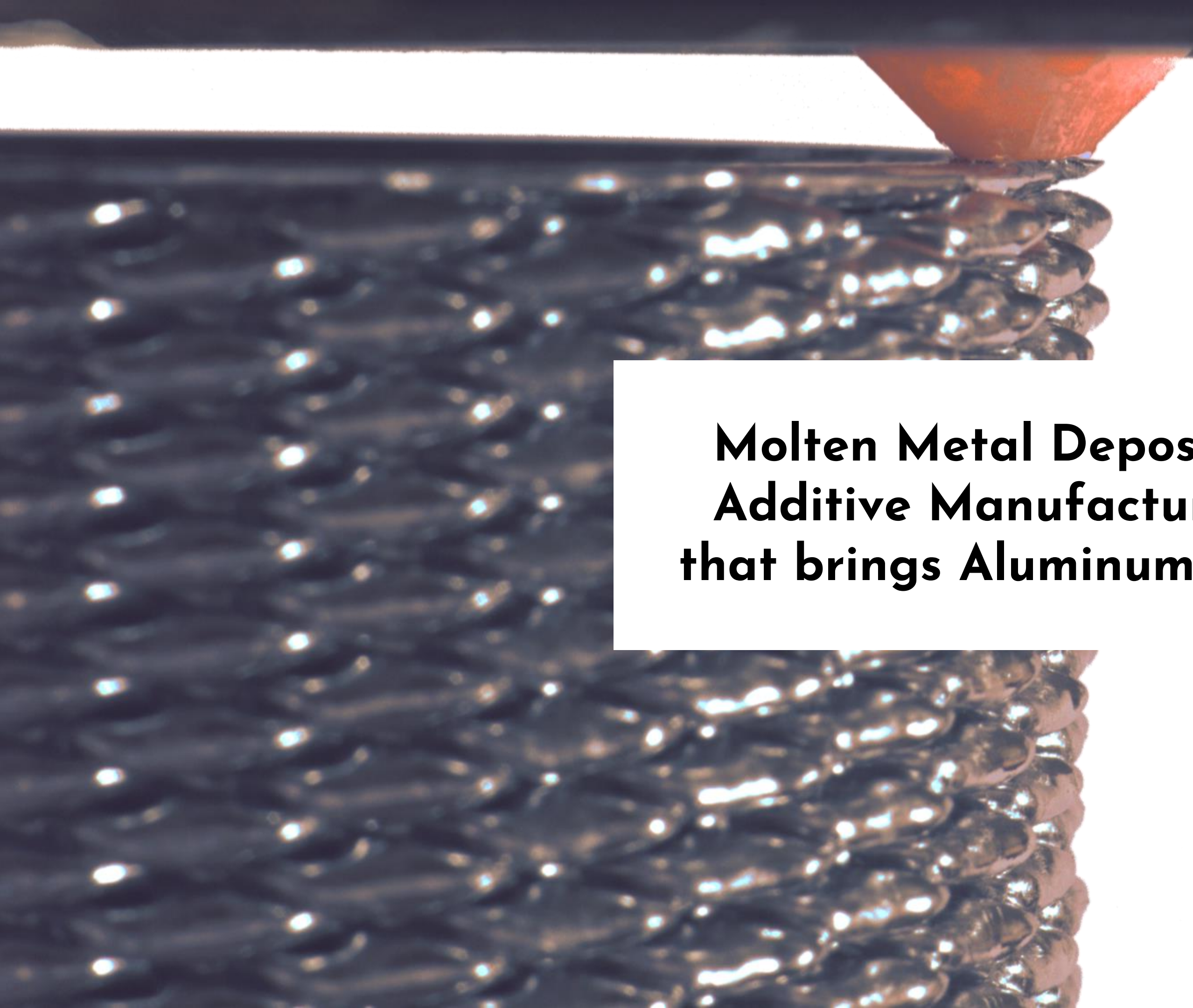


Molten Metal Deposition (MMD): A Novel Additive Manufacturing (AM) Technology that brings Aluminum AM towards Industry

AMAP June 19th, 2023

1. Aluminum Additive Manufacturing
2. ValCUN
3. Industrial hybrid manufacturing

16 Different Polymer Additive Manufacturing (AM) processes according to AM Power

Fused Deposition Modelling (FDM) =Fused Filament Fabrication (FFF)

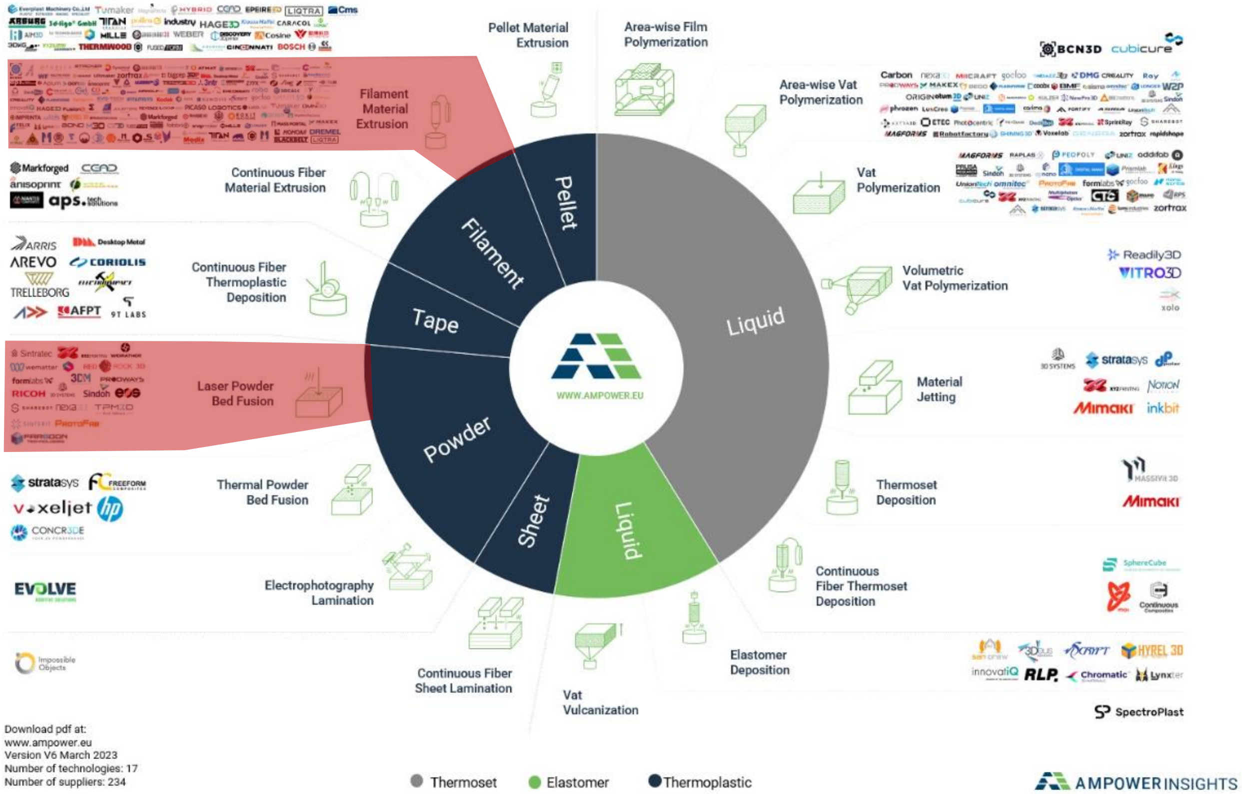
Most common polymer AM technology

Invented in 1980's

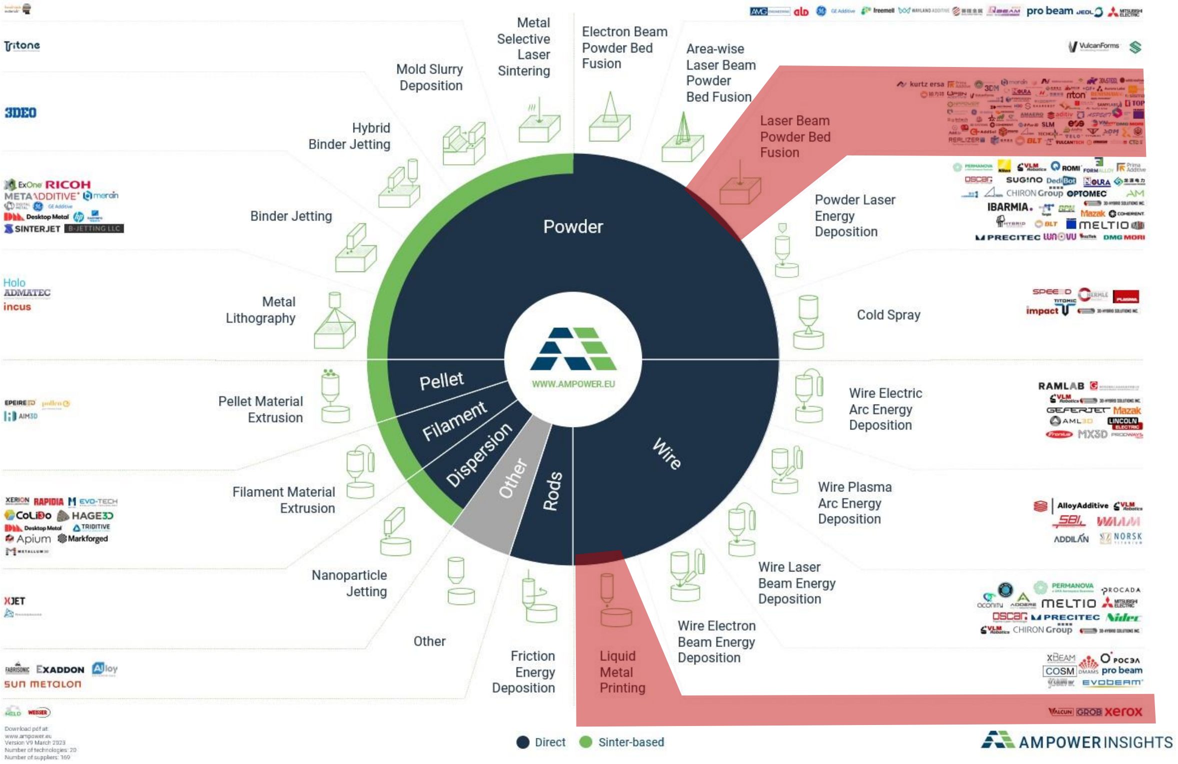
Most companies active in this scene

Selective Laser Melting (SLS)

Powder and laser based



18 Different metal Additive Manufacturing processes according to AM Power



Laser Powder Bed Fusion (LPBF) =Selective Laser melting (SLM)

Most common Metal AM technology

Invented in 1990's

Most companies active in this scene

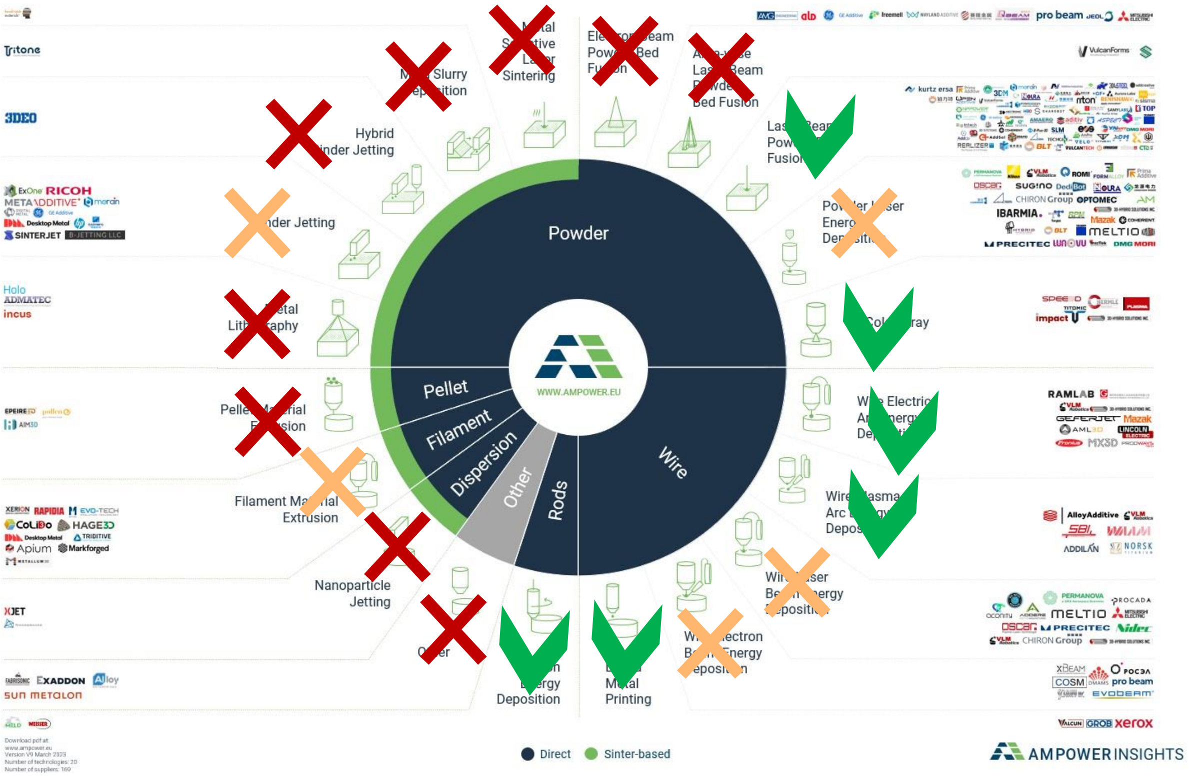
Molten Metal Deposition (MMD)

Focused on Aluminum

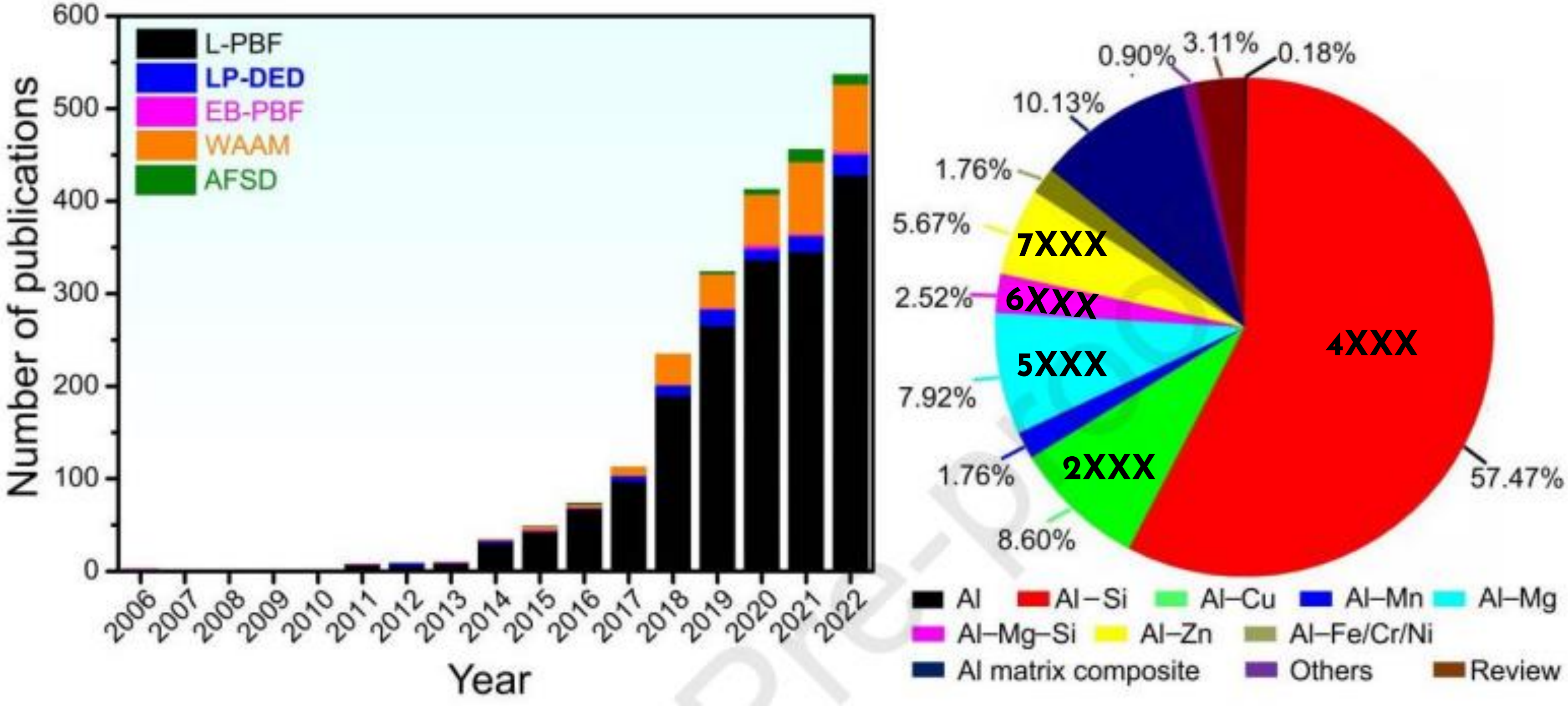
Invented by ValCUN

Categorized in Liquid Metal Printing

Aluminum is not the preferred material for metal AM

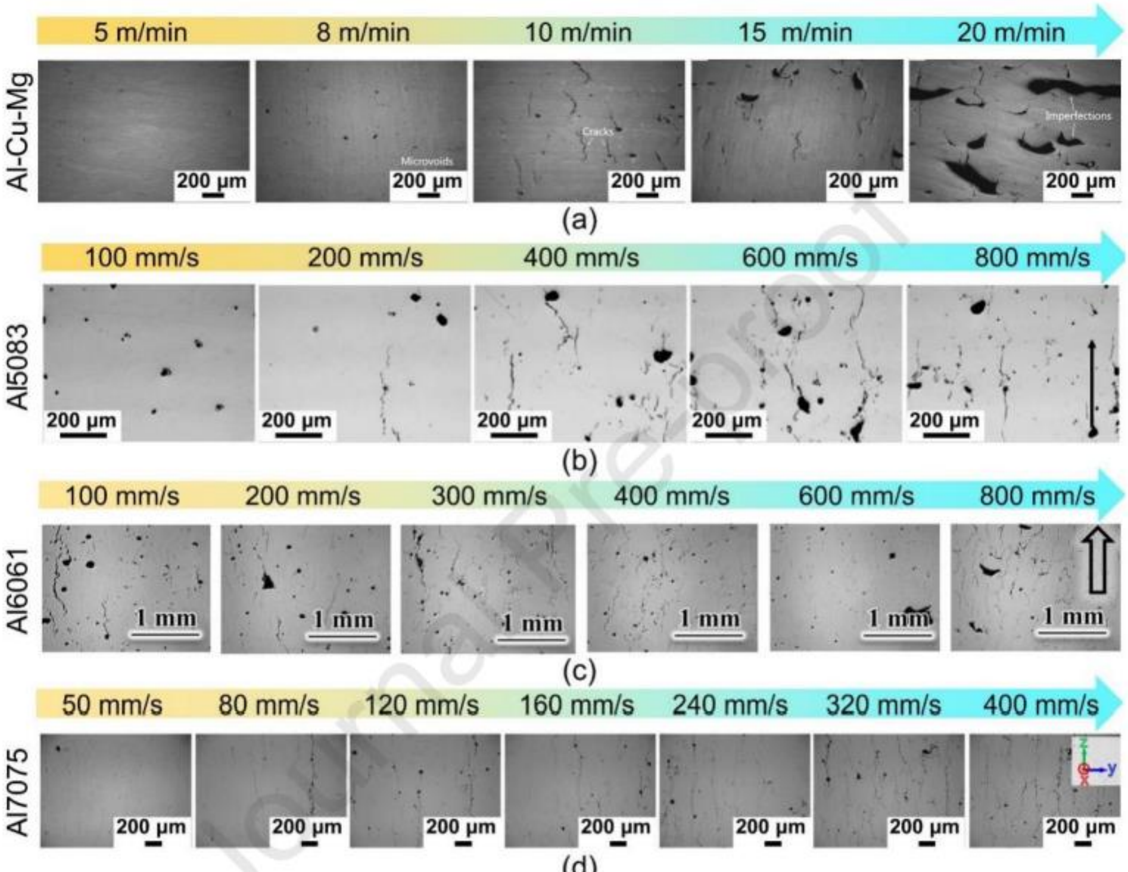


Aluminum Additive Manufacturing publications rise fast Dominated by LPBF and Al-Si allays



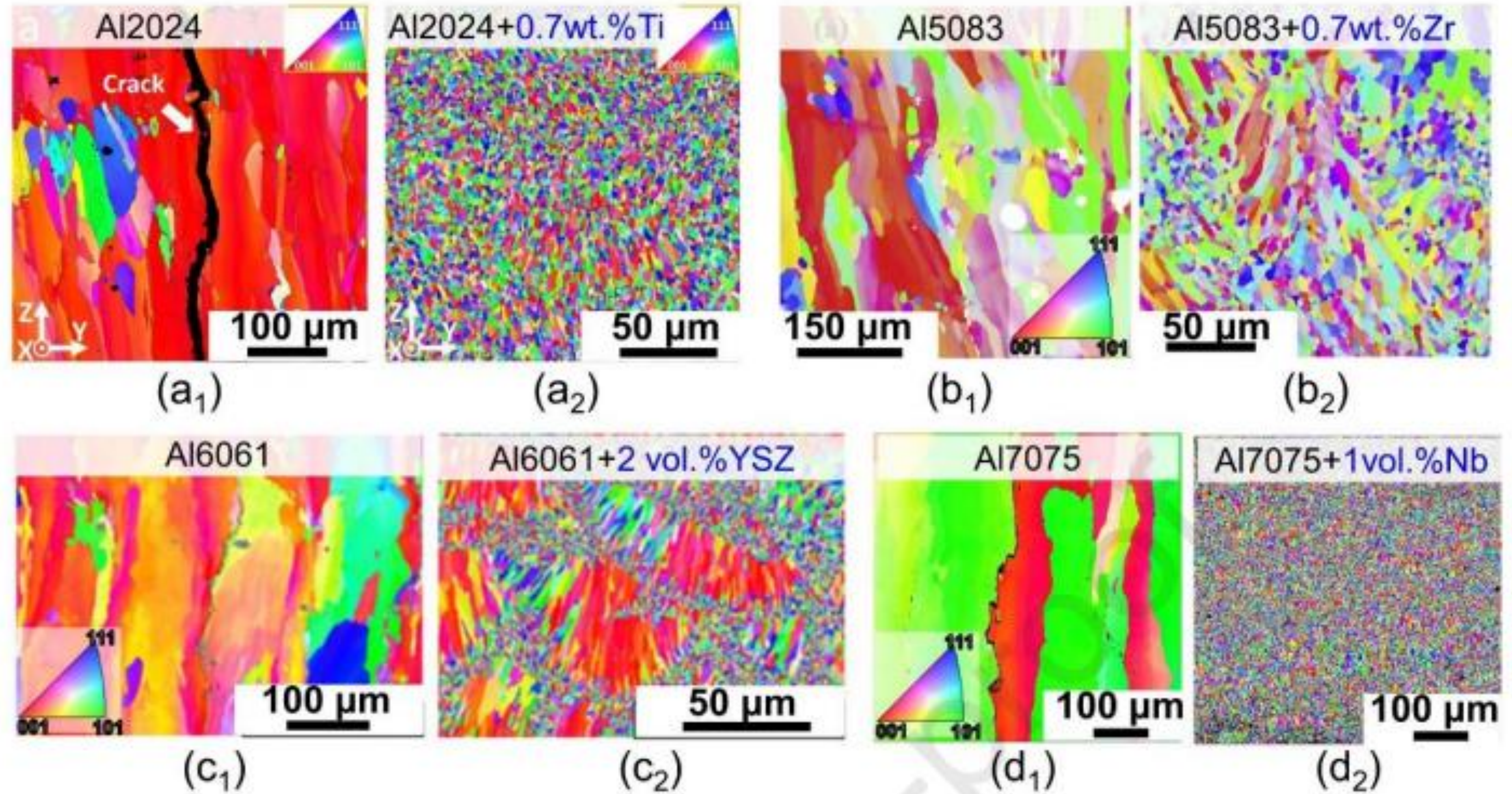
https://doi.org/10.1016/j.ijmachtools.2023.104047

Typical problems with aluminum LPBF are cracks and voids



https://doi.org/10.1016/j.ijmachtools.2023.104047

Modified alloys: crack suspectibility↓ & fluidity ↑ Skyrocketing price & non-standard solution

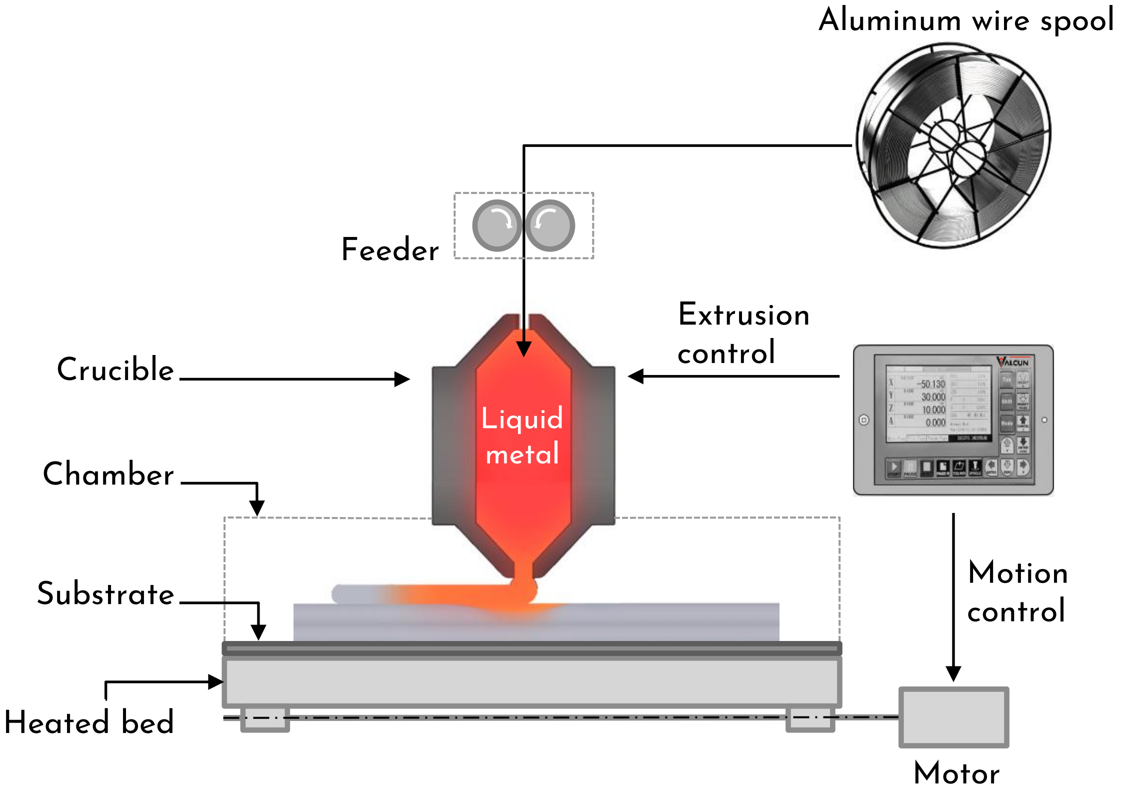


https://doi.org/10.1016/j.ijmachtools.2023.104047

Summary of Aluminum Additive Manufacturing

1. Aluminum Additive Manufacturing
2. Who is ValCUN
3. Industrial hybrid manufacturing

Molten Metal Deposition (MMD) technology



1. Aluminum wire is fed to the heating chamber
2. Aluminum is molten in the resistive heating chamber
3. Software generates toolpath and print parameters
4. Liquid aluminum is extruded through the nozzle
5. Extruded aluminum fuses with the previous layer building the part
6. Parts are finished when detached from the quick-release substrate

Molten Metal Deposition: Disrupting Metal Parts Production

MMD, ValCUN's proprietary technology, is fast, sustainable and deployable

Reducing Lead Times & Ensuring Parts Availability

- Direct, on-demand manufacturing
- Automatable pre & post-processing

Sustainable and Environmentally Friendly

- Energy efficient (up to 80% savings) and lower LCA
- No toxic chemicals

Deployable and Easy-to-Use

- Wire or granular feedstock, eliminating toxic powder usage
- Simple system with fast ramp-up

Initial Focus on Aluminum: Large, Untapped Mkt.

- ~$100Bn market (~25% of global metal spare parts mkt.)
- Most metal AM technologies not suitable for Aluminum

Automation of the MMD process

Pre & post processing
20 seconds to replace baseplate & restart print
Robotic baseplate replacement
1 Machining center per 5 to 10 MMD printers

In-line integration
The MMD printhead in an existing production line

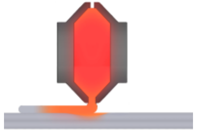
Lights out factory
Producing 24 / 7 with a daytime supervision

Less dangerous
Wire or granular feedstock, no lasers, no chemicals

Open platform technology for MMD and other AM research

Open parameter set

Primary parameters like T_{nozzle}, T_{bed}, $T_{chamber}$, flowrate, …
Gcode file is accessible

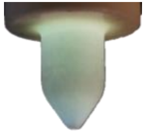


Open feedstock architecture

Other alloys and materials (eg. high-tech polymer)
ValCUN offers certified feedstocks

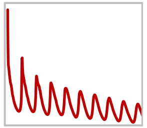
Open printhead architecture

Nozzles can be replaced for research
Other printheads can be installed



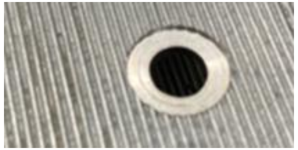
Open measurements and DAQ

All logged parameters are accessible
Additional sensors can be added



Some snippets from MMD parts

Near net shapes
Medium sized component (match box to shoe box)
Buy-to-fly ratio >70% is price competitive with CNC milling



Shell structures
For aesthetic applications
Can be coated like anodization

Lattice structures
For heat exchange or catalytic conversion

Heat exchangers & heat sinks
Aluminum is a good heat conductor
For single fluid or dual fluid

Features that can be built with MMD today, Process optimization will give more freedom than FFF

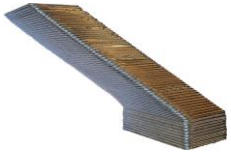
Track size

Coarse (width 4mm, height 2mm)

Fine (width 1.5mm, height 1mm)

Overhang & bridging
(without support)

Up to 75°



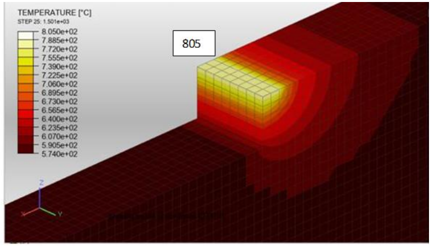
>25mm

Surface quality is adjustable

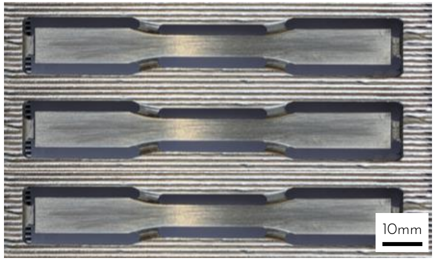
Low remelt

High remelt

Prediction of the Mechanical Properties by a Process → Structure → Property approach

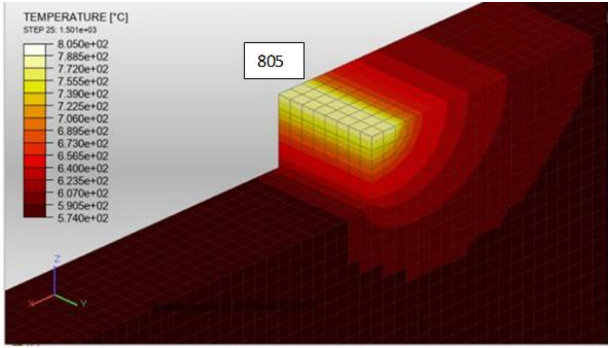


Solidification and grain growth equations are used to model the microstructure from thermal process modelling

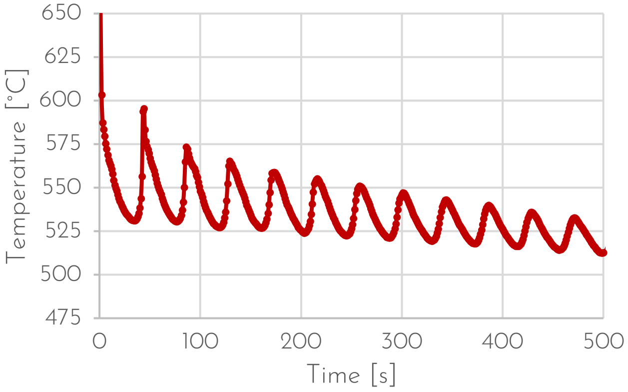


Hall-Petch type equations are used to determine the mechanical properties from microstructure

Thermal simulation give insight in the physical process and reduce the time to obtain an optimized parameter set

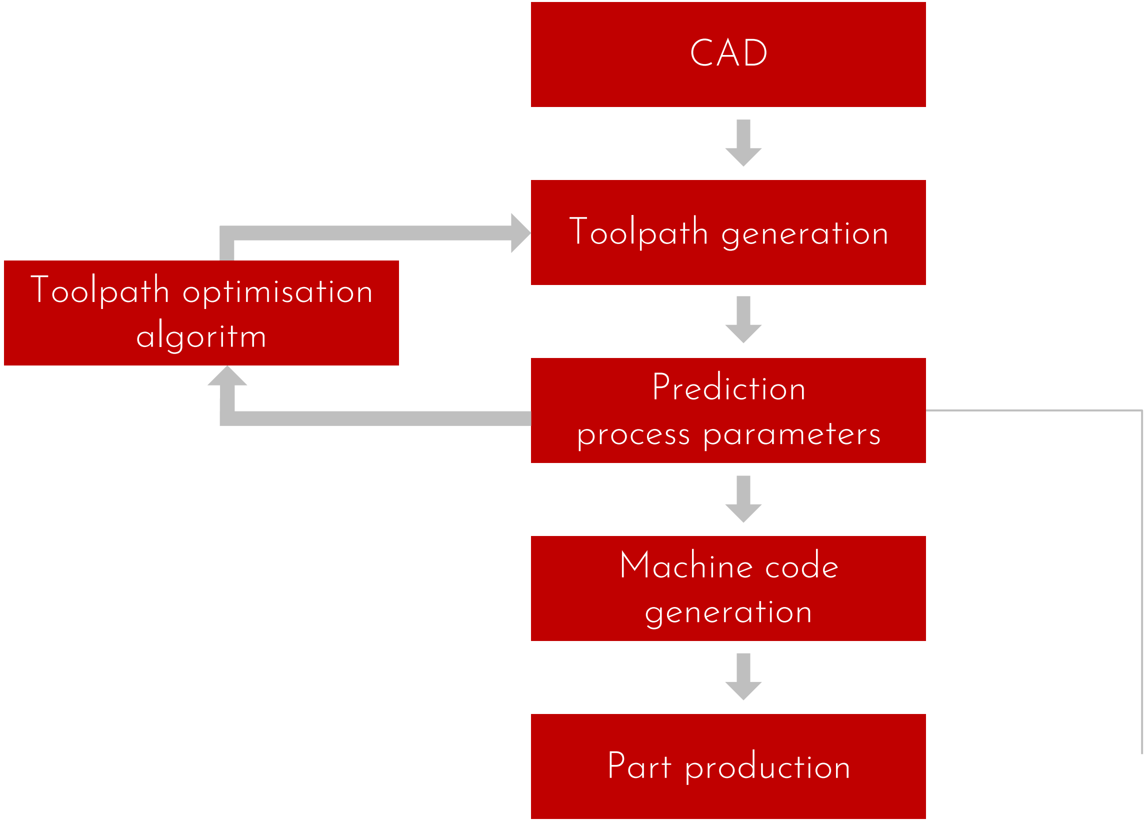


FEM simulations via element birth
Computational heavy (days/simulation)
Remelt depth of previous layer relates to bonding quality



Thermal history of every element is known
Simulation results are validated by experiments

Reducing calculation time for predicting the process parameters by AI algorithm

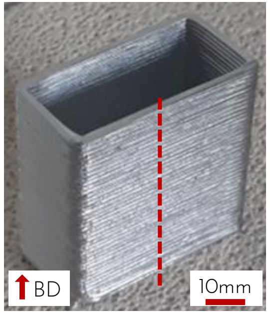


FEM based simulation
Element birth is computational intensive
Days / weeks to simulate parts

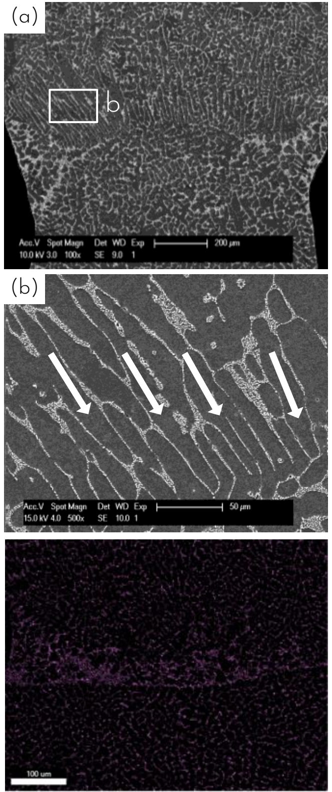
AI based prediction
FEM results for training data
Artificial Neural Network (ANN)
Seconds / minutes to predict part

Al-Si dendritic microstructure is observed after MMD of Aluminium 4043

As-built



Medium remelt

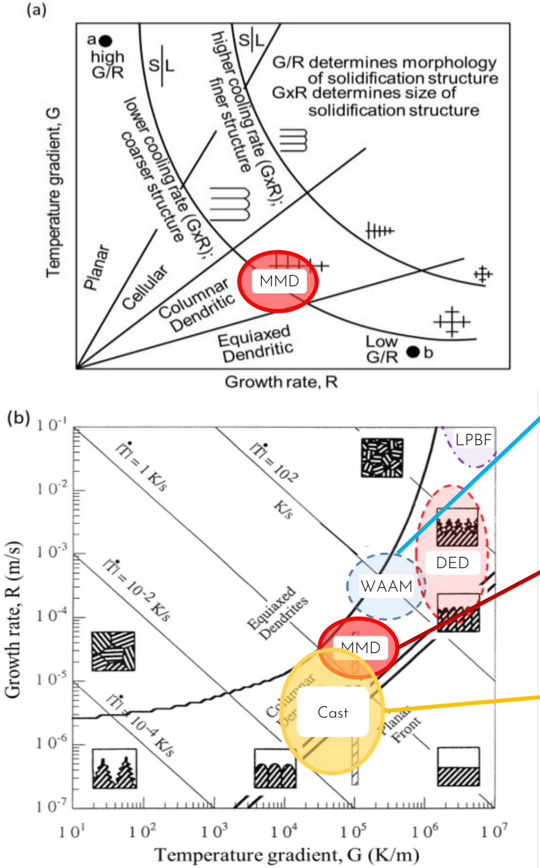


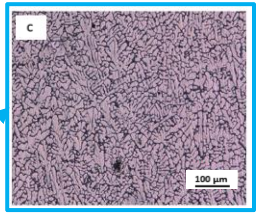
Different zones are observed in MMD samples

Dendritic growth is favored along the heat flux direction

Si-rich macro segregation is observed at the inter-layer boundaries towards the edges (EBSD Si map)

MMD has cooling rates & microstructures between Casting and WAAM / DED / LPBF

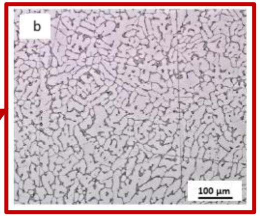




WAAM

*Cooling rate 50-200 K/s

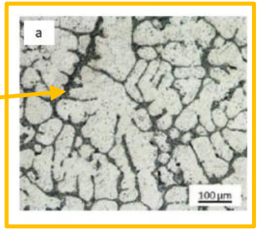
*Dendritic arm spacing 5-20 µm



MMD

*Cooling rate 10-50 K/s

*Dendritic arm spacing 10-30 µm



Casting

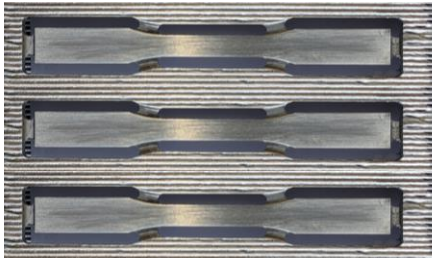
*Cooling rate 1-20 K/s

*Dendritic arm spacing 15-60 µm

Source: Kou 2002, Bermingham et al. 2020, Dobkowska et al. 2016, Qiang Liu et al. 2020

*Cooling rates and dendritic sizes are dependent on individual cases and exhibit much larger variations than mentioned here

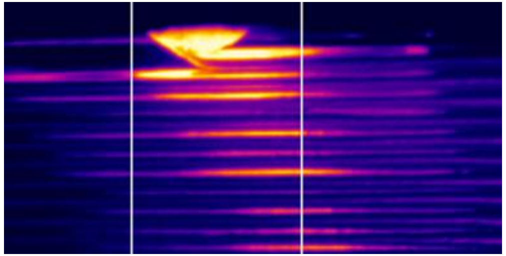
Mechanical properties are consistent Further optimization is needed




Courtesy: KU Leuven

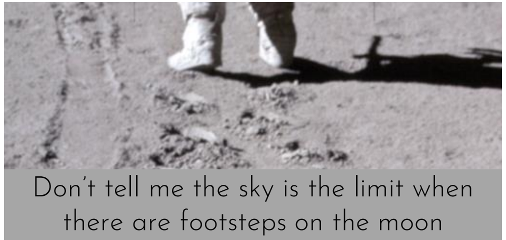
As printed Al 4043	**ValCUN Value**
Yield stress [MPa]	56.3±1.6
Tensile stress [MPa]	129.5±3.4
Elongation [%]	22.8±3.6

Process optimization and quality control by point and field measurements



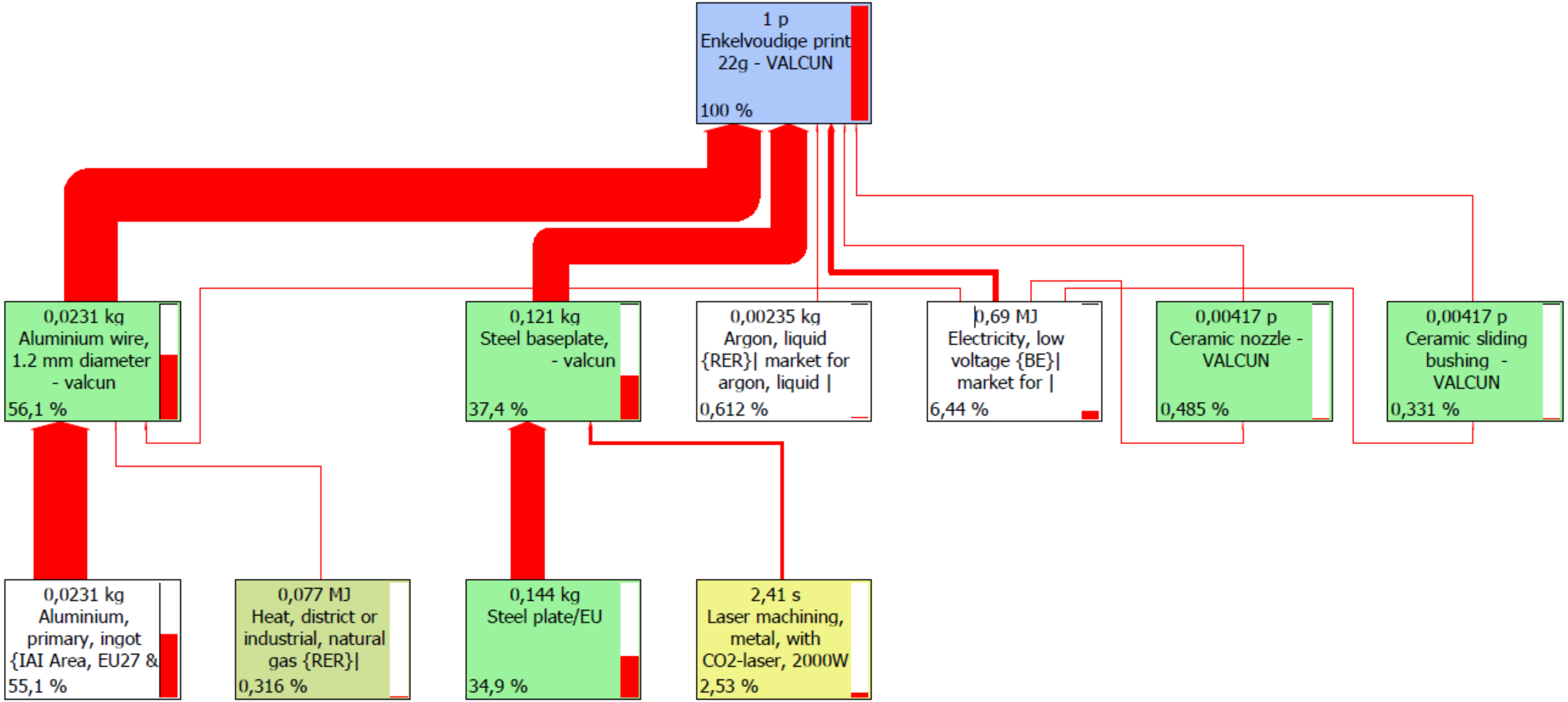
Thermal imaging
Temperature field at the surface of printed sample
Validation of numerical simulations
Remelt of underlaying track(s)

Optical imaging
Geometrical features are visualized
Geometrical quality can (partially) be measured
Error and anomaly detection can be automated



Additional techniques can be implemented
Sensor fusion for advanced QC and process parameter optimization
3D camera systems
Acoustic emission
etc.

Life Cycle Analysis (LCA) by the Univerisity of Leuven



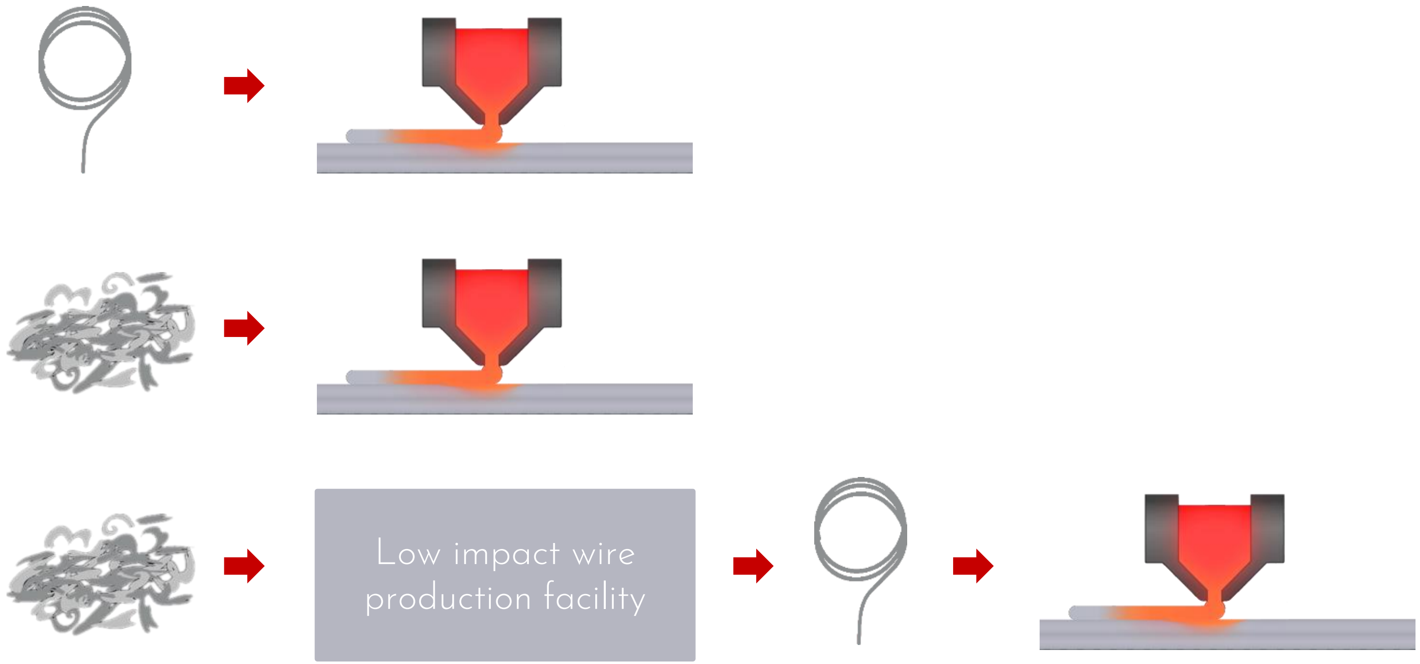
Alternative feedstock reduced LCA impact up to 50%

Quality of the feedstock determines the output quality
Industrial symbiosis is possible on all levels (support structure, postprocessing, secondary output streams, etc.)
LCA and market interest will determine the future direction

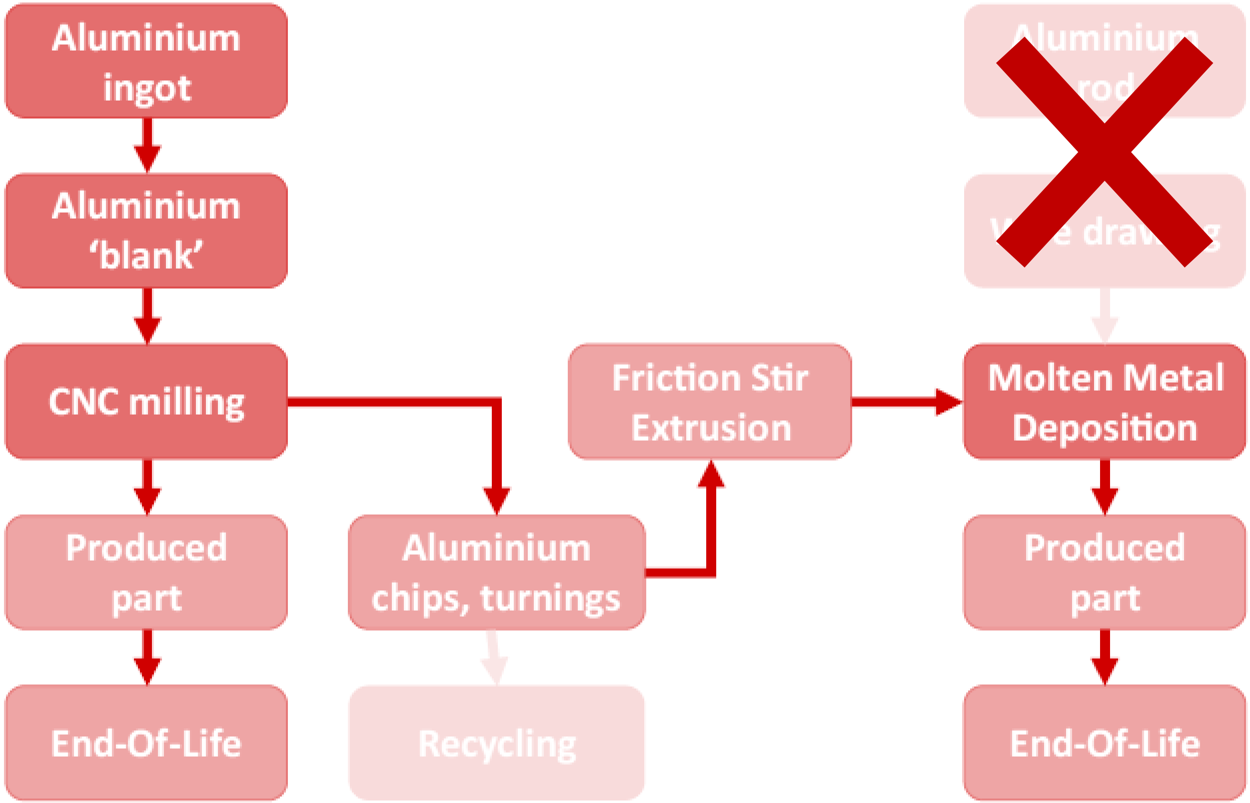
Current

Modified printhead

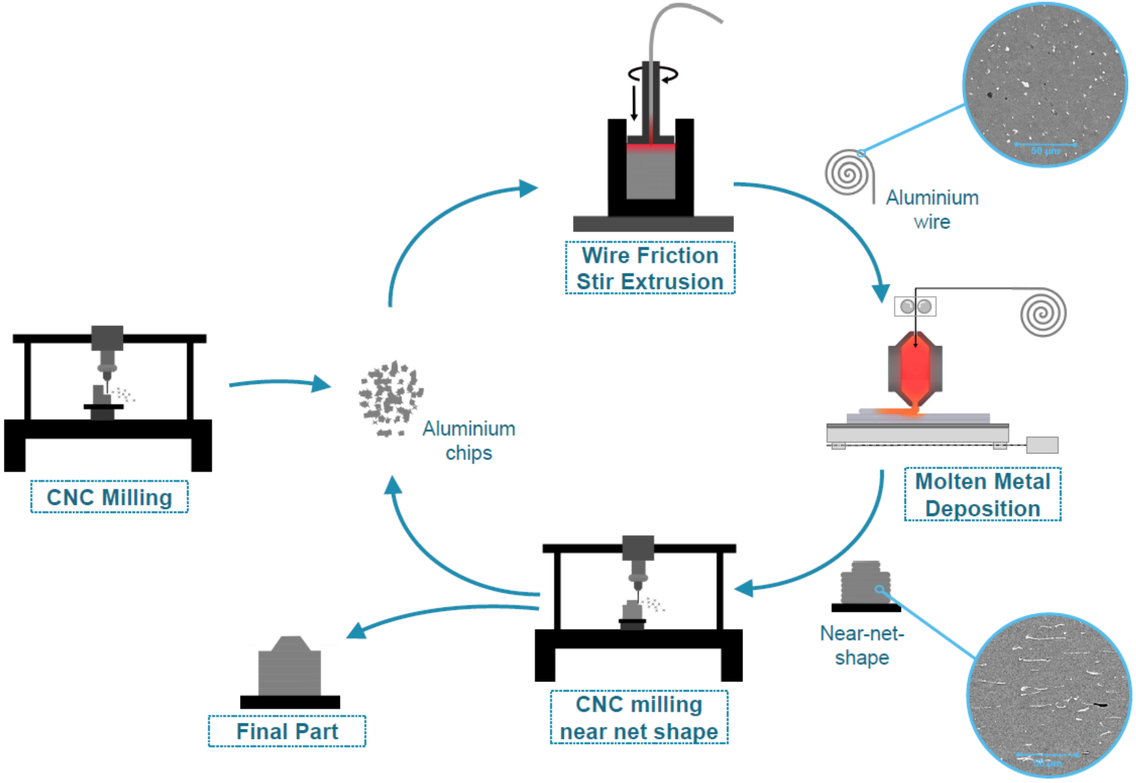
Intermediate wiredrawing



Industrial symbiosis between 2 industrial processes



Promising feasibility on 3D printing with chips



- Finely dispersed oxides through severe plastic deformation
- Fully dense material

- Oxide spread parallel to print layer-axis
- Alloying metals in inter-dendritic voids → thermal treatment

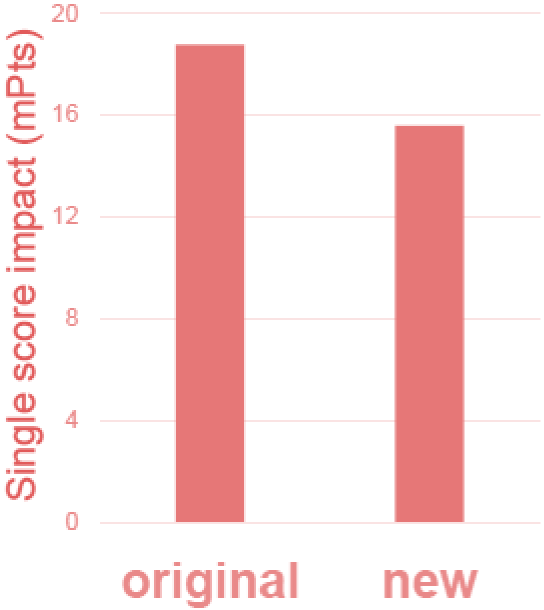
Industrial symbiosis reduces impact by 17%

Potential combined impact reduction of CNC milling + aluminium Molten Metal Deposition of **± 17%** based on prospective LCA

75% less impact for feedstock Molten Metal Deposition

Oxide presence only problematic if they make the material weaker than the interlayer adhesion of the printed part

Friction stir extrusion **shortens the distance** between aluminium chips ➔ usable wire



ValCUN's research team is an experienced hands-on team

**Dr. ir.
J. Galle**

Co-founder
CEO

**Dr. ir.
J. De Pauw**

Co-founder
CTO

**Dr. ir.
M. Saadatmand**

Multiphysics
Software

**Dr.ir.
C. Elangeswaran**

Material science

**Ing.
J. Broeckaert**

Mechanics

74
Publications

31
Presentations

26
Years of academic experience

12
Academic & research partners
(KULeuven, Ghent University,...)

Starting with Near-Net-Shape Applications & Expand into More Complex Use-Cases

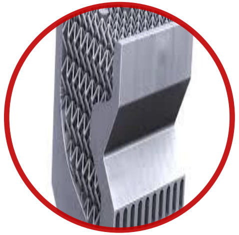
Today	Short Term	Mid-Term
Near-Net-Shape Applications (CNC)	Near-Net-Shape Applications (Casting)	Heat Sinks

Speed and cost efficiencies

- Greener solution: reducing waste and material usage
- Ideal for localized, deployable manufacturing
- 1000's of potential customers in the EU and the US

Speed and cost efficiencies

- Ideal for small and medium size batches (e.g. spare parts)
- Structural components that require minimal machining
- Hydraulic system parts



Out of the printer usability

- Ideal for small and medium size batches
- Electrical vehicles and High end computing
- $6.5Bn market in 2021 close to $10Bn in 2027E

1. Aluminum Additive Manufacturing
2. Who is ValCUN
3. Industrial hybrid manufacturing

Drivers for Hybrid Manufacturing

Production speed
AM is slow compared to rolling, extrusion, casting, …

Cost
AM is expensive compared to rolling, extrusion, casting, …

Complexity
Complexity is 'for free' with AM

An additional dimension can generated on 1D/2D products like rolling & extrusion

Additional features can be generated with casting like closed complex channels eg. For cooling

Drivers for Hybrid Manufacturing with MMD

Aluminum alloys
High strength alloys like 6xxx and 7xxx can be deposited
Heat treatment can be done

Residual stess
No bending in baseplate is observed
Limited residual stress

Printing feedstock
Wire instead of powders
'Clean' process compared to welding

Print geometry
MMD printhead can be installed inline with other production process
MMD printhead can be installed on robotic arm for more design freedom

Hybrid Manufacturing

Indirect process
Welding of 2 parts (AM part & conventional part)

Direct process
Deposit directly onto conventional part

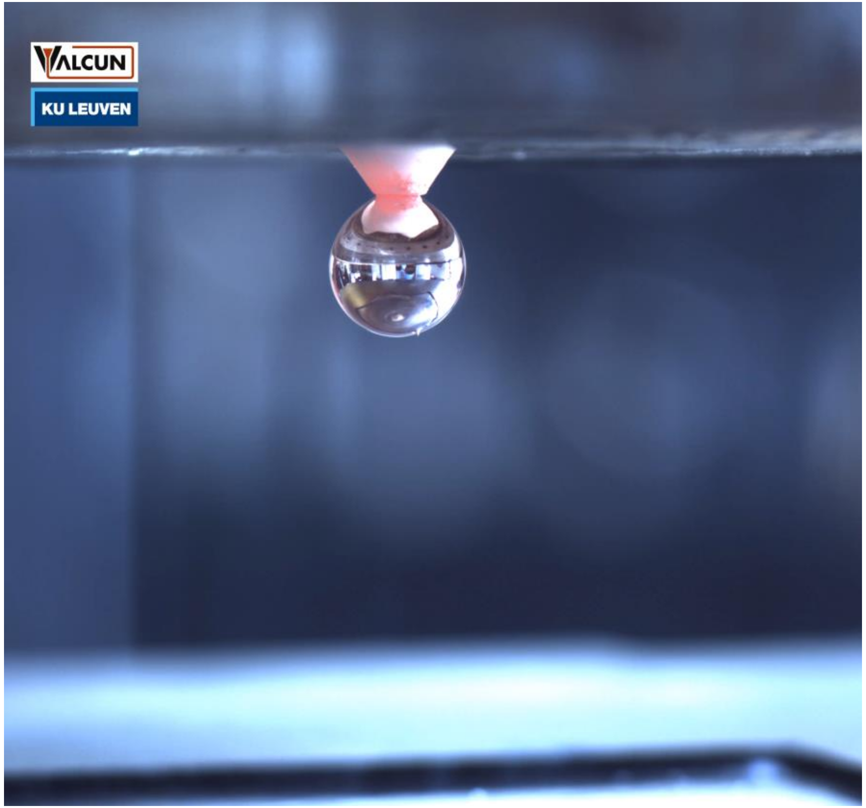
Indirect hybrid manufacturing feasibility during CoAMweld

Both horizontal and vertical 3Dprints can be welded

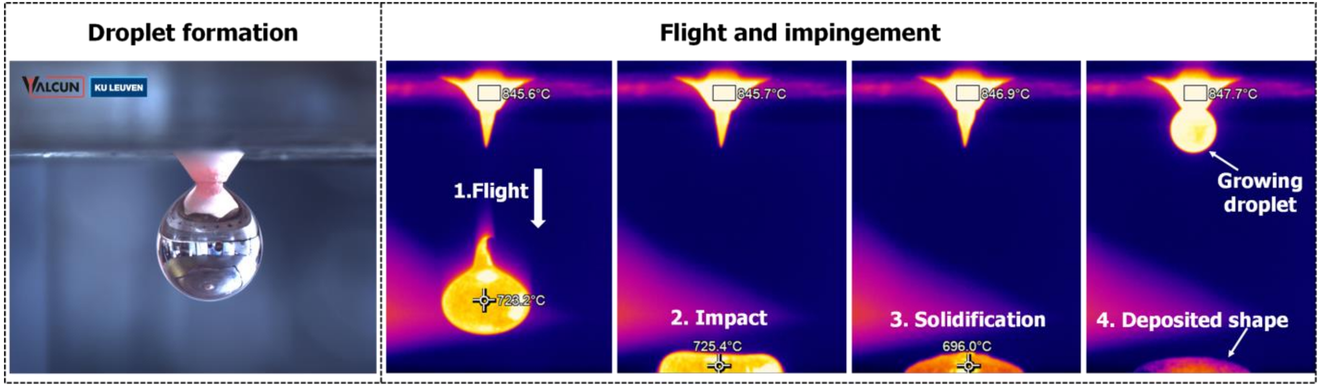
HAZ as expected

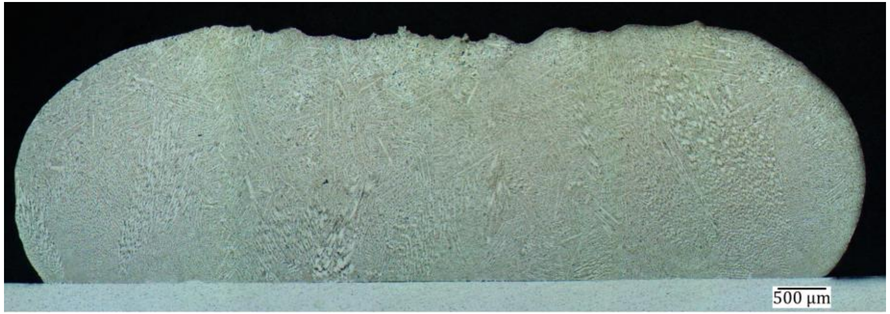
Research is ongoing

Direct hybrid manufacturing feasibility by KUL

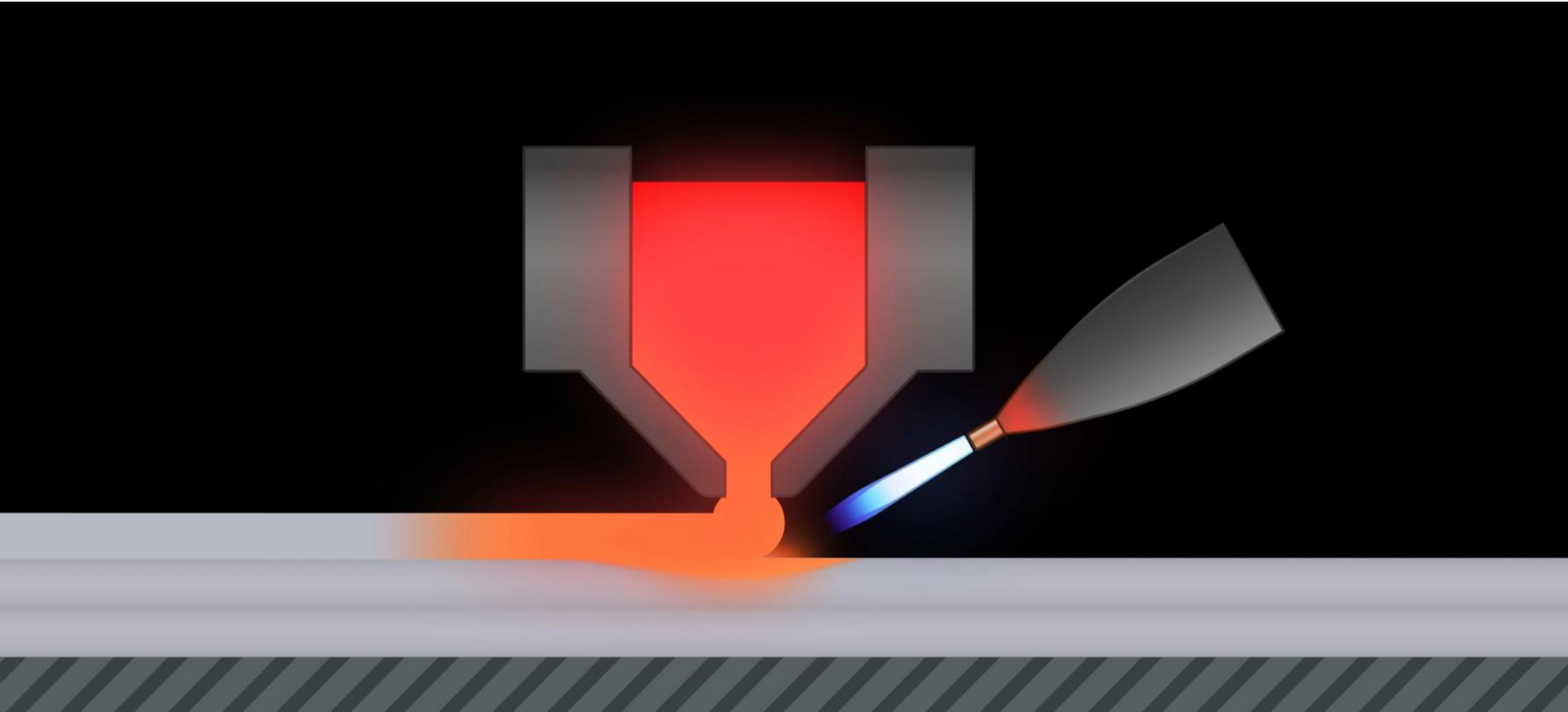


Droplet and aluminum sheet fuse at the interface





Direct hybrid manufacturing with local preheating



Let's collaborate for disruptive AM

Please reach us at

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