AM FOR COMPOSITE MATERIALS

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INTRODUCTION TO ADDITIVE MANUFACTURING
ME-413

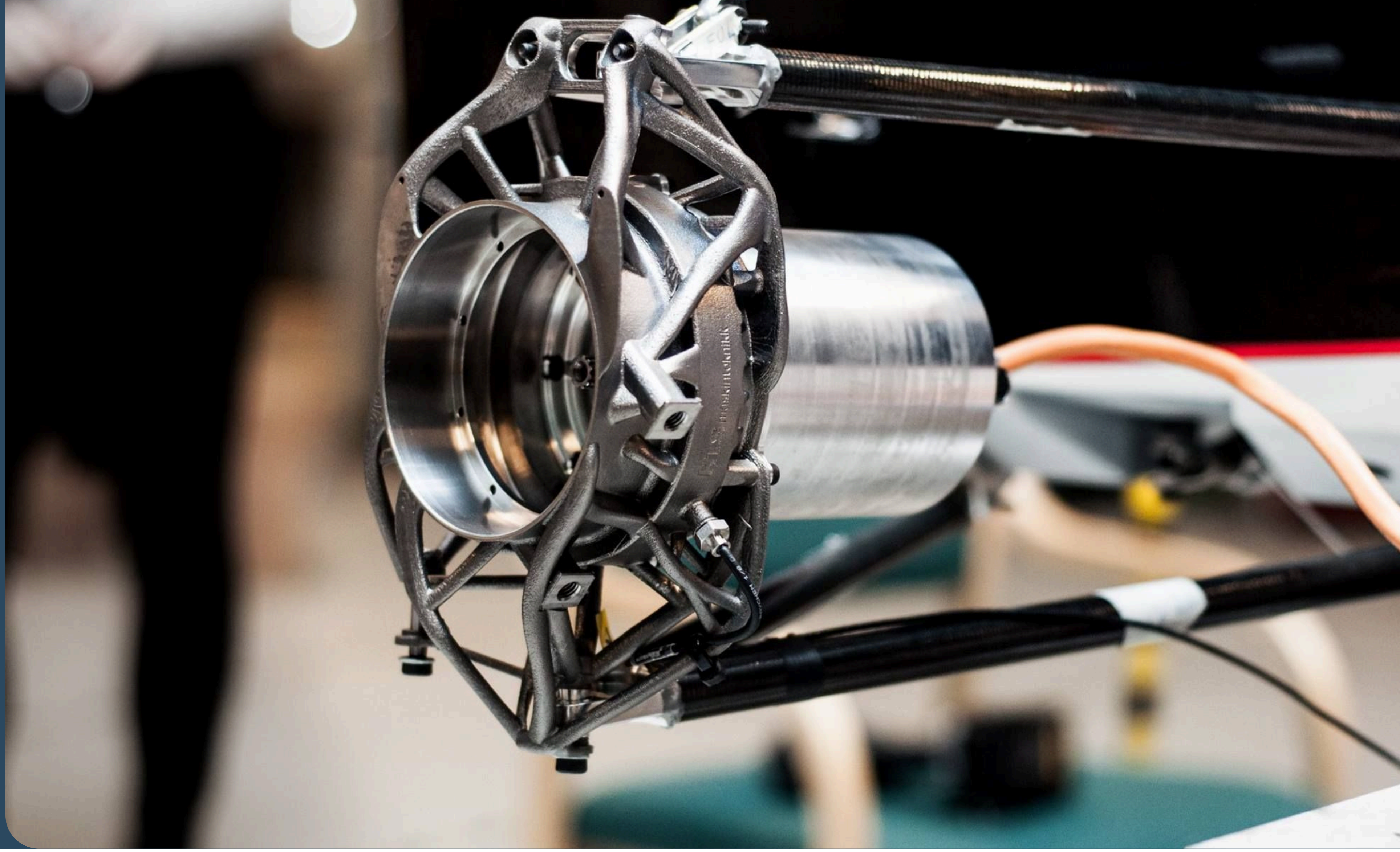
AGENDA

1. Introduction
2. AM of MMC
3. AM of Fibre-reinforced polymer composites
4. AM of Ceramic Composites
5. “Smart” Composite Materials
6. Conclusion

Introduction

- Additive Manufacturing (AM), or 3D printing. It has evolved from prototyping to producing end-use components.
- Composites Overview: Composites combine materials to achieve superior strength, durability, and functionality. They use reinforcements in a matrix to enhance performance
  - MMCs
  - FRPs
  - CMCs
  - Smart Composites

AM of MMCs



What are MMCs?

A metal matrix (e.g., Al, Ti) reinforced with ceramic particles (e.g., SiC, TiB2) or fibers.

Advantages

High strength, wear resistance, thermal stability.

Applications

Aerospace, automotive, tooling.

Why AM for MMCs?

Design Flexibility:
Enables complex geometries and lightweight structures.

Material Efficiency:
Reduced material waste compared to traditional methods

Tailored Properties (control of reinforcement distribution):

- TiB2 has a Young's modulus of 565GPa and a Vickers hardness of 2500HV, significantly improving stiffness and wear resistance.
- SiC has a high thermal conductivity and thermal stability and is this an ideal reinforcement for thermal management applications

Material Selection for MMCs

Matrix Materials:
Al, Ti, and Cu alloys.
Example: AlSi10Mg widely used for lightweight aerospace components.

Reinforcement Materials:
Ceramics like SiC, TiB2, Al2O3.
Properties: High hardness, thermal stability, wear resistance.

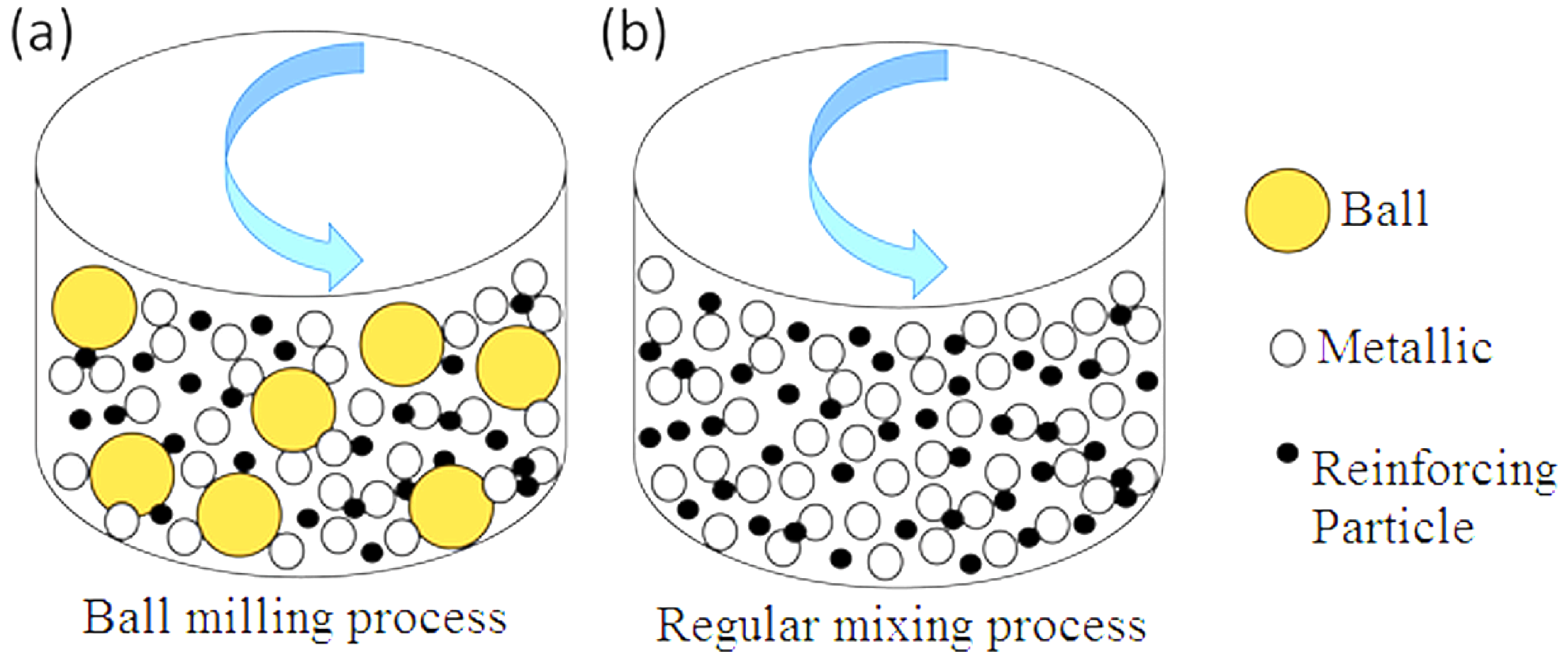
Challenge: Achieving uniform distribution of reinforcements

- In conventional methods, reinforcement often agglomerates, leading to poor wettability and bonding between the matrix and reinforcement

Material Selection for MMCs

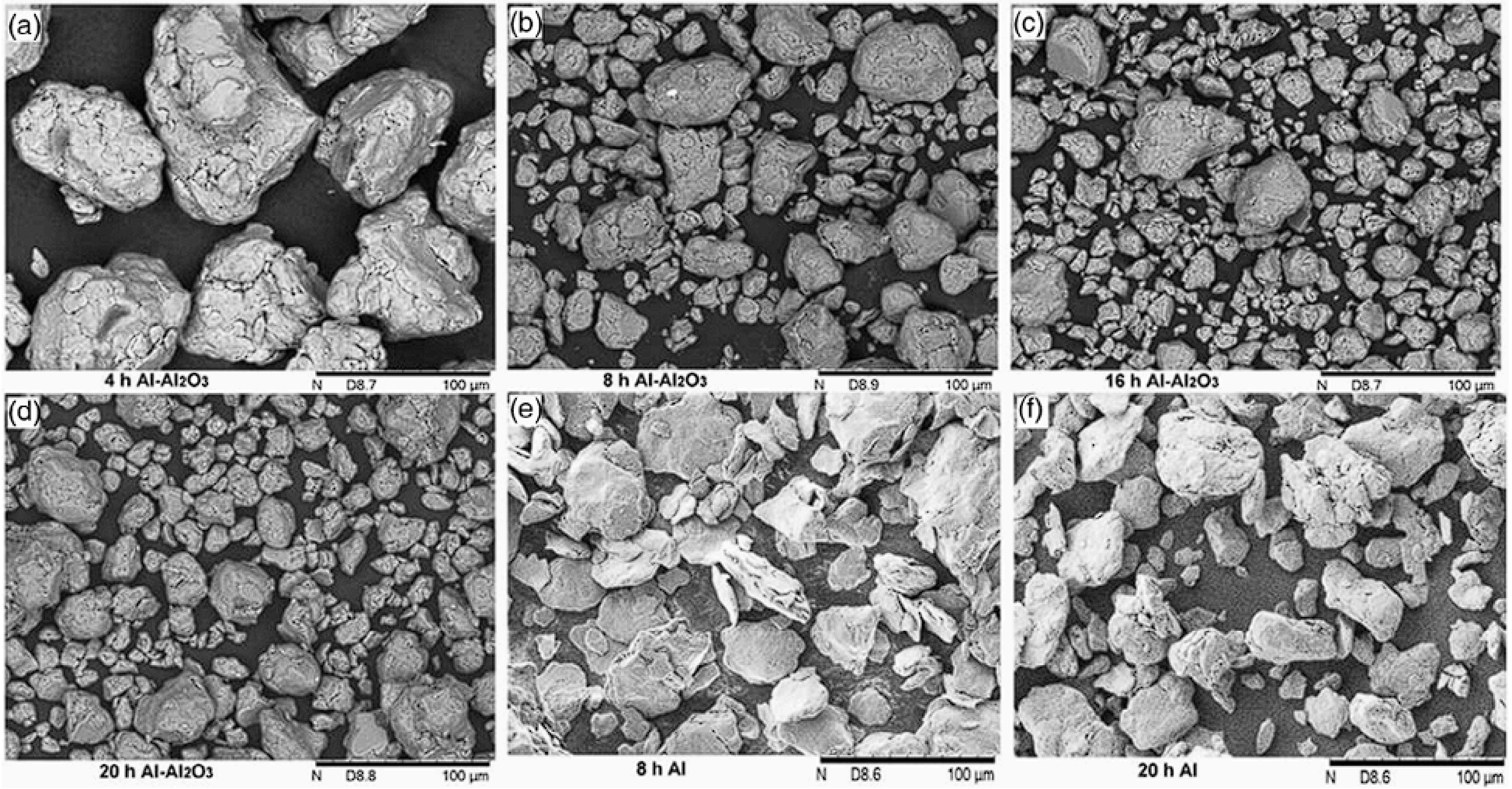
Challenge: Achieving uniform distribution of reinforcements

- Mechanical alloying, such as high-energy ball milling, has proven effective in producing composite powders where each particle is reinforced with ceramic material.



Material Selection for MMCs

Challenge: Achieving uniform distribution of reinforcements



Morphological evolution of Al–Al2O3 composites and Al powders ball-milled for up to 20h.

AM Techniques for Metal Matrix Composites

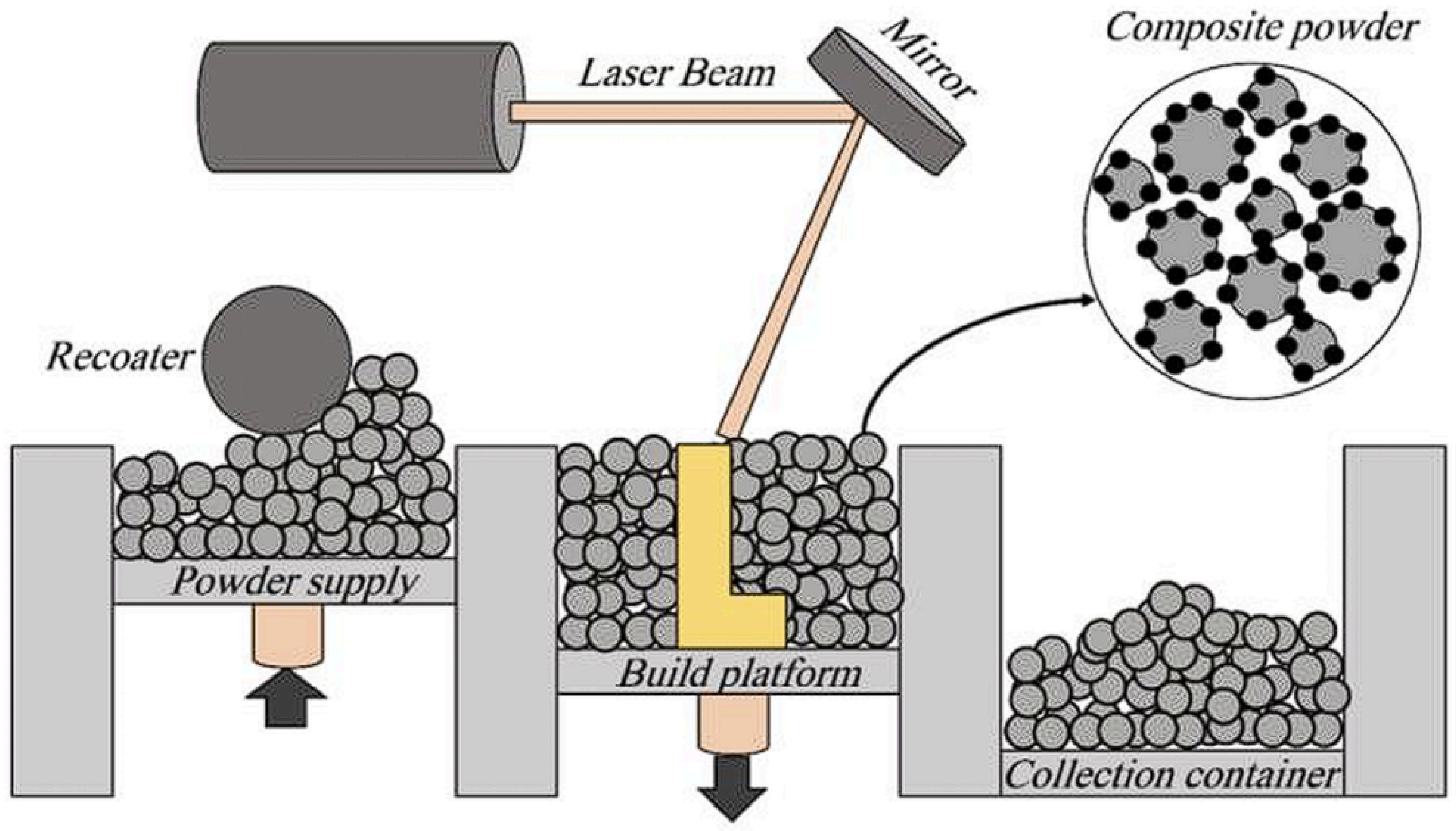
01.
Selective Laser Melting (SLM)

02.
Directed Energy Deposition (DED)

03.
Binder Jetting (BJ)

SLM Process for MMCs

- High-powered laser to melt and fuse metal powders layer by layer.
- Near-net-shape, time- and cost-effective manufacturing technique.

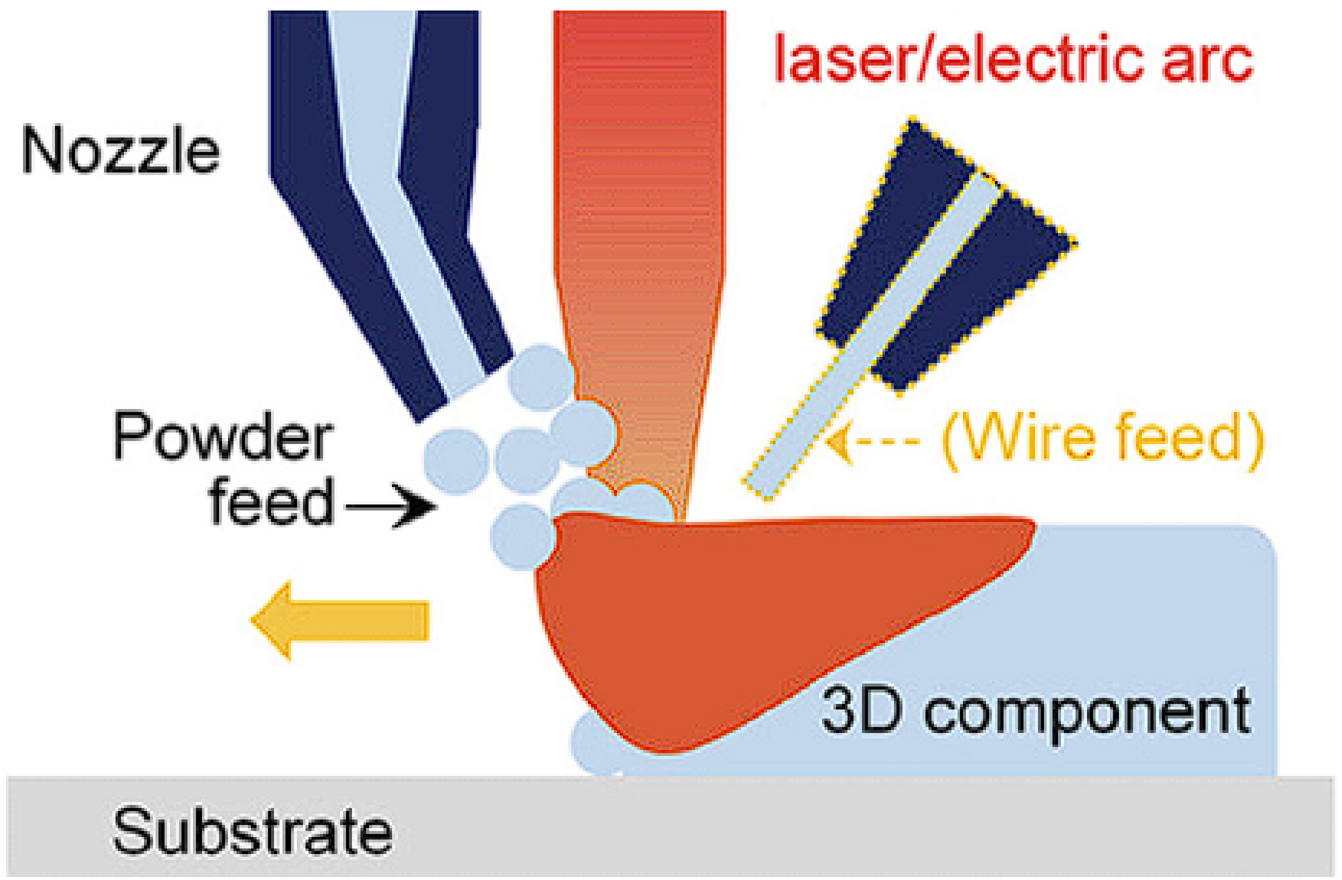


Advantages and Challenges

- The high cooling rates associated with SLM result in fine-grained microstructures.
- Challenges in processing high-melting-point materials, like intermetallics, still persist.

DED Process for MMCs

- Use lasers or electron beams, to melt and deposit feedstock material (powder or wire) onto a substrate
- Allows for the creation of near-net-shape components with highly controllable microstructures

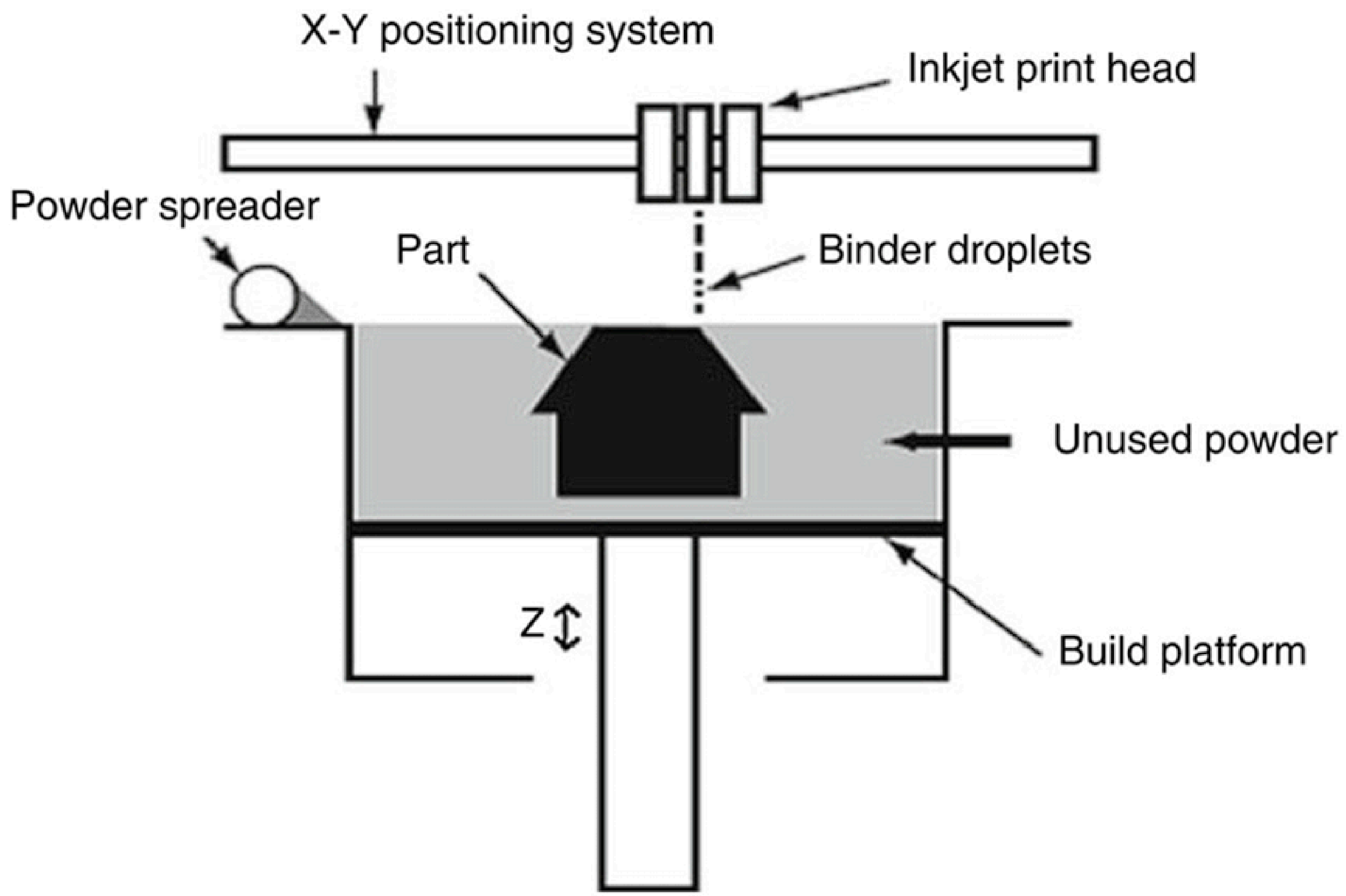


Advantages and Challanges

- DED delivers material directly into the molten pool, enabling the addition of reinforcement phases in situ, into titanium or aluminum alloys.
- Suffers from poor resolution and lower surface quality, which necessitate additional post-processing

BJ Process for MMCs

- Selectively ejects binder droplets onto a powder bed, layer by layer.
- The use of reactive sintering or infiltration allows for the formation of reinforcing phases directly during the sintering process.



Advantages and Challanges

- Commonly used because of its low costs and allows for the creation of complex shapes.
- Challenges remain in optimizing the process parameters to achieve desired mechanical properties and in dealing with potential issues like reinforcement dissolution during infiltration

Post-Processing of MMCs

Necessity:

- Reduce porosity, residual stresses, surface roughness

Methods

- **Sintering** improves the density and structural integrity.
- **Heat treatment, machining, or surface finishing techniques** are utilized to reduce residual stresses and improve surface quality.
- **Hot Isostatic Processing (HIP)** reduces porosity and enhances density.

Applications of AM for MMCs

Aerospace and Defense:

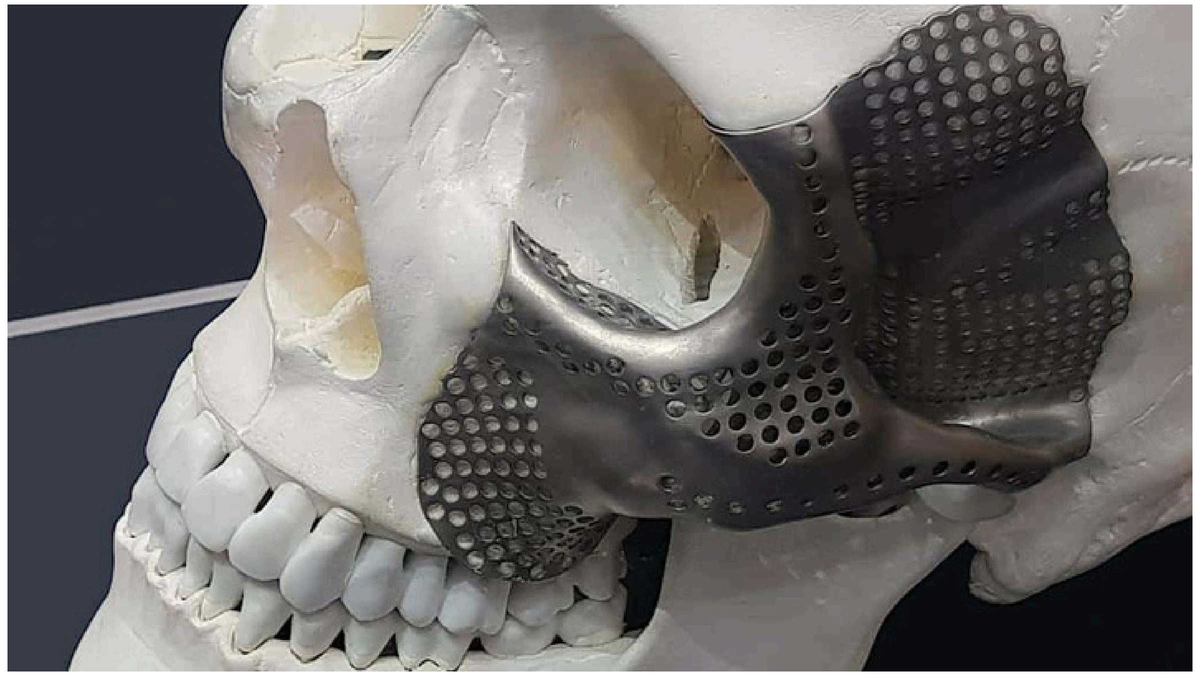
- Lightweight components: turbine blades, heat exchangers, structural parts
- Thermal management: heat sinks, thermal shields
- Wear-resistant components: bearings, gear components, missile casings

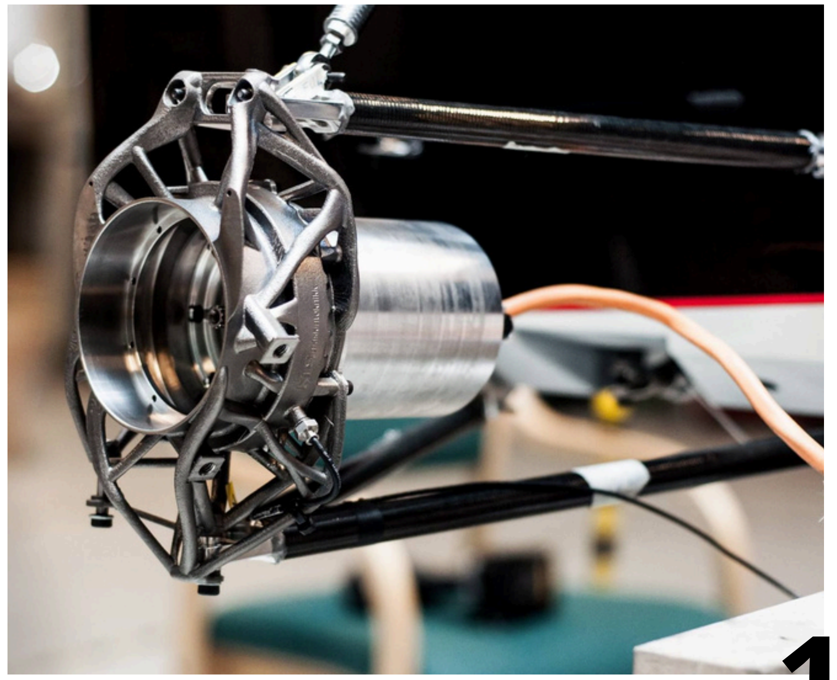
Automotive Industry:

- Engine components: engine blocks, cylinder heads, pistons
- Brake rotors and pads
- Suspension systems: lightweight suspension arms and joints

Biomedical Applications:

- Orthopedic implants
- Dental applications: customized dental crowns, prosthetics





Challenges and Further Directions

01.

Optimization of Material Properties

- uniformity of reinforcement distribution
- the matrix-reinforcement interface
- the formation of defects

- Enhanced control over the microstructure in terms of reinforcement dispersion and interfacial bonding

- Develop advanced feedstocks and techniques,

Challenges and Further Directions

02.

Development of Standardized Processes and Parameters

- lack of guidelines for achieving optimal process conditions

- Standardizing process parameters for various MMCs to improve reproducibility and quality control

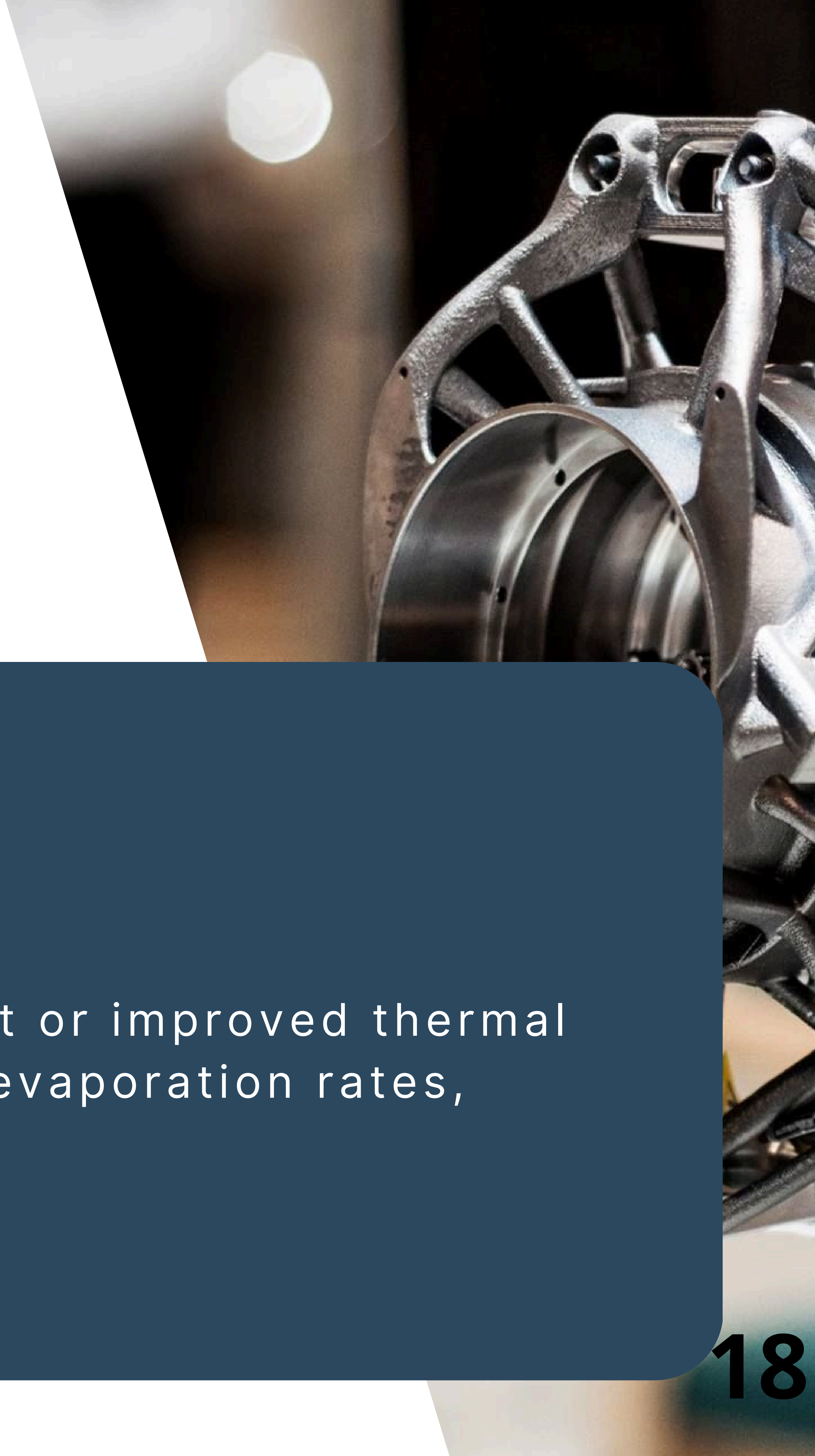
Challenges and Further Directions

03.

Hybrid Manufacturing

- combining AM with traditional methods
- enhance the mechanical properties of MMCs by improving part density, reducing residual stresses, and fine-tuning material properties through post-processing

Challenges and Further Directions



04. New Material Systems

- Mg and Cu alloys offer unique benefits, such as lower weight or improved thermal conductivity, but face challenges related to oxidation, high evaporation rates, and reinforcement distribution
- hybrid composites combining multiple reinforcements

AM for FRPCs

FRPCs

- Fiber-Reinforced Polymer Composites

Two types of fiber

- Short (also known as chopped or milled)
- Continuous

Materials for FRPCs

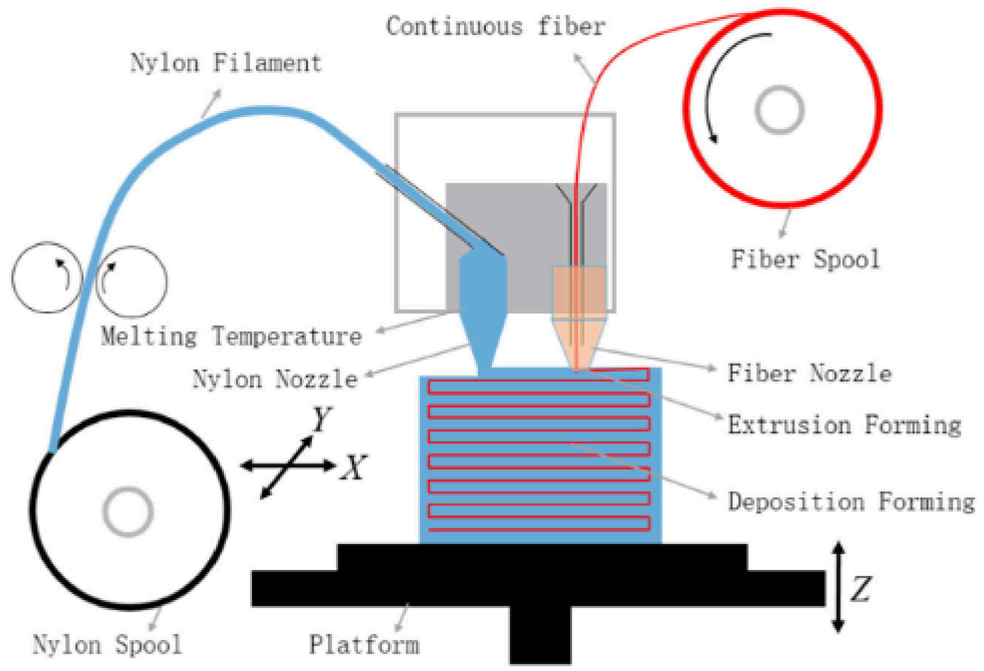
Polymer matrix

- PLA
- ABS
- Nylon
- PEEK
- ULTEM

Fiber

- Carbon fiber
- Fiberglass
- Kevlar

FRPC FDM



Short Fiber

- fiber incorporated into filament
- Simply prints as basic FDM

Continuous Fiber

- fiber and polymer are separated
- Polymer printed as shell
- fiber as an infill

FRPC other technics

SLS

- short fiber mixed with polymer
- Modest improvement
- Negative influence on part quality

SLA

- Fiber mixed with resin
- Tried but very limited
- difficulty of fiber-filled resin

Performance

FRPCs

- tensile properties better at 5wt%
- Toughness and Yield strength less than plastic
- Flexural properties better at 5wt%
- worse when 10wt%
    - misalignment
    - porosity
    - delamination

Continuous fiber

- High anisotropy
- large choice of properties
- needs numerical analysis

AM Commercial

Desktop 3D Printer

- Markforged
- Anisoprint

Industrial 3D Printer

- Desktop Metal

Robotic arms

- Arevo Inc.
- Mantis Composite

AM Application

Aerospace

- Fire retardant parts
- respect flame,toxicity and smoke standard

Automobil

- lightweight
- Fuel efficiency

Energy

- Wind turbines blades
- insulative components

AM of CMC

What are CMC?

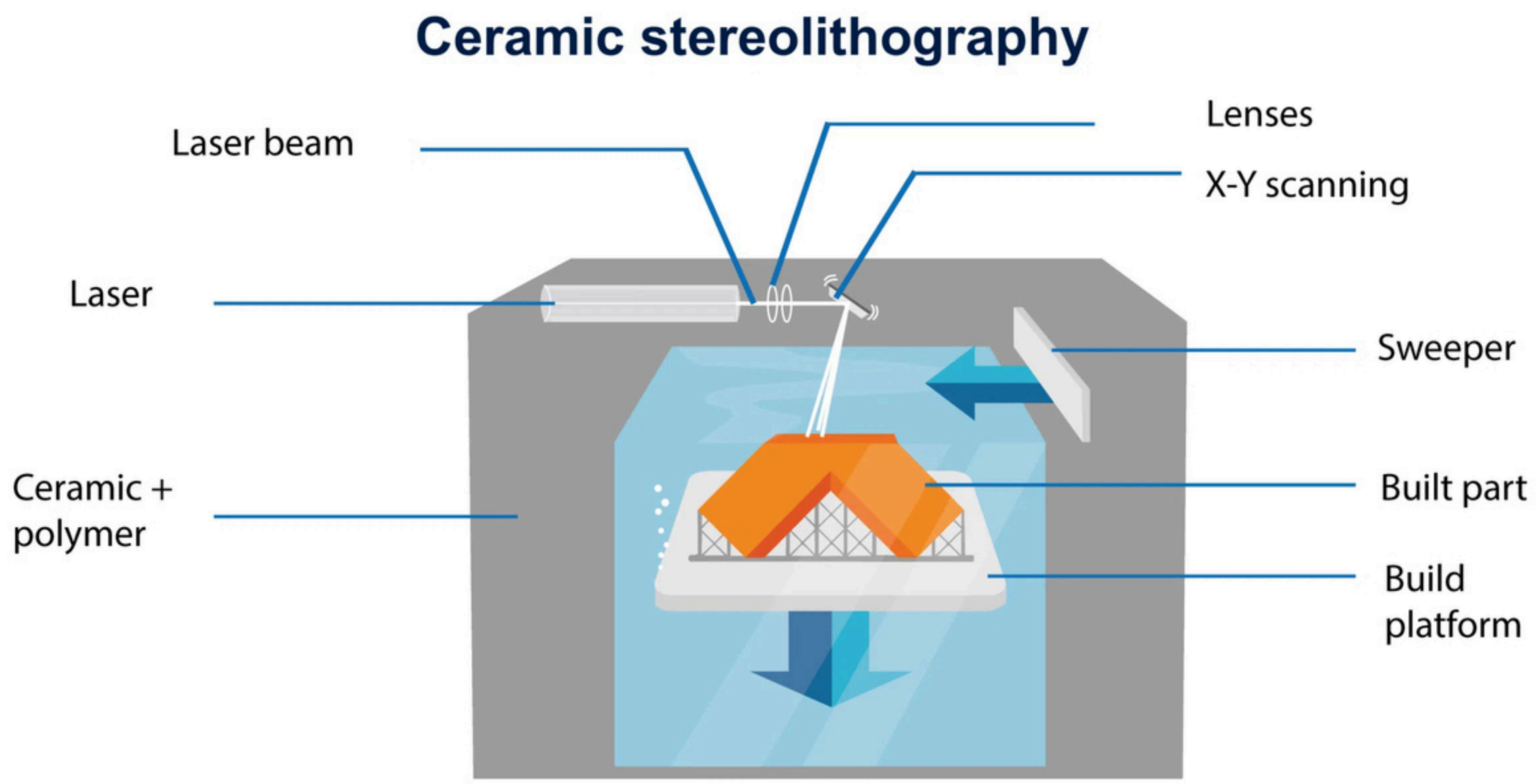
- Ceramic Matrix Composites (CMC)
- Provides design flexibility
- Allows for complex geometries

Why do they exist?

- High-temperature performance
- Lightweight
- Enhanced toughness

Stereolithography

- Slurry: Ceramic powders, photoinitiators
- Photopolymerization triggered by UV light (binding)
- Sinterization

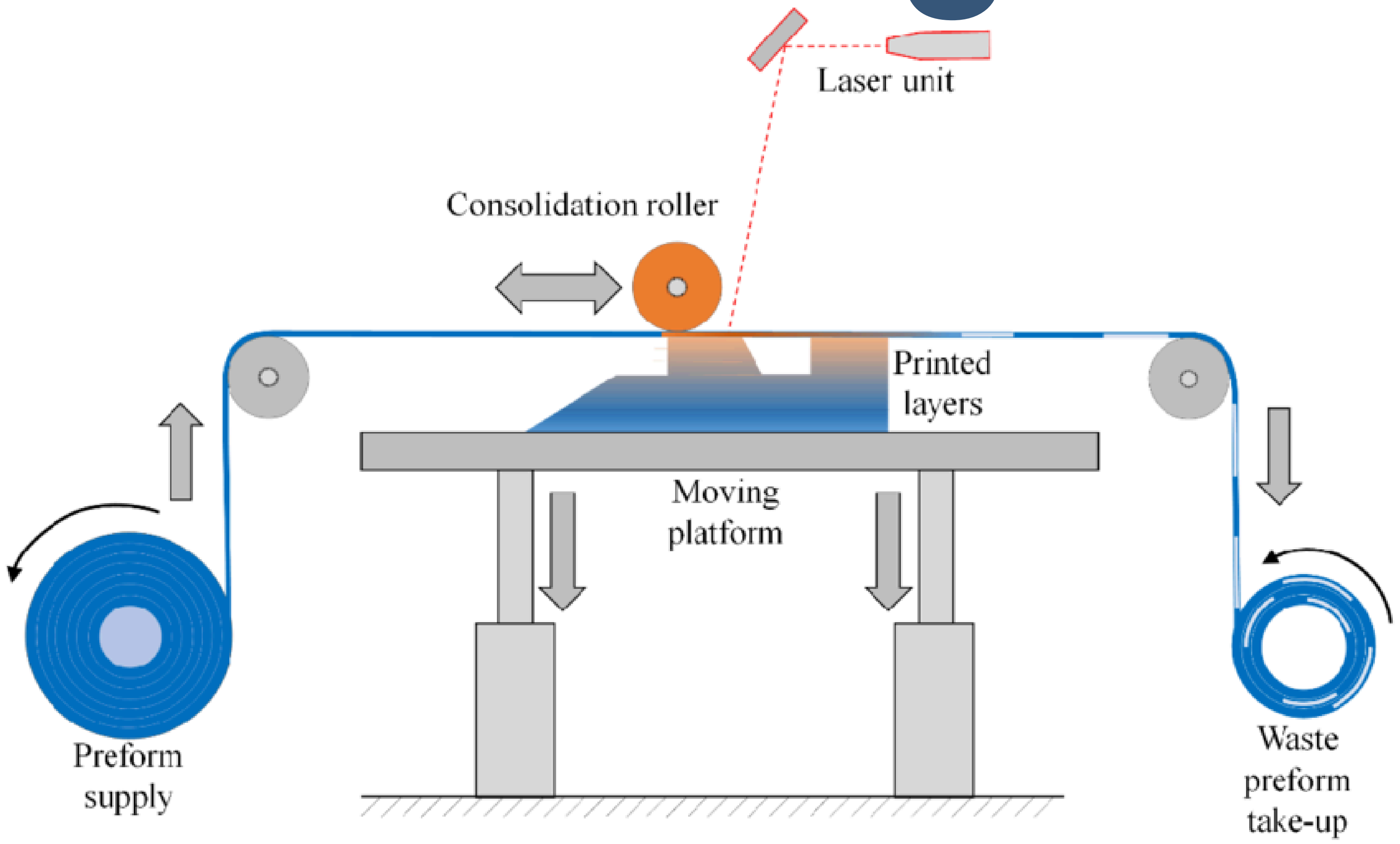


Features

- High resolution, smooth surfaces and complex geometries
- Volume shrinkage, cracking during binding
- Ideal for complex geometries, not for thick wall components

Laminated Object Manufacturing

- Bonding of ceramic materials (pressure or adhesive)
- Laser cuts layers of ceramic
- Post-processing:Pyrolysis and Quasi-isostaic powder pressing

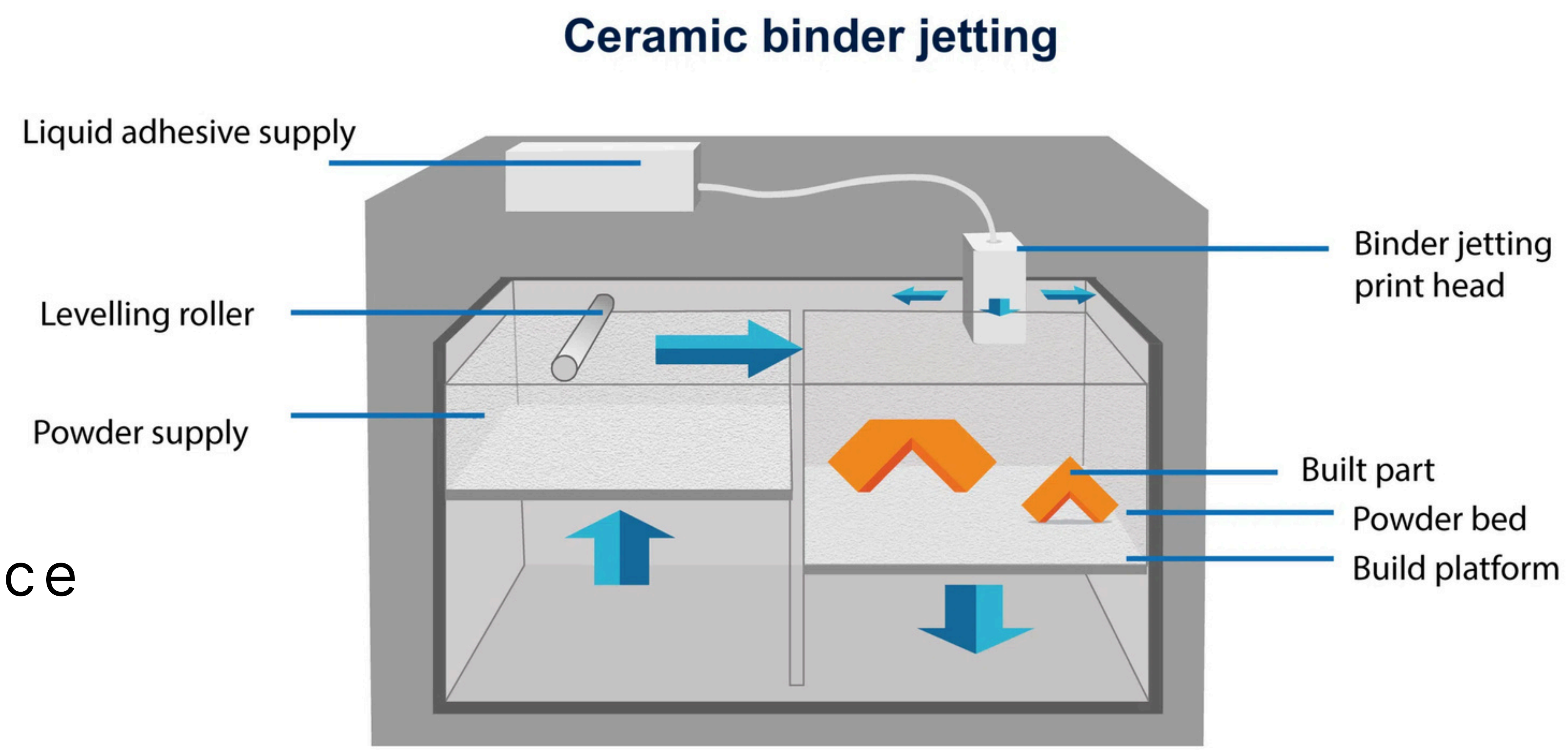


Features

- Handles low thermal stress, large scale monolithic
- Material waste
- Limits of geometric complexity

Binder Jetting

- Liquid binder sprayed onto layers of ceramic powder
- Sintered to bond particles and enhance strength.
- Post-processing (e.g., infiltration) improves density and surface finish.

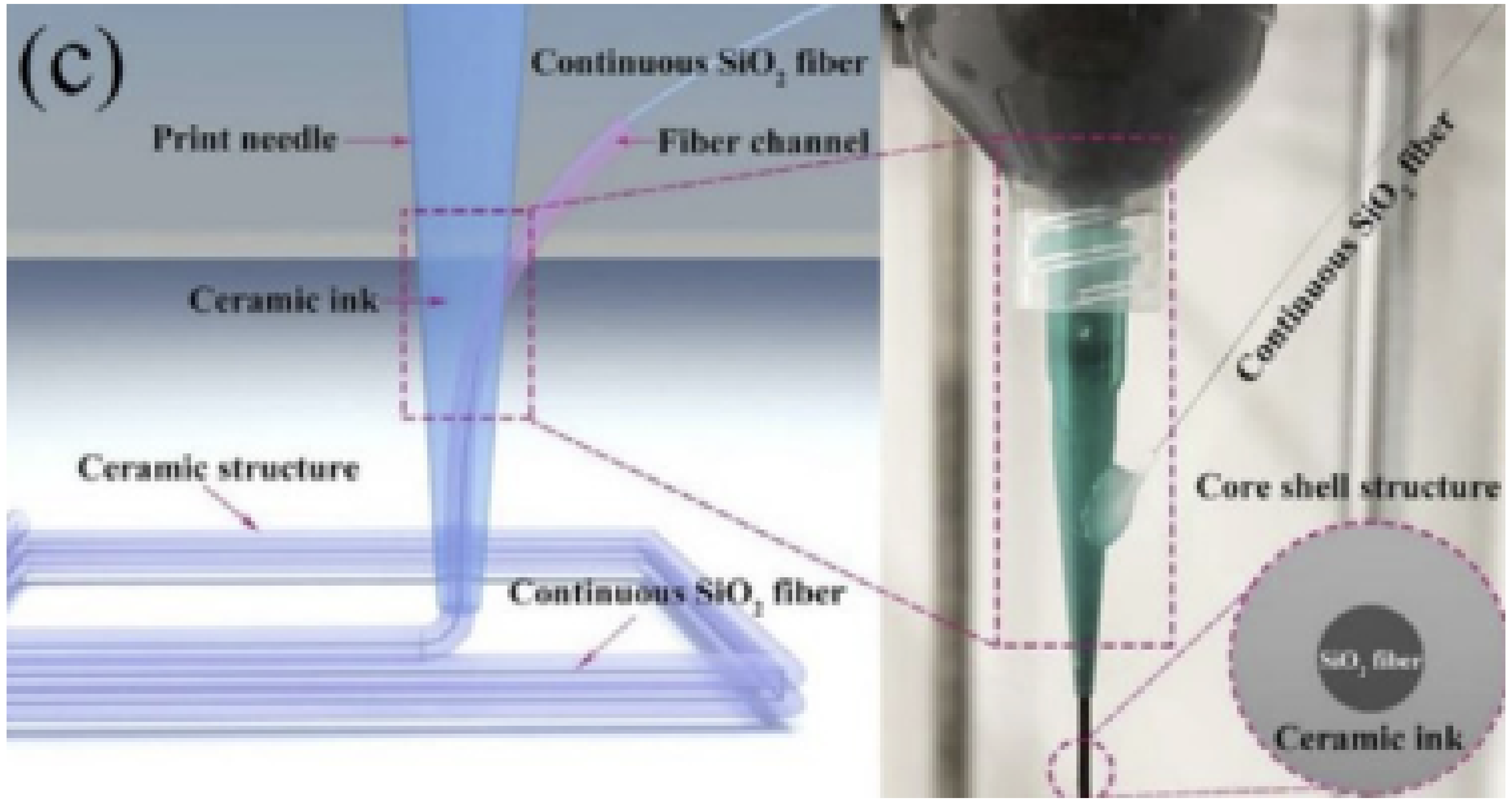


Features

- High design freedom, scalability
- Low density before sintering
- Requires post-processing for enhanced properties.

Direct Ink Writing

- Extrusion of ceramic parts through a nozzle
- Shear stress aligns fibers/whiskers in direction of printing
  - Intentional anisotropy
- High porosity



Features

- Cost-effective and versatile
- Useful for whiskers and fibres
- Lower resolution
- Nozzle clogging

ADVANTAGES & DISADVANTAGES

Technique	Advantages	Disadvantages
SLA	High resolution, smooth surfaces and complex geometries	Volume shrinkage, cracking during binding
SLS	High-speed processing	High porosity
SLM	No post-sintering	Sensible to cracking
LOM	Reduced deformation risk low thermal stress	Material waste
BJ	Design freedom, no support structure needed	Porosity, extra post-processing processes
IJP	Precise	Nozzle clogging
H-AM	Flexible integration of materials, architectures and AM techniques	More R&D

AM OF CMC

Particulates & Whiskers

- Increased flexural and compressive strength and fracture toughness
- Crack deflection
- Densification
- **Zirconia, Alumina**

Fibres

- High damage tolerance
- Improved flexural strength
- Nozzle clogging
- **Silica fiber-reinforced phospate ceramic**

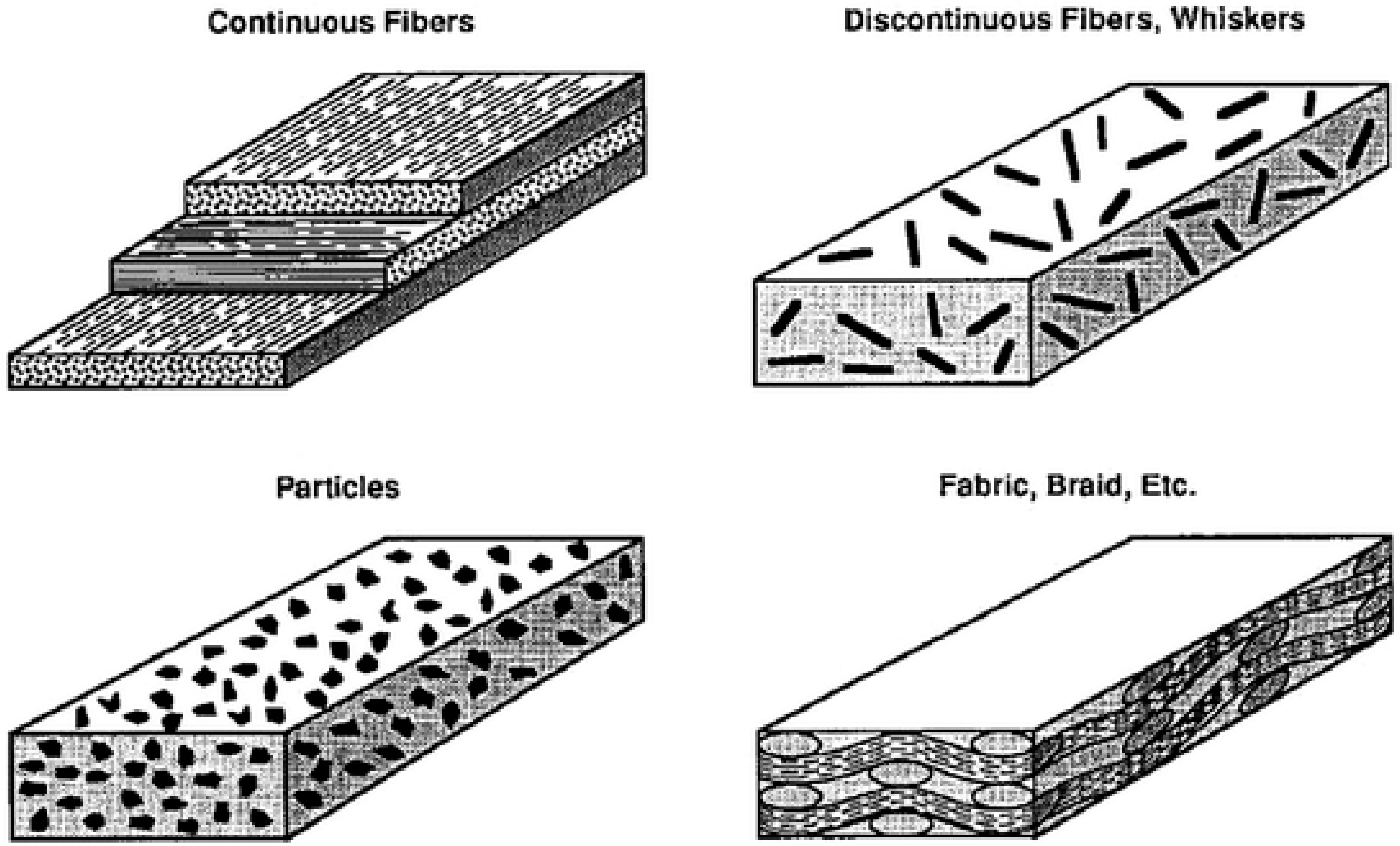
Carbon Based Nanoreinforcements

- CNT and Graphene
- Improved strength, biocompatibility and fracture toughness
- **SiO_2–CaO–P_2O_5**

Bioinspired Reinforcements

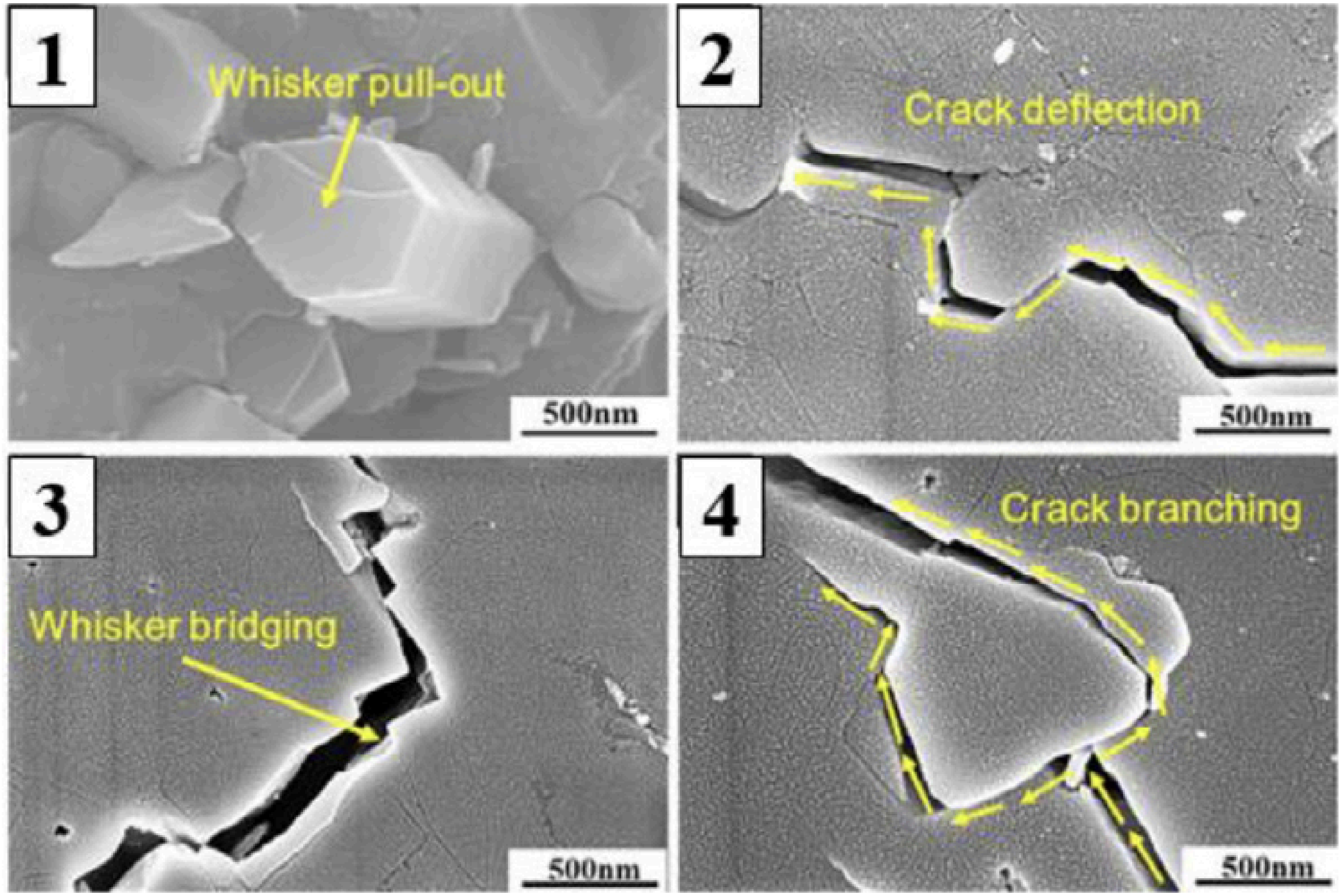
- Nacre-inspired structures
- Fracture strain increase
- Hard to scale on an industrial level
- **Beta-Tricalcium Phosphate**

AM OF CMC



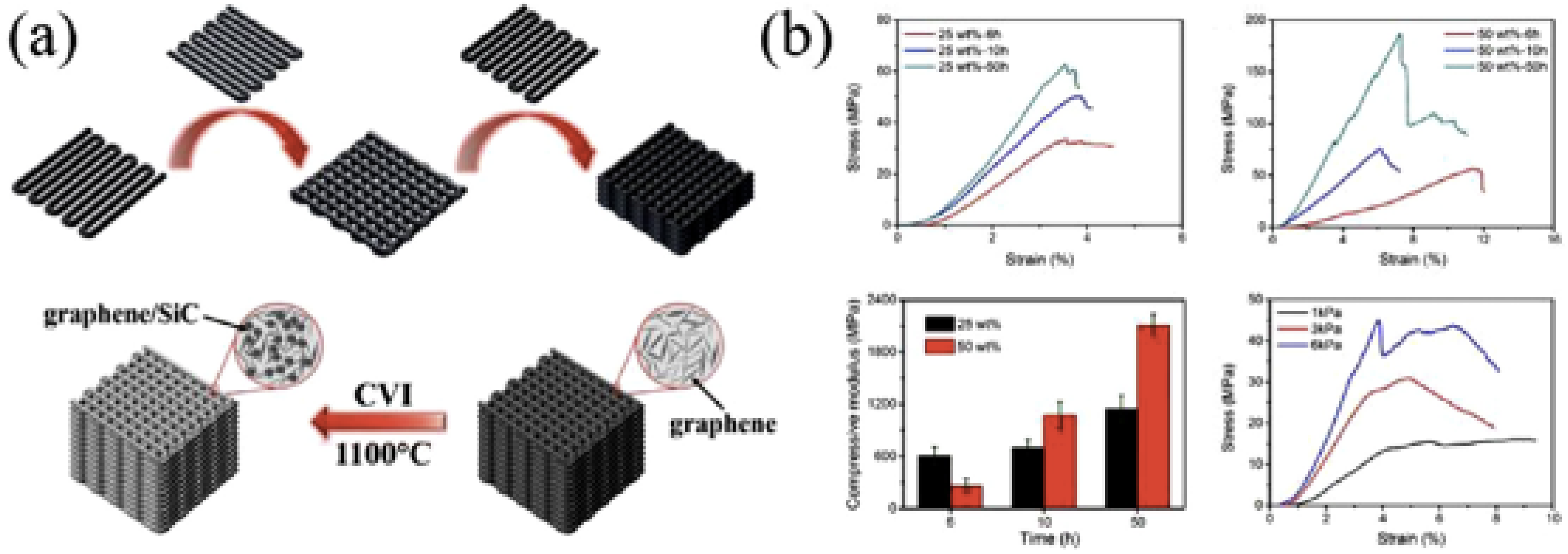
Composite Structures

AM OF CMC



Whisker Reinforced Ceramic Microstructure

AM OF CMC



Graphene Reinforced Ceramic Composite

AM-PRODUCED CMC APPLICATIONS

01.
Biomedical

- Bone scaffolds
- Bone grafts
- Dental prosthetics
- Implants

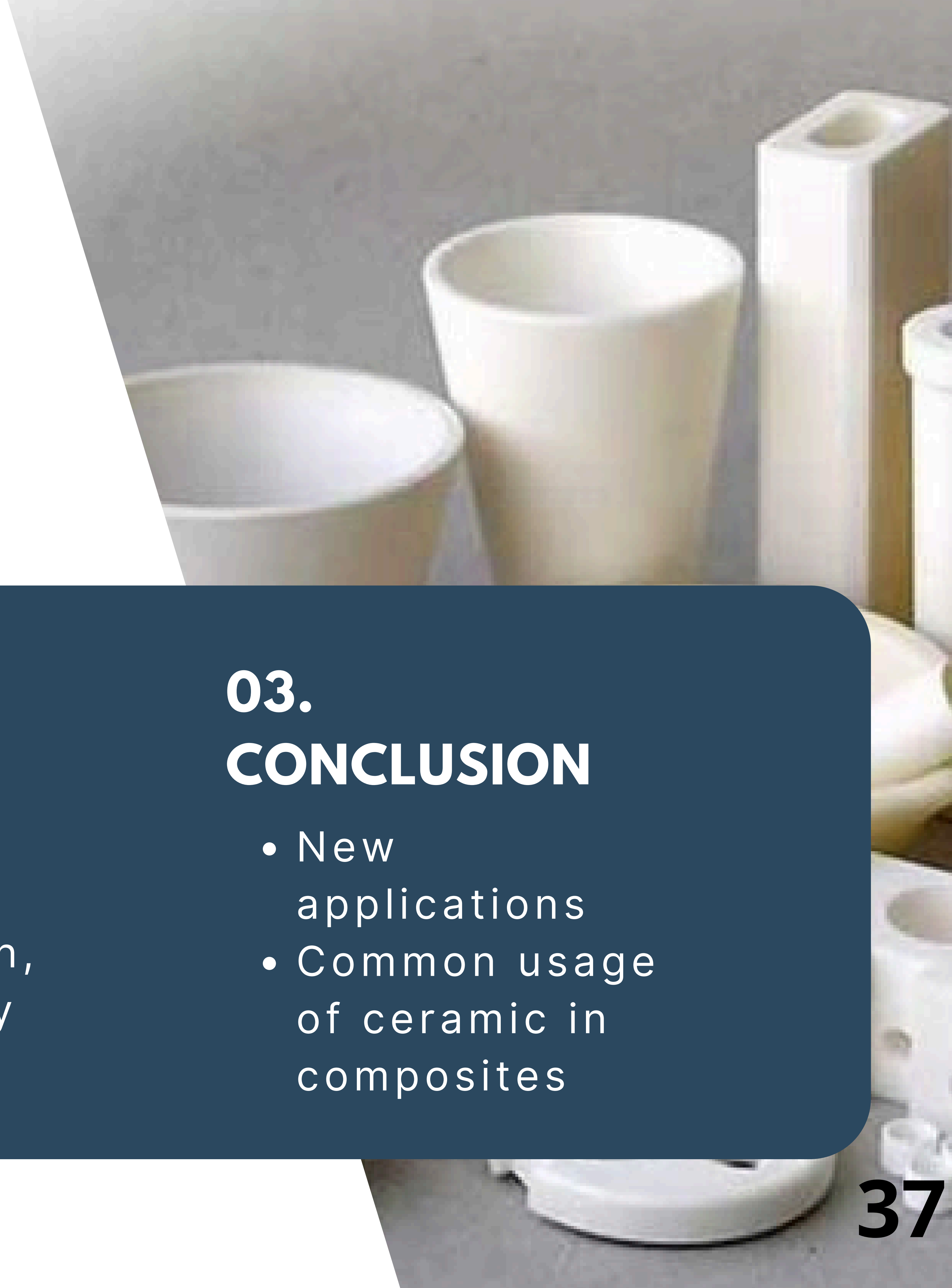
02.
Aerospace

- Thermal protection
- Heat shields in rotary and stationary components
- Jet engine igniters

03.
Energy

- Solar cells
- Solid Oxide Fuell Cells
- Batteries

Future directions



01. ADVANTAGES

- Reduces material waste
- Complex geometries
- Vast aplications

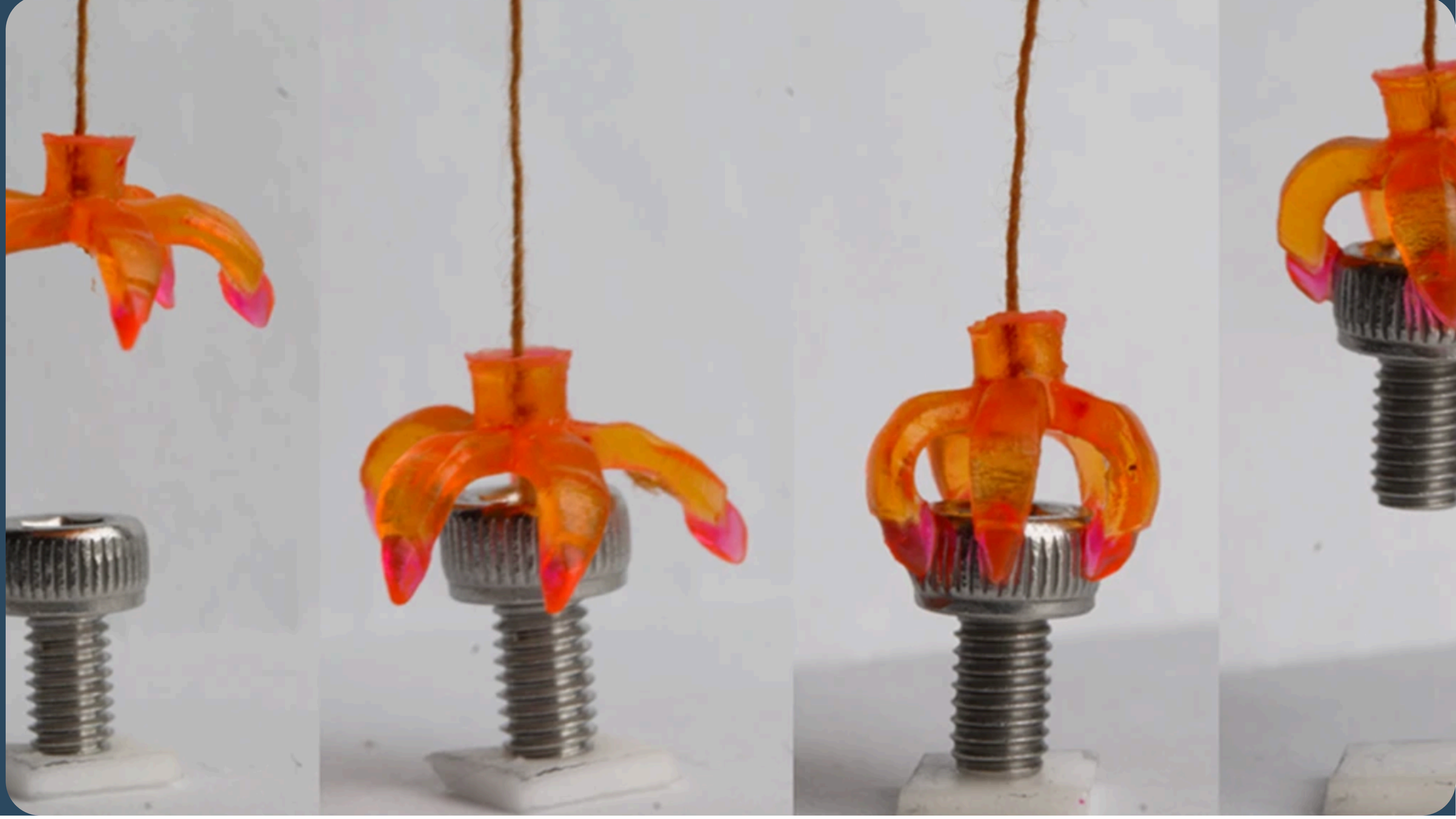
02. CHALLENGES

- Natural properties limit techniques
- Layer delamination, undesired porosity

03. CONCLUSION

- New applications
- Common usage of ceramic in composites

Smart Composite



Ge, Q., Sakhaei, A., Lee, H. et al. Multimaterial 4D Printing with Tailorable Shape Memory Polymers. Sci Rep 6, 31110 (2016). https://doi.org/10.1038/srep31110

What is a Smart composite ?

Materials that respond dynamically to environmental stimuli (e.g., heat, pressure, light, magnetic fields).

Stimuli : Temperature, Moisture, Light, Stress, Magnetic fields ...

Smart composite

Key capacities

- Sensing
- Actuation
- Self-repair
- Energy Management

Importance

Bridging the gap between traditional materials and multifunctional applications.

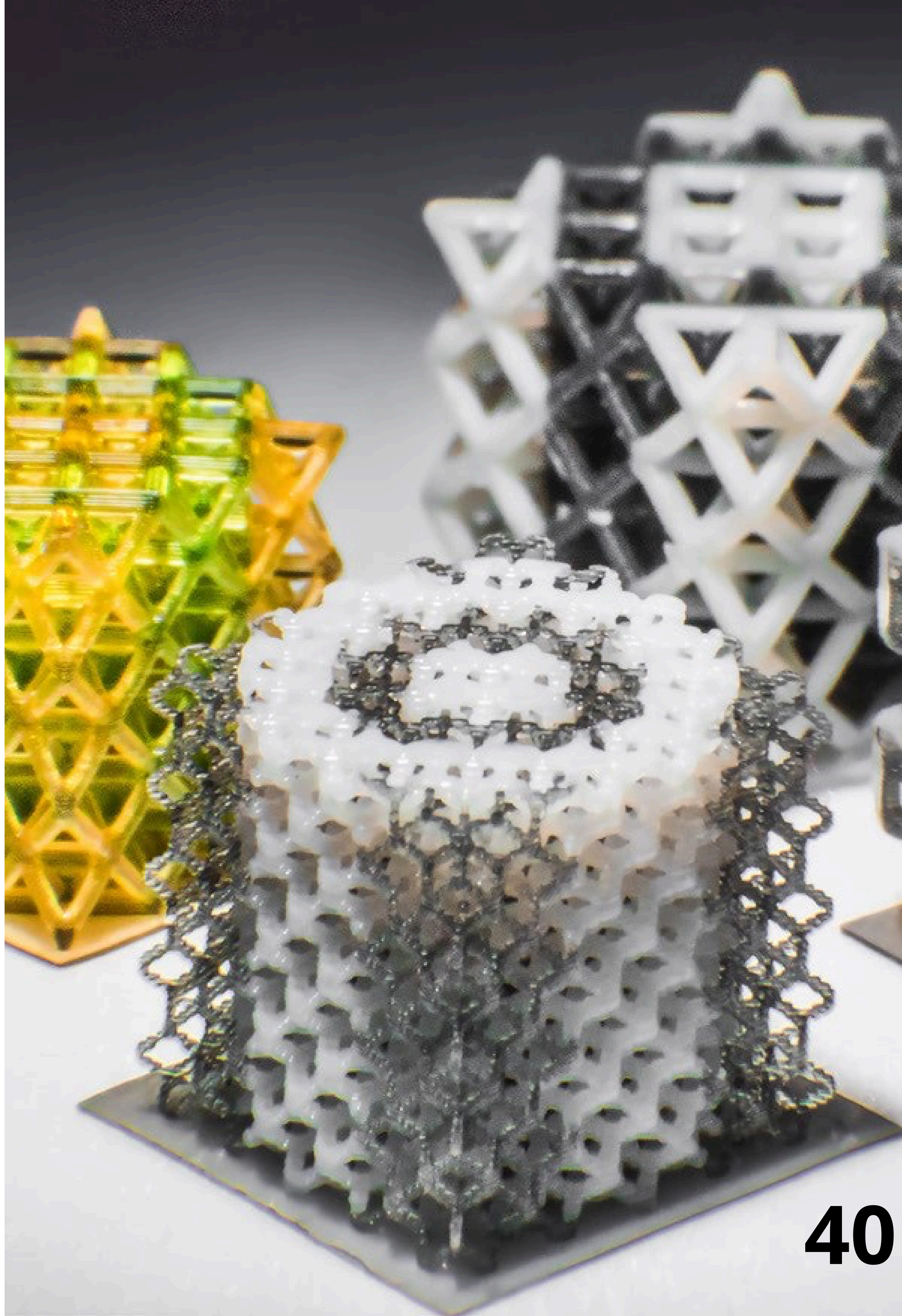
Smart composite & AM

AM's role

Enables precise, layer-by-layer integration of complex structures.

Compatibility

Tailored for hybrid designs combining structural and responsive functionalities.



Smart composite : Types

Piezoelectric

Generate electric charge under mechanical stress.

e.g.: *Sensors, Energy harvesting*

Shape-Memory Alloys (SMA)

Return to a pre-defined shape when heated

e.g.: *Actuators, Medical stents*

Magnetostrictive Materials

Change shape under magnetic fields.

e.g.: *Vibration control, Robotics*

Self-Healing Polymers

Repair damages autonomously, enhancing durability.

Smart composite : Materials

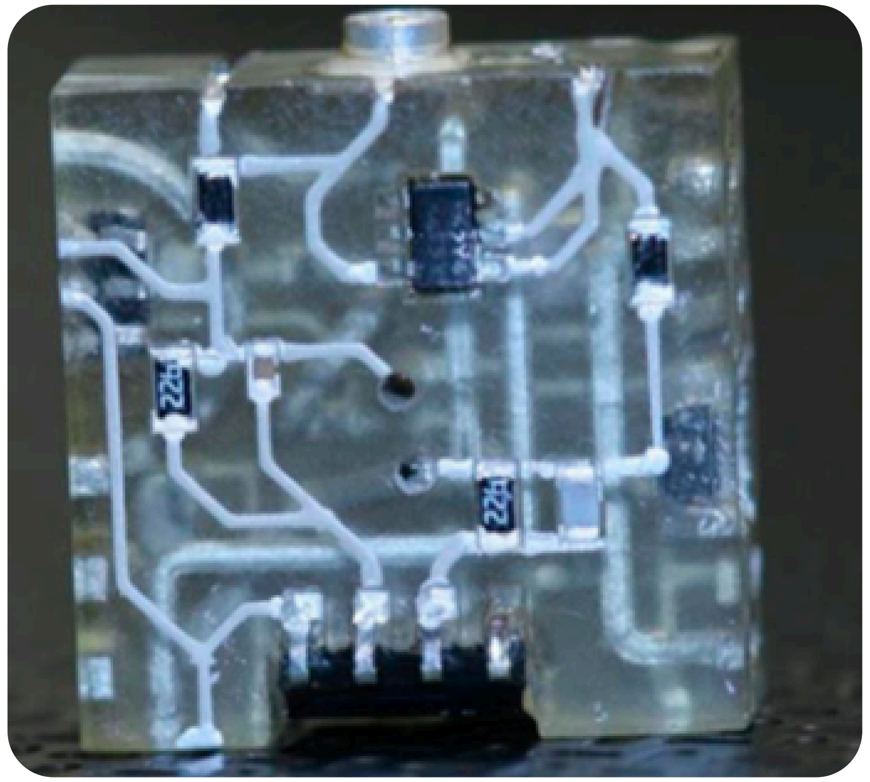
Matrix Materials

- Polymers : Lightweight, flexible
- Metals : High strength and conductivity
- Ceramics : Thermal stability and insulation

Functional Fillers

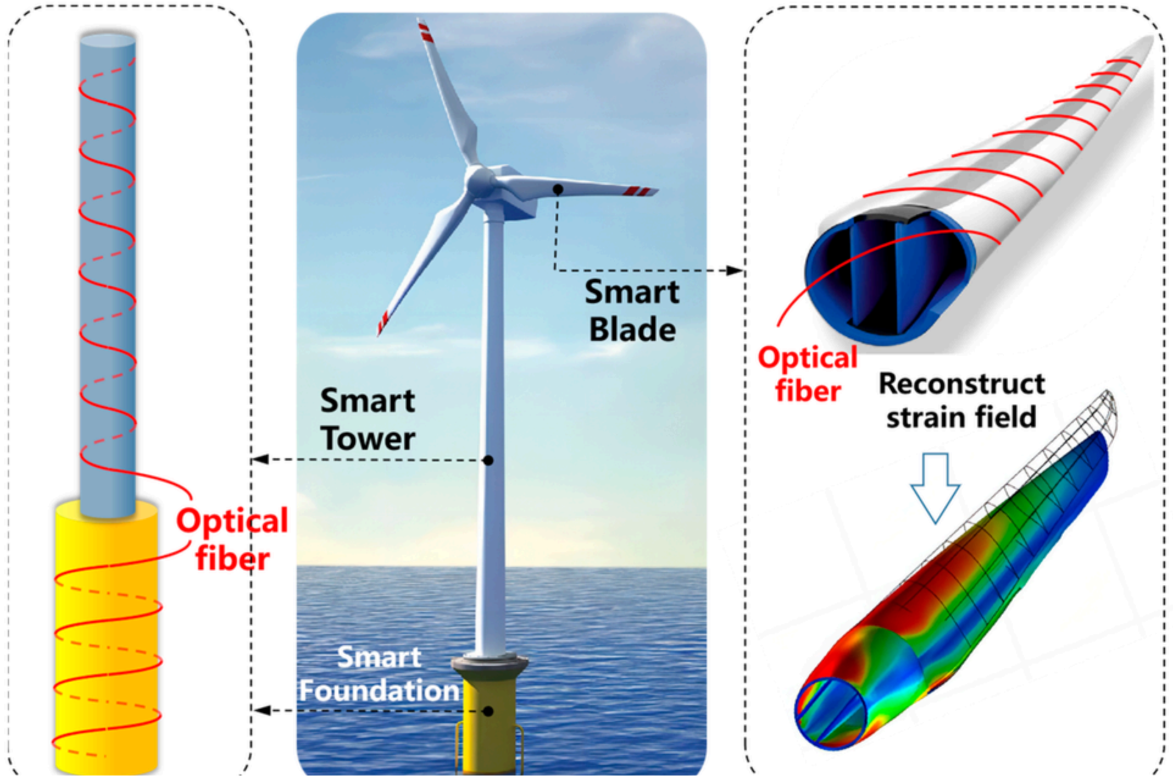
- Macroscale : Fibers for mechanical strength
- Microscale : Particles for localized functionalities
- Nanoscale : Nanotubes, graphene for electrical, thermal, and mechanical enhancements

Smart composite : Functional elements



3D printer signal conditioning circuit

Gardan, J. (2019). Smart materials in additive manufacturing: state of the art and trends. Virtual and Physical Prototyping, 14(1), 1–18. Taylor & Francis. https://doi.org/10.1080/17452759.2018.1518016



3D Surface Strain Measurement using DOFS

Yang, T.; Tao, T.; Guo, X.; Yang, Y.; Liu, S. Preliminary Test for 3D Surface Strain Measurement in the Tower and Foundation of Offshore Wind Turbines Using DOFS. Sensors 2023, 23, 6734. https://doi.org/10.3390/s23156734

In-situ integration

Embedding sensors, actuators, and conductive pathways during the AM process

Smart composite : Functionalities

Energy management *previous slide*

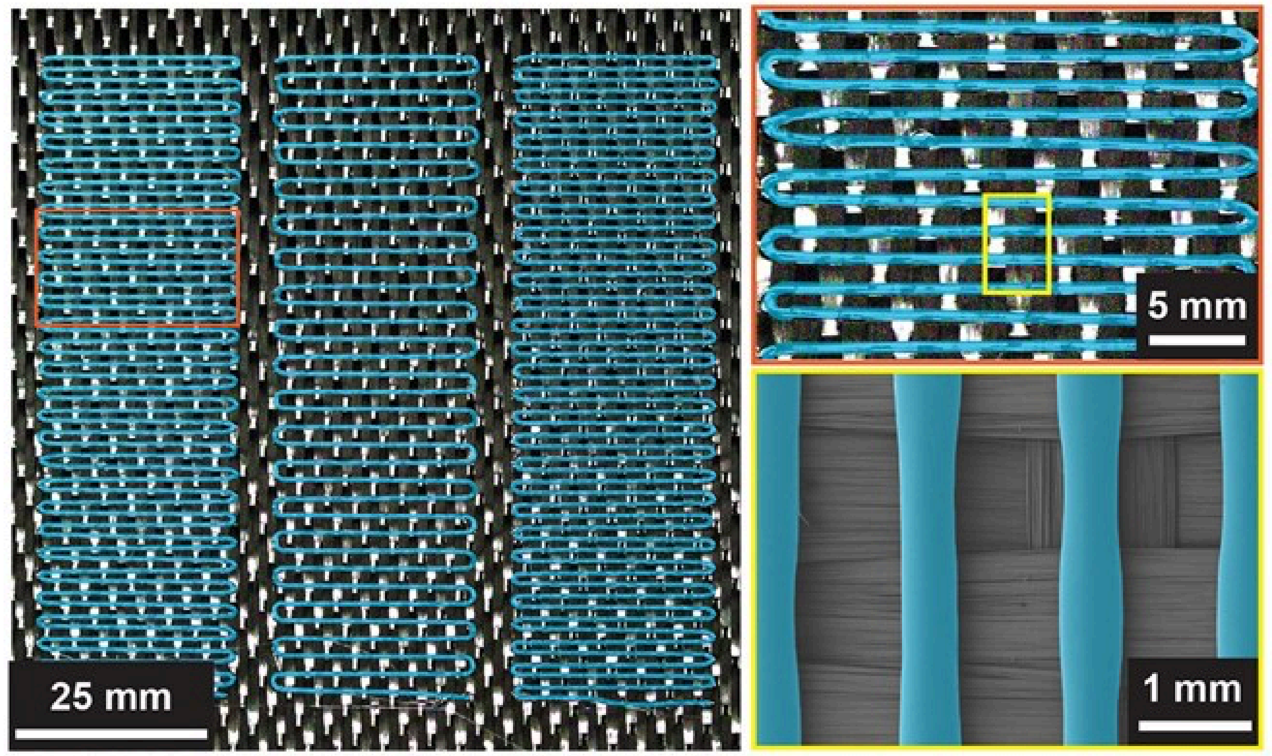
Sensing *previous slide*

Actuation

Complex flower morphologies.
Simple flowers composed of 90°/0° bilayers oriented with respect to the long axis of each petal

Gardan, J. (2019). Smart materials in additive manufacturing: state of the art and trends. Virtual and Physical Prototyping, 14(1), 1–18. Taylor & Francis. https://doi.org/10.1080/17452759.2018.1518016

Self-Healing

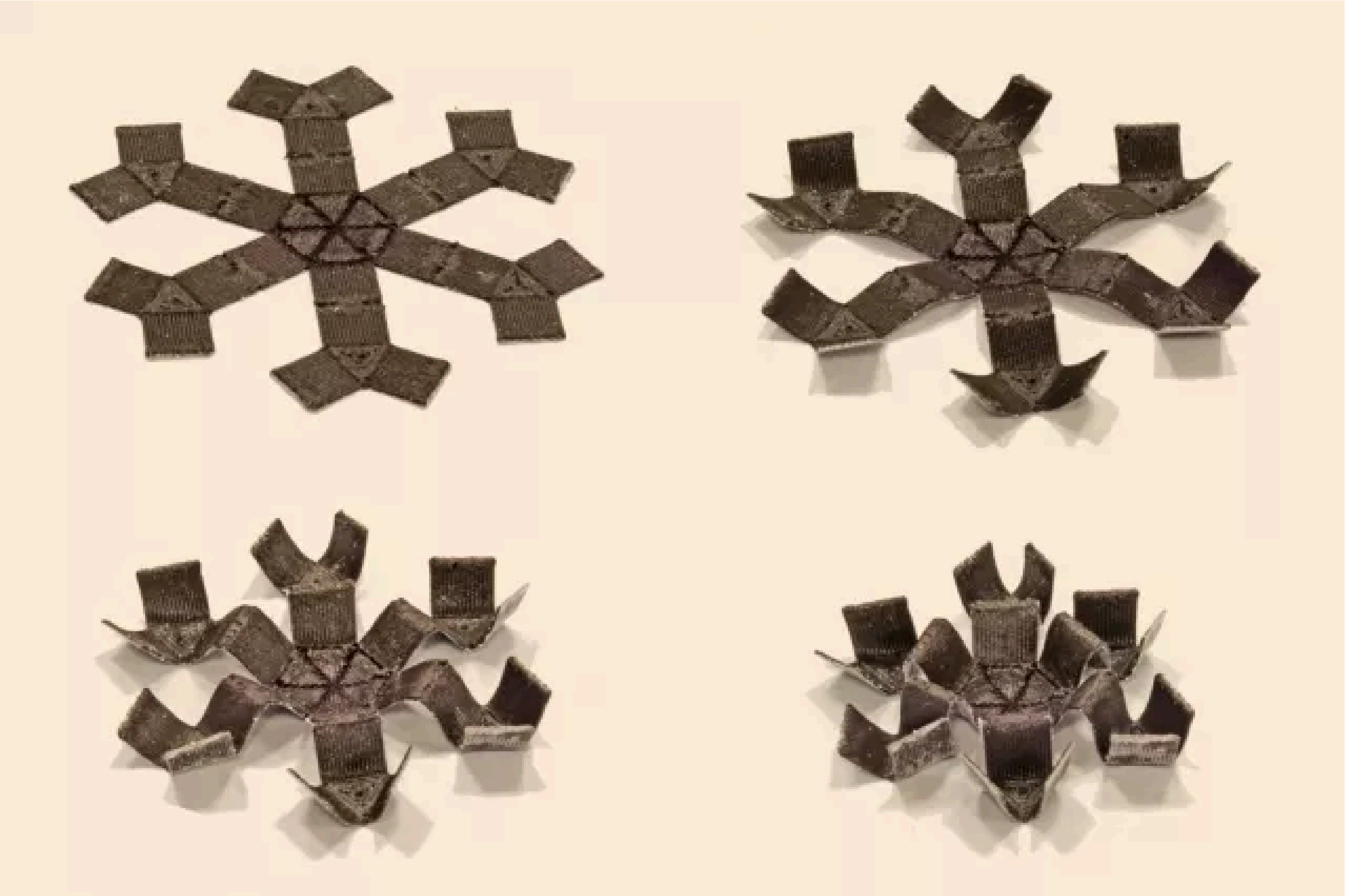


3D-printed thermoplastic on woven carbon fiber reinforcement

https://www.compositesworld.com/news/novel-composite-aims-to-resolve-self-healing-material-challenges

Smart composite : Applications

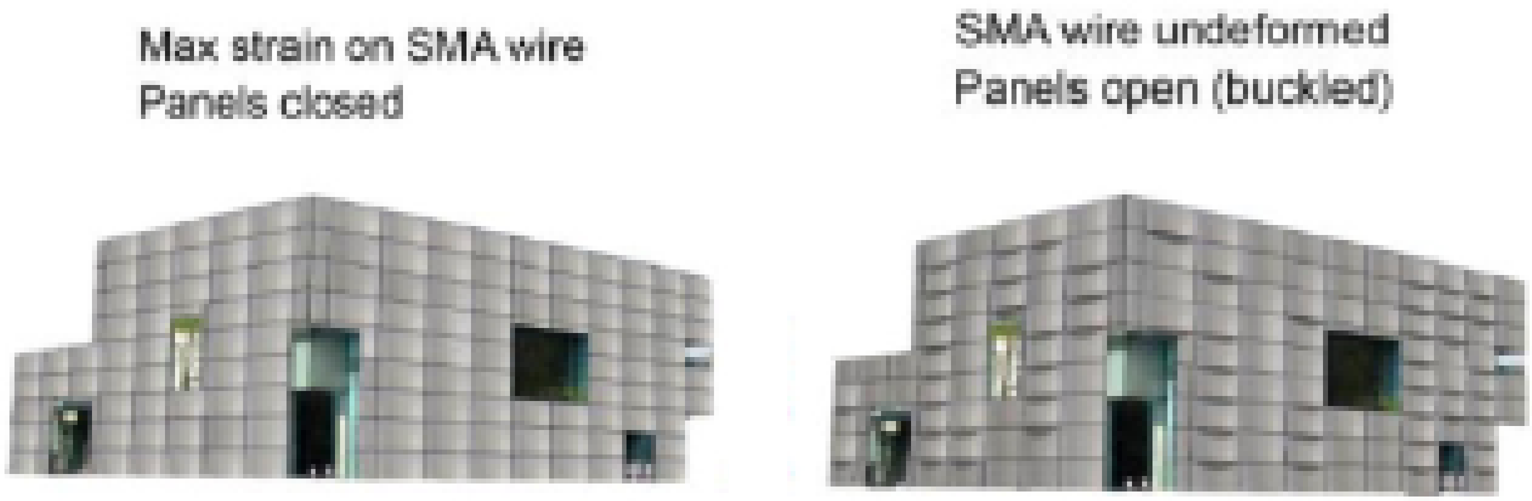
Soft robotics



3D-printable ink with magnetic particles, aligning them via an electromagnet around the printer nozzle.

https://www.engineering.com/3d-printed-soft-robots-can-be-controlled-by-magnets/

Building



Conceptual design of a responsive façade using SMA.

Formentini, M., & Lenci, S. An innovative building envelope (kinetic façade) with Shape Memory Alloys used as actuators and sensors, p. 220-31.

Smart composite Challenges

- Precision and scalability
- Consistent quality of multi-material prints
- Manufacturing speed
- Availability of materials

Conclusion

- Revolutionizing Material Design
- Key Advantages
  - Complex geometries
  - Customizable material properties and functionality
- Future Directions
  - Addressing challenges in reinforcement dispersion, residual stresses, and fiber alignment
  - Advances in hybrid manufacturing, post-processing techniques, and nano-reinforcements
  - Unlocking new possibilities in lightweight, high-performance, and adaptive material solutions for advanced industries