ADVANCES IN METAL ADDITIVE MANUFACTURING

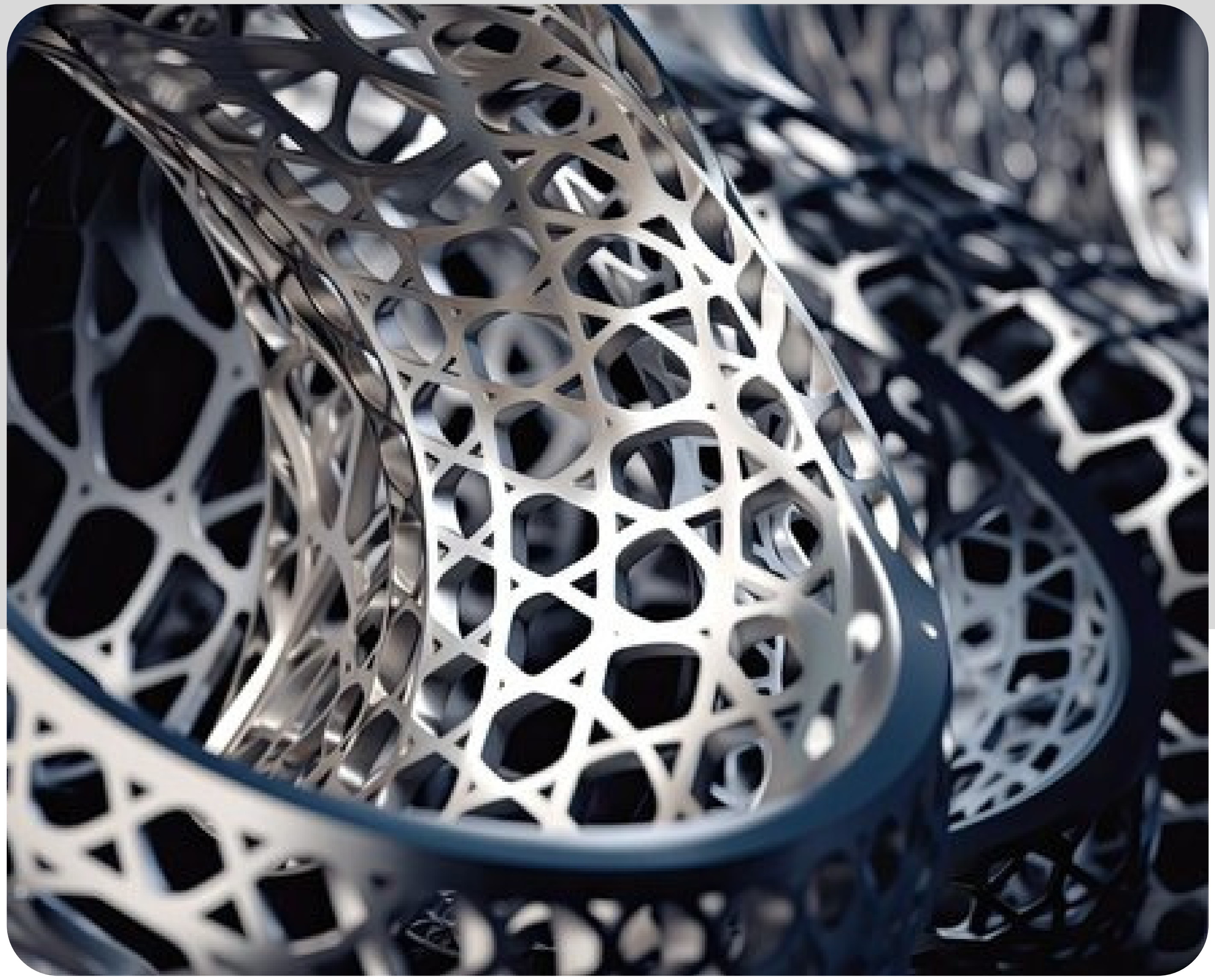


Image source: https://stock.adobe.com/fr/search?k=metal+additive+manufacturing&asset_id=601517941

Presented by:
Jeanne Cherng Yi Lee, Agasthya Vivek, Anastasia Meijer, Manuel Pascual, Dalia Somekh

INTRODUCTION

Images source:
https://www.apple.com/newsroom/2025/11/mapping-the-future-with-3d-printed-titanium-apple-watch-cases/

Image source:
https://www.geaerospace.com/news/articles/manufacturing/manufacturing-milestone-30000-additive-fuel-nozzles

01 Emerging Trends in L-PBF

02 In-Situ Monitoring, ML, and closed-loop Control of L-PBF

03 Wire Arc Additive Manufacturing

04 Metal Multi-Material Additive Manufacturing

05 Laser Colours

Presenter: Agasthya Vivek

EMERGING TRENDS IN L-PBF

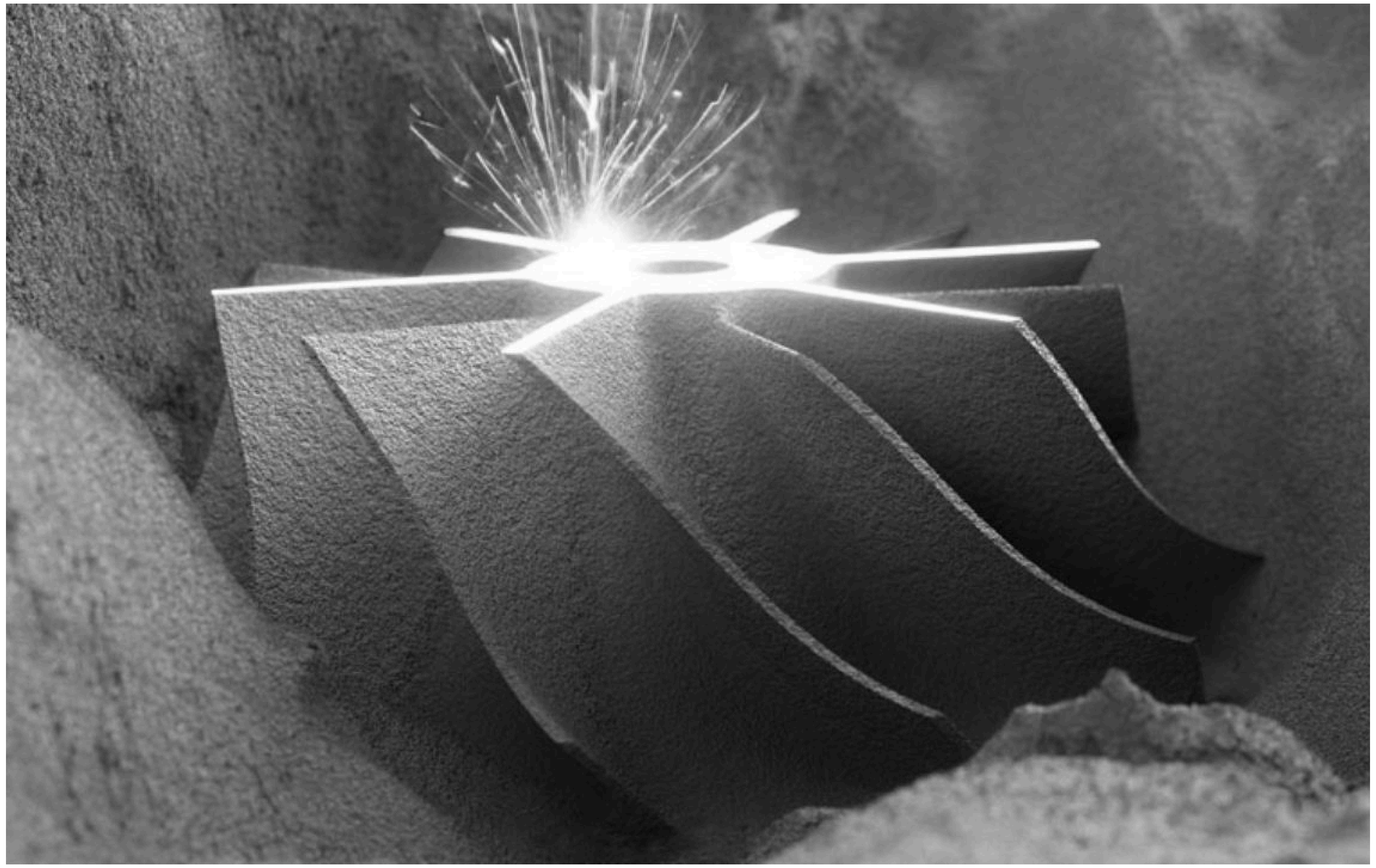


Image source: https://www.3dnatives.com/en/direct-metal-laser-sintering100420174-2/

01 New alloying systems

- High-Entropy Alloys (HEAs)
- Shape Memory Alloys (SMAs)

02 New technical solutions

- Remelting strategies
- Multi-laser systems
- Spattering
- Powder Recycling

Presenter: Jeanne Lee

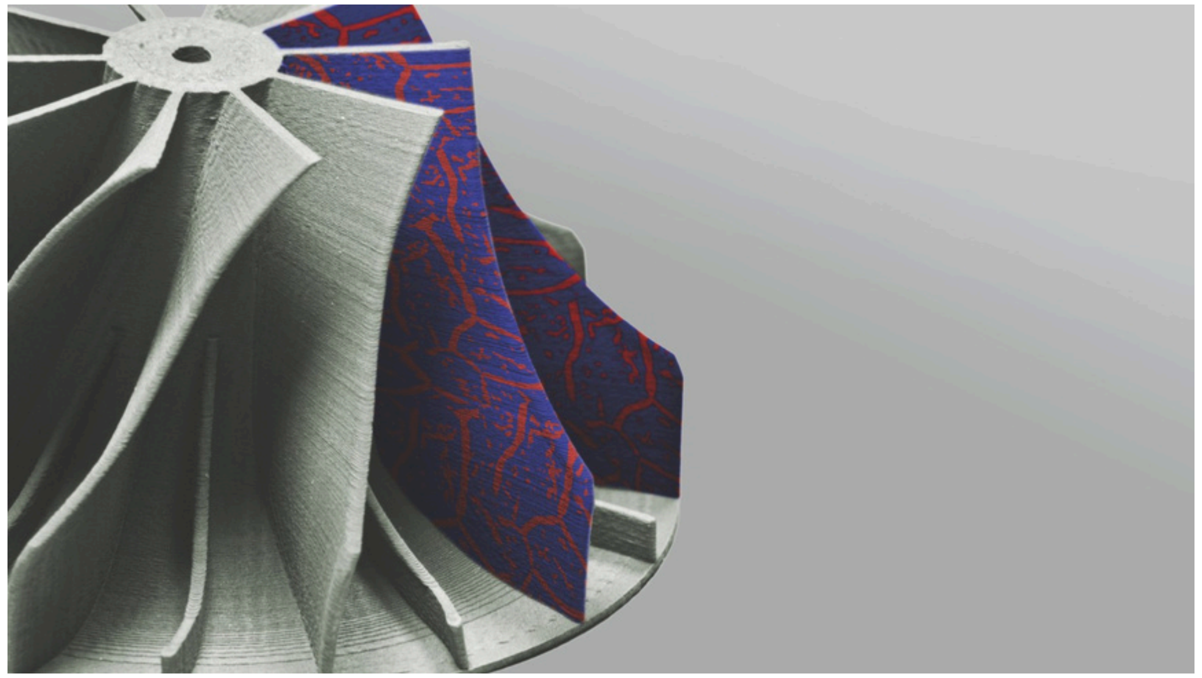
NEW ALLOYING SYSTEMS

High-Entropy Alloys (HEAs)

- Alloys composed of five or more principal elements with near-equimolar concentrations (5–35 at.% each)

Challenges with traditional methods :

- Segregation
- Cracking
- Intermetallic compounds
- Difficult control of temperature (different melting points)



"Scientists at Fraunhofer IWS printed 3D high-entropy demonstrator structures made of the Cantor alloy CrMnFeCoNi process."
Image source : https://www.iws.fraunhofer.de/en/newsandmedia/press_releases/2019/presseinformation_2019-13.html

- Niu et al.: Relative density of 98.4% in an AlCoCrFeNi HEA printed by L-PBF
- Agrawal et al.: Produced FeMnCoCrSi HEAs with no observable cracking, only 0.1% porosity, and a columnar ε-phase microstructure that enhanced work-hardening and resulted in a very favourable strength-ductility balance.

Presenter: Jeanne Lee

NEW ALLOYING SYSTEMS
Shape Memory Alloys

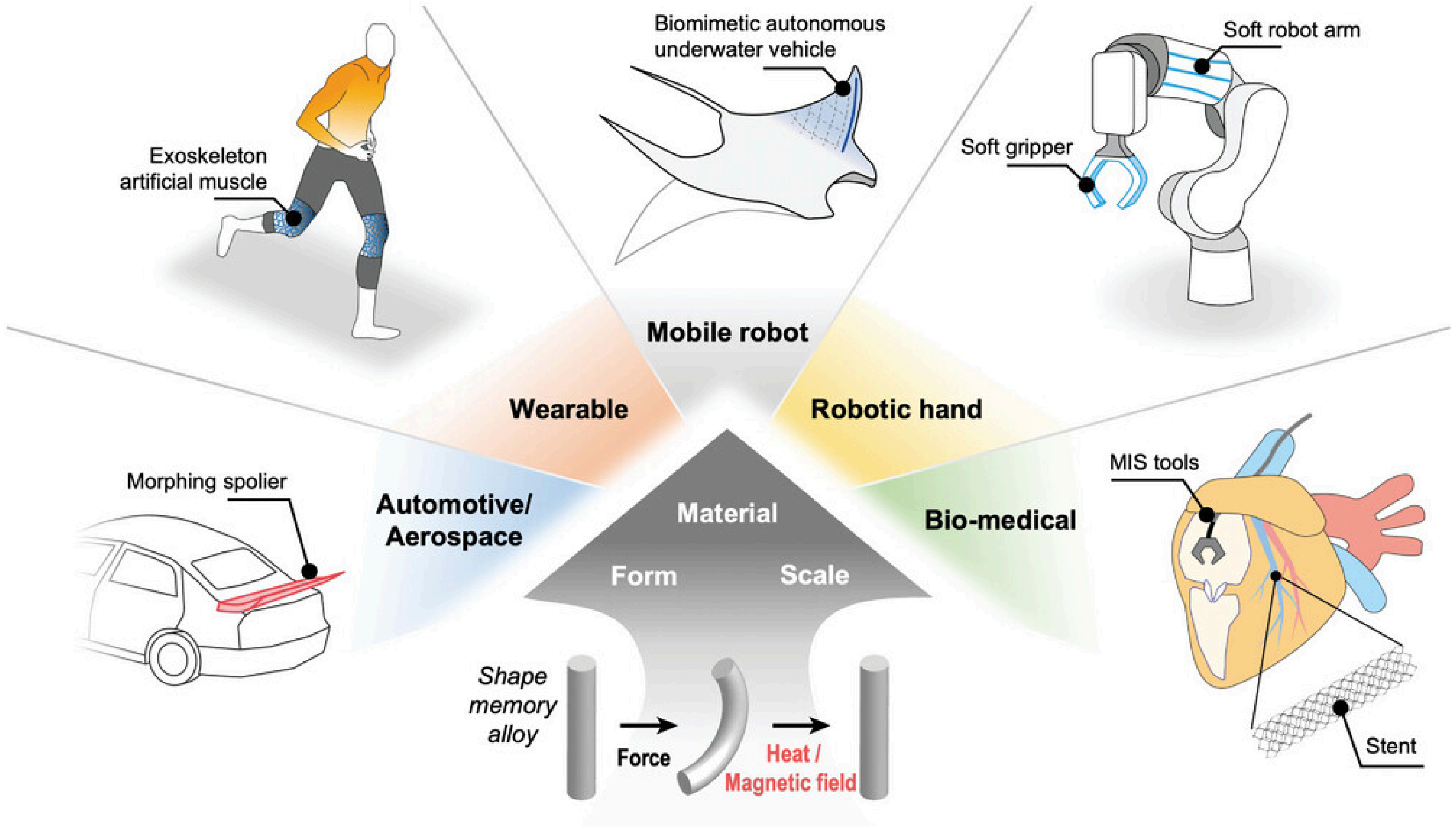


Image source: Kim, S., Heo, K., Rodrigue, H., Lee, T., Pané, S., Han, W., & Ahn, H. (2023). Shape Memory Alloy (SMA) Actuators: The Role of Material, Form, and Scaling Effects. Advanced Materials, 35(33), 2208517. https://doi.org/10.1002/adma.202208517

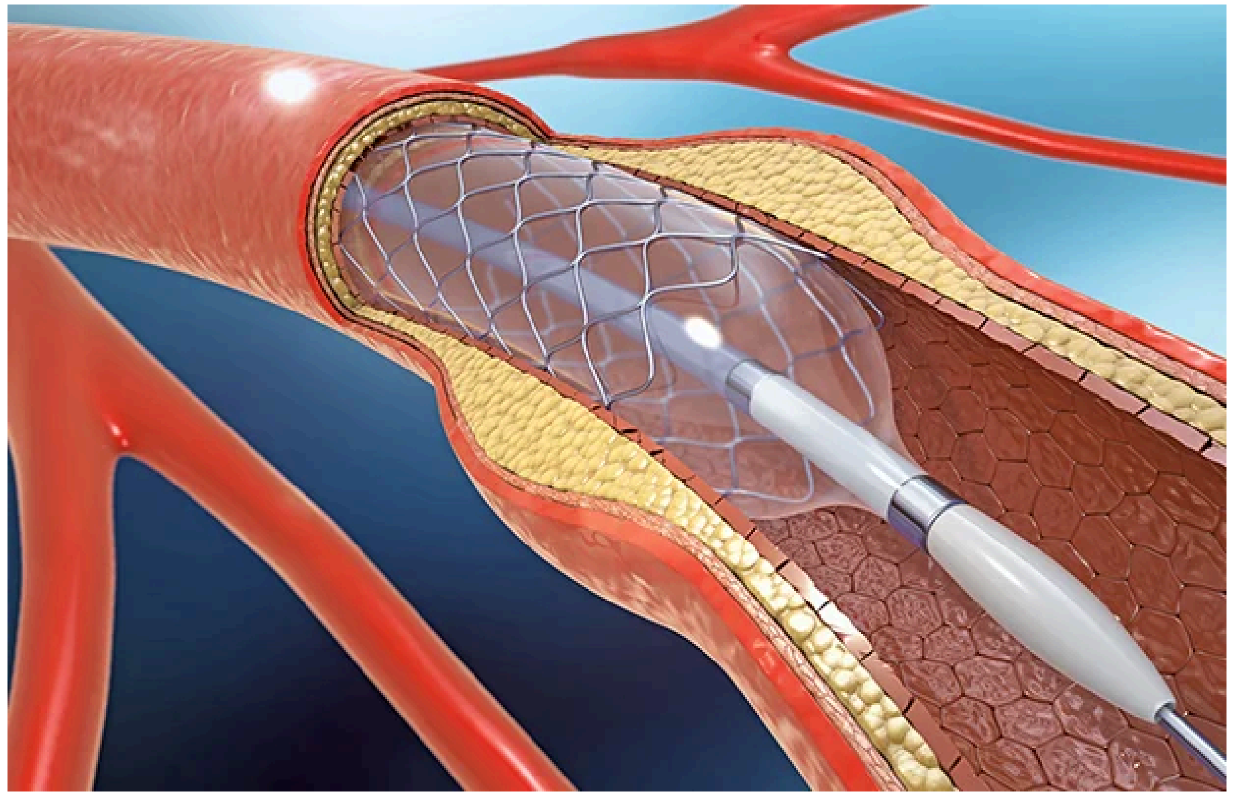


Image source: https://www.bhf.org.uk/informationsupport/heart-matters-magazine/medical/how-do-stents-work

- Lu et al : fabricated NiTi using L-PBF and achieved a shape memory recovery ratio of 98.7% and 4.99% recoverable strain after 10 loading–unloading cycles

Presenter: Jeanne Lee

NEW TECHNICAL SOLUTIONS

Remelting

- Approach where the same powder layer is scanned multiple times during L-PBF
- Remelting has become a widely used strategy to enhance part quality, particularly in terms of density and surface finish.

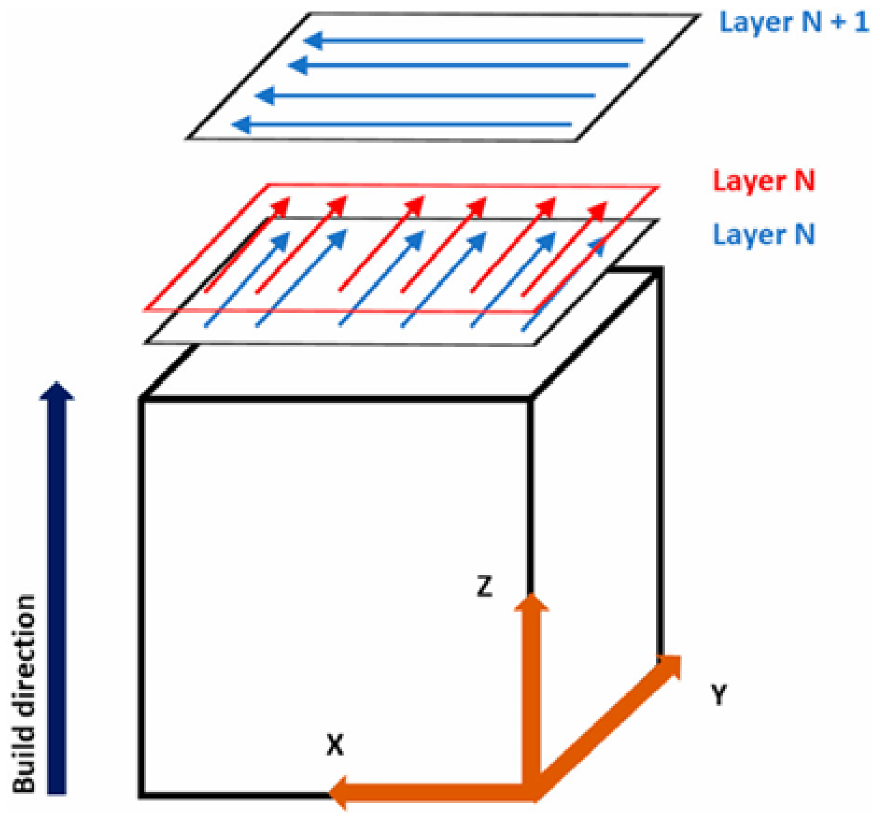


Image source: S. L. Sing and W. Y. Yeong. Laser powder bed fusion for metal additive manufacturing: perspectives on recent developments. Virtual and Physical Prototyping, 15(3):359–370, 2020.

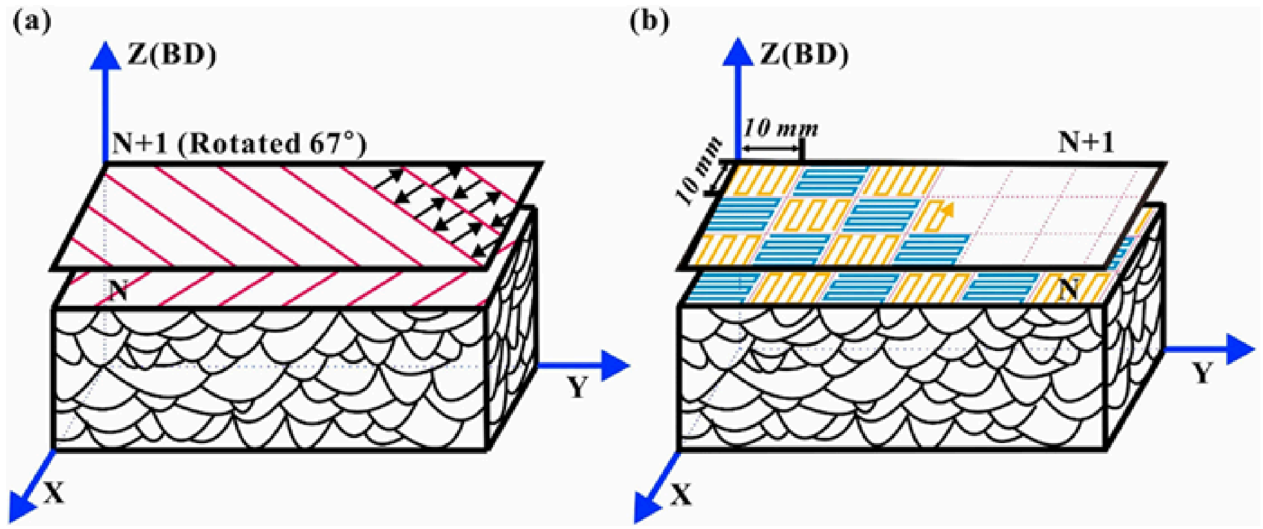


Image source: Y. C. Wang, L. M. Lei, L. Shi, H. Y. Wan, F. Liang, and G. P. Zhang. Scanning strategy dependent tensile properties of selective laser melted gh4169. Materials Science and Engineering: A, 788:139616, 2020.

- Xiong et al.: Remelting pure tungsten reduced both grain size and defects
- Yu et al.: Remelting in the same direction significantly reduced porosity compared to remelting in the opposite direction.

Presenter: Jeanne Lee

NEW TECHNICAL SOLUTIONS

Multi-laser systems

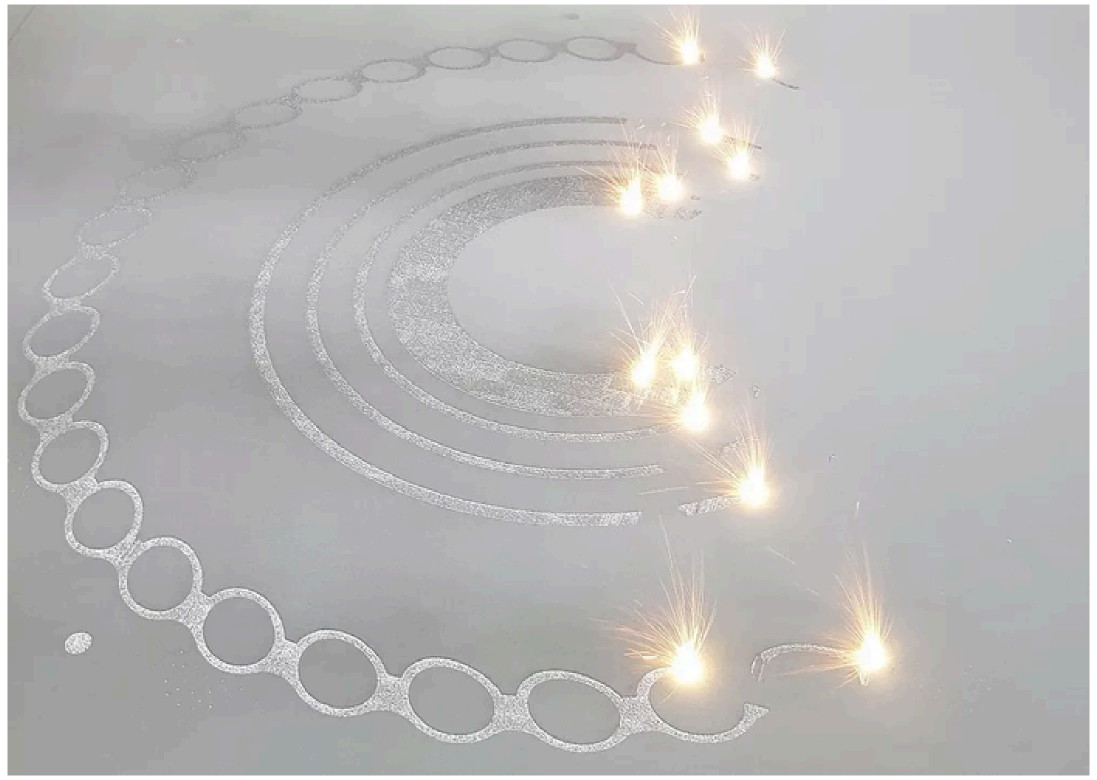


Image source:
https://www.canadianmetalworking.com/canadianmetalworking/article/metalworking/get-more-with-multi-laser-additive-manufacturing

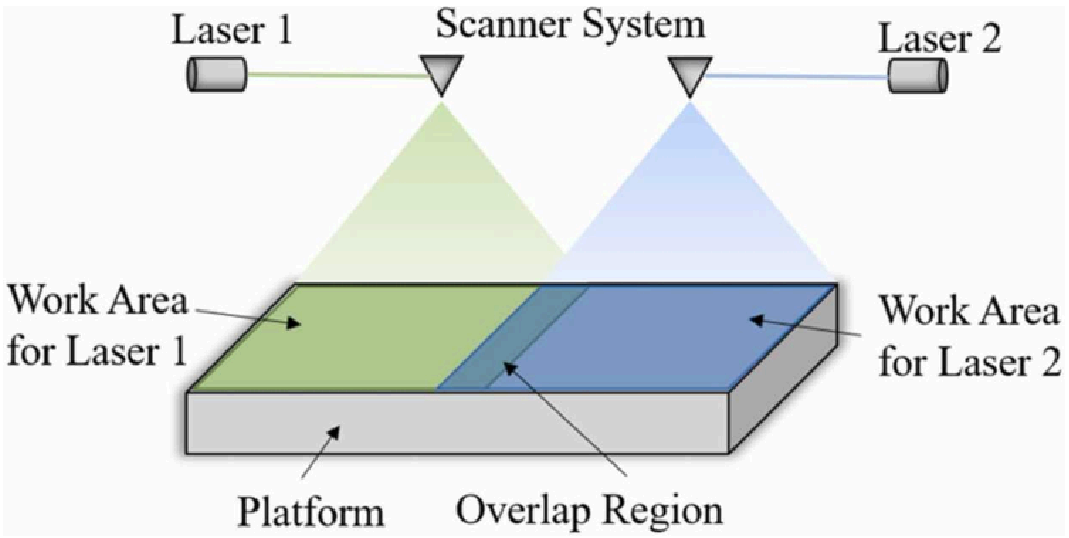


Image source: He, C., Ramani, K.S. & Okwudire, C.E. (2023). An intelligent scanning strategy (SmartScan) for improved part quality in multi-laser PBF additive manufacturing. Additive Manufacturing, 64, 103427.

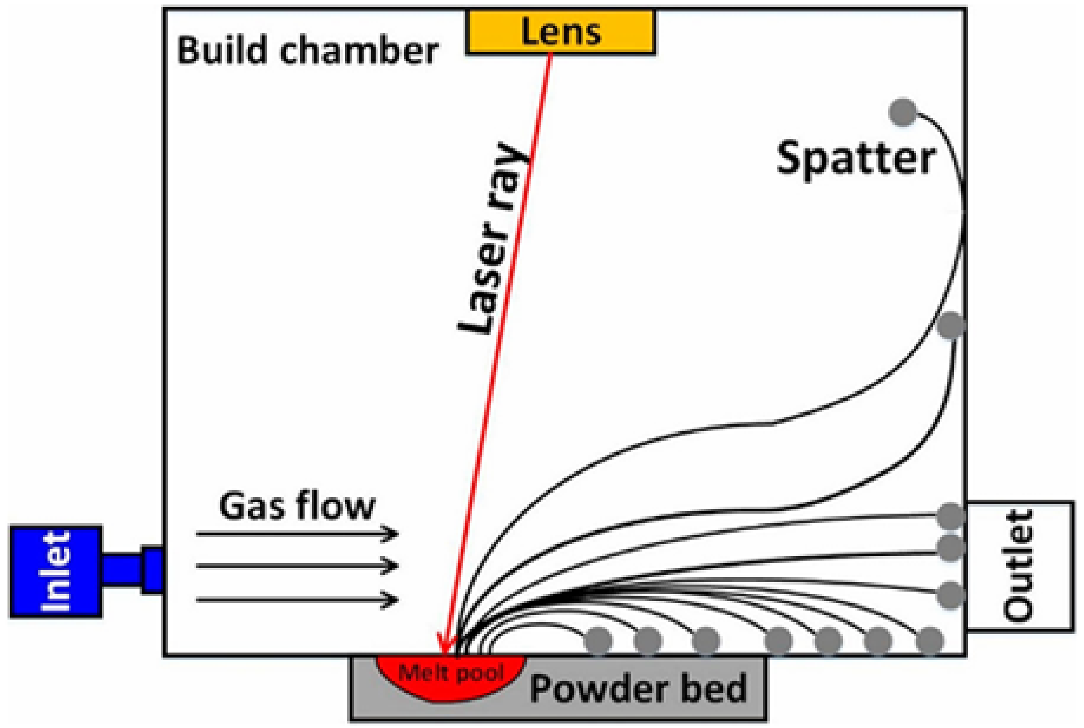
- Wong et al. : Multi-laser setups can increase build rates without compromising density or significantly modifying the microstructure of parts
- Tsai et al. : Diffractive optical element and a galvanometric scanner to split a single laser into multiple simultaneously scanning beams.

Presenter: Jeanne Lee

NEW TECHNICAL SOLUTIONS

Spattering

- Cold spatter: un-melted powder displaced by gas flow.
- Hot spatter: molten droplets ejected from the melt pool.
- Recondensed particles: condensate that forms from metal vapor and settles onto the powder bed.



- Zhang et al : added an extra row of gas nozzles beneath the existing ones which significantly improved spatter removal rate from 69% to 93%.
- Pauzon et al : mixtures of He and Ar, taking advantage of helium's higher thermal conductivity and heat capacity. Results : build rate to increase by up to 40% + fully dense parts

Image source: Xiaobing Zhang, Bo Cheng, and Charles Tuffile. Simulation study of the spatter removal process and optimization design of gas flow system in laser powder bed fusion. Additive Manufacturing, 32:101049, 2020.

Presenter: Jeanne Lee

NEW TECHNICAL SOLUTIONS

Powder Recycling

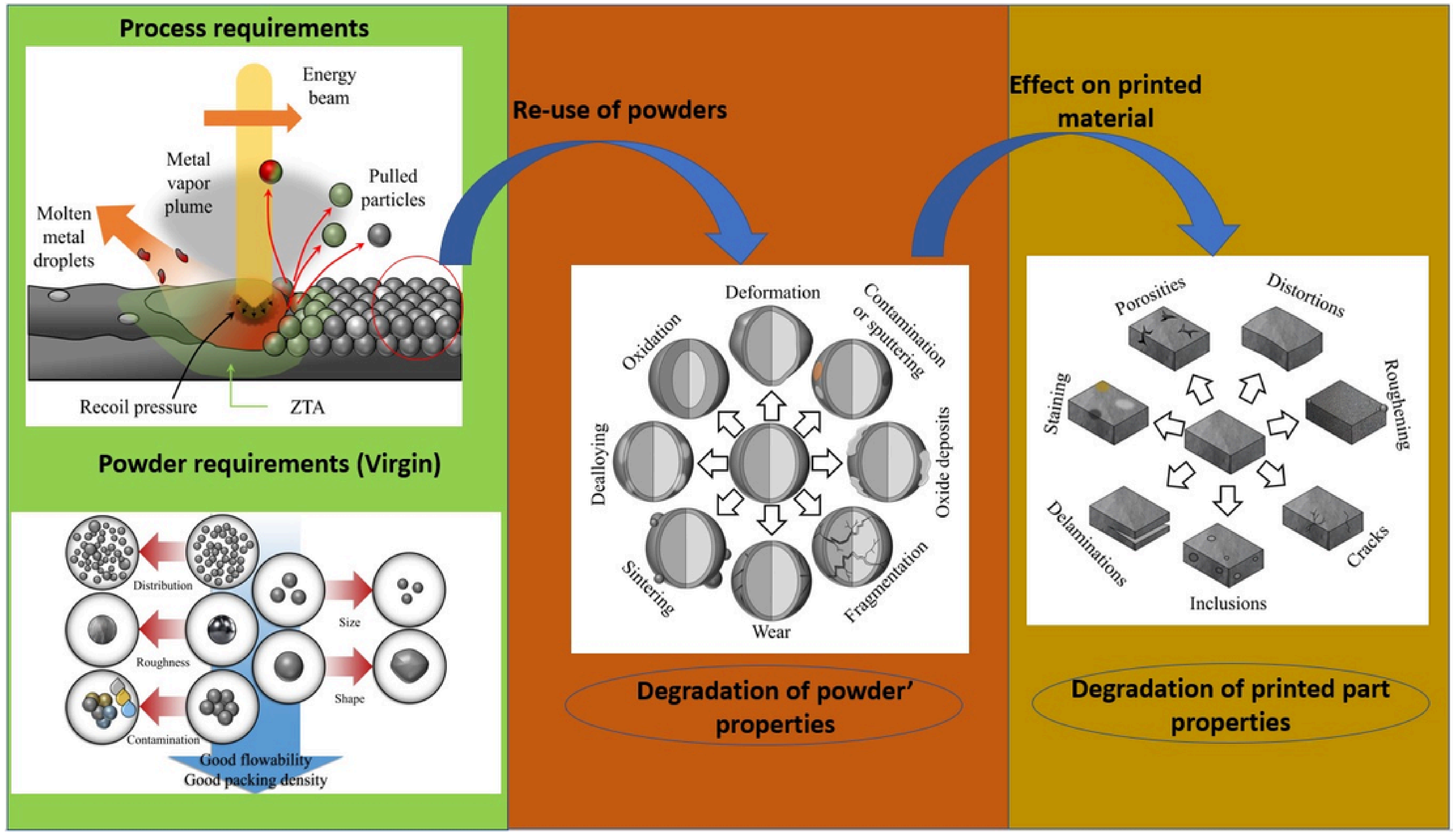


Image source: A. Lanzutti and E. Marin, "The Challenges and Advances in Recycling/Re-Using Powder for Metal 3D Printing: A Comprehensive Review," Metals, vol. 14, no. 8, Article 886, 2024. doi: 10.3390/met14080886.

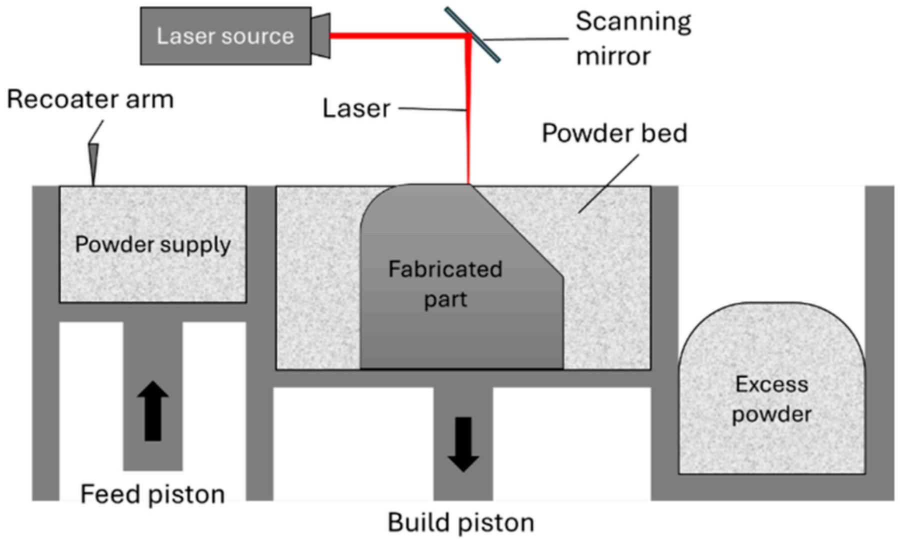
- Carrion et al. : Ti6Al4V powders reused for 15 cycles
    - improved flowability due to narrower PSD
    - no significant changes in microstructure, tensile strength, fatigue behaviour.
- Sutton et al : similar PSD narrowing in 304L stainless steel
    - BUT detected an increase in oxygen content
    - microstructural changes after 7 cycles.
- Cordova et al. : oxygen content doubled in AlSi10Mg after 6 cycles
    - negatively affected ductility
- Wang, Ye, et al. : CoCrW powders reused 6 times resulted in reduced mechanical performance

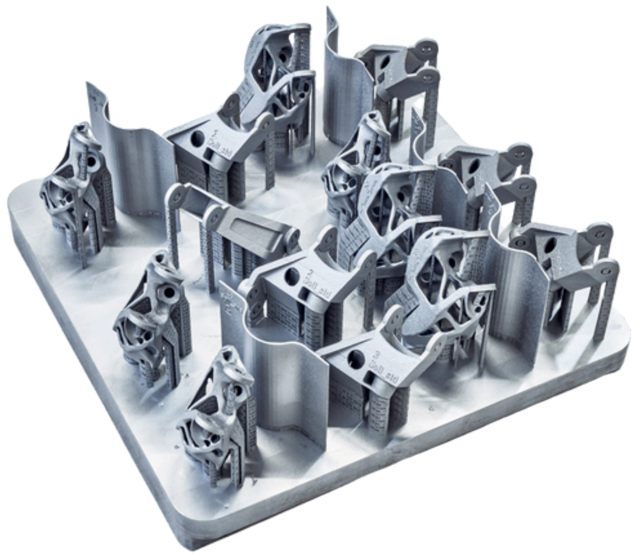
- To reduce degradation of mechanical properties, industries blend 12–22% of virgin powder into recycled batches

Presenter: Jeanne Lee

IN-SITU MONITORING, ML, AND CLOSED-LOOP CONTROL OF L-PBF

Build-then-inspect





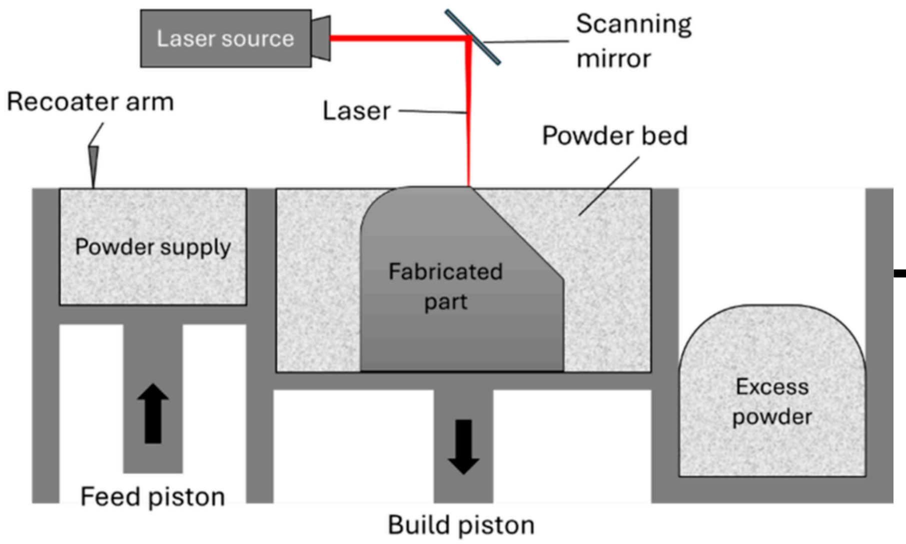
Inspection

Parameter Tuning

Presenter: Dalia Somekh

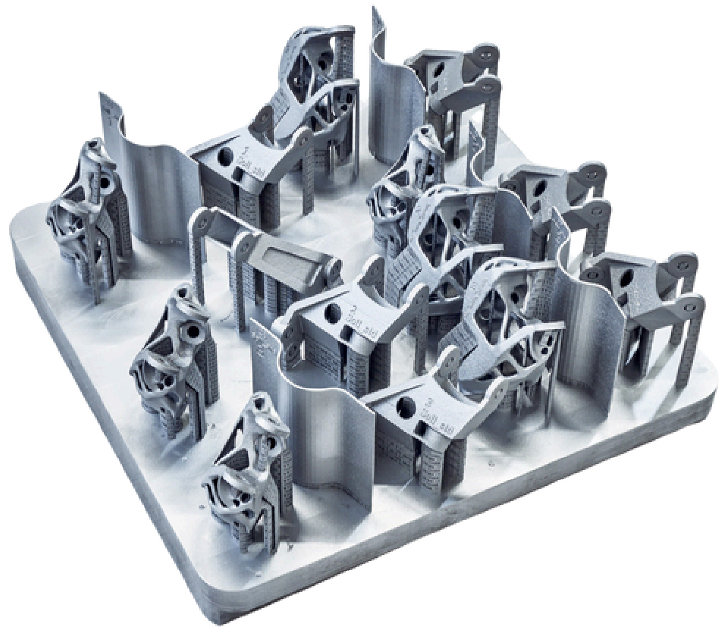
IN-SITU MONITORING, ML, AND CLOSED-LOOP CONTROL OF L-PBF

New Paradigm



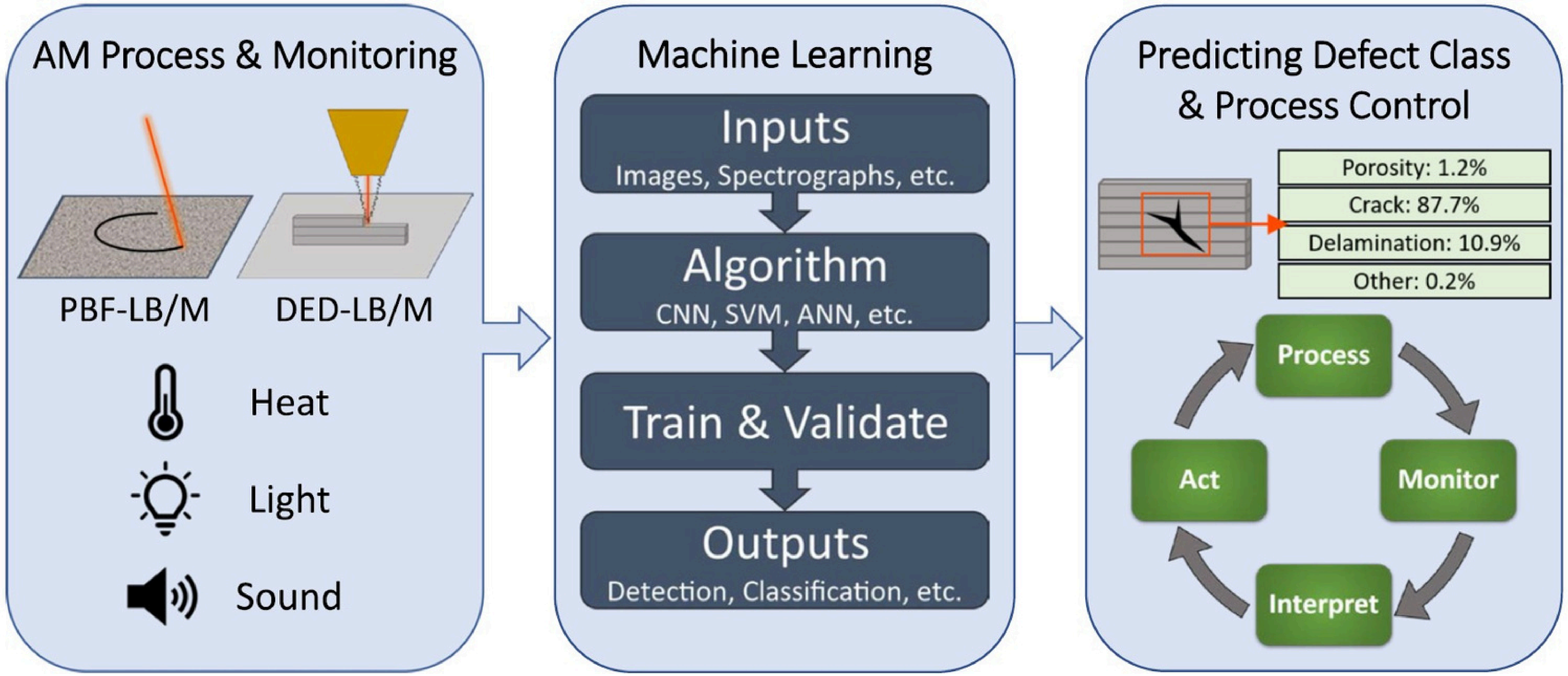
Inspection

Parameter Tuning



Presenter: Dalia Somekh

IN-SITU MONITORING, ML, AND CLOSED-LOOP CONTROL OF L-PBF



Images source: *T. Herzog, M. Brandt, A. Trinchi, A. Sola, and A. Molotnikov. Process monitoring and machine learning for defect detection in laser-based metal additive manufacturing. Journal of Intelligent Manufacturing, 35:1407–1437, 2024.*

Presenter: Dalia Somekh

TYPES OF DEFECTS IN L-PBF

01 Geometrical Defects

02 Surface Quality Defects

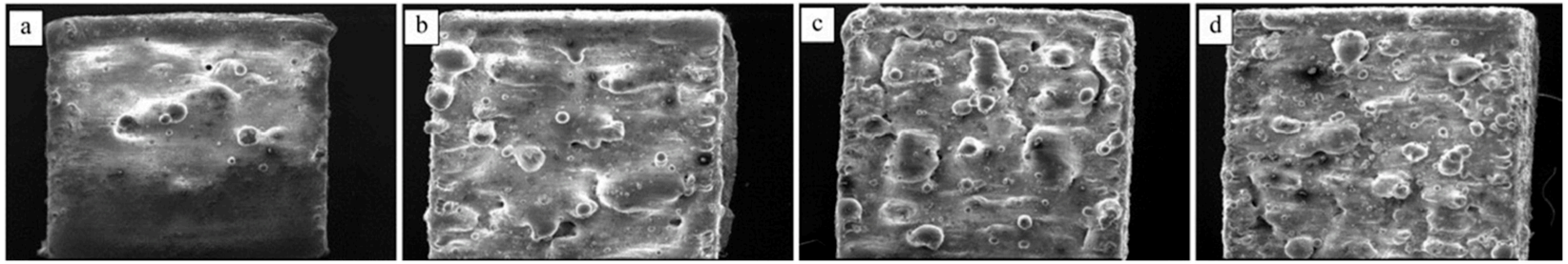
03 Microstructure Defects (Porosity)

04 Mechanical Defects

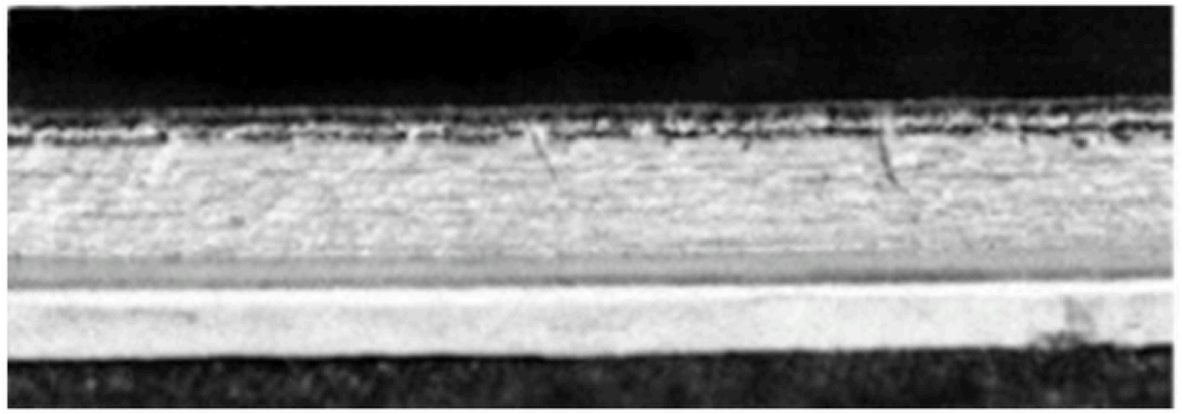
TYPES OF DEFECTS IN L-PBF

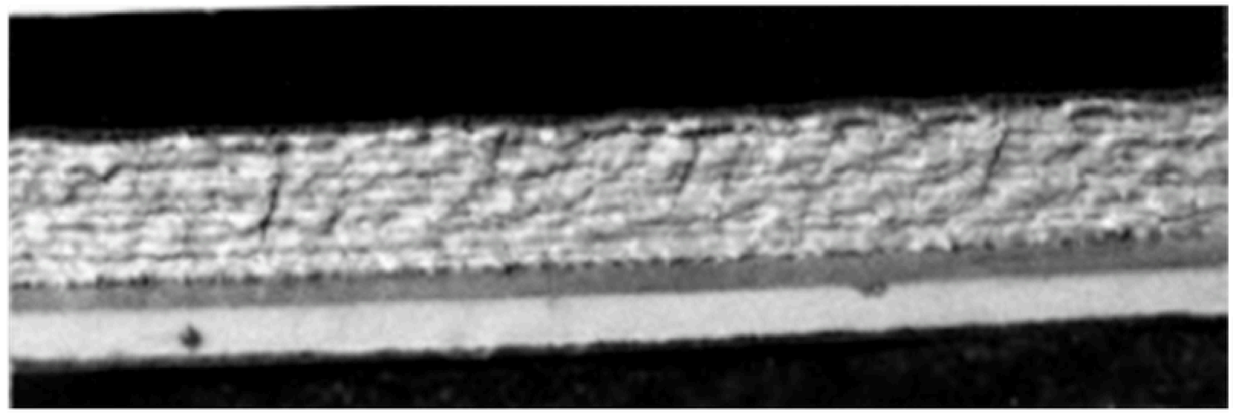
02 Surface Quality Defects

Balling



Surface Oxidation





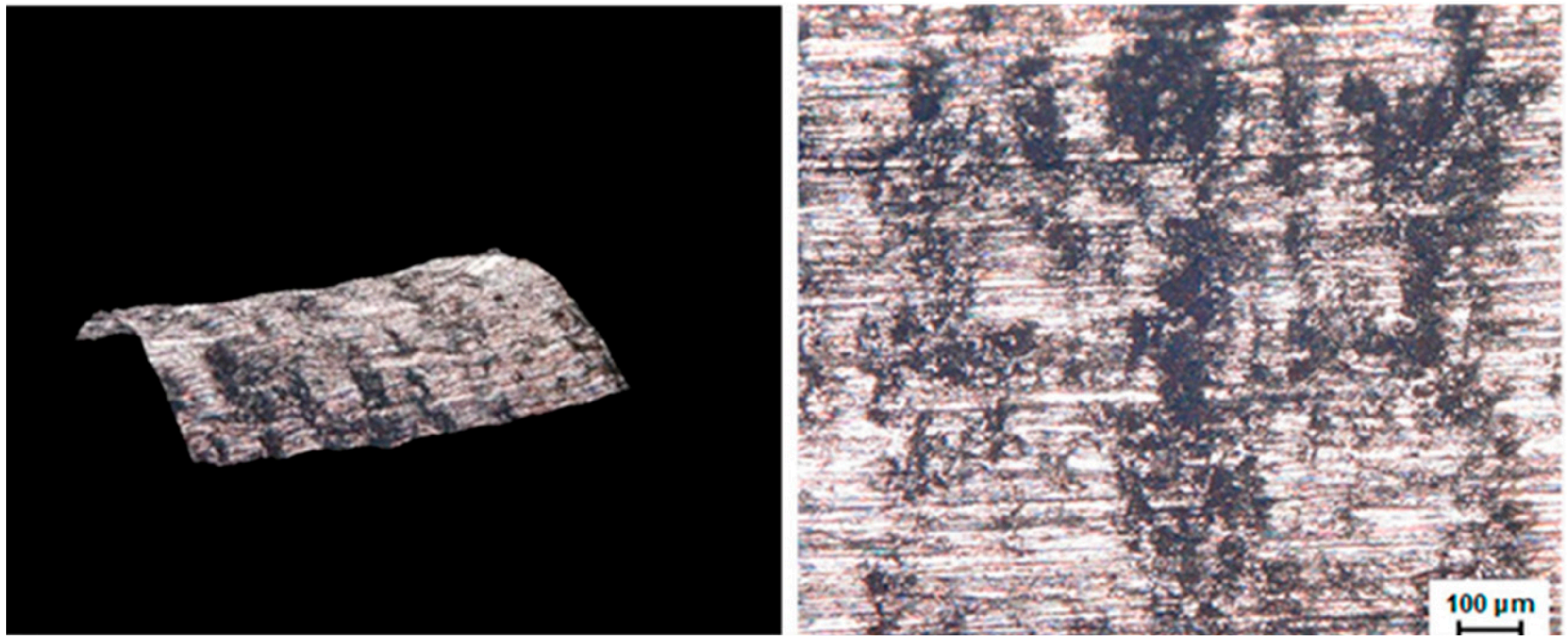
<u>Images source</u>: *D. Guillen, S. Wahlquist, and A. Ali. Critical review of LPBF metal print defects detection: Roles of selective sensing technology. Appl. Sci., 14(15):6718, 2024.*

Presenter: Dalia Somekh

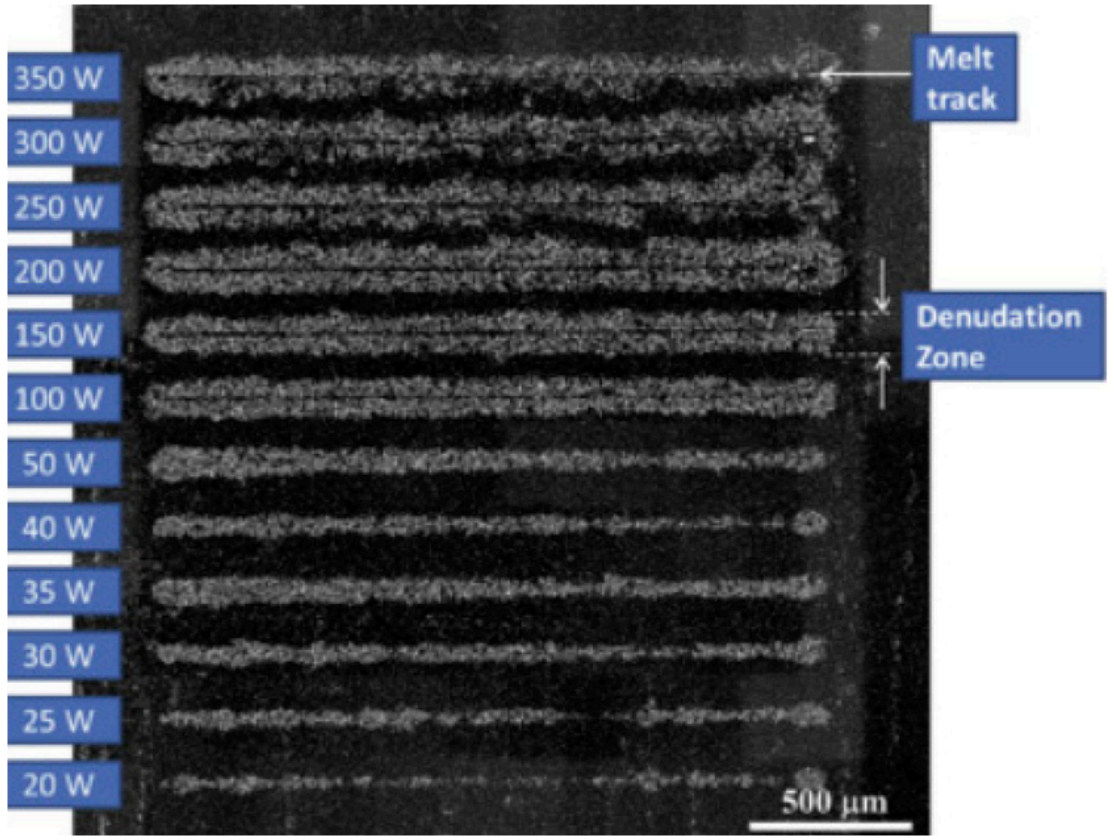
TYPES OF DEFECTS IN L-PBF

02 Surface Quality Defects

Surface Roughness



Denudation



Images source: *D. Guillen, S. Wahlquist, and A. Ali. Critical review of LPBF metal print defects detection: Roles of selective sensing technology. Appl. Sci., 14(15):6718, 2024.*

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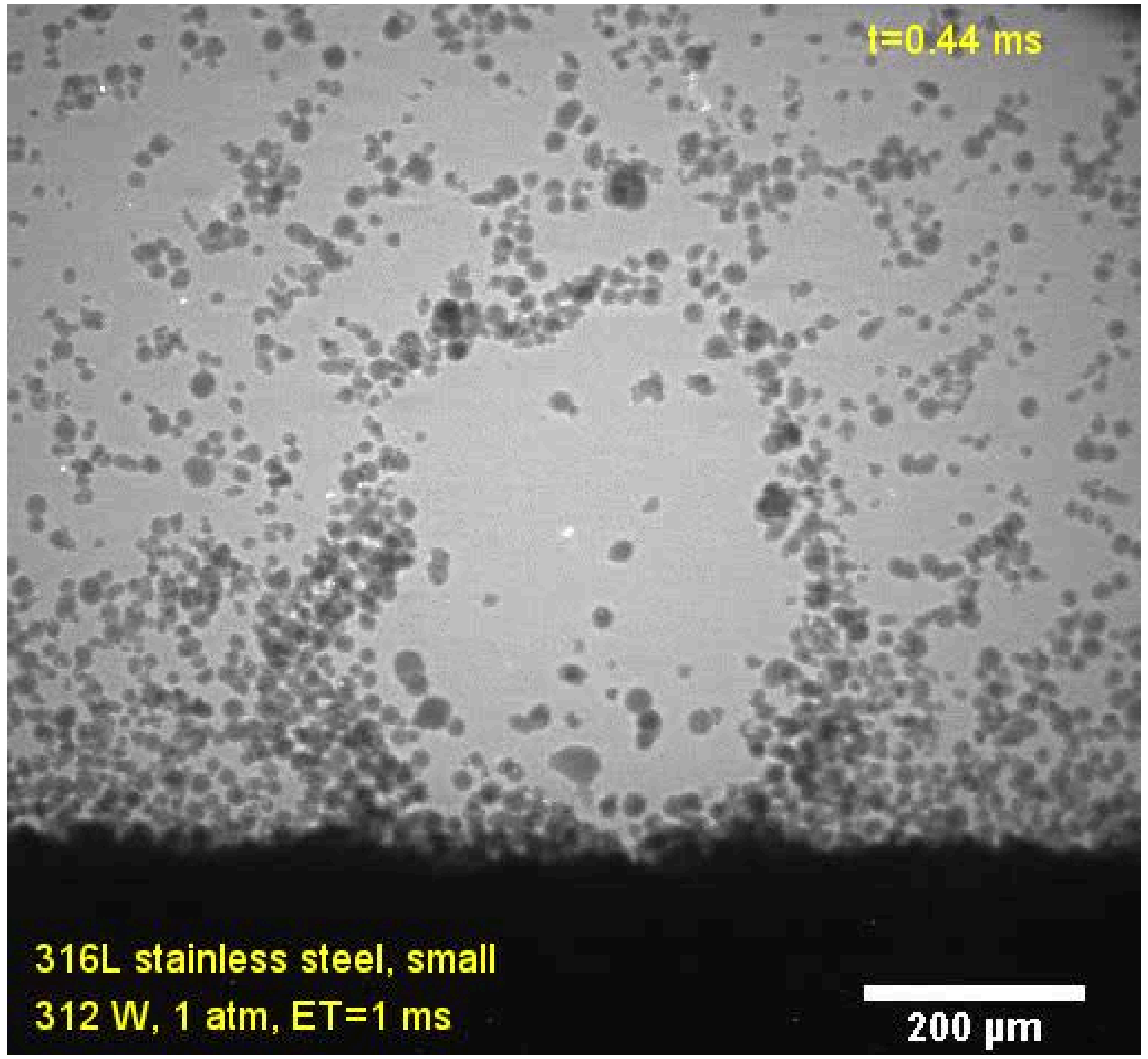
TYPES OF DEFECTS IN L-PBF

02 Surface Quality Defects

Vaporization



Video source: *Guo, Q., Zhao, C., Escano, L. I., Young, Z., Xiong, L., et al. Transient Dynamics of Powder Spattering in L-PBF Revealed by In-Situ X-ray Imaging, Acta Materialia, vol. 151, pp. 169–180, 2018.*

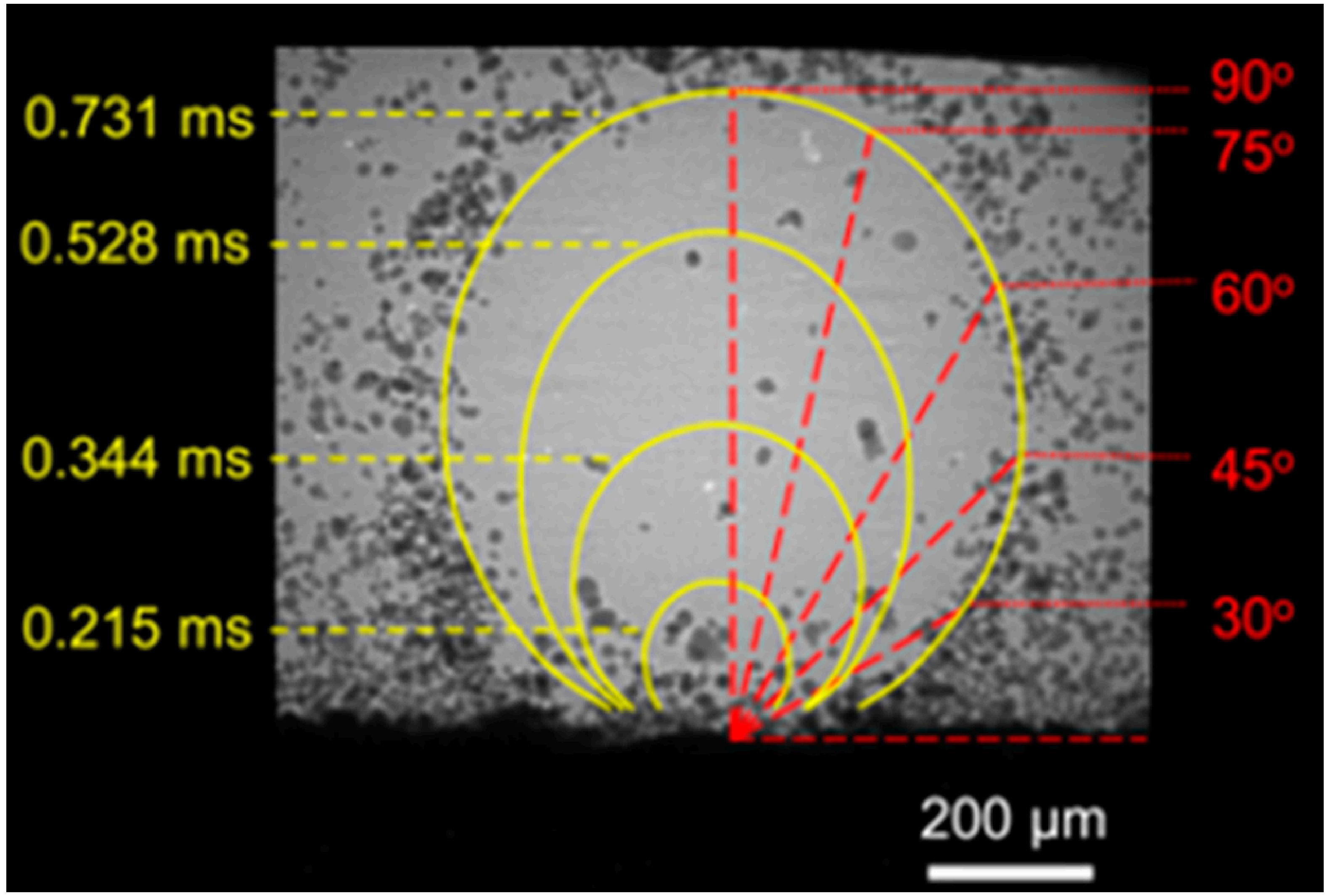


Image source: *D. Guillen, S. Wahlquist, and A. Ali. Critical review of LPBF metal print defects detection: Roles of selective sensing technology. Appl. Sci., 14(15):6718, 2024.*

TYPES OF DEFECTS IN L-PBF

01 Geometrical Defects

02 Surface Quality Defects

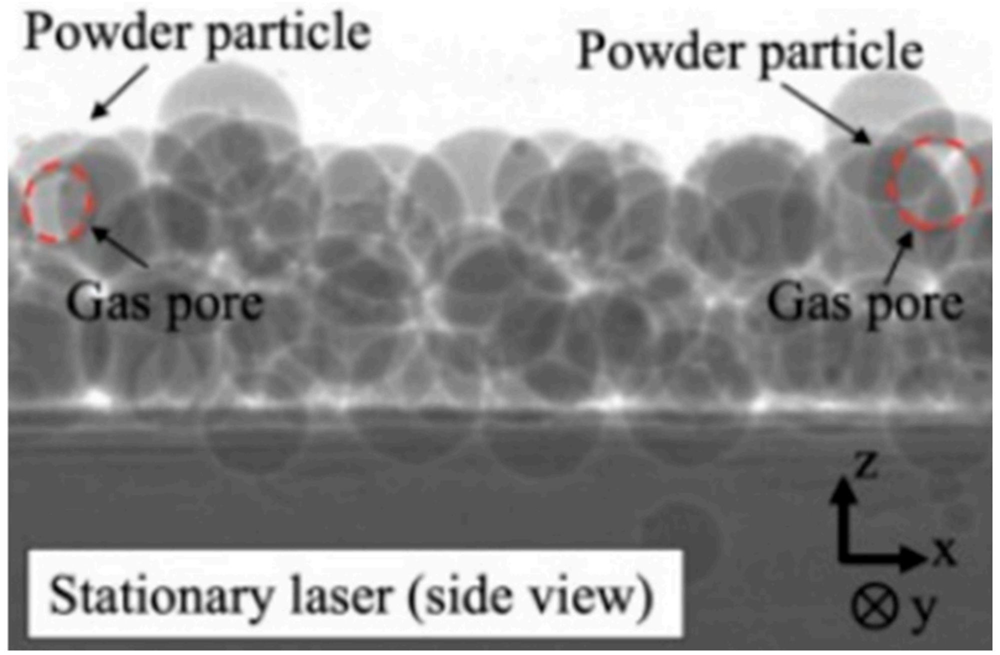
03 Microstructure Defects (Porosity)

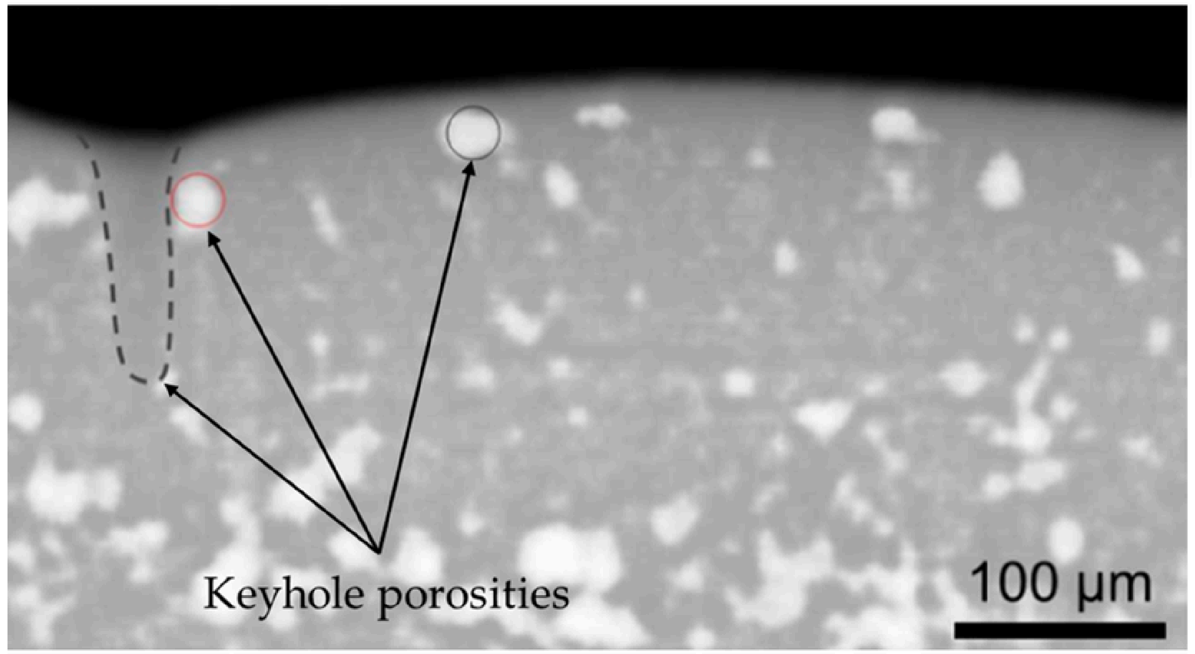
04 Mechanical Defects

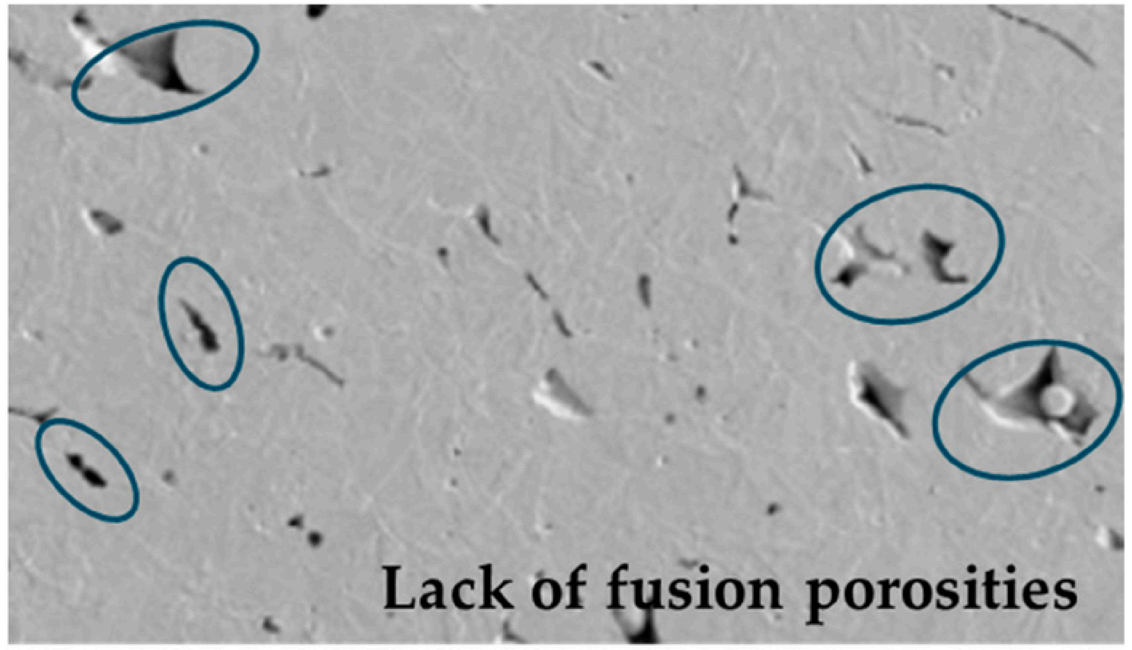
TYPES OF DEFECTS IN L-PBF

03 Microstructure Defects (Porosity)

Gas Porosity	Keyhole Porosity	Lack-of-Fusion Porosity







Images source: *D. Guillen, S. Wahlquist, and A. Ali. Critical review of LPBF metal print defects detection: Roles of selective sensing technology. Appl. Sci., 14(15):6718, 2024.*

TYPES OF DEFECTS IN L-PBF

01 Geometrical Defects

02 Surface Quality Defects

03 Microstructure Defects (Porosity)

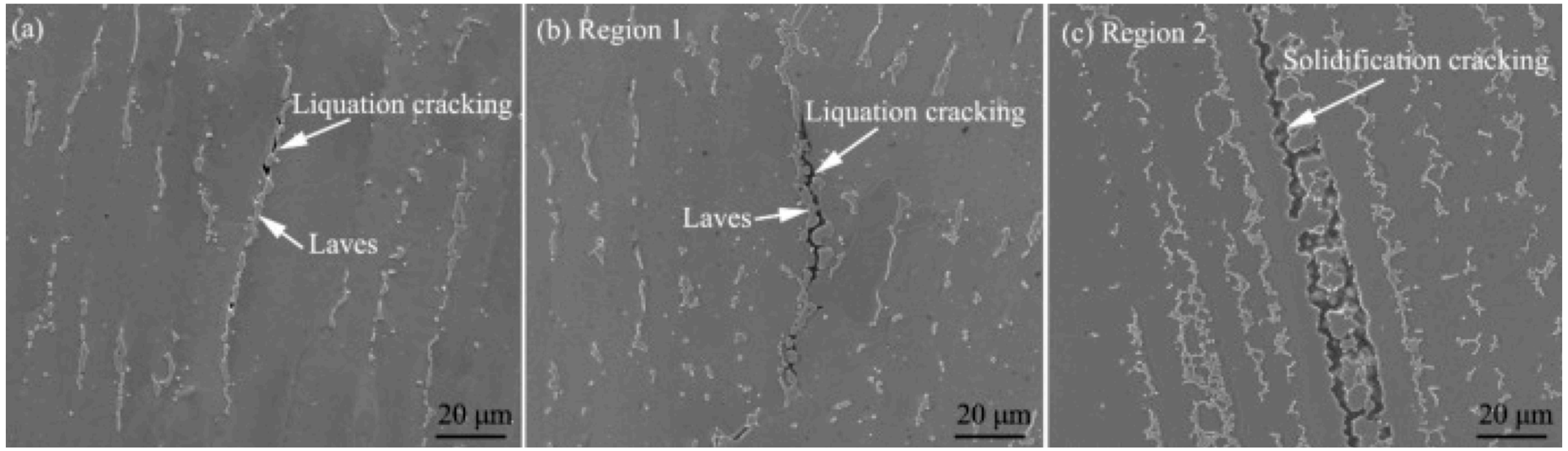
04 Mechanical Defects

Presenter: Dalia Somekh

TYPES OF DEFECTS IN L-PBF

04 Mechanical Defects

Liquation and Solidification Cracking	Delamination



Images source: *D. Guillen, S. Wahlquist, and A. Ali. Critical review of LPBF metal print defects detection: Roles of selective sensing technology. Appl. Sci., 14(15):6718, 2024.*

IN-SITU MONITORING TECHNOLOGIES

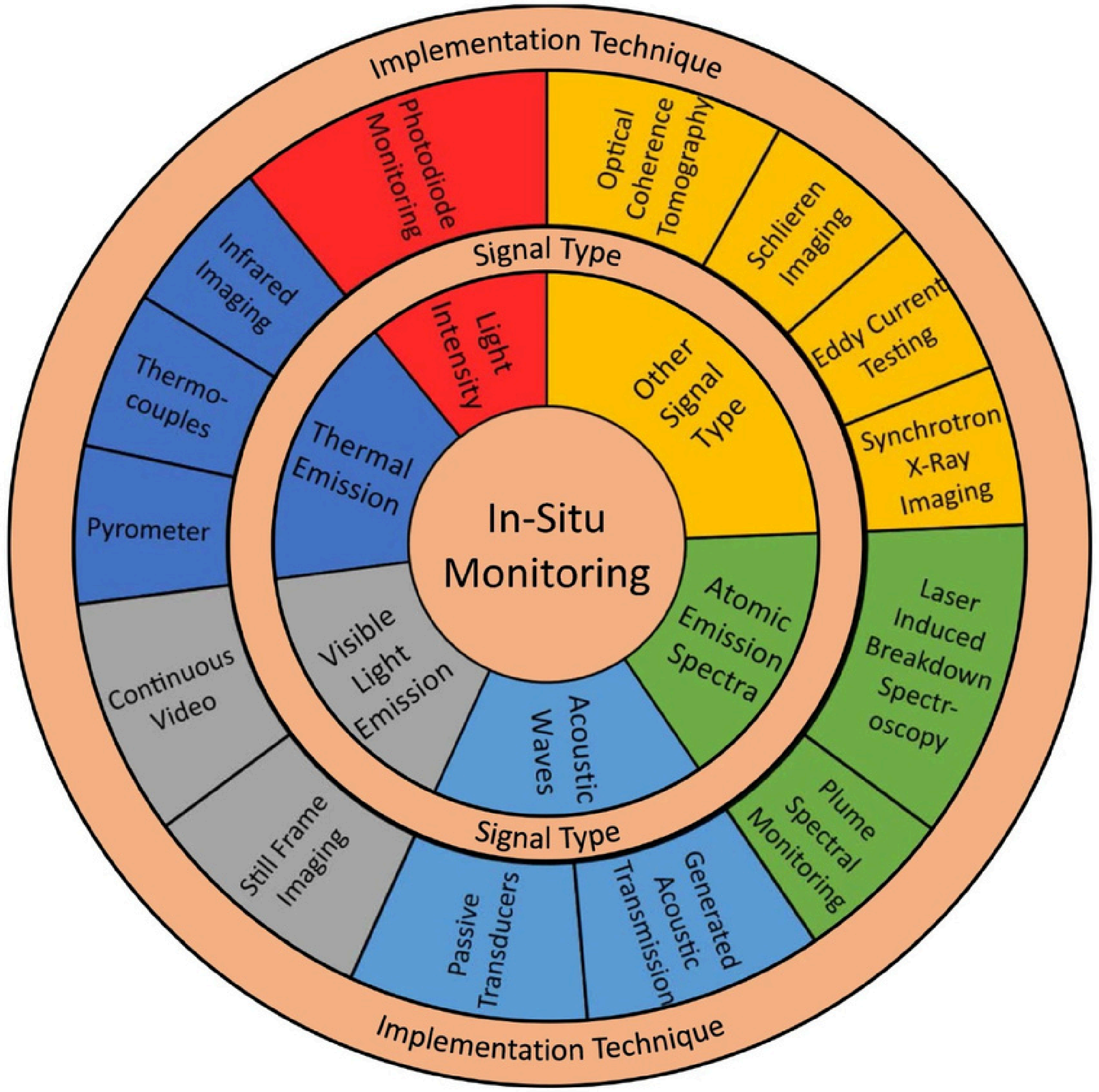
Optical Monitoring

Infrared and Thermal Monitoring

Coaxial Photodiodes

Acoustic Emission Monitoring

Layer-wise Surface Measurement



Images source: *T. Herzog, M. Brandt, A. Trinchi, A. Sola, and A. Molotnikov. Process monitoring and machine learning for defect detection in laser-based metal additive manufacturing. Journal of Intelligent Manufacturing, 35:1407–1437, 2024.*

MACHINE LEARNING ALGORITHMS

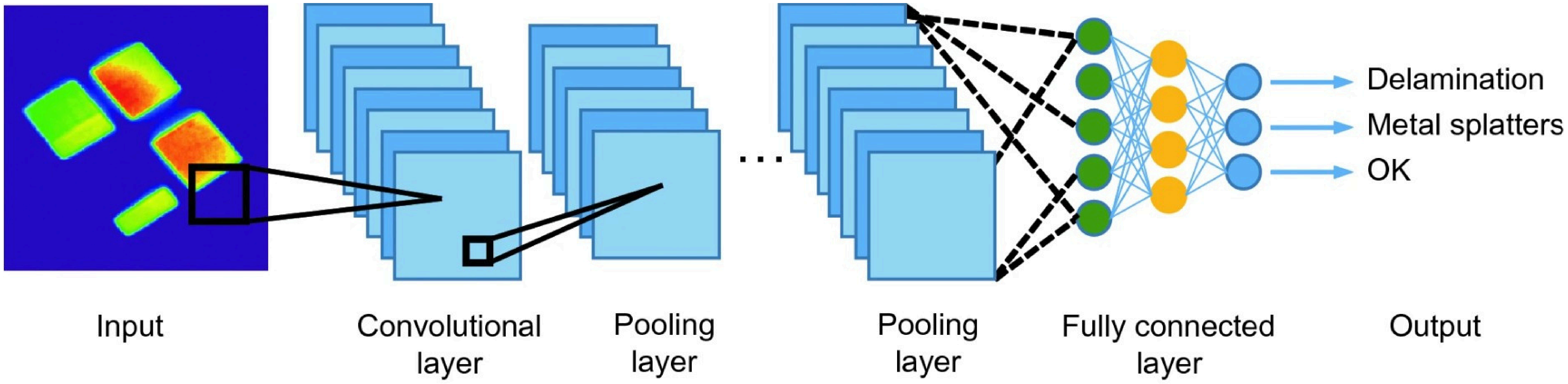
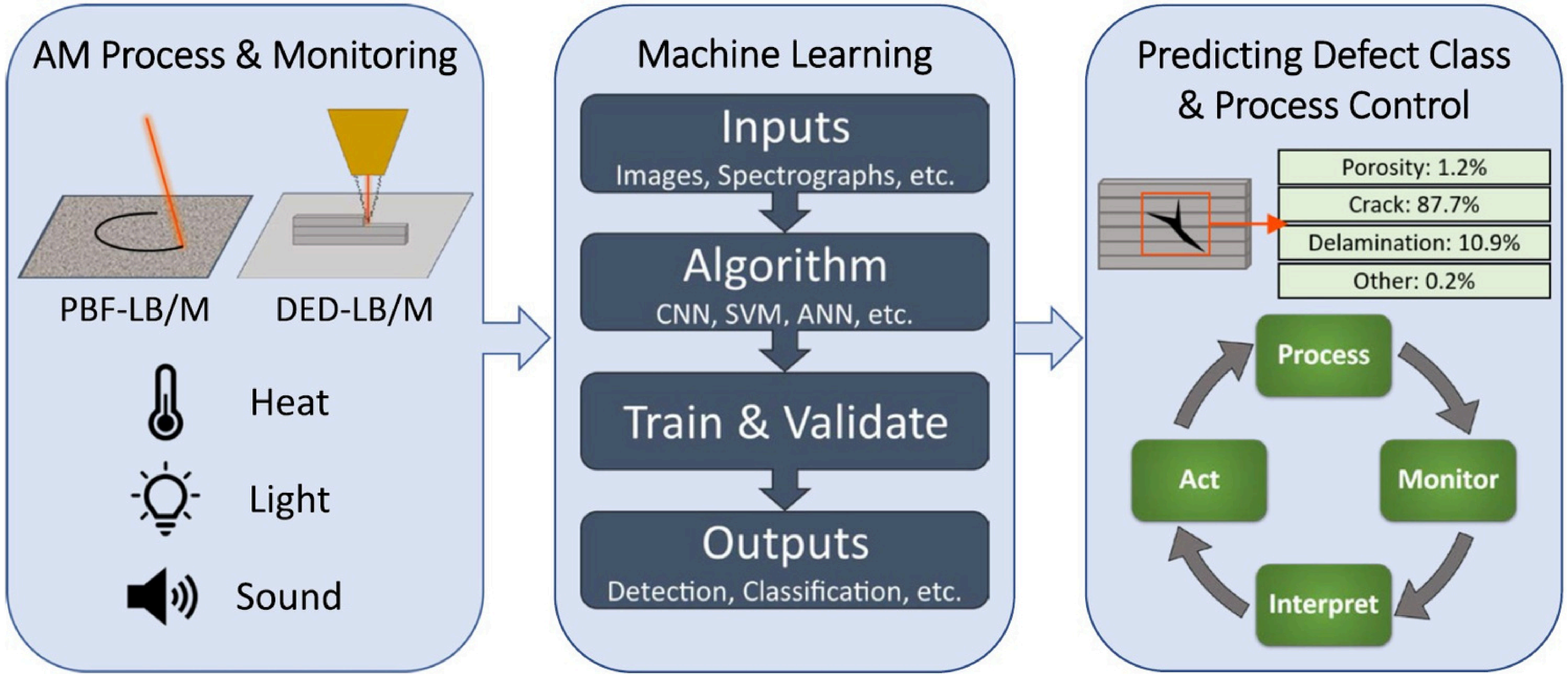


Image source: *Holger Baumgartl, Jan Tomas, Ralf Buettner, and Manuel Merkel. A deep learning-based model for defect detection in laser powder-bed fusion using in-situ thermographic monitoring. Progress in Additive Manufacturing, 5:277–285, 2020.*

CLOSED-LOOP CONTROL



- Laser power
- Scan speed
- Hatch spacing
- Local re-scan

Images source: *T. Herzog, M. Brandt, A. Trinchi, A. Sola, and A. Molotnikov. Process monitoring and machine learning for defect detection in laser-based metal additive manufacturing. Journal of Intelligent Manufacturing, 35:1407–1437, 2024.*

Presenter: Dalia Somekh

ADVANTAGES AND CHALLENGES

Advantages	Challenges
Improved part quality	Sensor integration and cost
Enhanced industrial readiness	High data rates
Reduced post-processing	Model transferability
Wider process windows	Explainability and certification
	Control stability

WIRE ARC ADDITIVE MANUFACTURING

01 What and how?

02 Defects

03 Advances

Images source: K. Carter. "Advantages of wire-arc additive manufacturing". Thermal processing. https://thermalprocessing.com/advantages-of-wire-arc-additive-manufacturing/. Accessed 29.11.2025.

Presenter: Anastasia Meijer

WHAT IS WAAM?

Definition

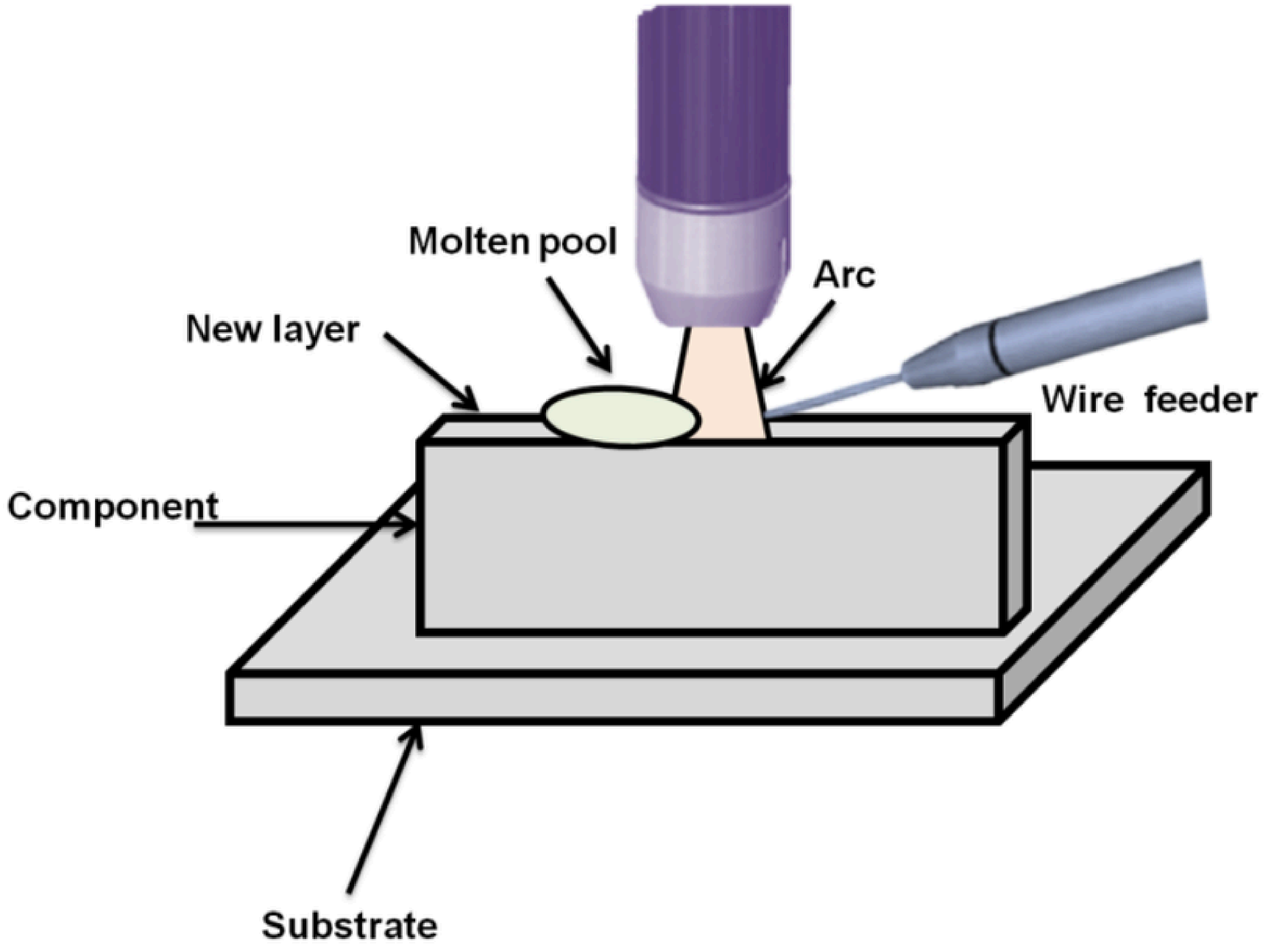
- Directed Energy Deposition
- 60% less time than powder
- 85% less energy than powder

Current applications

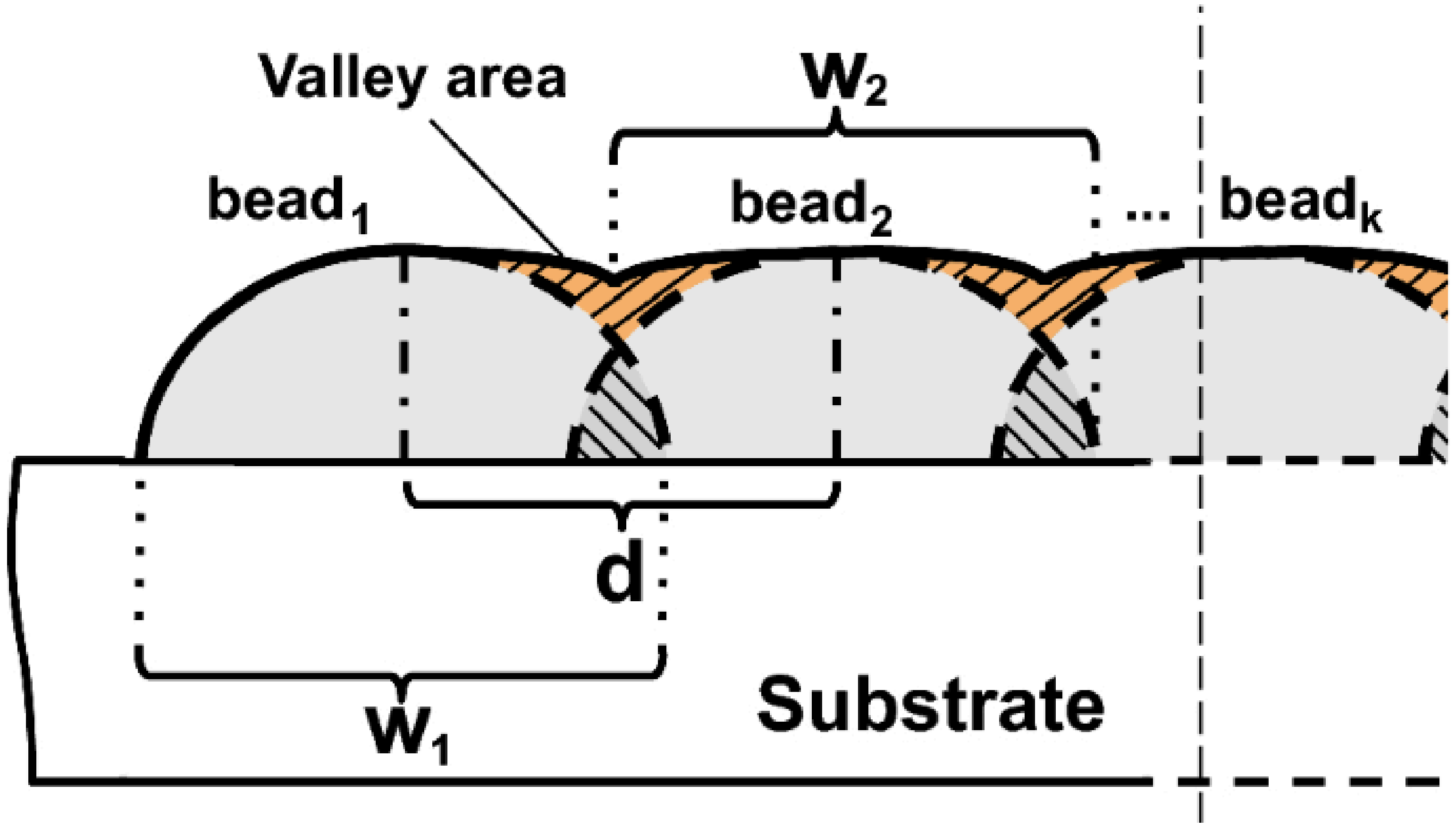
- Large parts & repair
- Low cost
- High deposition rate
- Lightweight materials
- Automotive, aerospace, etc

HOW DOES WAAM WORK?

Wire arc



Bead stacking



Images source: Couto, M.O., Rodrigues, A.G., Coutinho, F. et al. Mapping of Bead Geometry in Wire Arc Additive Manufacturing Systems Using Passive Vision. J Control Autom Electr Syst 33, 1136–1147 (2022). 10.1007/s40313-021-00880-0
R. K. Singha, K. Venkadeshwaranb, B. P. Singhc, and G. K. Kantak. Assessing the pros and cons of wire-arc additive manufacturing for material production. MalquePublishing, 2024.

Presenter: Anastasia Meijer

DEFECTS IN WAAM

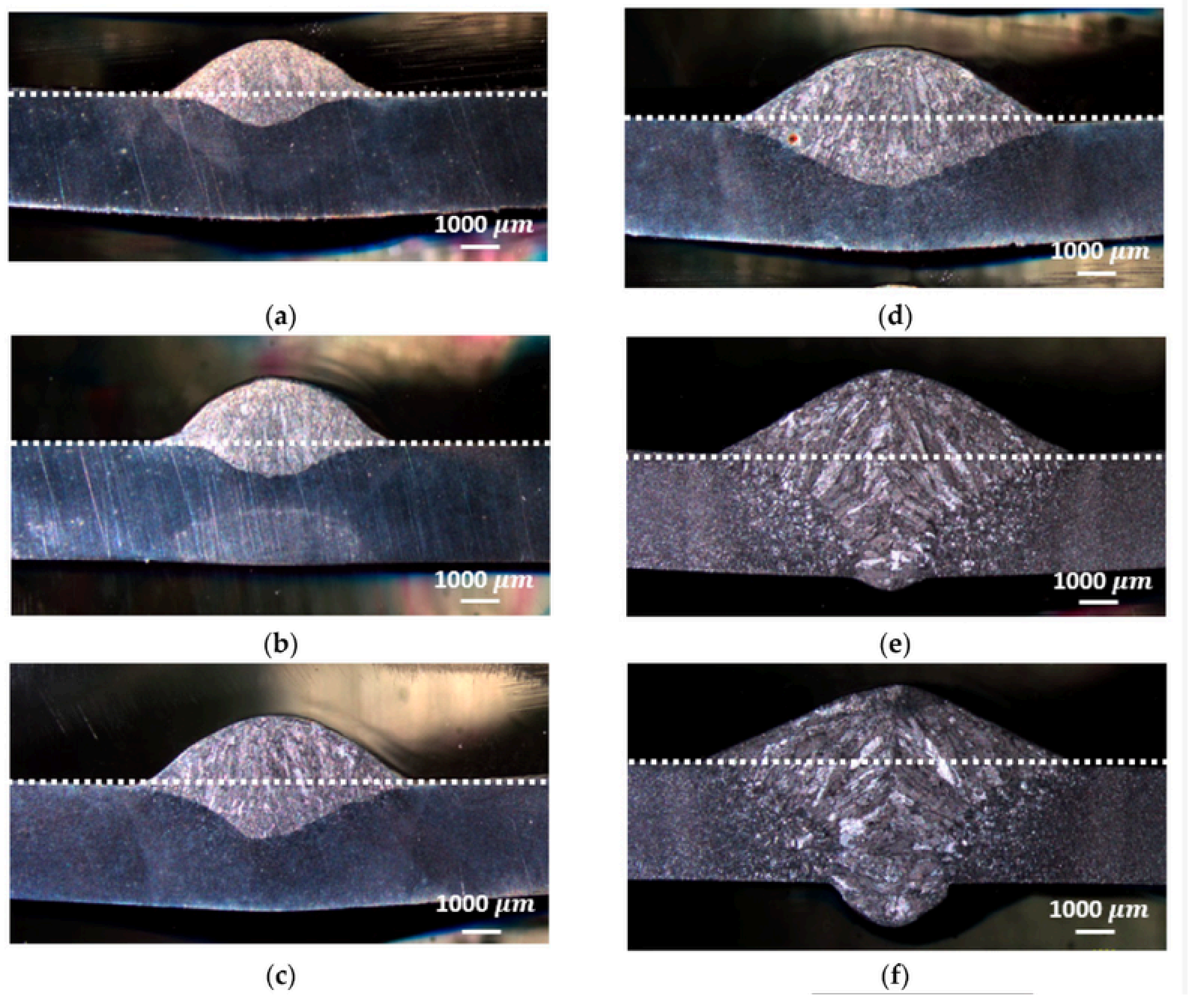
01 Geometric Defects

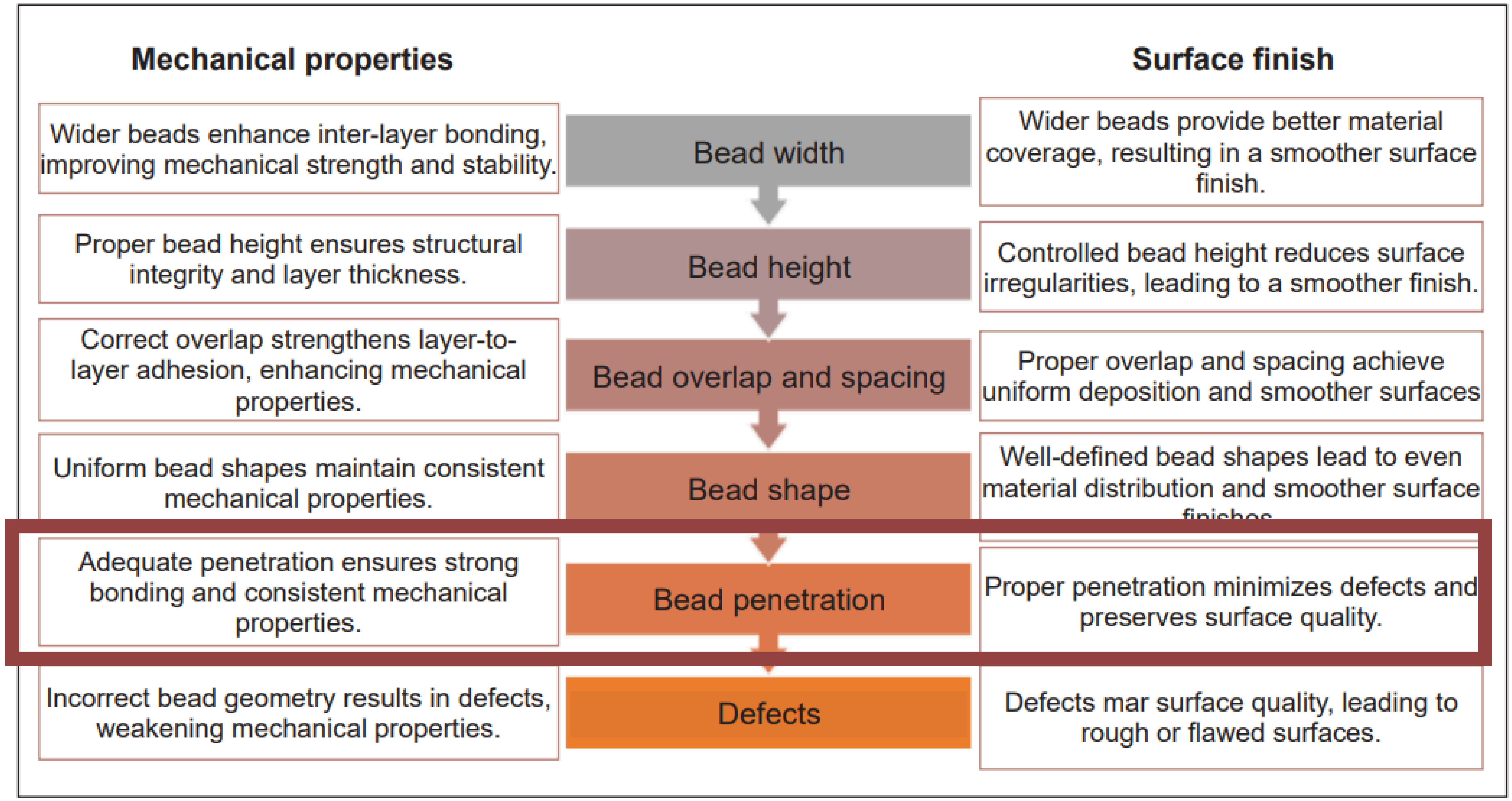
02 Process-induced defects

03 Residual stress defects

GEOMETRIC DEFECTS

Bead defects



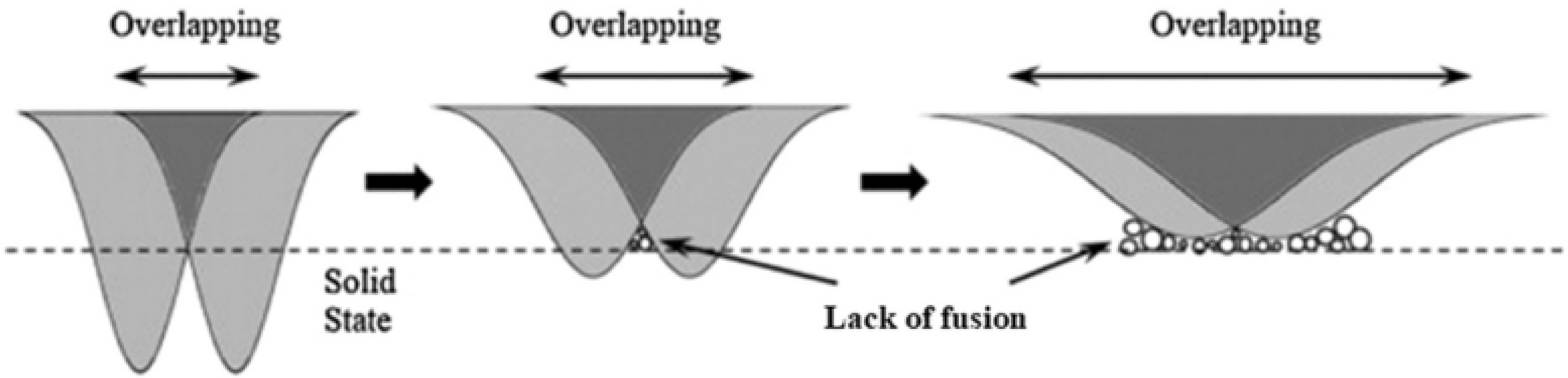


Images source: Z. K. Wani and A. B. Abdullah. Bead geometry control in wire arc additive manufactured profile - a review. Pertanika Journal of Science and Technology, 32(2):917–942, 2024.
L. Zhang, G. Okudan, A. D. C. Basantes-Defas, et al. Characterization of GMAW (Gas Metal Arc Welding) Penetration Using Ultrasonics. Materials, 13(10): 2307, 2020

Presenter: Anastasia Meijer

PROCESS-INDUCED DEFECTS

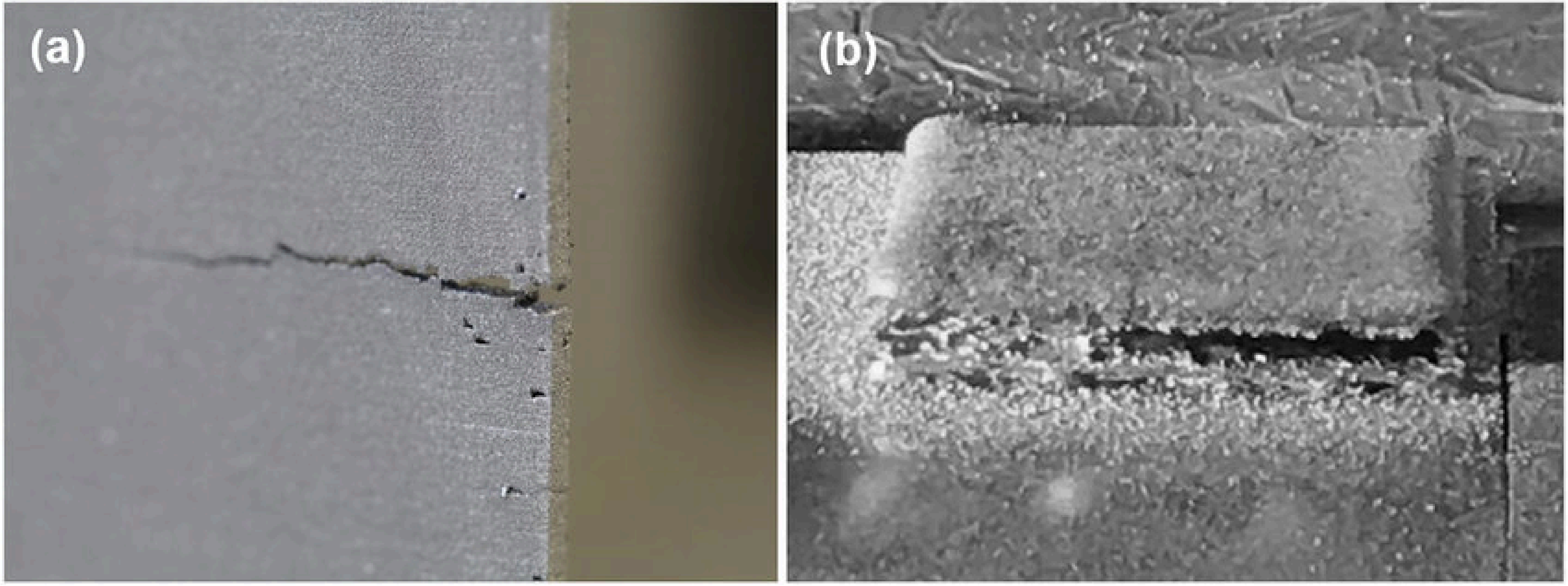
Lack-of-fusion



Images source: Y. Cai, J. Xiong, H. Chen, and G. Zhang. A review of in-situ monitoring and process control system in metal-based laser additive manufacturing. Journal of Manufacturing Systems, 70:309–326, 2023.

RESIDUAL STRESS DEFECTS

Residual stress



Images source: S. Liu, Y. Shin. Additive manufacturing of Ti6Al4V alloy: A review. Materials & Design, 164:107552, 2018. 10.1016/j.matdes.2018.107552

Presenter: Anastasia Meijer

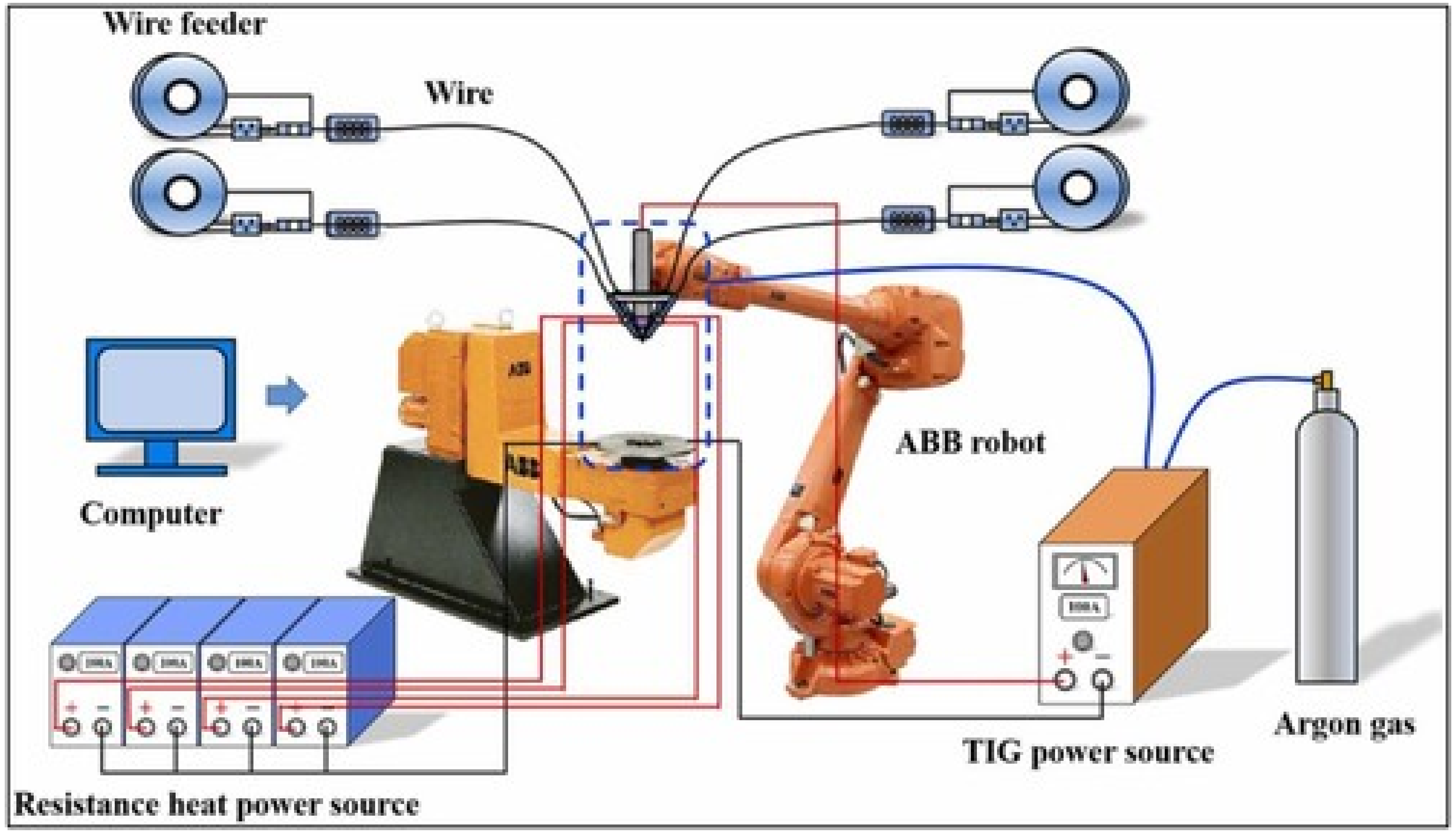
ADVANCES IN WAAM

01 MWAAM

02 Machine Learning

03 Digital Twin

MWAAM

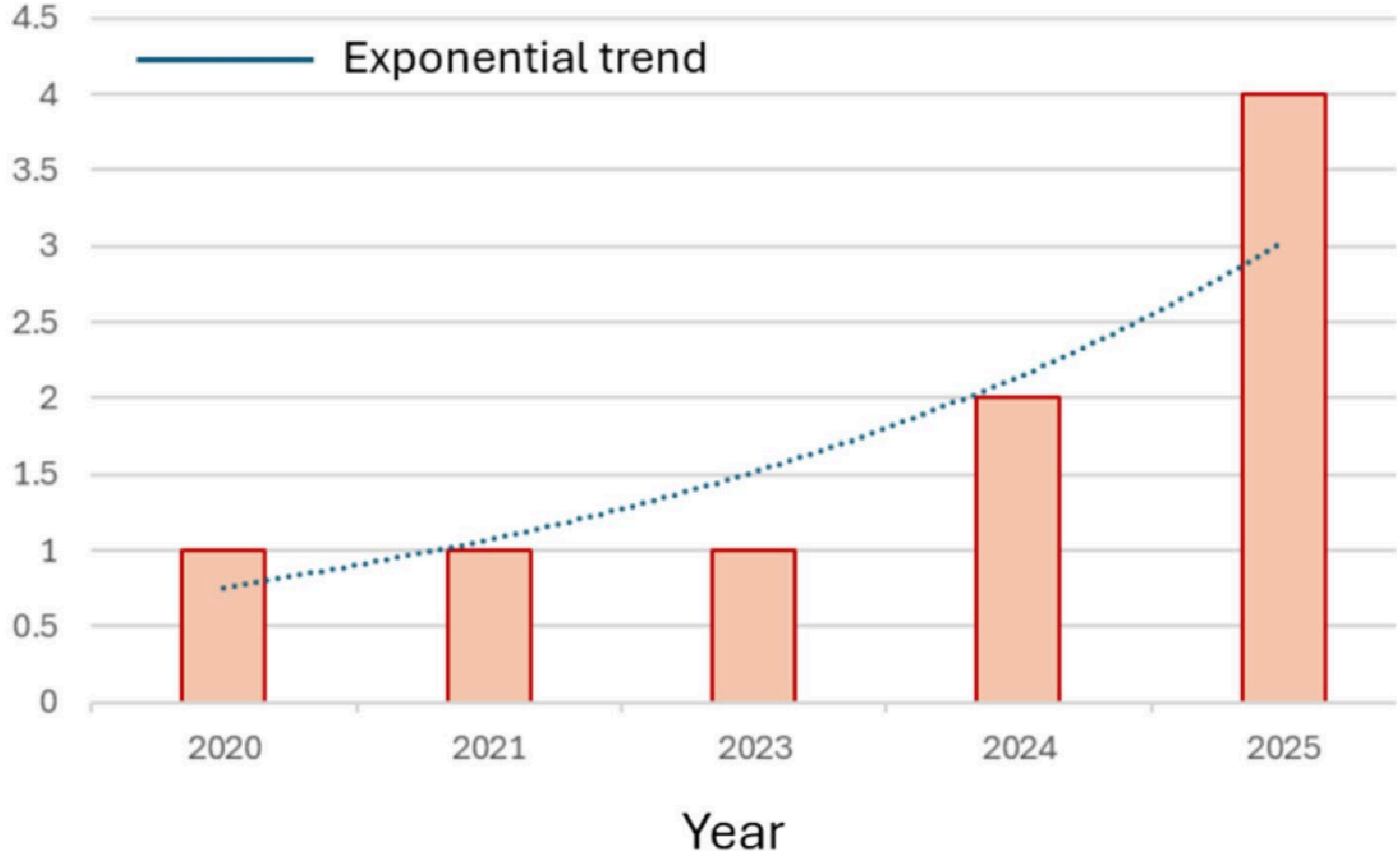


Images source: A. Hamrani, F. Z. Bouarab, A. Agarwal, K. Ju, & H. Akbarzadeh. Advancements and applications of multiple wire processes in additive manufacturing: a comprehensive systematic review. Virtual and Physical Prototyping, 18(1), 2023. 10.1080/17452759.2023.2273303

Presenter: Anastasia Meijer

MACHINE LEARNING

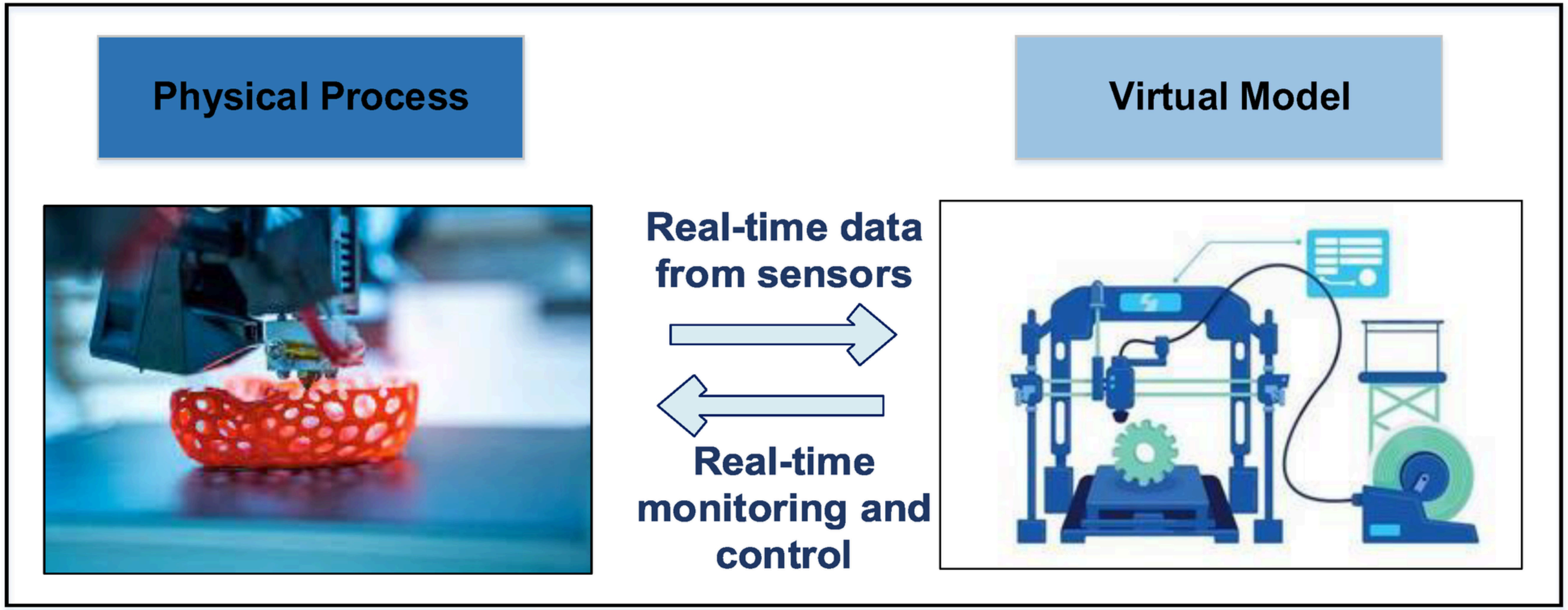
No. Publications on intelligent optimisation of the WAAM process.



Images source: G. Mattera, S.P. Chozaki, and J. Norrish. Advances in machine learning for parameters optimisation and in-situ monitoring of wire arc additive manufacturing. Weld World, 2025.

Presenter: Anastasia Meijer

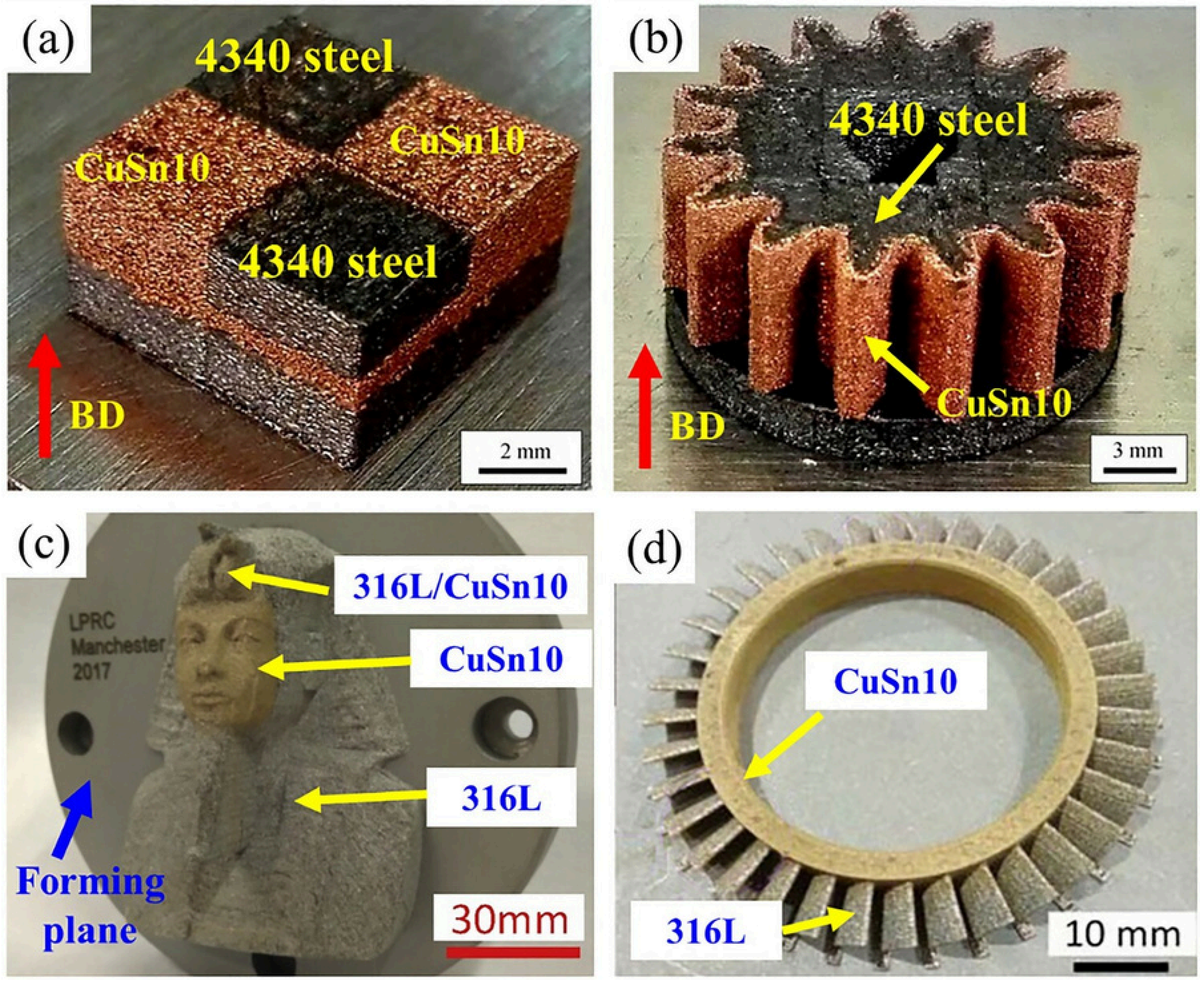
DIGITAL TWIN



Images source: S. B. Amor, N. Elloumi, A. Eltaief, et al. Digital Twin Implementation in Additive Manufacturing: A Comprehensive Review. Processes 2024, 12(6), 1062. 10.3390/pr12061062

Presenter: Anastasia Meijer

METAL MULTI-MATERIAL ADDITIVE MANUFACTURING



01 Material combinations

02 Processes

03 Advantages

04 Applications

05 Challenges

Image source: D. Wang et al., 'Recent progress on additive manufacturing of multi-material structures with laser powder bed fusion', Virtual and Physical Prototyping, vol. 17, no. 2, pp. 329–365, Apr. 2022, doi: 10.1080/17452759.2022.2028343.

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MATERIAL COMBINATIONS

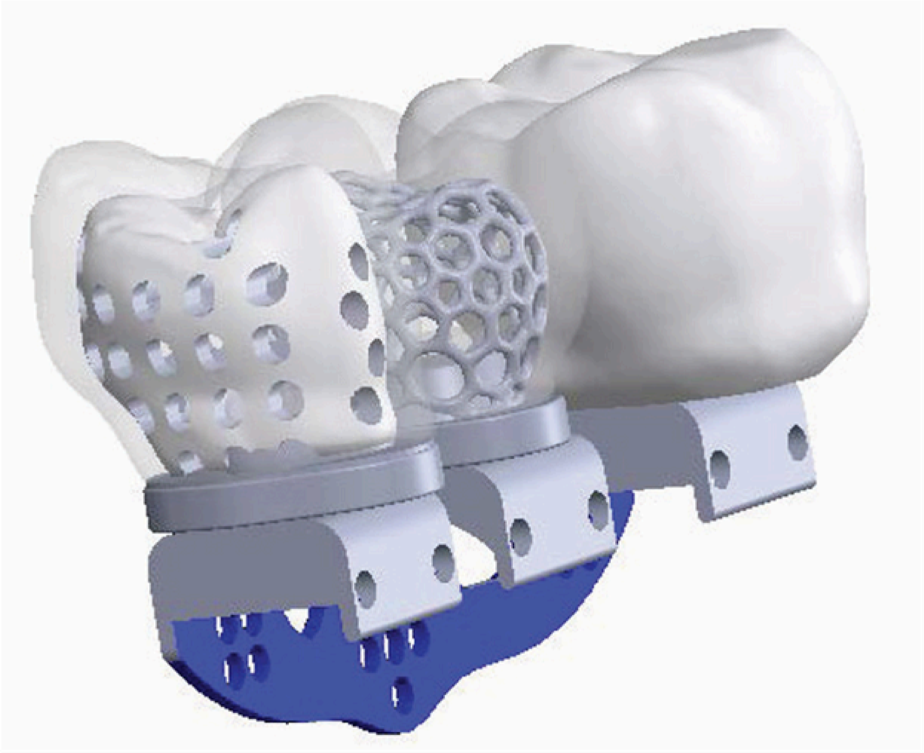


Image source: M. Silva, R. Felismina, A. Mateus, P. Parreira, and C. Malça, 'Application of a Hybrid Additive Manufacturing Methodology to Produce a Metal/Polymer Customized Dental Implant', Procedia Manufacturing, vol. 12, pp. 150–155, Jan. 2017, doi: 10.1016/j.promfg.2017.08.019.

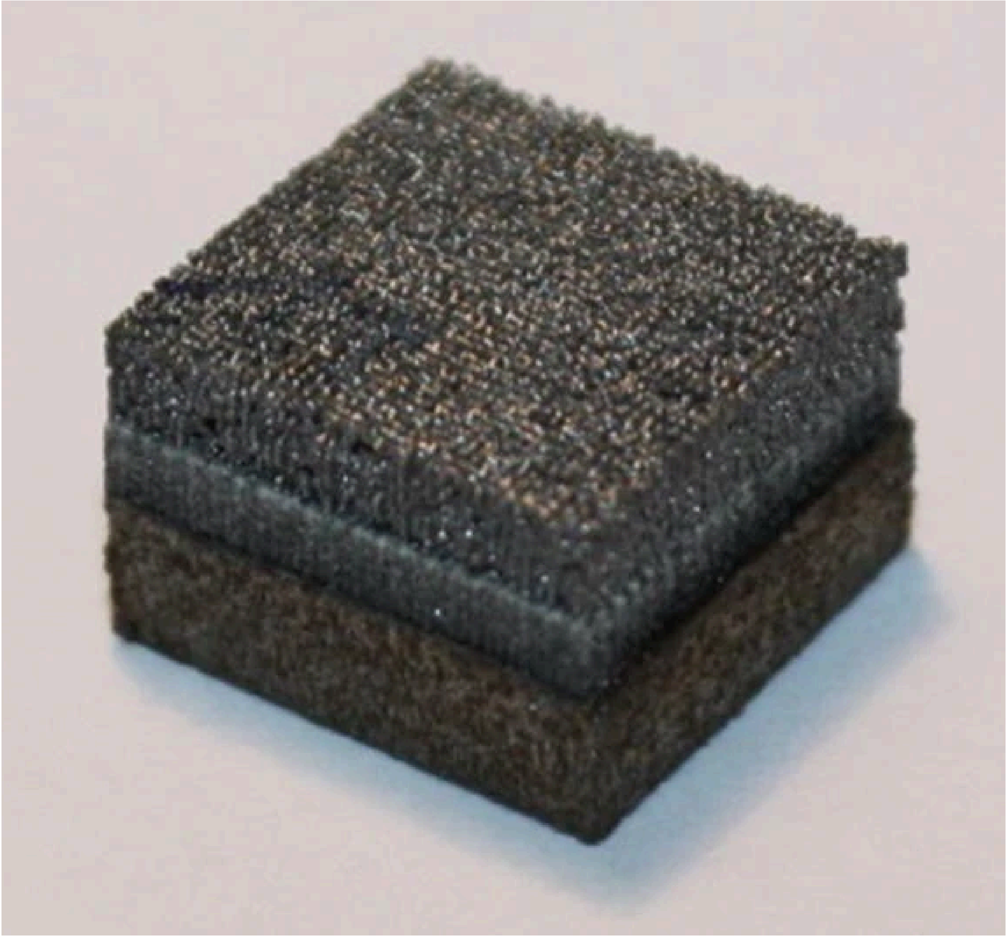
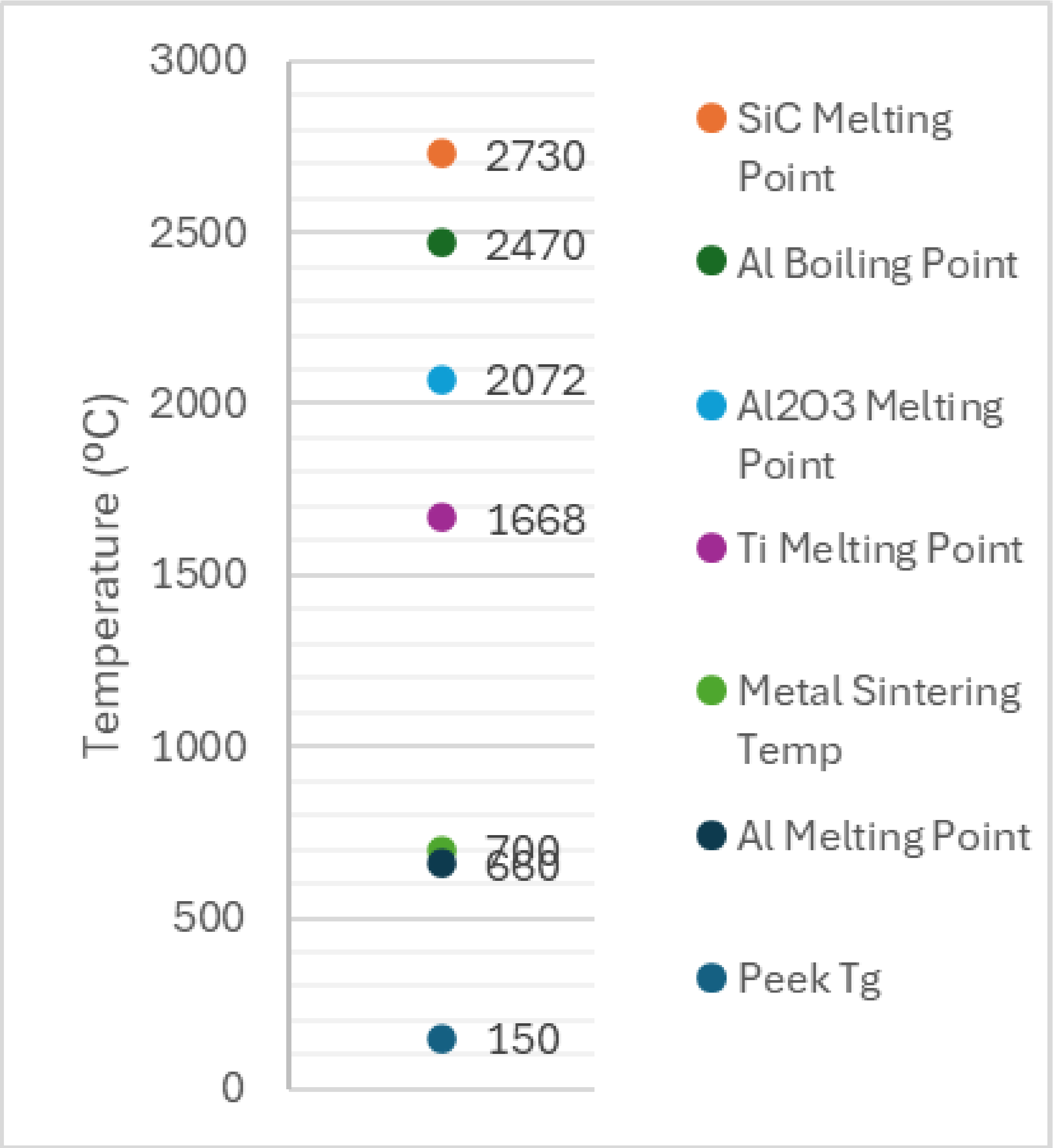


Image source: J. Koopmann, J. Voigt, and T. Niendorf, 'Additive Manufacturing of a Steel–Ceramic Multi-Material by Selective Laser Melting', Metall Mater Trans B, vol. 50, no. 2, pp. 1042–1051, Apr. 2019, doi: 10.1007/s11663-019-01523-1.



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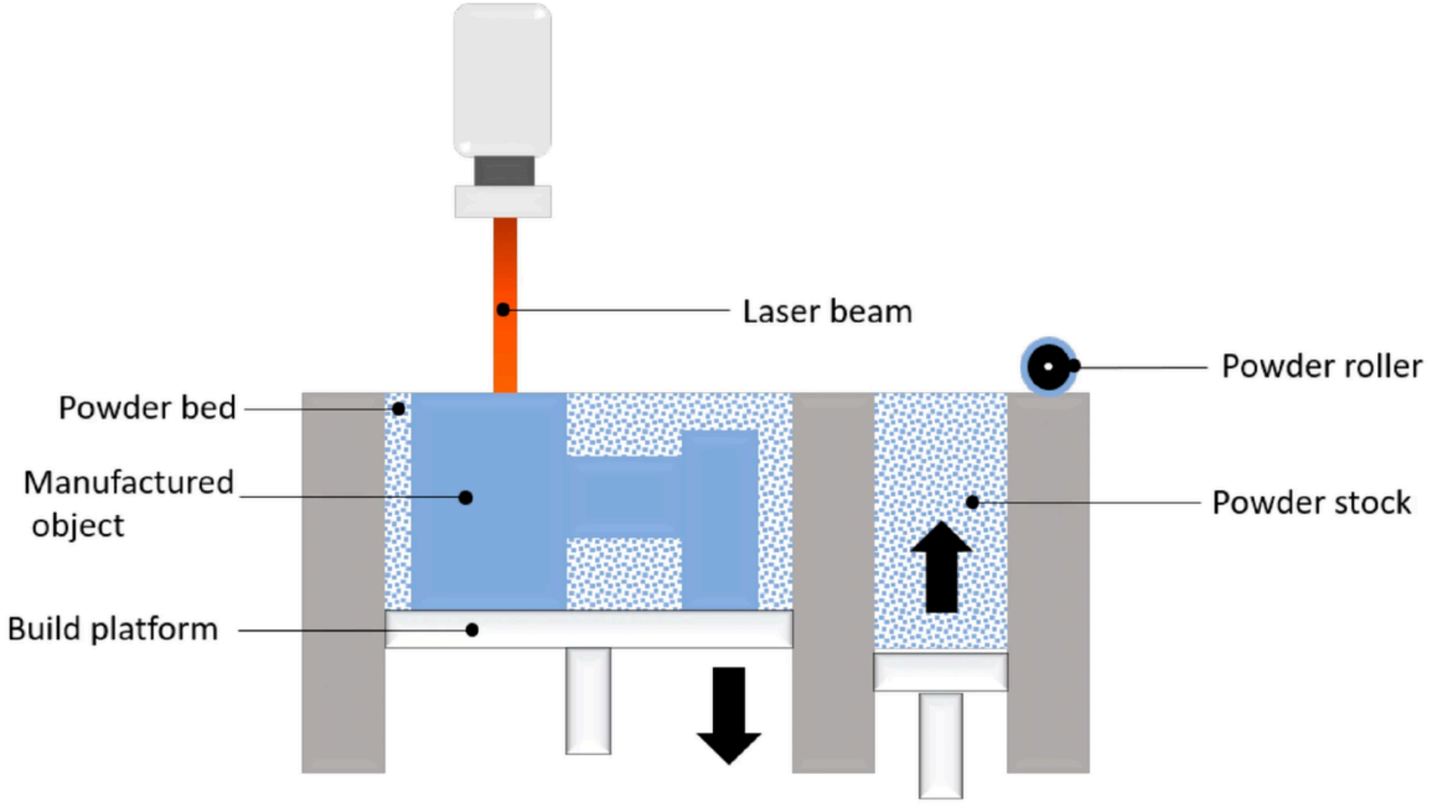
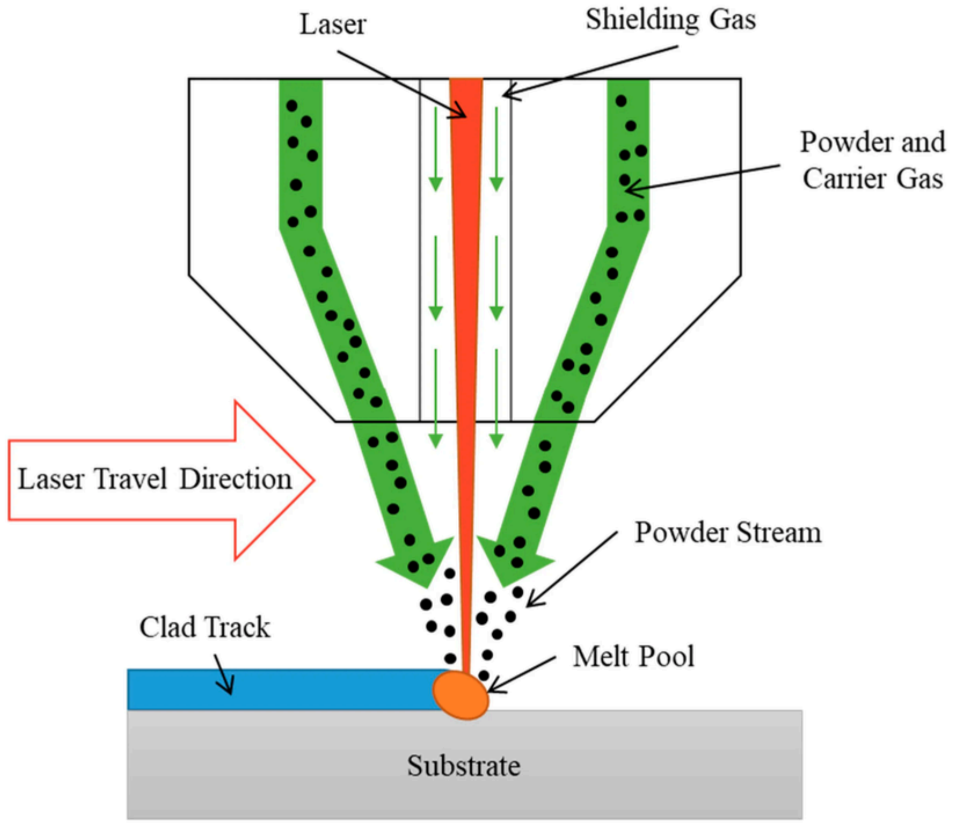
PROCESSES

L-PBF



Images source: Y. Feng, Y. Liu, J. Wang, and R. Li, 'Research on Simulation and Optimization of Traveling Induction Heating Process for Welding Deformation Rectification in High Strength Steel Sheet', Metals, vol. 13, no. 2, p. 425, Feb. 2023, doi: 10.3390/met13020425.

L-DED



Images source: K. T. Cho, L. Nunez, J. Shelton, and F. Sciammarella, 'Investigation of Effect of Processing Parameters for Direct Energy Deposition Additive Manufacturing Technologies', Journal of Manufacturing and Materials Processing, vol. 7, no. 3, p. 105, June 2023, doi: 10.3390/jmmp7030105.

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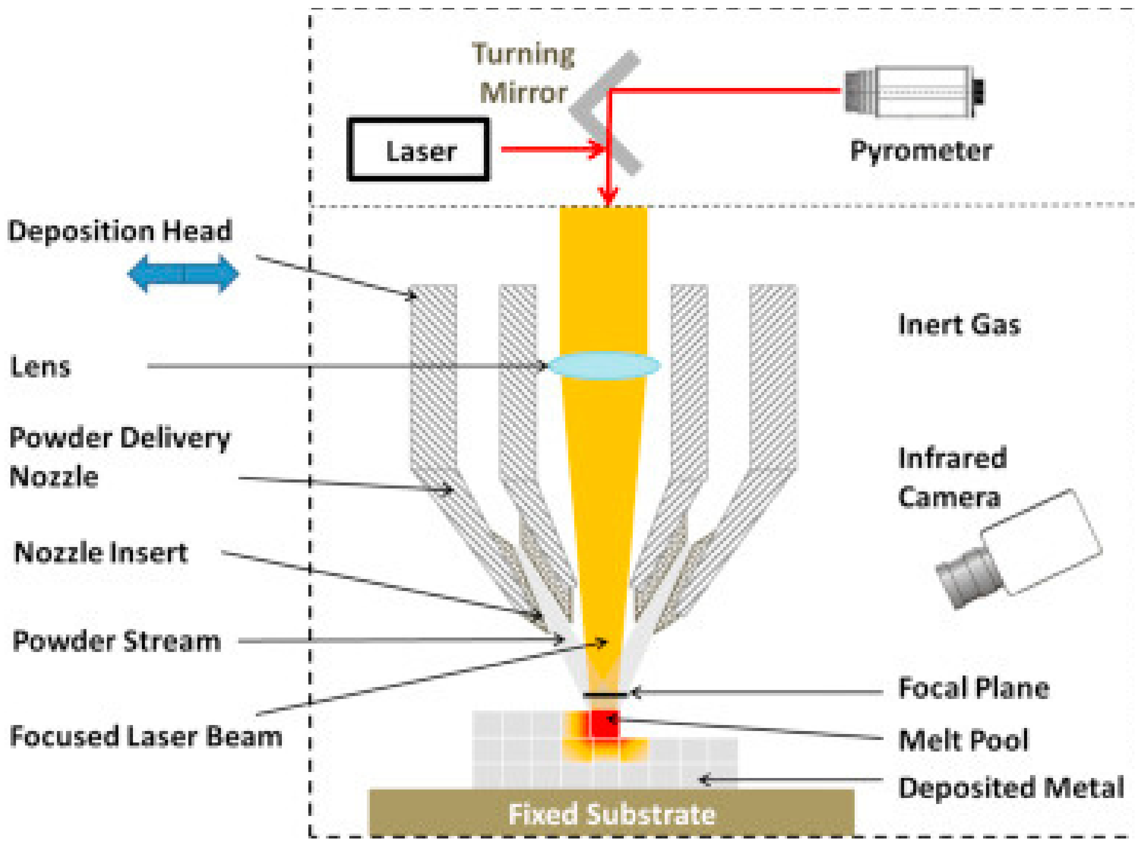
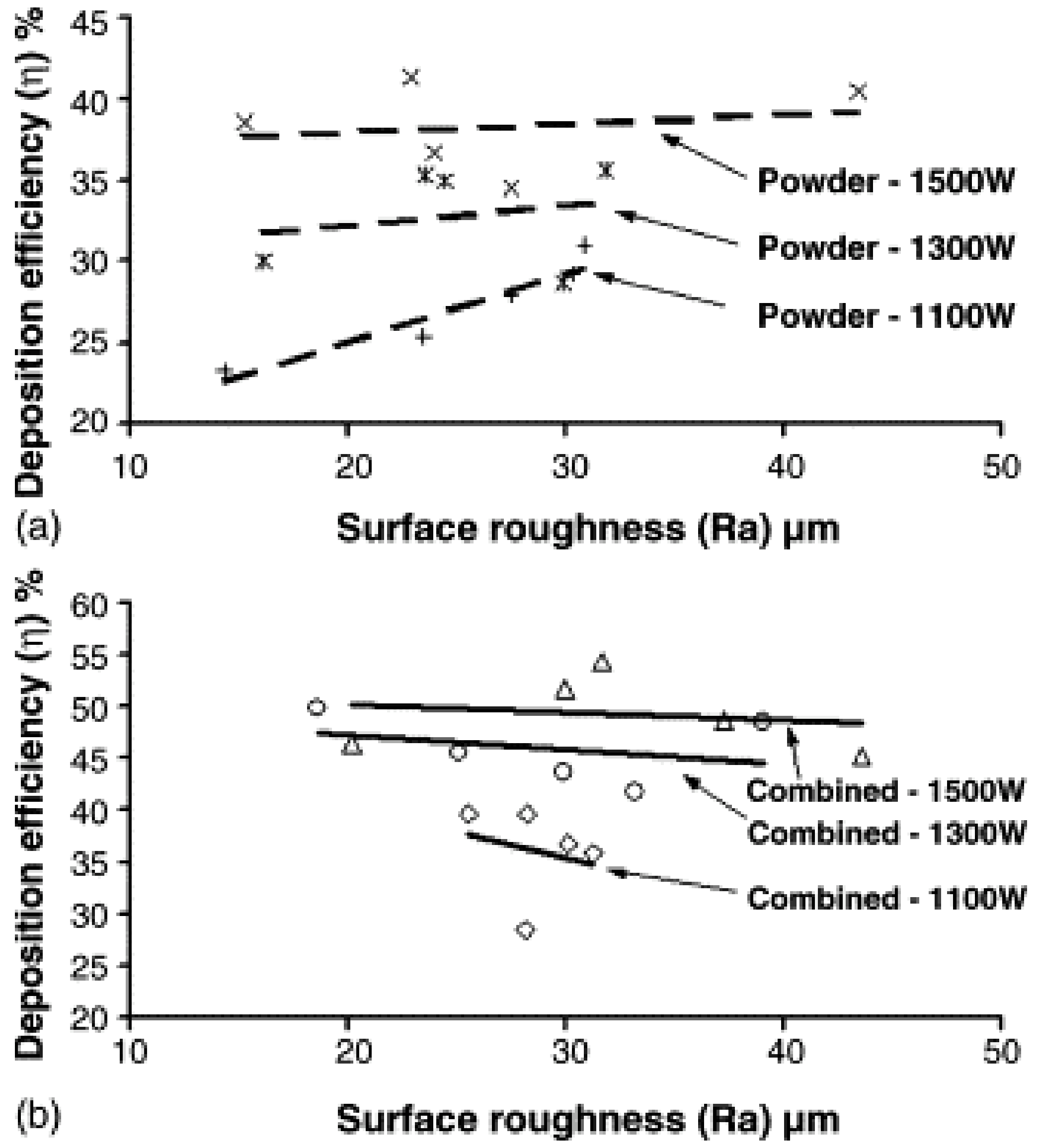
PROCESSES

L-DED



Images source: S. M. Thompson, L. Bian, N. Shamsaei, and A. Yadollahi, ‘An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics’, Additive Manufacturing, vol. 8, pp. 36–62, Oct. 2015, doi: 10.1016/j.addma.2015.07.001.



Images source: W. U. H. Syed, A. J. Pinkerton, and L. Li, ‘Combining wire and coaxial powder feeding in laser direct metal deposition for rapid prototyping’, Applied Surface Science, vol. 252, no. 13, pp. 4803–4808, Apr. 2006, doi: 10.1016/j.apsusc.2005.08.118.

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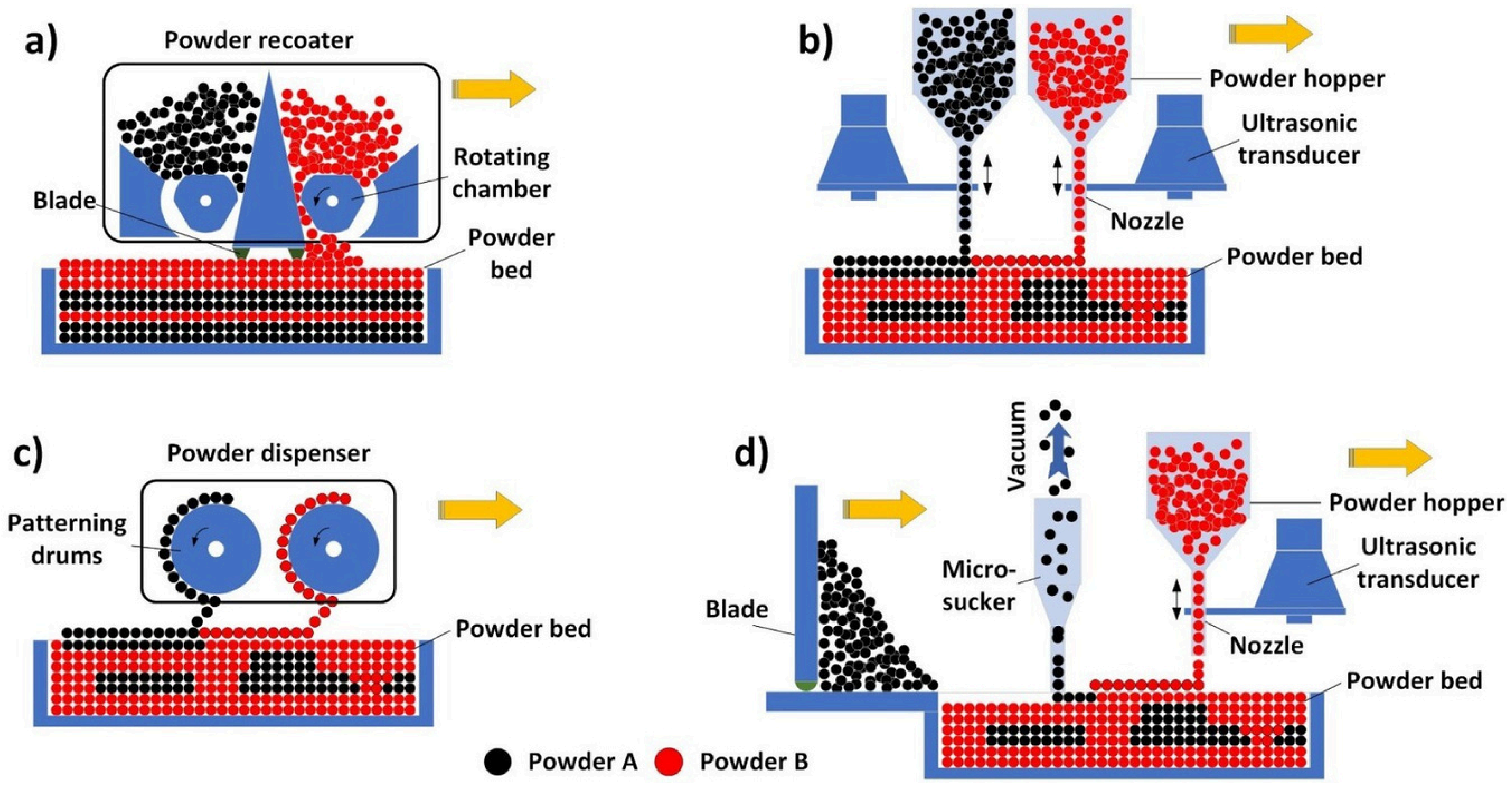
PROCESSES

L-PBF



Images source: C. Wei and L. Li, 'Recent progress and scientific challenges in multi-material additive manufacturing via laser-based powder bed fusion', Virtual and Physical Prototyping, vol. 16, no. 3, pp. 347–371, May 2021, doi: 10.1080/17452759.2021.1928520.

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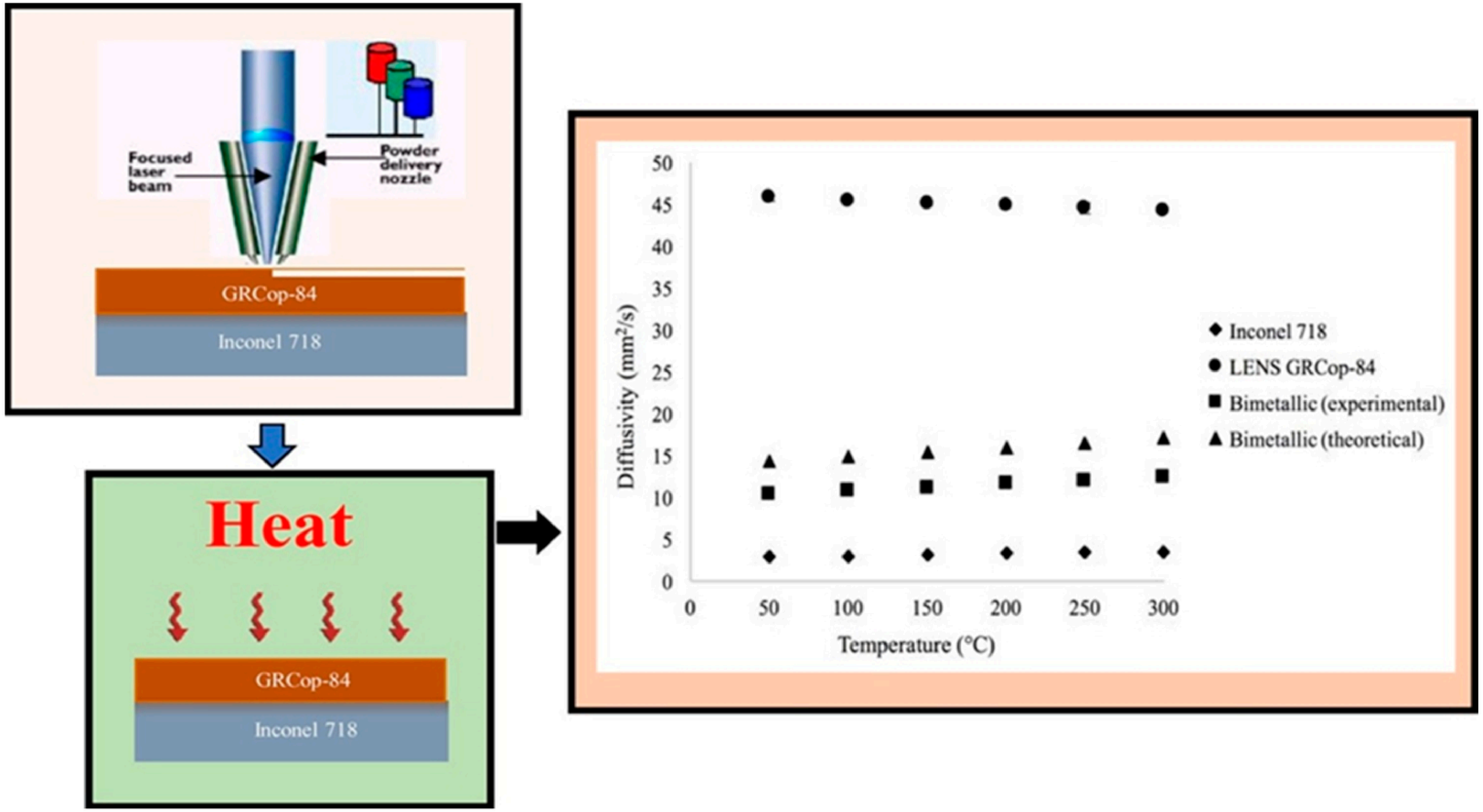
ADVANTAGES

Production Based	Property Based
Lighter assemblies	Oxidation Resistance
Cheaper Multi-Material Parts	Wear Resistance and Toughness
Faster Production	Biocompatibility
	Functionally Graded Properties

APPLICATIONS

Aerospace



Images source: B. Onuike, B. Heer, and A. Bandyopadhyay, 'Additive manufacturing of Inconel 718—Copper alloy bimetallic structure using laser engineered net shaping (LENS™)', Additive Manufacturing, vol. 21, pp. 133–140, May 2018, doi: 10.1016/j.addma.2018.02.007.

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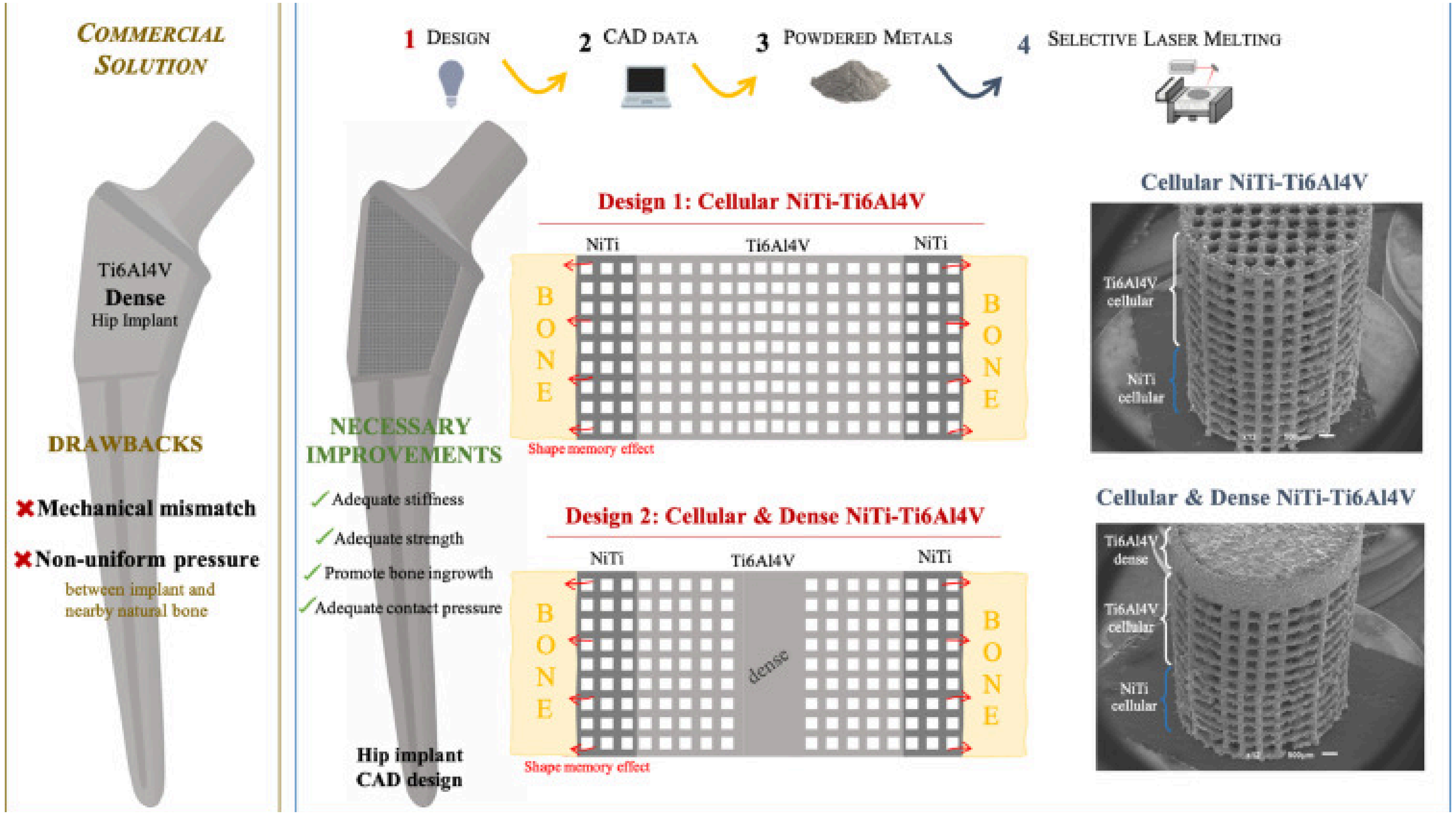
APPLICATIONS

Bio-medical



Images source: F. Bartolomeu, M. M. Costa, N. Alves, G. Miranda, and F. S. Silva, 'Additive manufacturing of NiTi-Ti6Al4V multi-material cellular structures targeting orthopedic implants', Optics and Lasers in Engineering, vol. 134, p. 106208, Nov. 2020, doi: 10.1016/j.optlaseng.2020.106208.

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CHALLENGES

Formation of Brittle Intermetallics

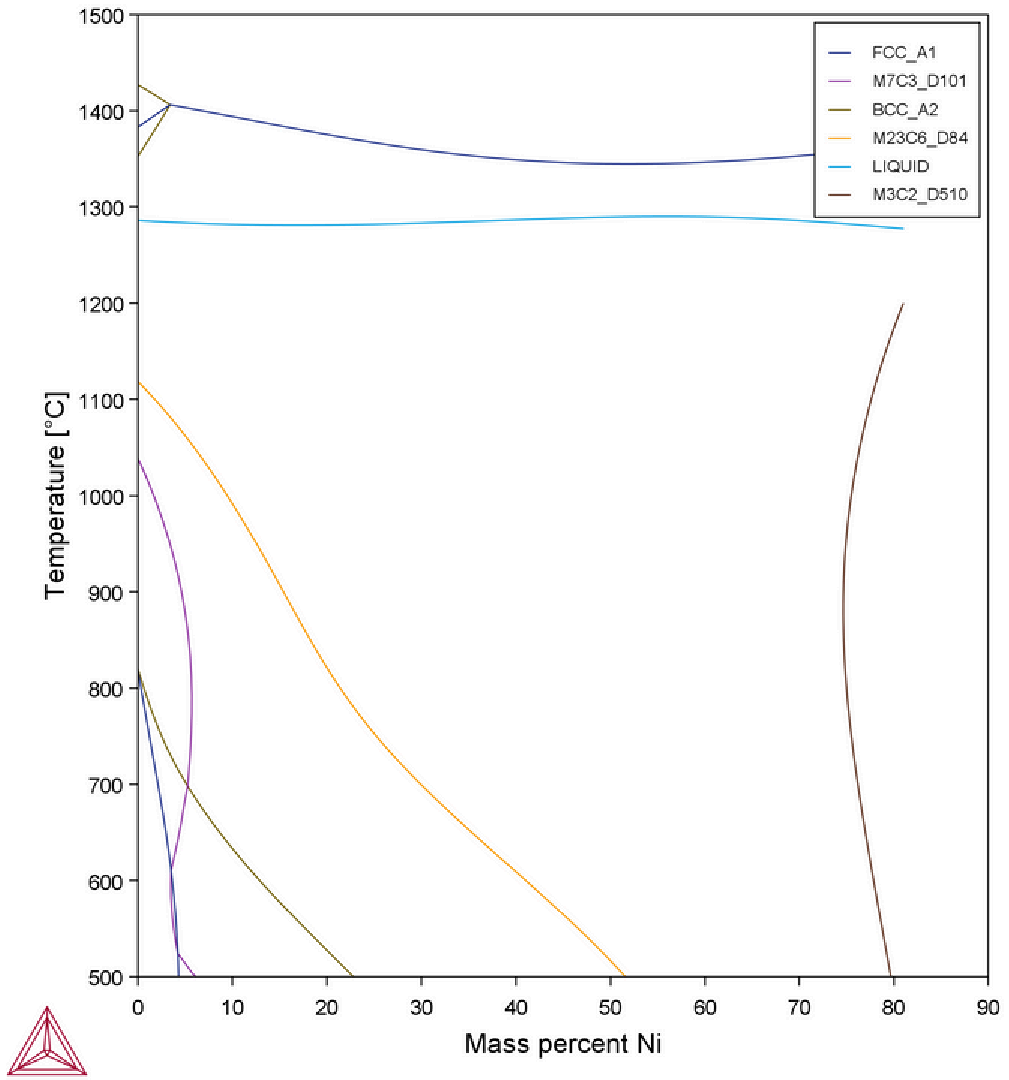
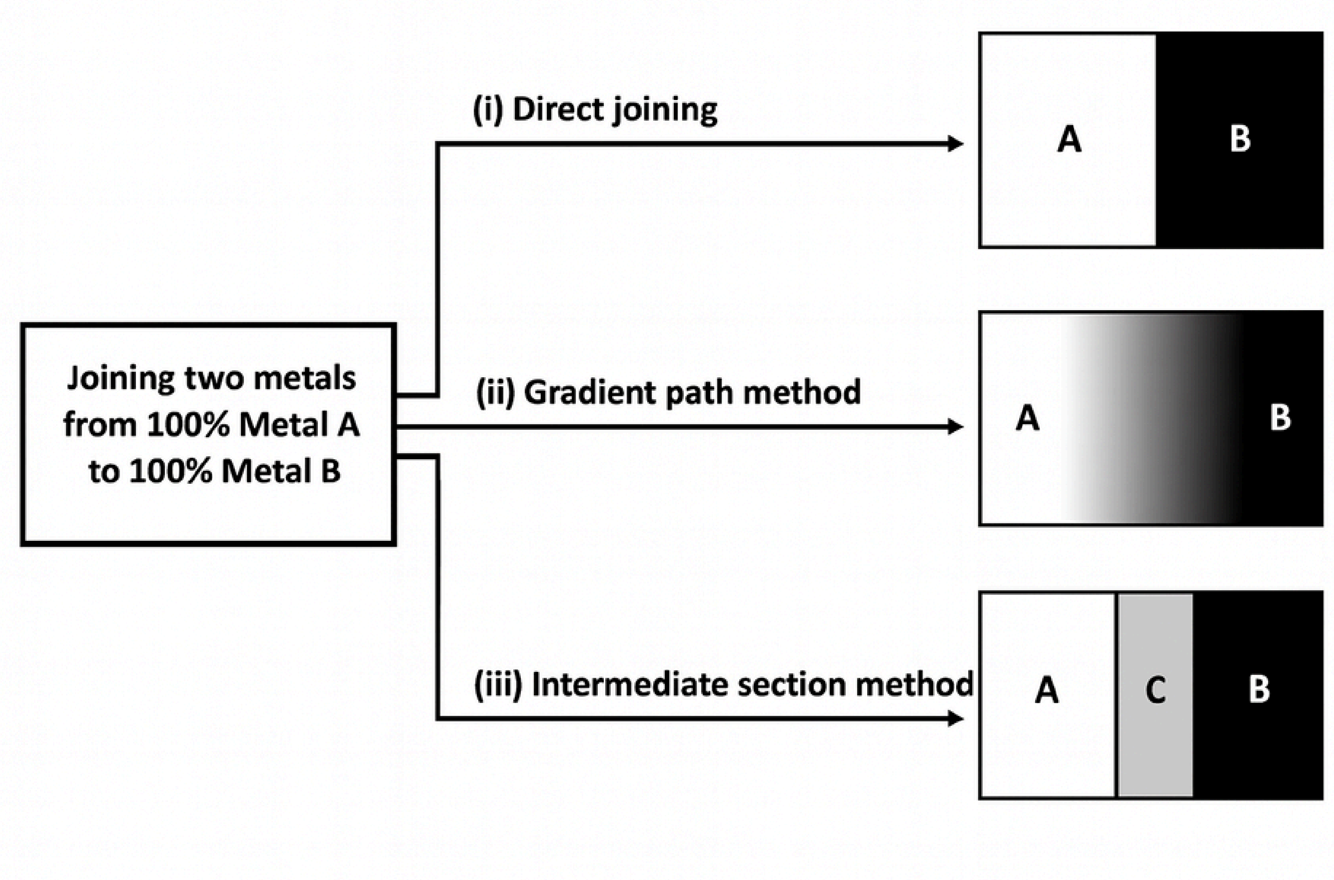


Image by author

Interfacial cracking



Images source: L. Yan, Y. Chen, and F. Liou, 'Additive manufacturing of functionally graded metallic materials using laser metal deposition', Additive Manufacturing, vol. 31, p. 100901, Jan. 2020, doi: 10.1016/j.addma.2019.100901.

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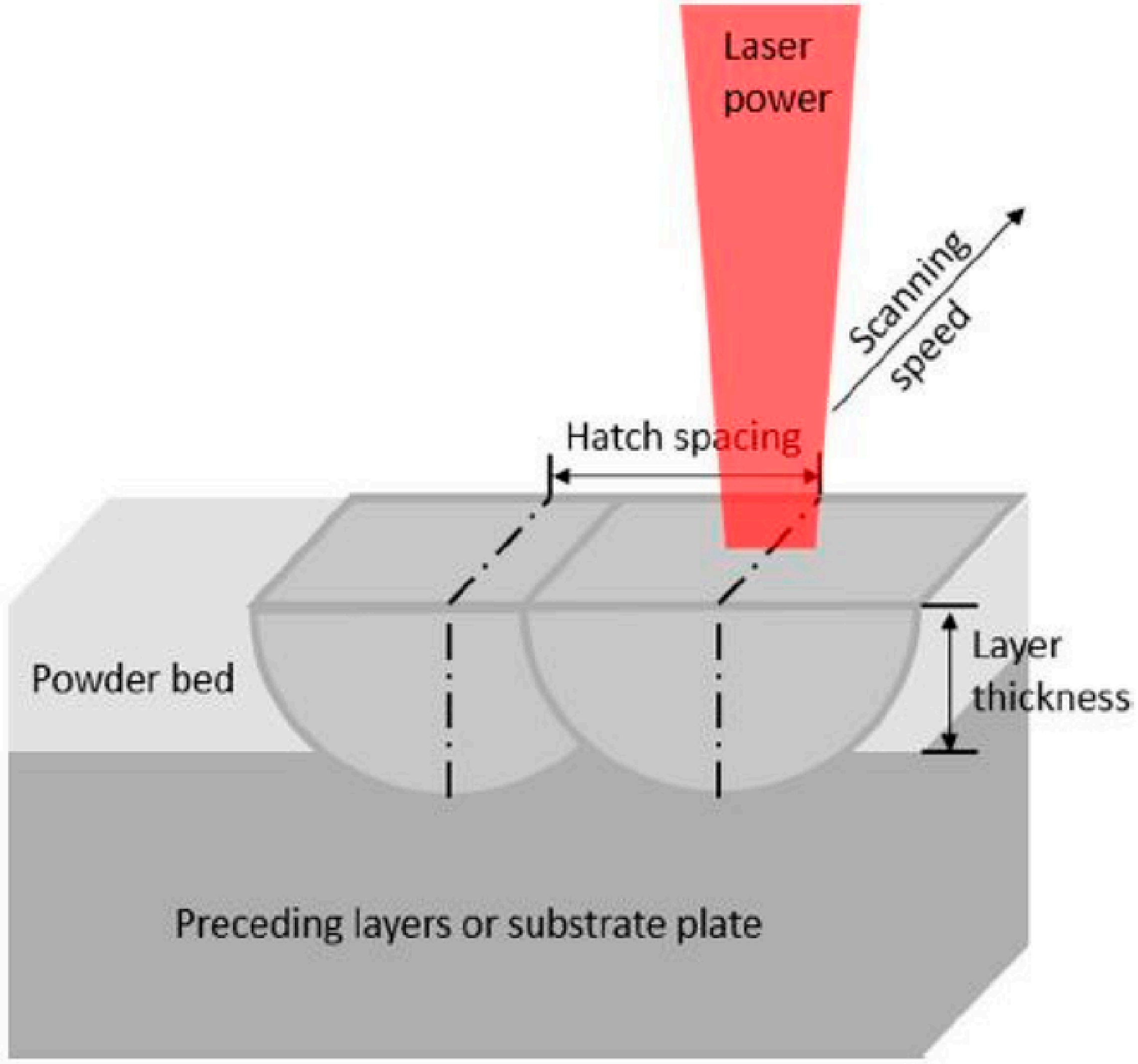
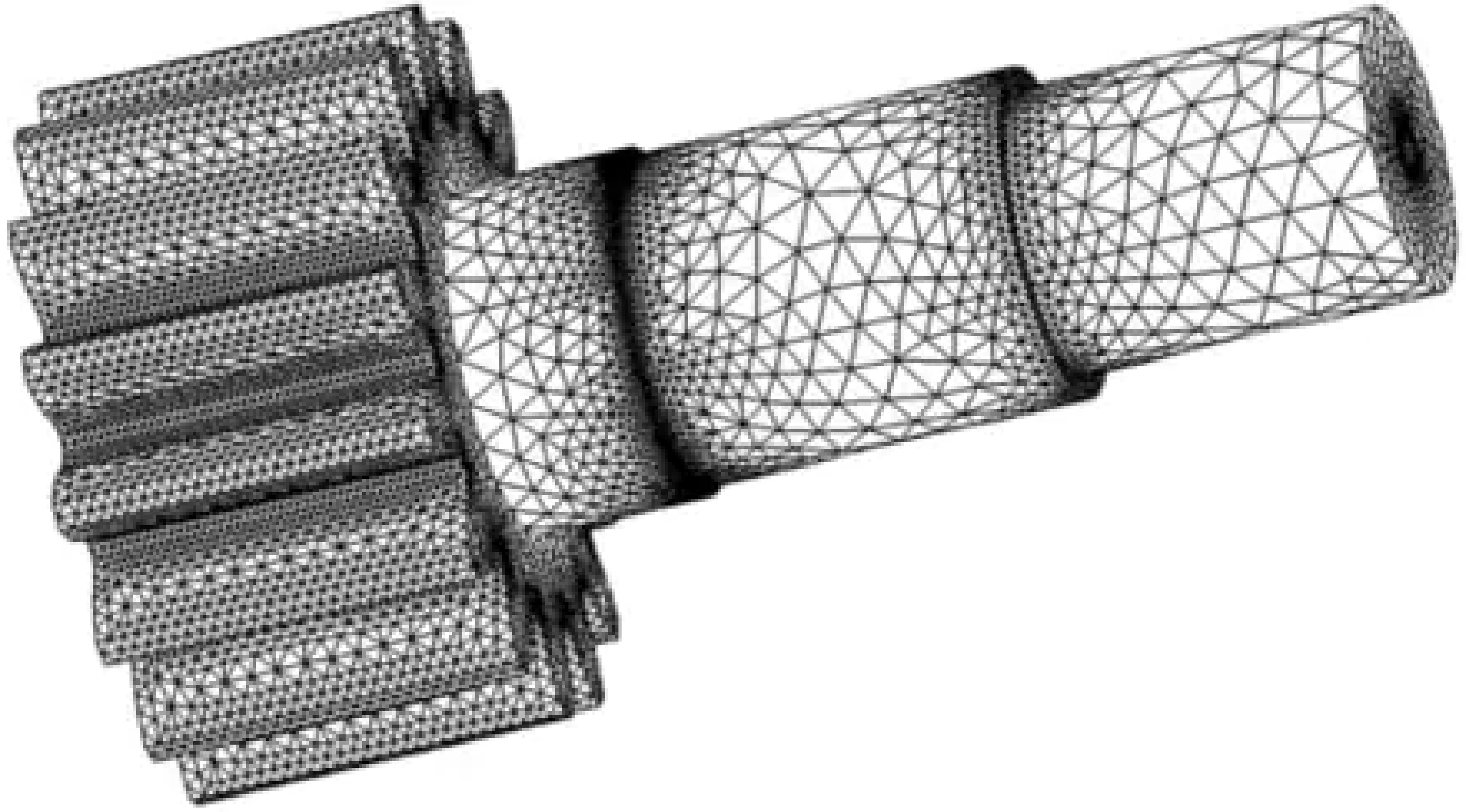
CHALLENGES

Process Parameter Optimisation



Images source: https://www.researchgate.net/figure/LPBF-process-parameters-laser-power-scanning-speed-hatch-spacing-and-layer-thickness_fig2_348093851

CAD and File Formats



Images source: ‘What is an STL File? – 3D Printing Basics’, Sculpteo. Accessed: Nov. 30, 2025. [Online]. Available: https://www.sculpteo.com/en/3d-learning-hub/create-3d-file/what-is-an-stl-file/

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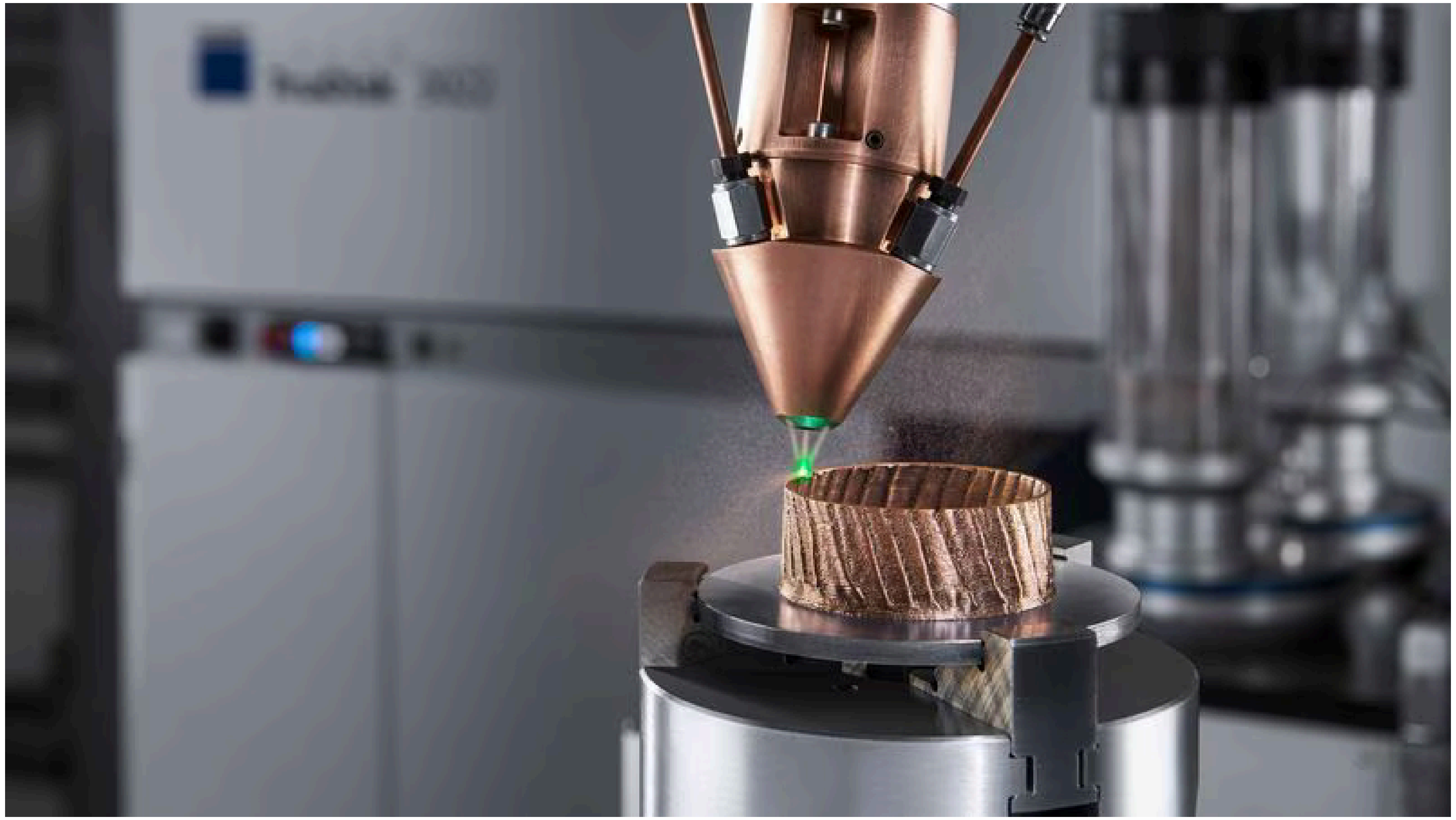
LASER COLOUR TECHNOLOGY



01 Concepts introduction

02 Classic techniques

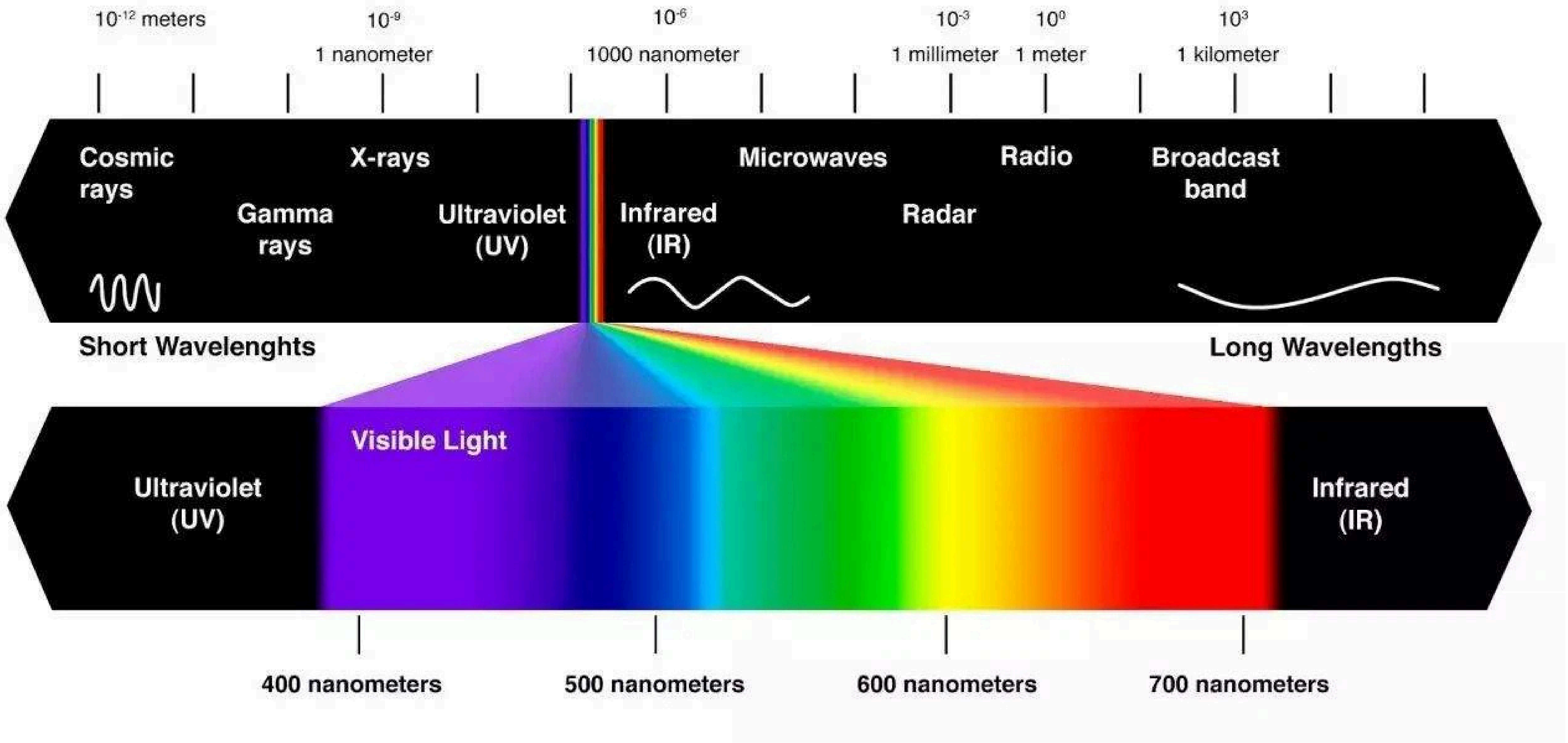
03 New technology

04 Applications

Images source: https://www.trumpf.com/en_SG/solutions/applications/additive-manufacturing/laser-metal-deposition/

Presenter: Manuel

CONCEPT INTRODUCTION



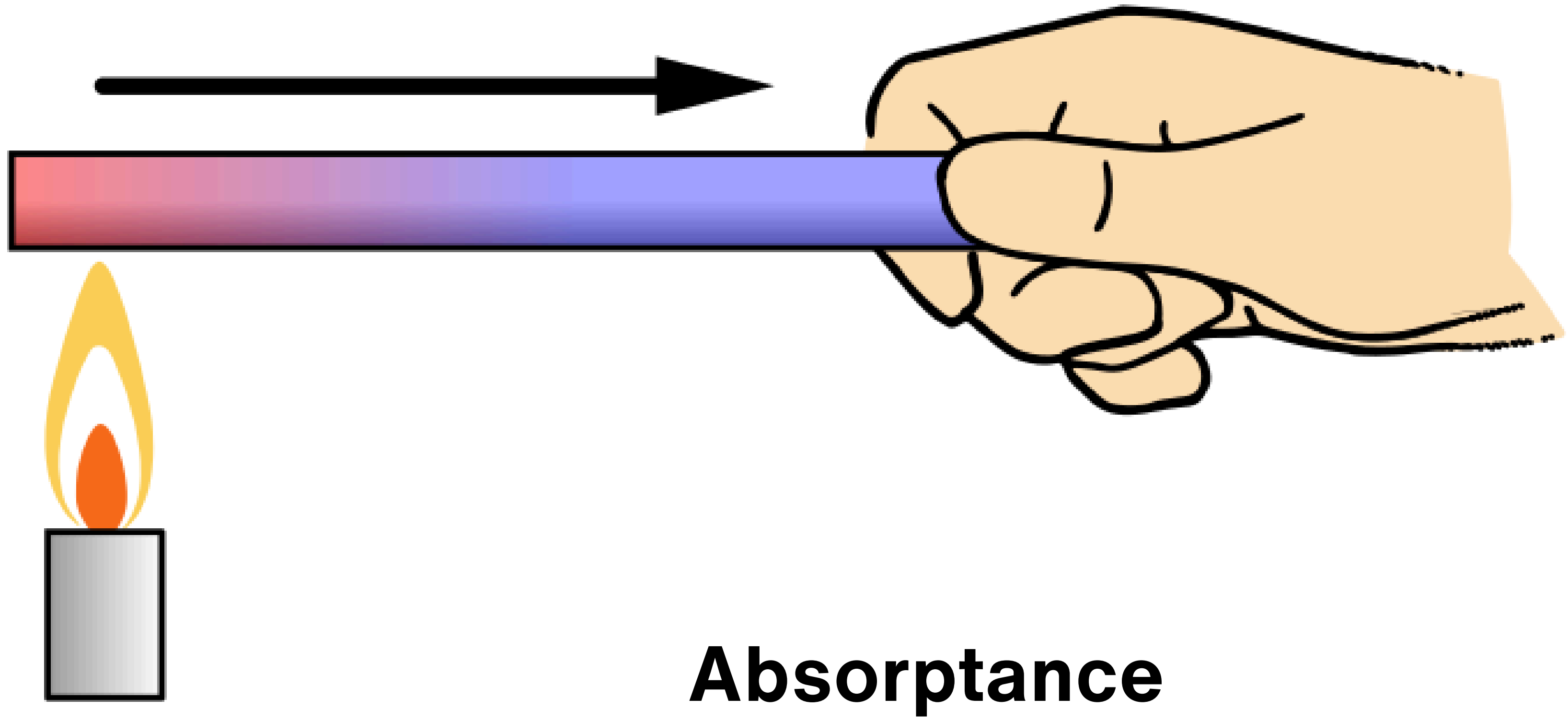
Laser colour or wavelength

Blue	445-480 nm
Green	512-532 nm
Infrared	1030-1080 nm

Images source: https://www.s-laser.com/info/what-is-the-wavelength-of-the-laser-50866750.html

Presenter: Manuel

CONCEPT INTRODUCTION



Absorptance

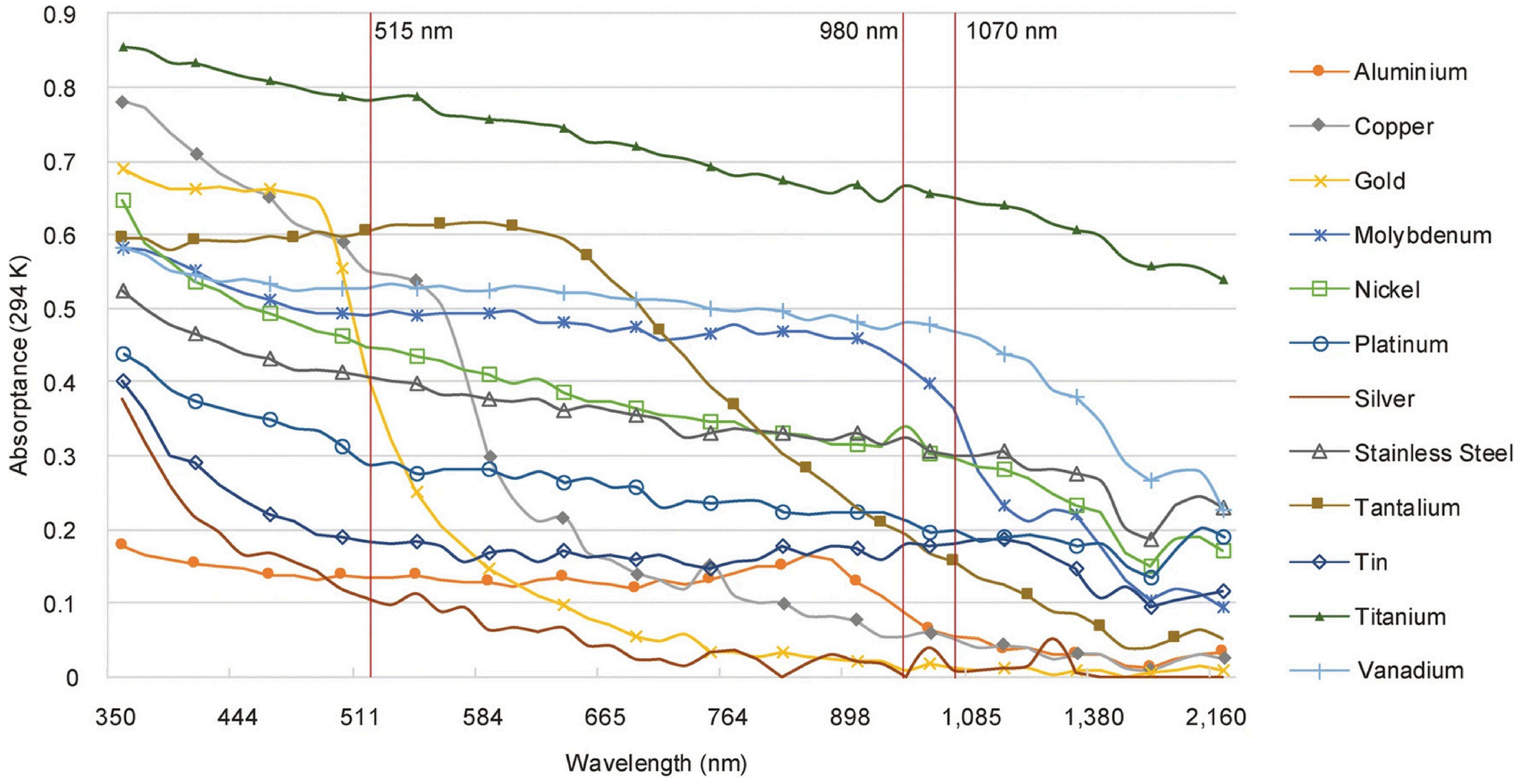
Reflectiveness and conductivity

Higher absorptance means less energy needed

Images source: https://toppng.com/free-image/reflective-gold-texture-PNG-free-PNG-Images_137424
https://commons.wikimedia.org/wiki/File:Heat-conduction.svg

Presenter: Manuel

CONCEPT INTRODUCTION



Images source: https://link.springer.com/article/10.1007/s00170-020-05117-z

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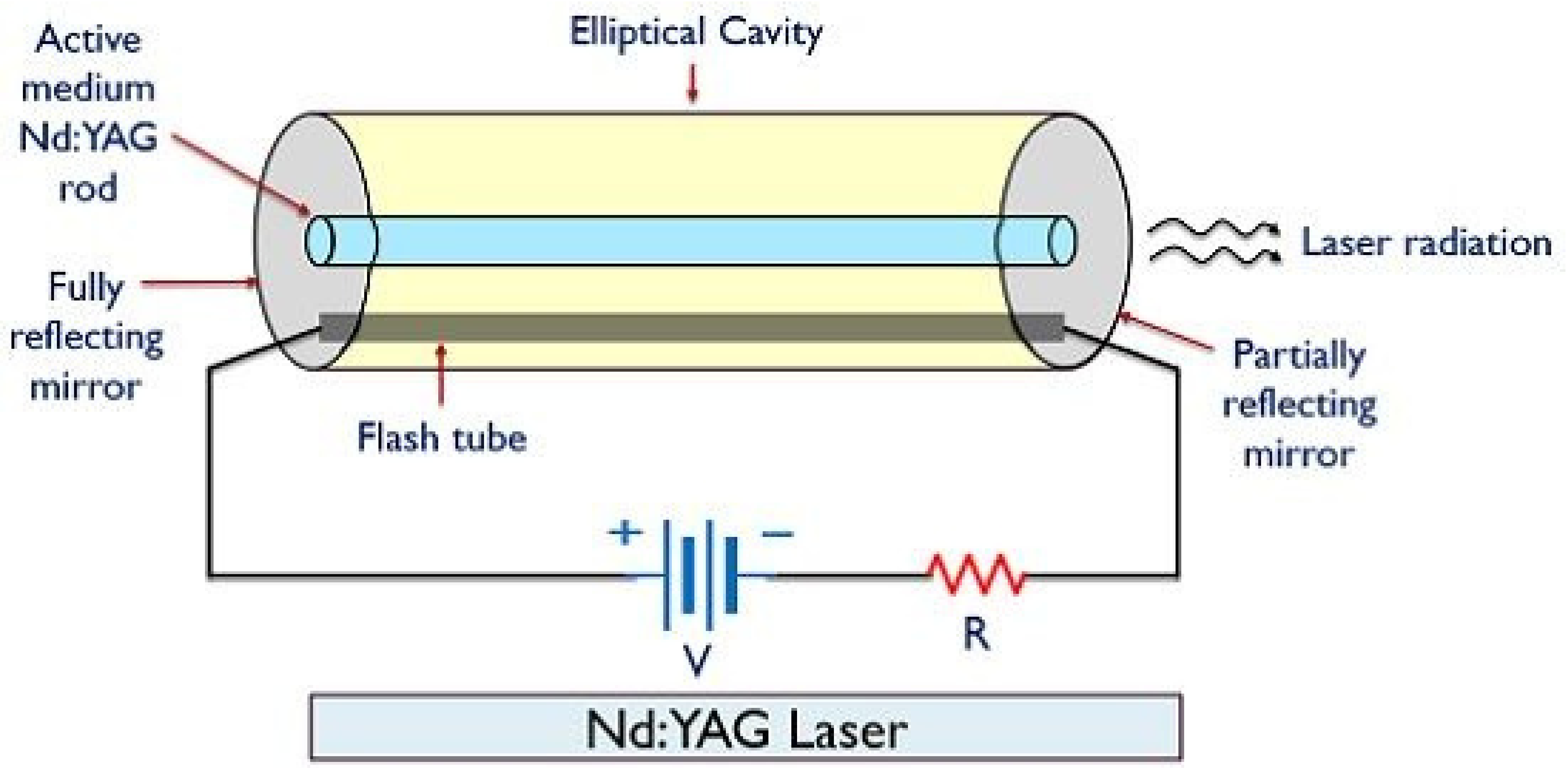
CLASSIC TECHNIQUES



INFRARED LASER

- Nd:YAG
  Nd ion 3+
  Yttrium Aluminium Garnet
  Crystal matrix

- CO_2
  ~10600 nm wavelength
  Electrical discharge energized gas

Images source: https://circuitglobe.com/ndyag-laser.html

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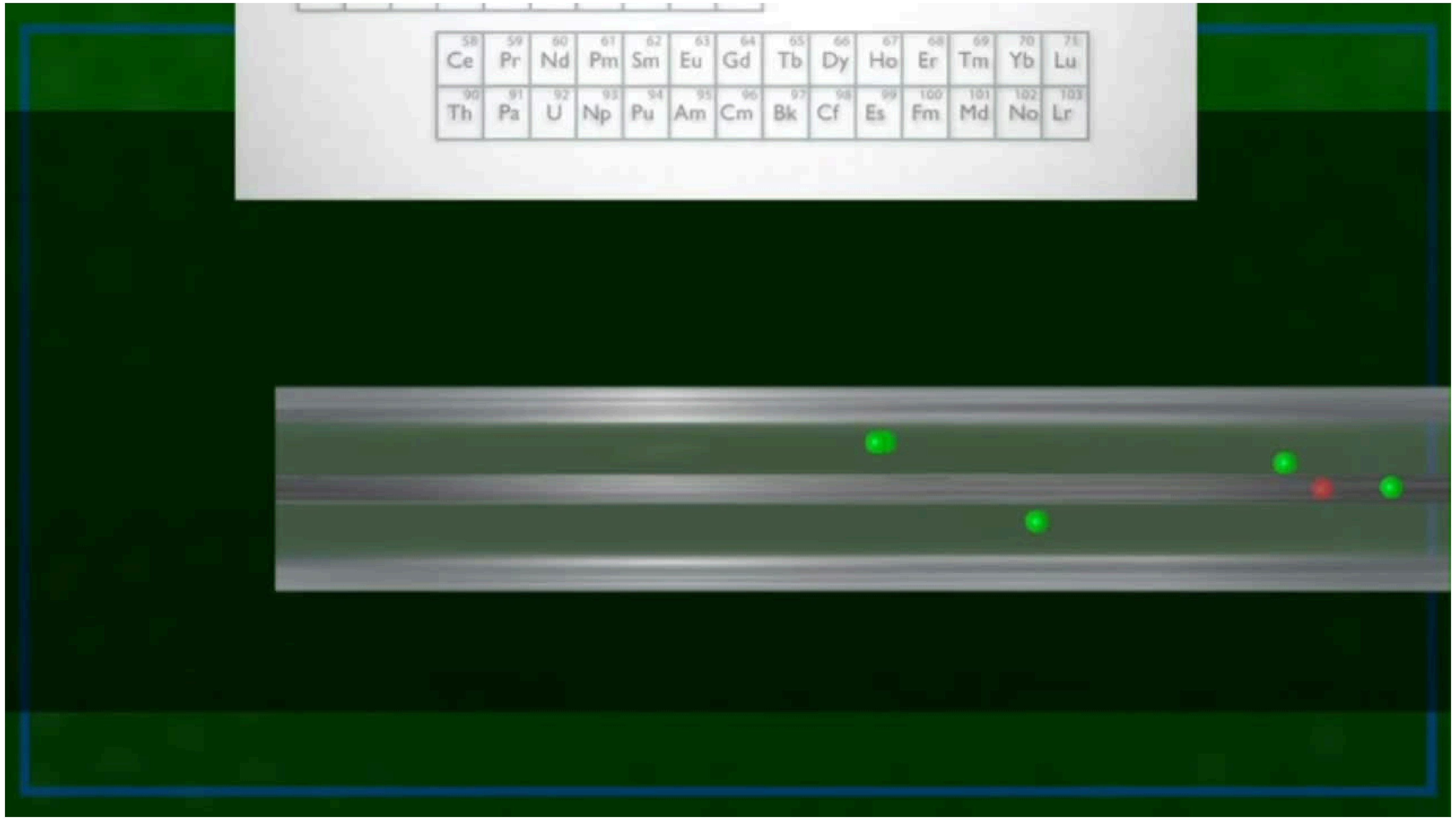
CLASSIC TECHNIQUES



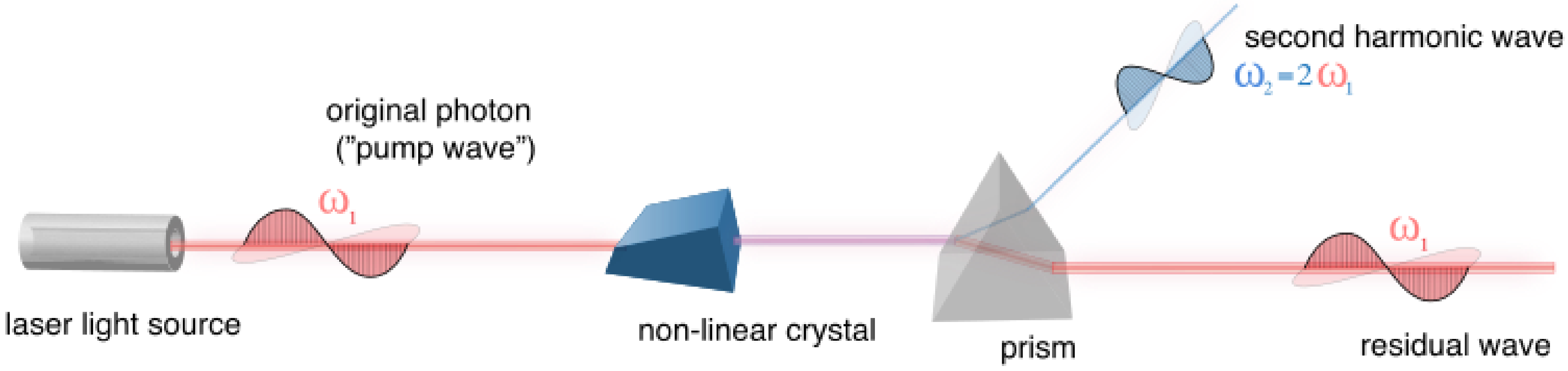
INFRARED LASER

- Ytterbium-doped fibre lasers
  High efficiency
  High beam quality
  Scalability

Images source: https://www.youtube.com/watch?v=ofEqFlqkiS0

Presenter: Manuel

CLASSIC TECHNIQUES



GREEN LASER

* Second Harmonic Generation (SHG)

Non-linear crystal conversion

1064 nm ⟶ 532 nm

High optical sensitivity

Limited power output

Images source: https://en.wikipedia.org/wiki/Second-harmonic_generation

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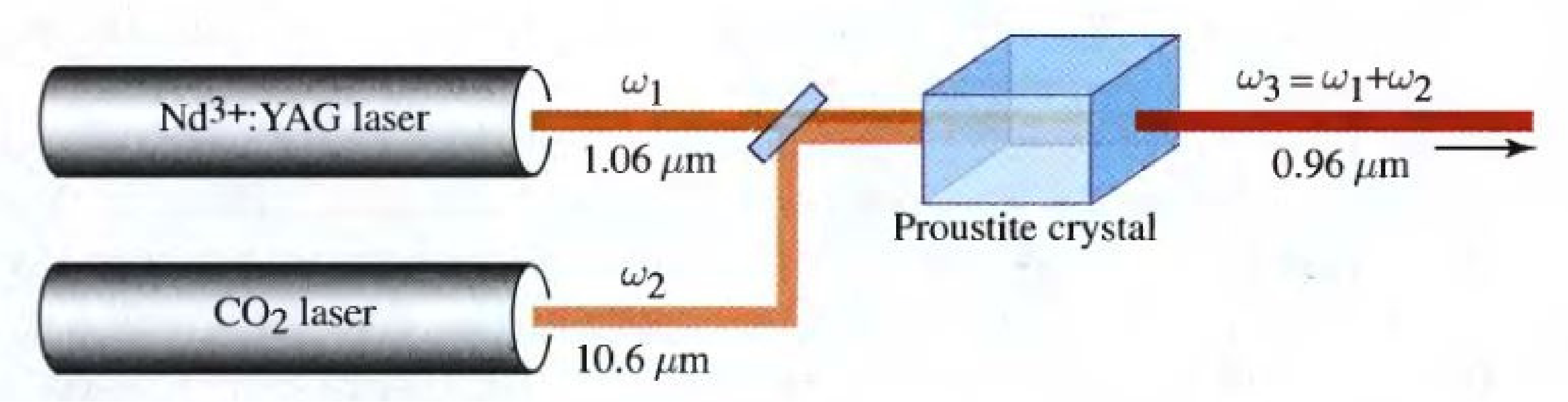
CLASSIC TECHNIQUES



BLUE LASER

- Solid state lasers based on Pr:YLF and Ti:Sapphire
  Limited power output
- Sum-Frequency Generation (SFG)
  Power too low for industrial use

Images source: https://shop.crylink.com/products/ti-sapphire
https://physics.stackexchange.com/questions/427571/sum-harmonic-and-sum-frequency-generation

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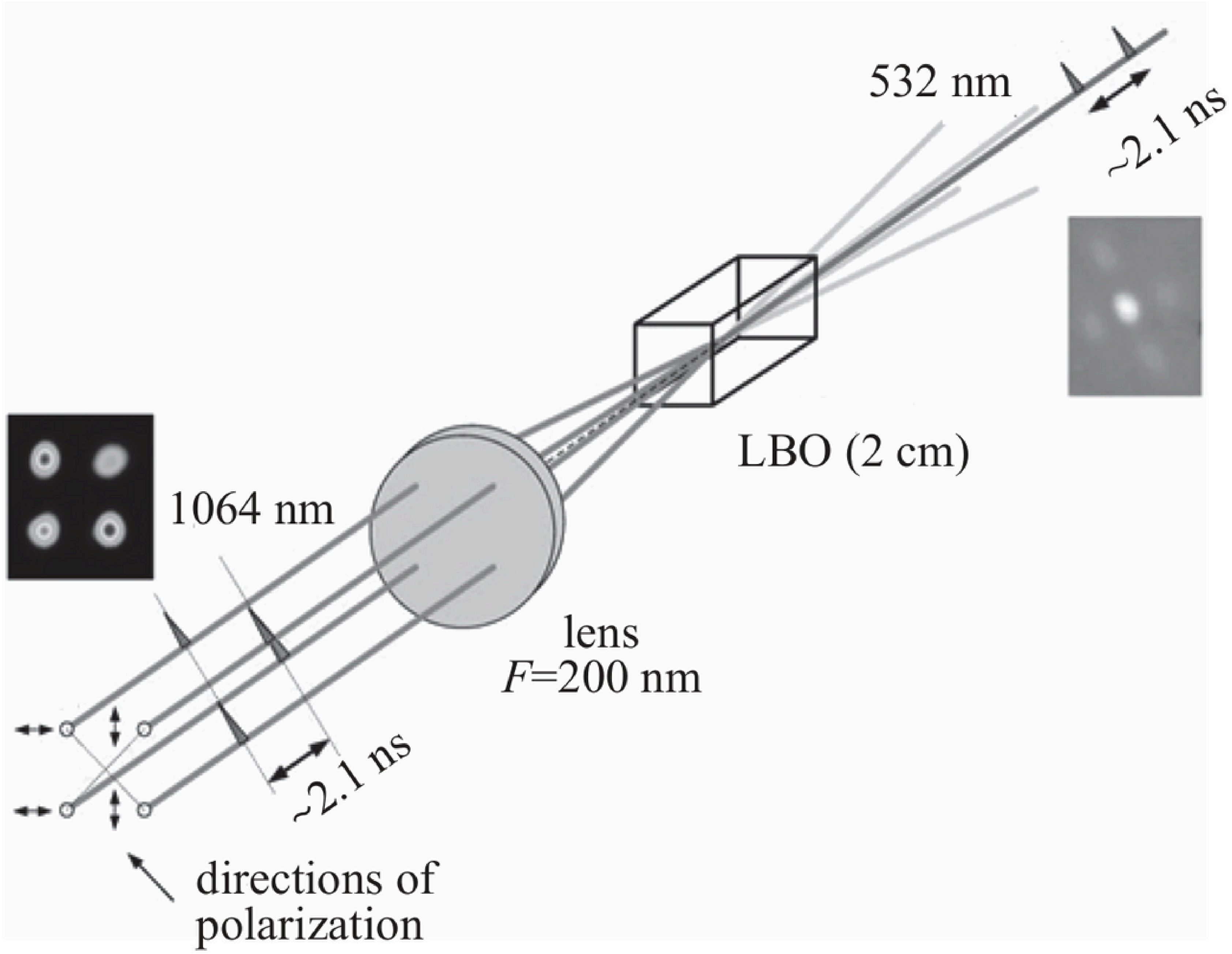
NEW TECHNIQUES



GREEN LASER

High power frequency doubling

High power source
Non-linear crystal (LBO, BBO, PPLN)
Hundreds of watts output
Temperature control system

Images source: Tian Ma, Fuquan Li, and Honghuan Lin. Recent progress of high power green laser based on frequency doubling technology for fiber laser. Optics and Laser Technology, 2023

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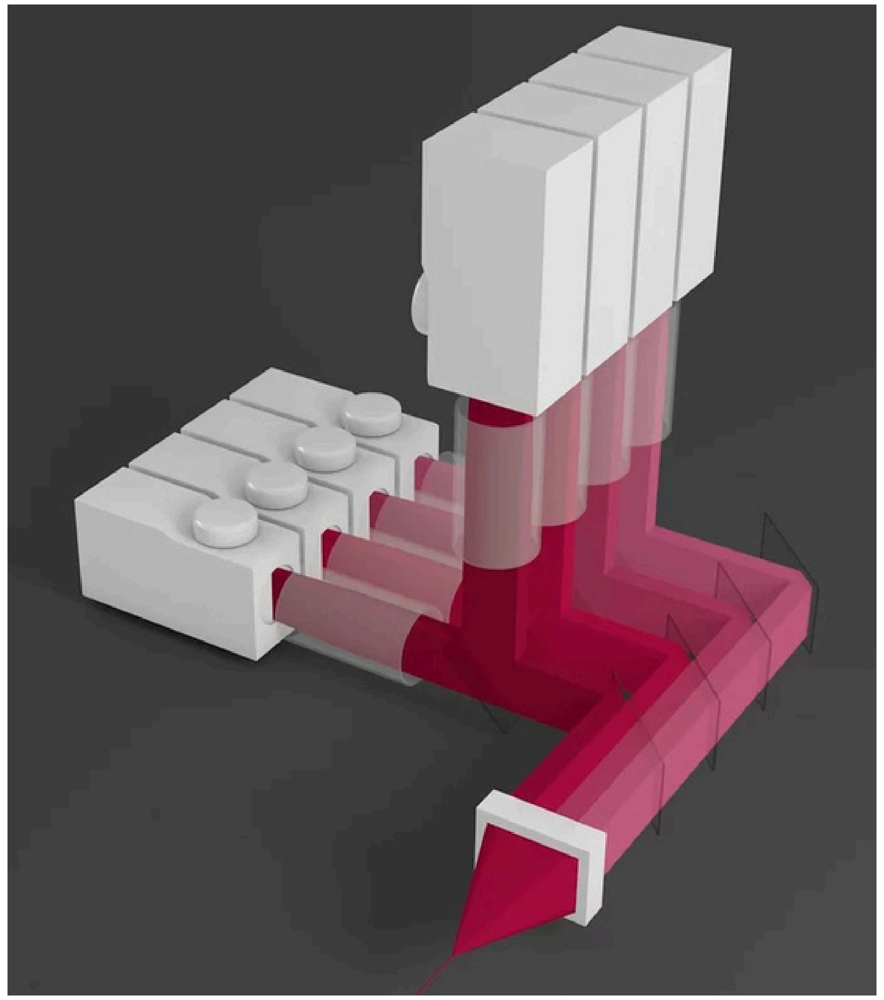
NEW TECHNIQUES



BLUE LASER

High power diode stacking

High electro-optical efficiency
1 - 10 kW
Higher power means less quality beam

Images source: https://www.laserline.com/en-int/high-power-diode-lasers/
https://www.laserline.com/en-int/ldmseries/

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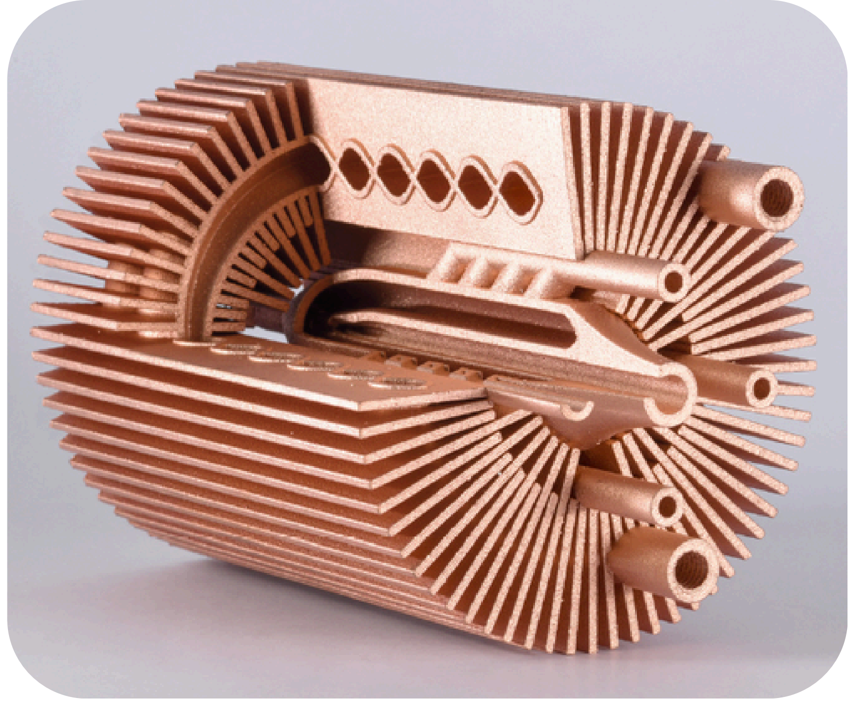
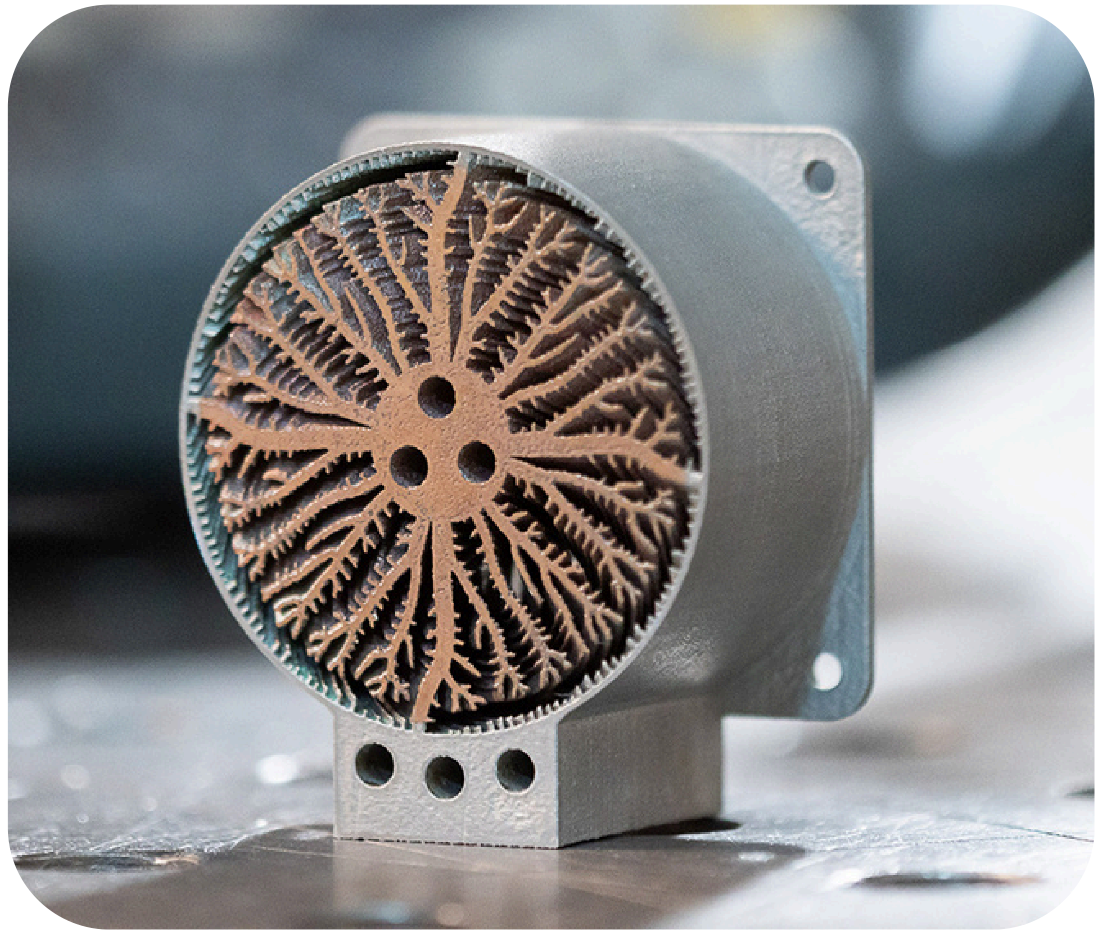
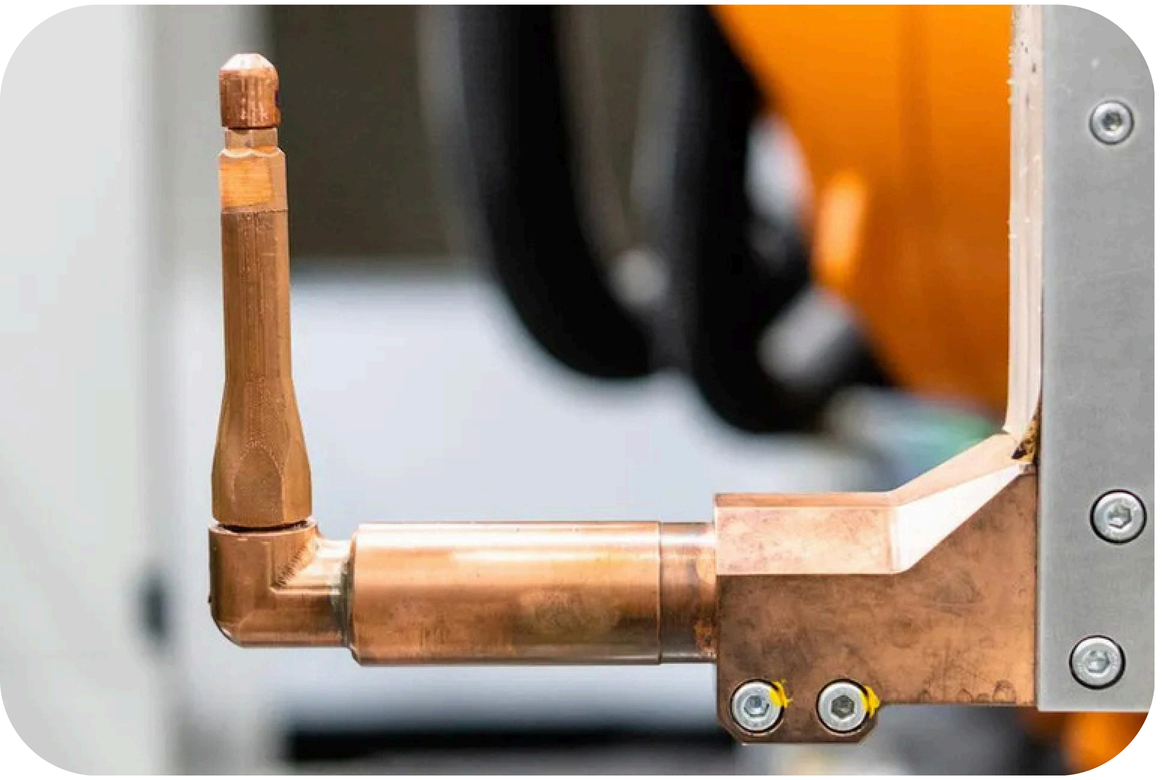
APPLICATIONS







Working with new materials

Aerospace industry

Electric vehicle industry

In situ alloying

Images source: https://www.linkedin.com/pulse/processing-copper-alloys-dmls-technology-mahemaa-rajasekaran
https://www.additivemanufacturing.media/news/researchers-use-additive-manufacturing-to-make-aircraft-propulsion-systems-more-eco-friendly
https://www.forbes.com/sites/edgarsten/2020/02/13/copper-3d-printing-breakthrough-could-cut-costs-boost-ev-power/

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THANK YOU FOR LISTENING