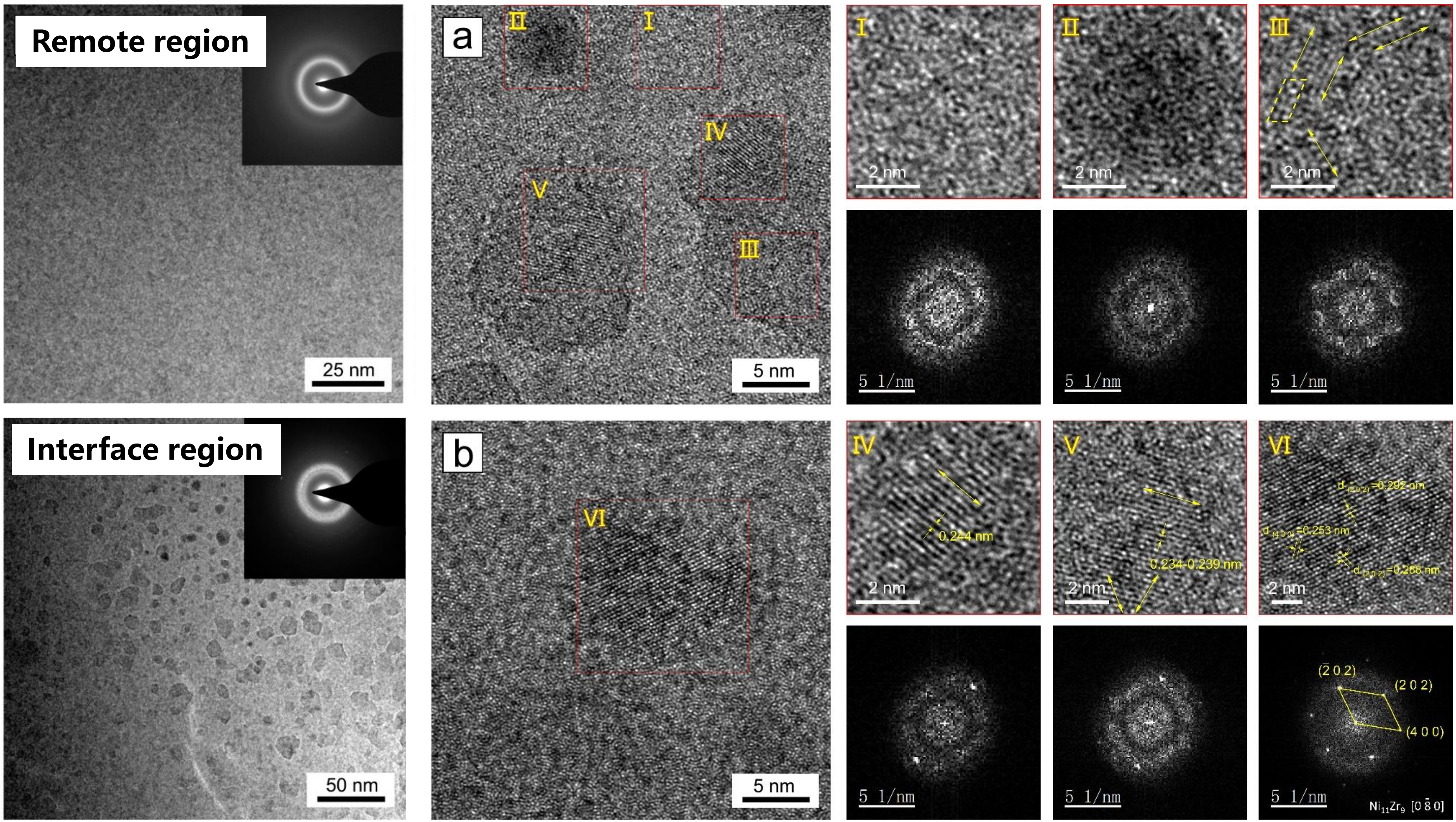






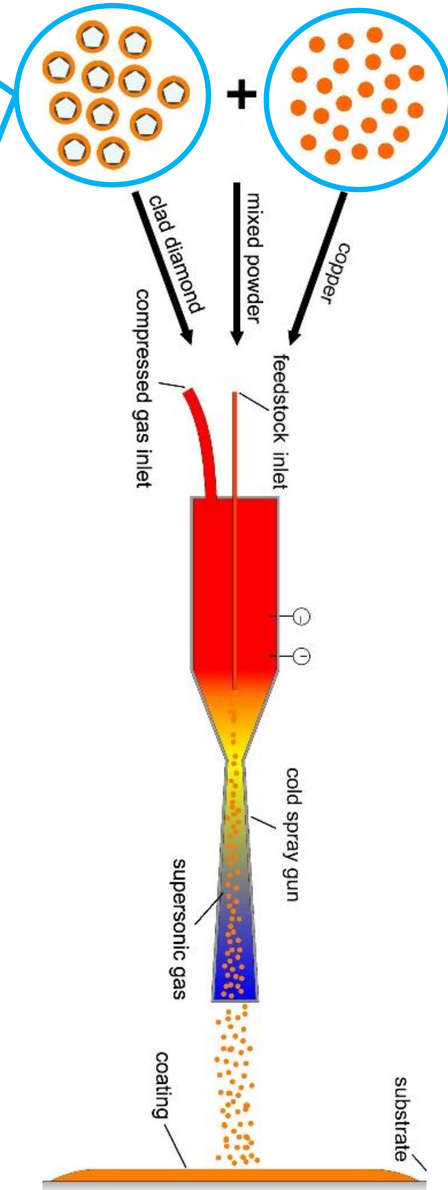
有限元数值分析非晶颗粒在形成涂层过程中的变形行为

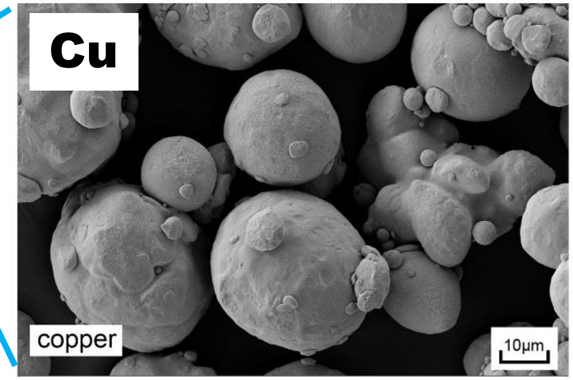
冷喷涂非晶合金耐磨涂层



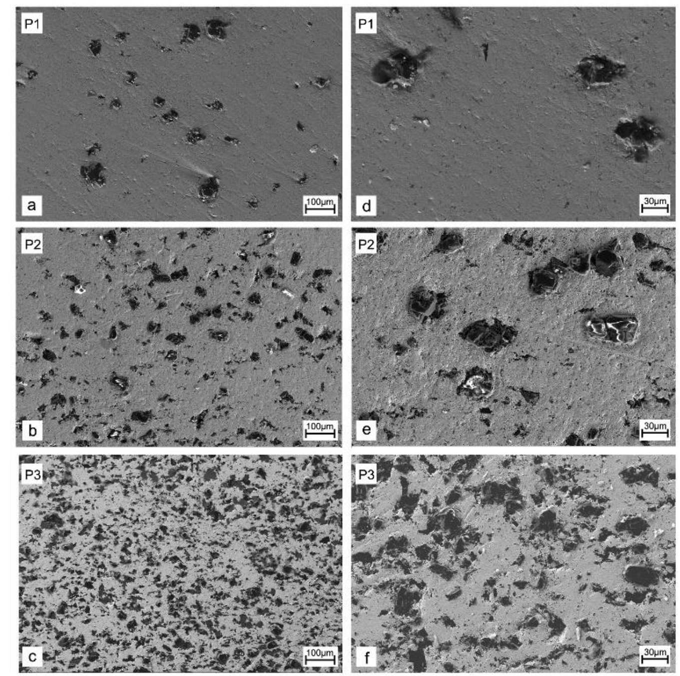
Crystallization behaviours

冷喷涂金属基复合材料耐磨涂层



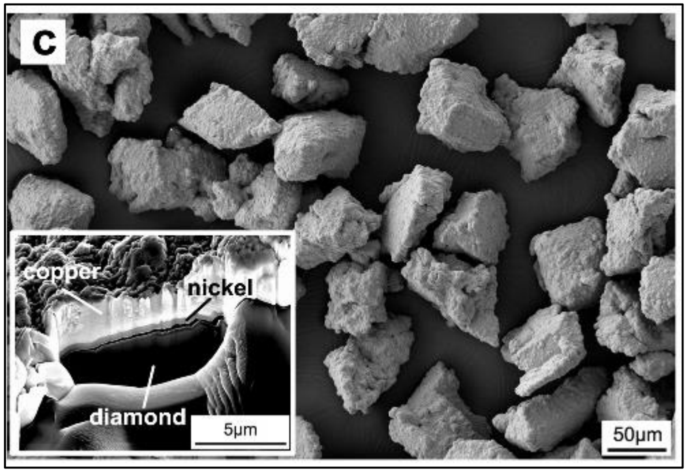


	Diam-P	Diam-C	Diam-R
	5.9%	12.6%	213.6%
	25%	30.5%	122%
	50%	43.2%	86.4%



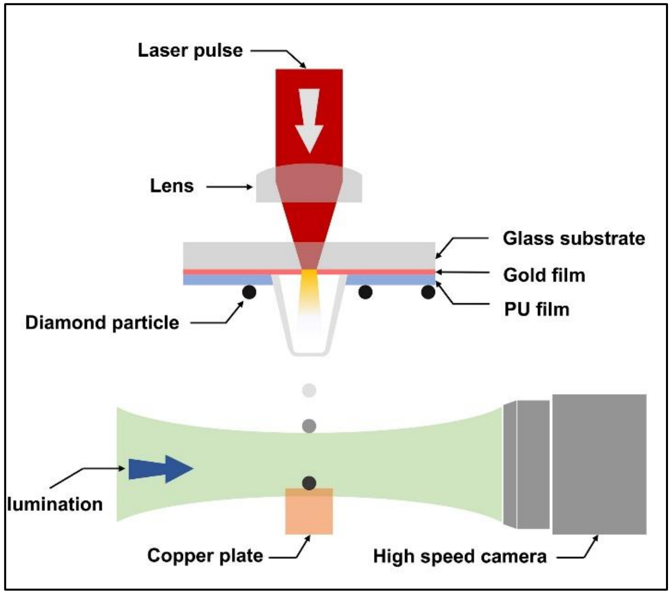
Cross-sections

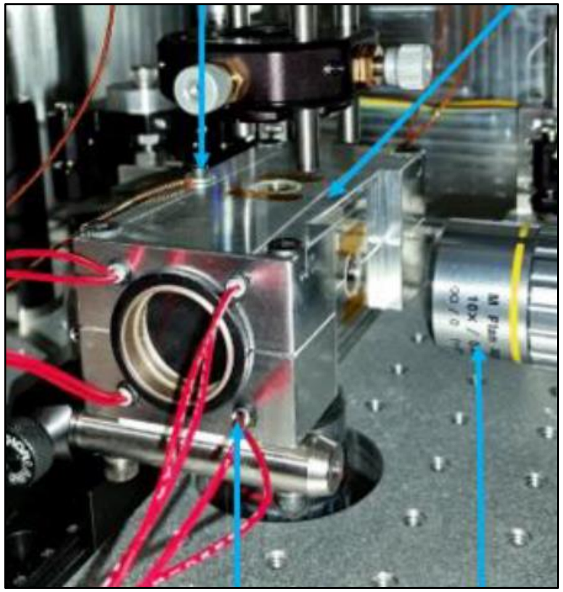
In-situ observation



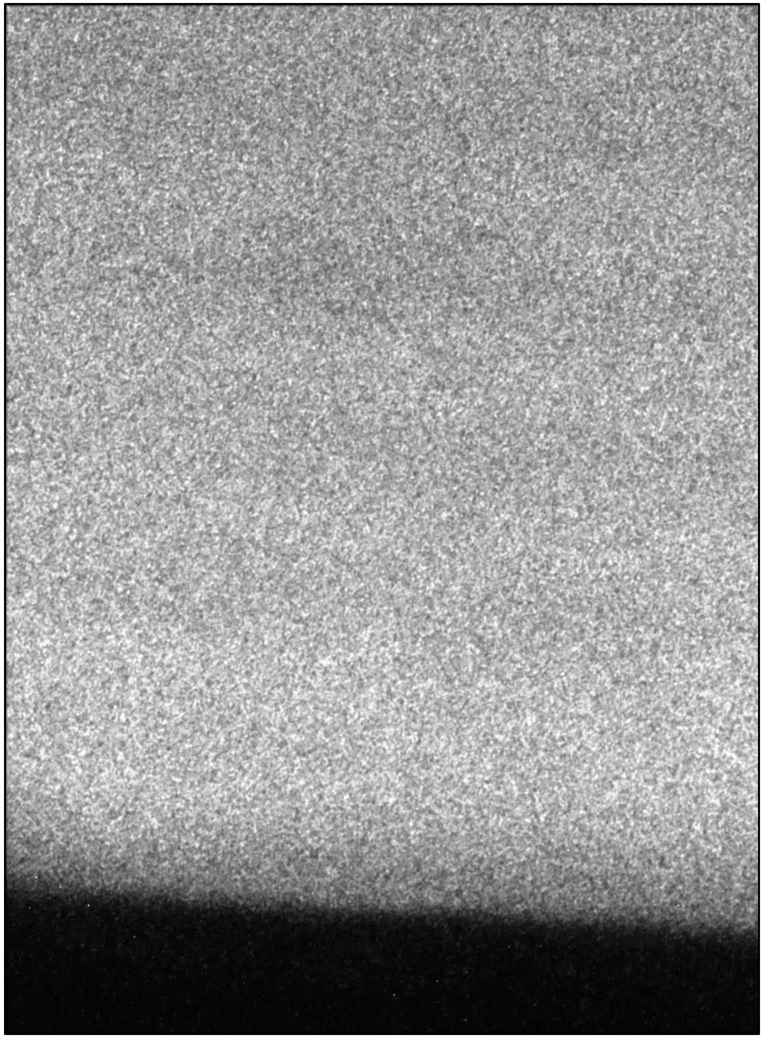
- Cu-coated diamond
- Size: 47-53m/s
- Shape: irregular
- Element six

- Single particle
- 100-1000m/s
- 1um-100um
- 10ns
- MIT

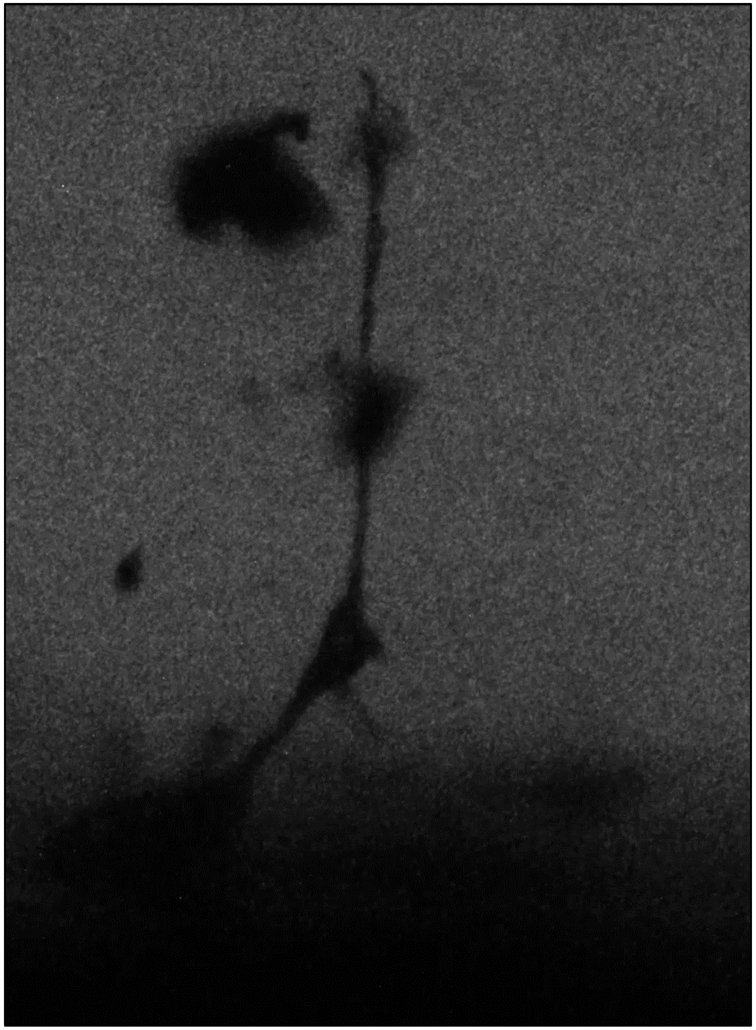




冷喷涂金属基复合材料耐磨涂层

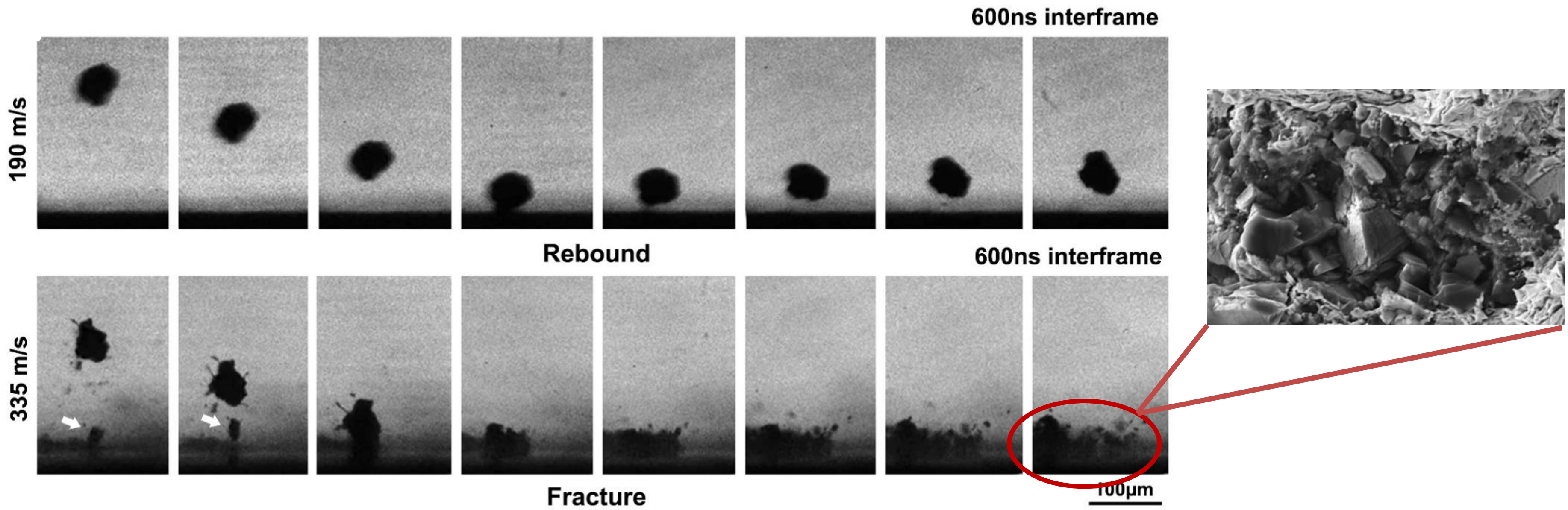


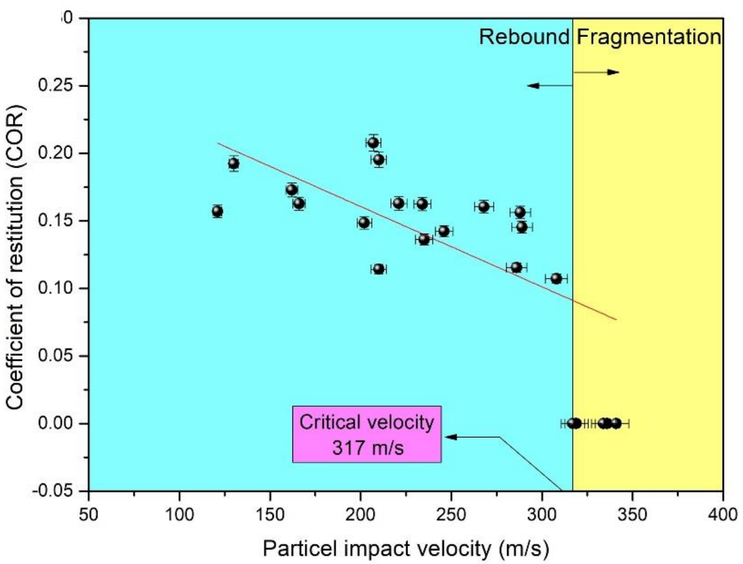
Low velocity



High velocity

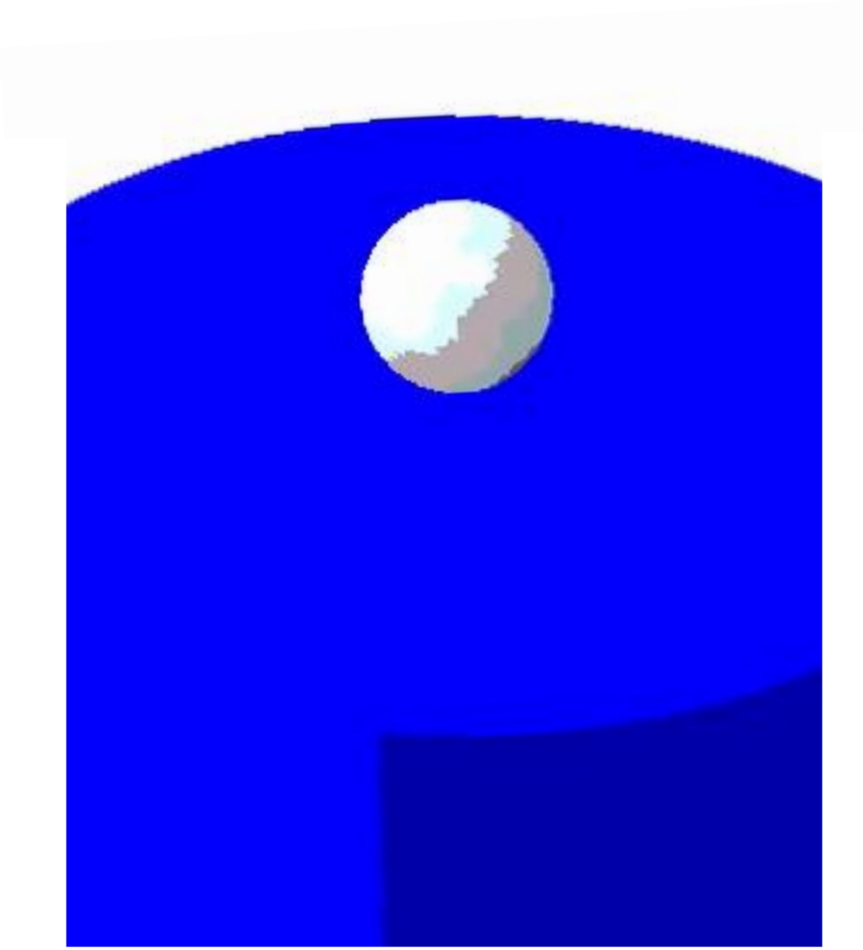
冷喷涂金属基复合材料耐磨涂层



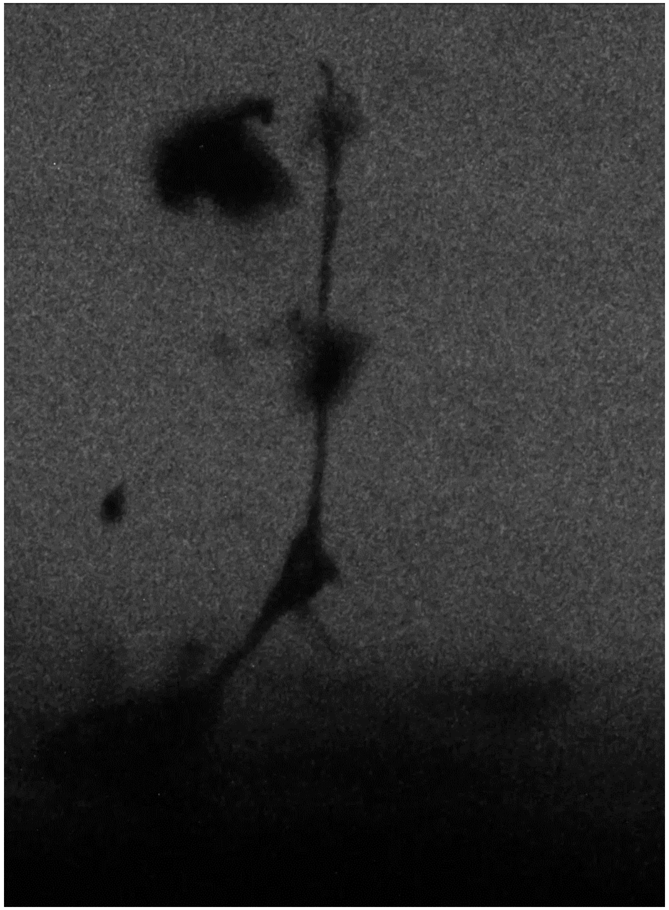


- Repeat the impact test with increased velocity, and plot the data into a chat
- Find out a critical velocity
- Threshold for rebound/fragmentation
- 317m/s for this case

冷喷涂金属基复合材料耐磨涂层

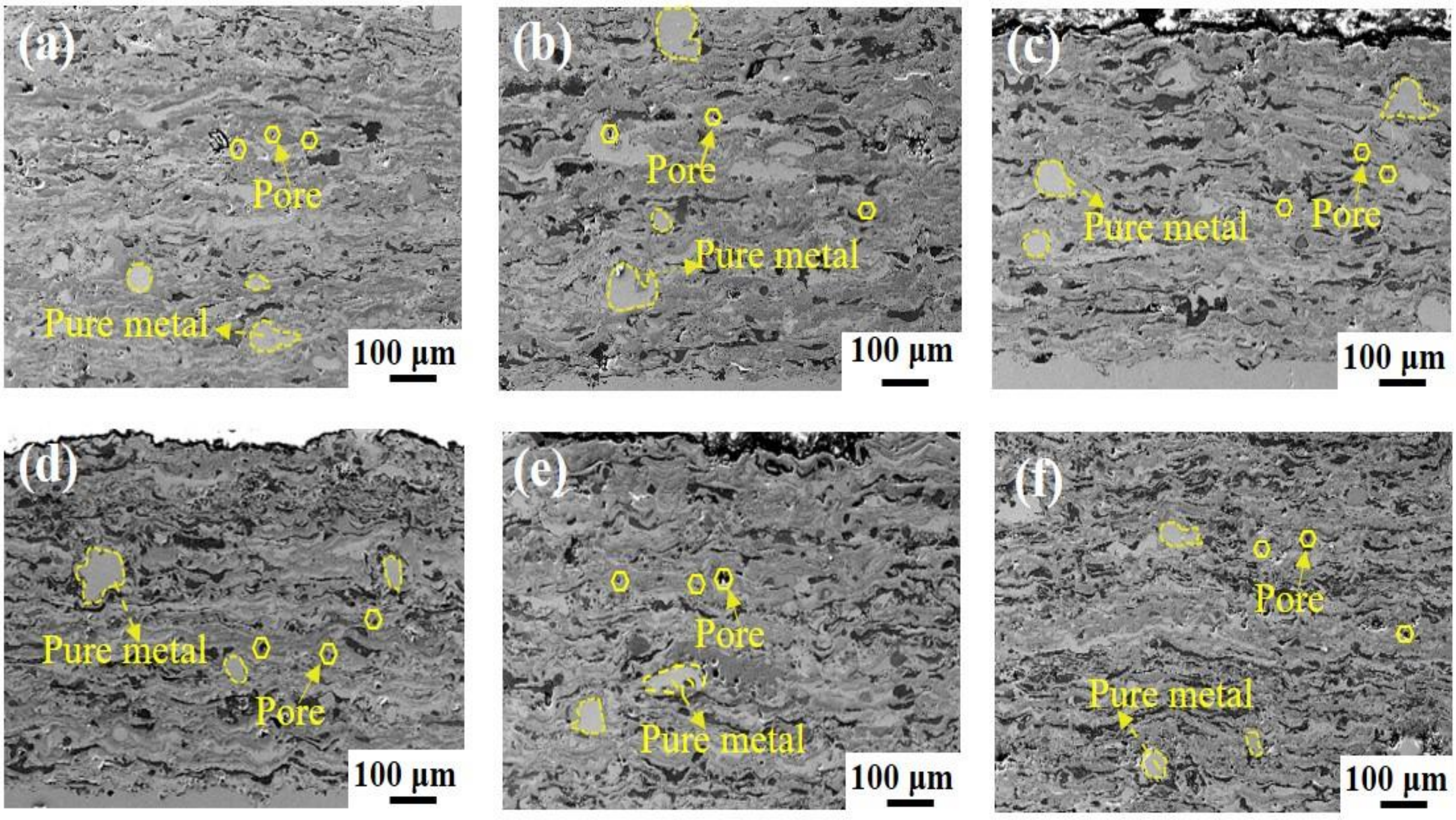


Numerical simulation



In-situ observation

等离子喷涂高熵合金耐磨涂层



采用等离子喷涂制备的高熵合金耐磨涂层

Other 3D-Printing technologies in Trinity

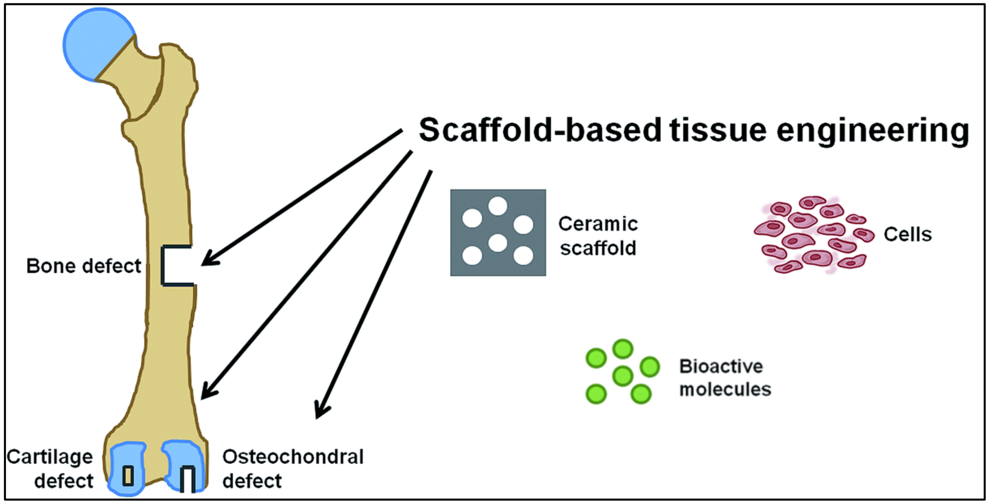
3D printing of β-TCP

Why β-TCP and DLP?

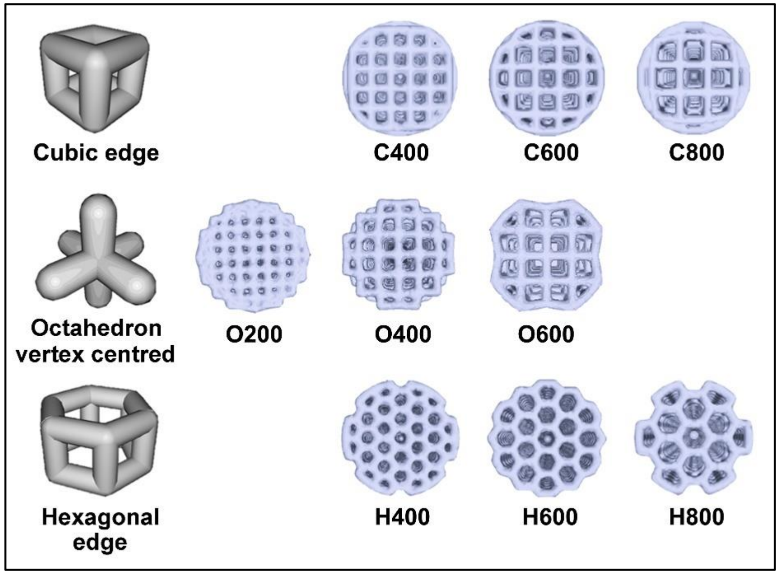
- Bone defect healing
- Bioactive
- Degradable
- High precision
- Customization

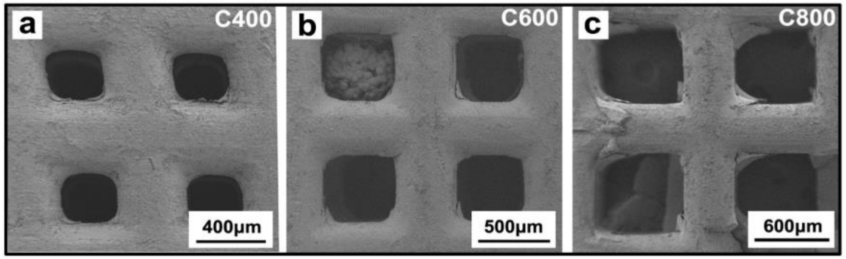
Challenge?

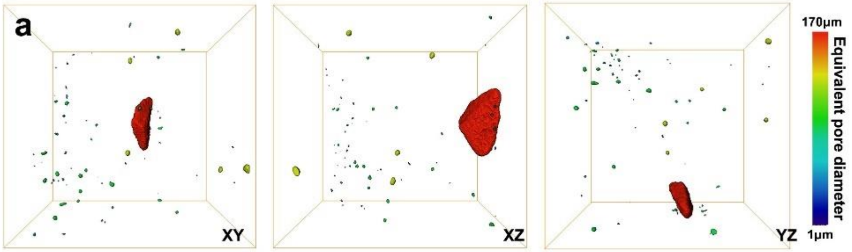
- Feedstock design
- Microstructure defects
- Brittle and low strength
- Lack of in-vitro/in-vivo tests
- Control of degradation rate

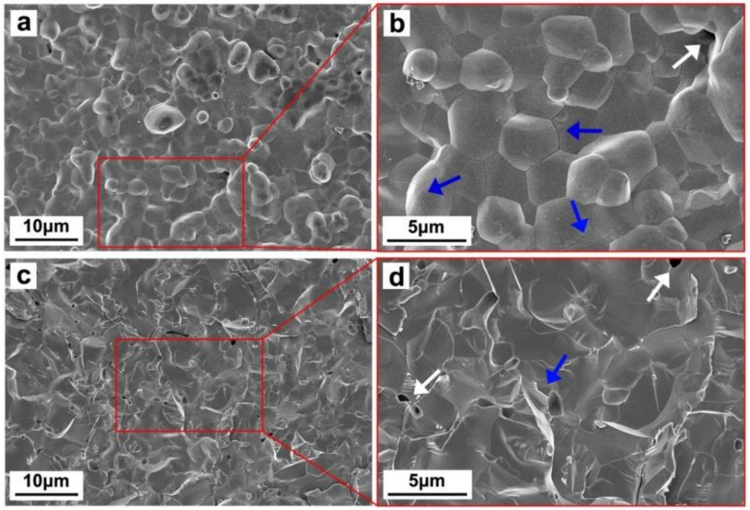


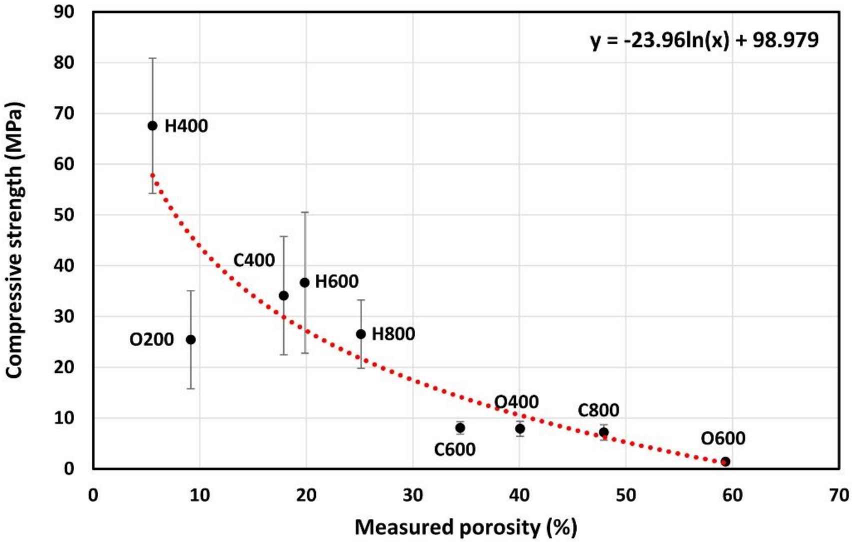
3D printing of β-TCP











3D printing of β-TCP

Project Goal: to develop a β-TCP scaffold having excellent mechanical and biological properties for bone defects healing

DLP lattice scaffolds

① **Scaffold design: unit cell structure, strut diameter, pore size, porosity, and geometric correction.**

② **Printing parameters: layer thickness, exposure time, etc.**

③ **Sintering parameters: dwelling time, maximum temperature, cooling, etc.**

④ **Bioinstructive additives: bioactive proteins, growth factors, cells, etc.**

Microstructure

① **Micro- or nano- porosity**

② **Micro-cracks**

③ **Grain size**

Mechanical

① **Roughness**

② **Elastic module**

③ **Compressive strength**

Biological

① **Biocompatibility**

② **Osteoconductivity**

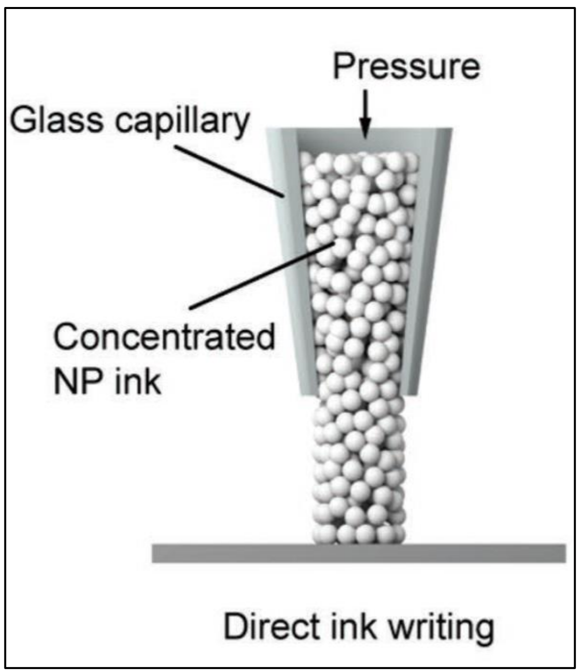
③ **Osteoinductivity**

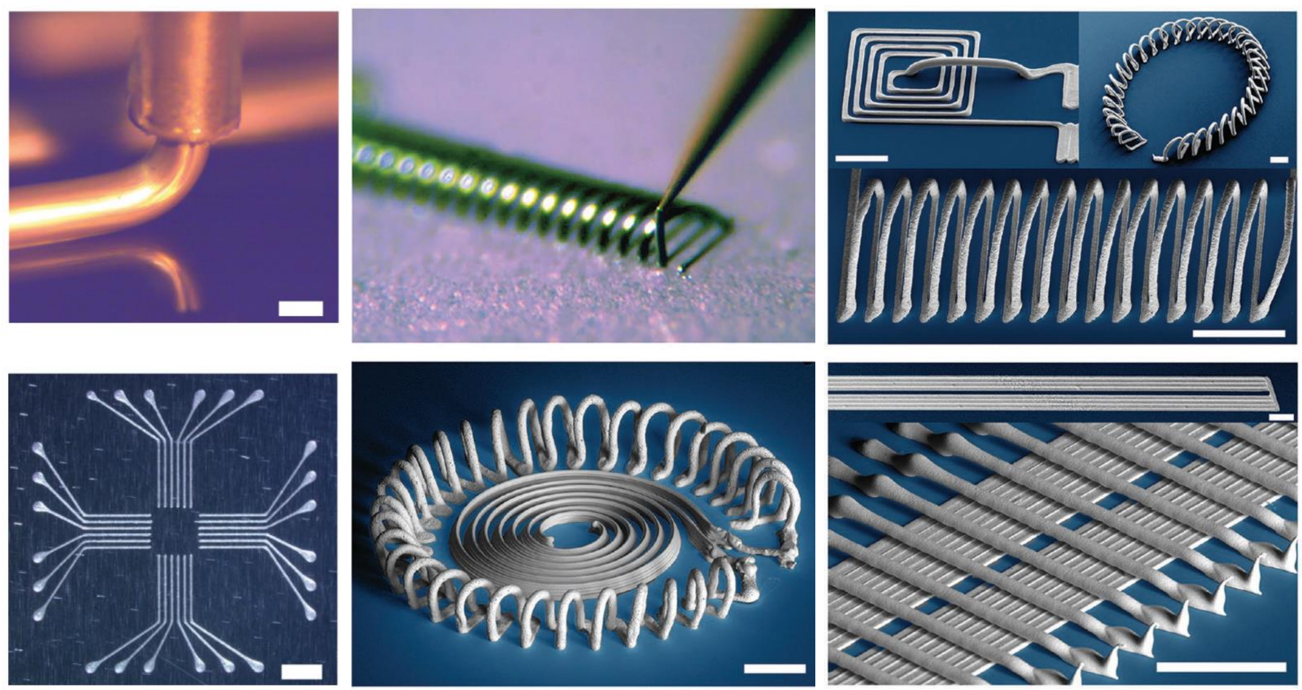
④ **Degradability**

"The" scaffolds

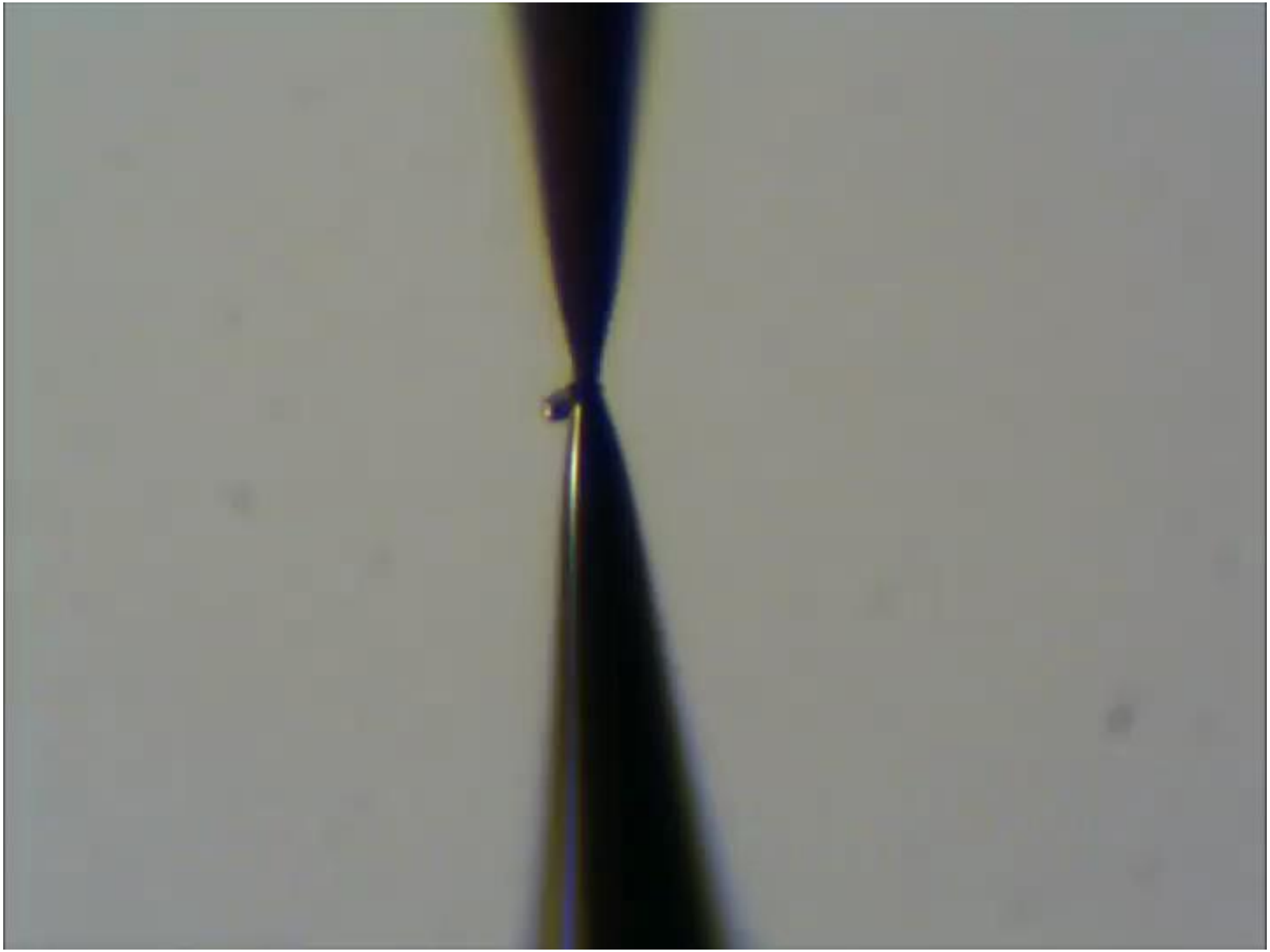
Micro-Scale Additive Manufacturing

- **Direct ink writing (DIW)**: shear-thinning nanoparticle ink is extruded through a micrometer- sized glass nozzle and deposit on substrate
- **Characteristics**: tiny components, most cutting-edge, high cost of ink
- **Key components**: ink, nozzle and feeding mechanism





Micro-Scale Additive Manufacturing



Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

谢谢各位老师同学
请大家批评指正

European Space Agency

Marie Curie Actions

I-Form Advanced Manufacturing Research Centre

Science Foundation Ireland — For what's next

Enterprise Ireland — where innovation means business

Irish Research Council — An Chomhairle um Thaighde in Éirinn

AMBER — Advancing Materials for Impact

European Innovation Council