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Design of Metal AM Parts for Aerospace & Defense – DED

Course Introduction

Prof. Dr. Ulaş Yaman

Welding Technology and NDT Center

Middle East Technical University



CenSec
CENTER FOR DEFENSE, SPACE & SECURITY



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PERFORMANCE REVIEW INSTITUTE



Fraunhofer
IPT



SICNOVA



AILEEN Project



- centres of vocational Excellence in aerospace & defence for advanced manufacturing
- AILEEN addresses the **shortage of skilled personnel** for the Aerospace & Defence Sectors by setting up **CoVEs** for Advanced Manufacturing (AM), supporting the recovery of the Aerospace sector, developing innovative methodologies and tools, with the nomination of the first Centres of Vocational Excellence in AM, to guarantee specialized sectoral training, and the transfer of excellence knowledge and activities in the field of education and training.

AILEEN Project



Design of AM Parts for Aerospace & Defence



- **Course 2 – Design of Metal AM Parts for A&D – Part 2 DED**
- **Target:** Designers
- **Objectives:** Provide an insight into the specific design requirements of metal AM parts produced by DED with reference to the specific A&D sector requirements and applications.
- **Precedence:** CU00 Overview on AM process, Introduction to AM for Aerospace & Defence
- **Entry Level:** Level 6
- **Overall Duration:** 2 days (14 hours)

Trainers



– Prof. Dr. Ulaş Yaman

- 12 years of experience in AM
- 4 years of experience in DED
- 2 years of experience in NDT

– Gökhan Can

- 15 years of experience in AM
- 10 years of experience in DED

– Ahmet Hakan Dursun

- 2 years of experience in AM and DED

– Dr. Süha Tirkeş

- 2 years of experience in DED

Course 2 – Design of Metal AM Parts for A&D – Part 2 DED



– Day 1

Topics	Hours
Course introduction	0.5
Overview of the design workflow for metal AM DED	0.5
Introduction to DED	1.5
Part suitability for DED	0.5
Design for DED; • Feature generation • Process resolution & surface finish • Part Finishing & Inspection of DED parts • Stress management	4

Course 2 – Design of Metal AM Parts for A&D – Part 2 DED



– Day 2

Topics	Hours
Process simulation and software tools	0.5
Data preparation for production	0.5
Design exercise	3
Build Preparation Exercise	0.5
Review of DED part issues	0.5
Standards relevant to design for DED	0.5
Design documentation to comply with standards/ traceability	0.5
Maintaining the digital thread	0.5
Future opportunities & challenges	0.5

Course 2 – Design of Metal AM Parts for A&D – Part 2 DED



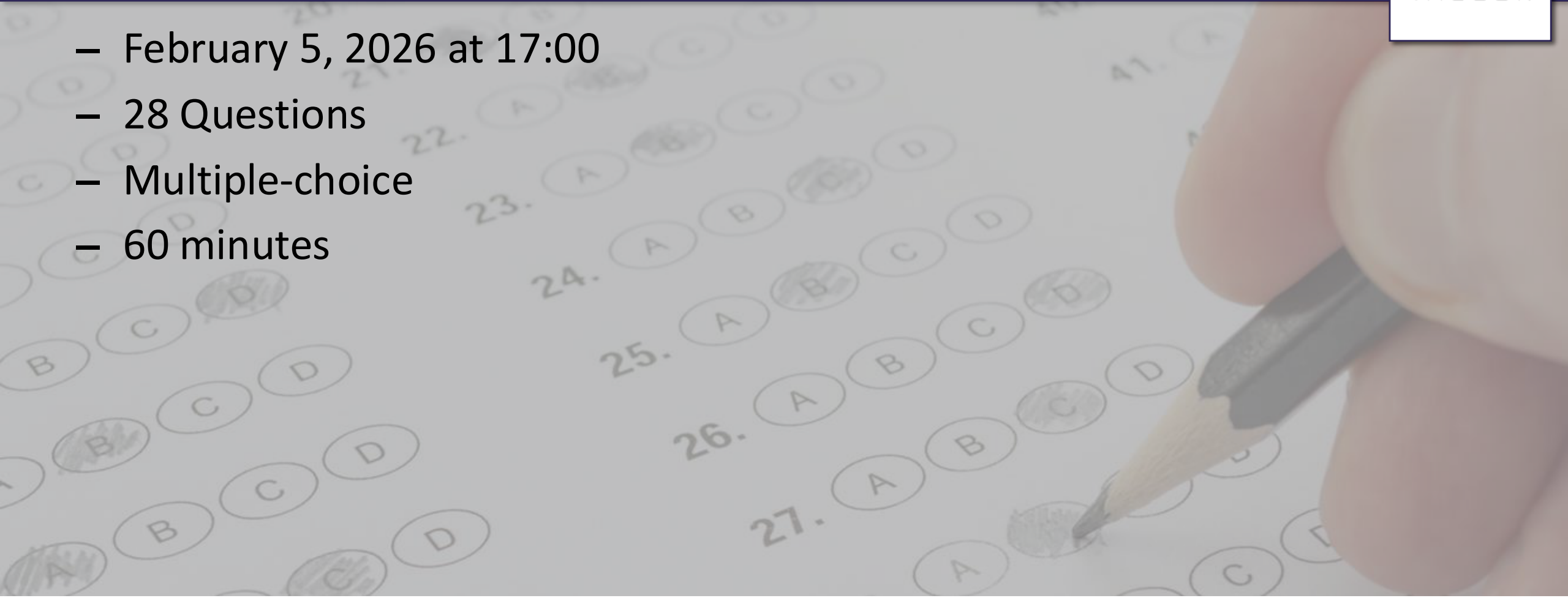
– Day 2

- **Design Exercise and Data Preparation for Production**
 - **Install Rhinoceros3D**
 - 90 Days Free Trial
- **Demonstration of the robotic DED-Arc system**
 - 6 + 2 degrees of freedom

Examination



- February 5, 2026 at 17:00
- 28 Questions
- Multiple-choice
- 60 minutes



Certificate of Completion



CERTIFICATE OF COMPLETION

AILEEN PILOT COURSE

Country, City | timeframe

This certificate is awarded to

for the completion of **insert course name here** organized through the Erasmus+ project AILEEN (Project No. 101103507).

Signature

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PRI Qualification





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Design of Metal AM Parts for Aerospace & Defence – DED

Design Workflow for DED
Introduction to DED
Part Suitability for DED

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ODÜ | **KATAMER**



**TURKISH
AEROSPACE**

Mercantec

IPH

mtc where progress happens

SICNOVA

**Laser
AKADEMIE**

**ASTURIAS HUB
DEFENSA**



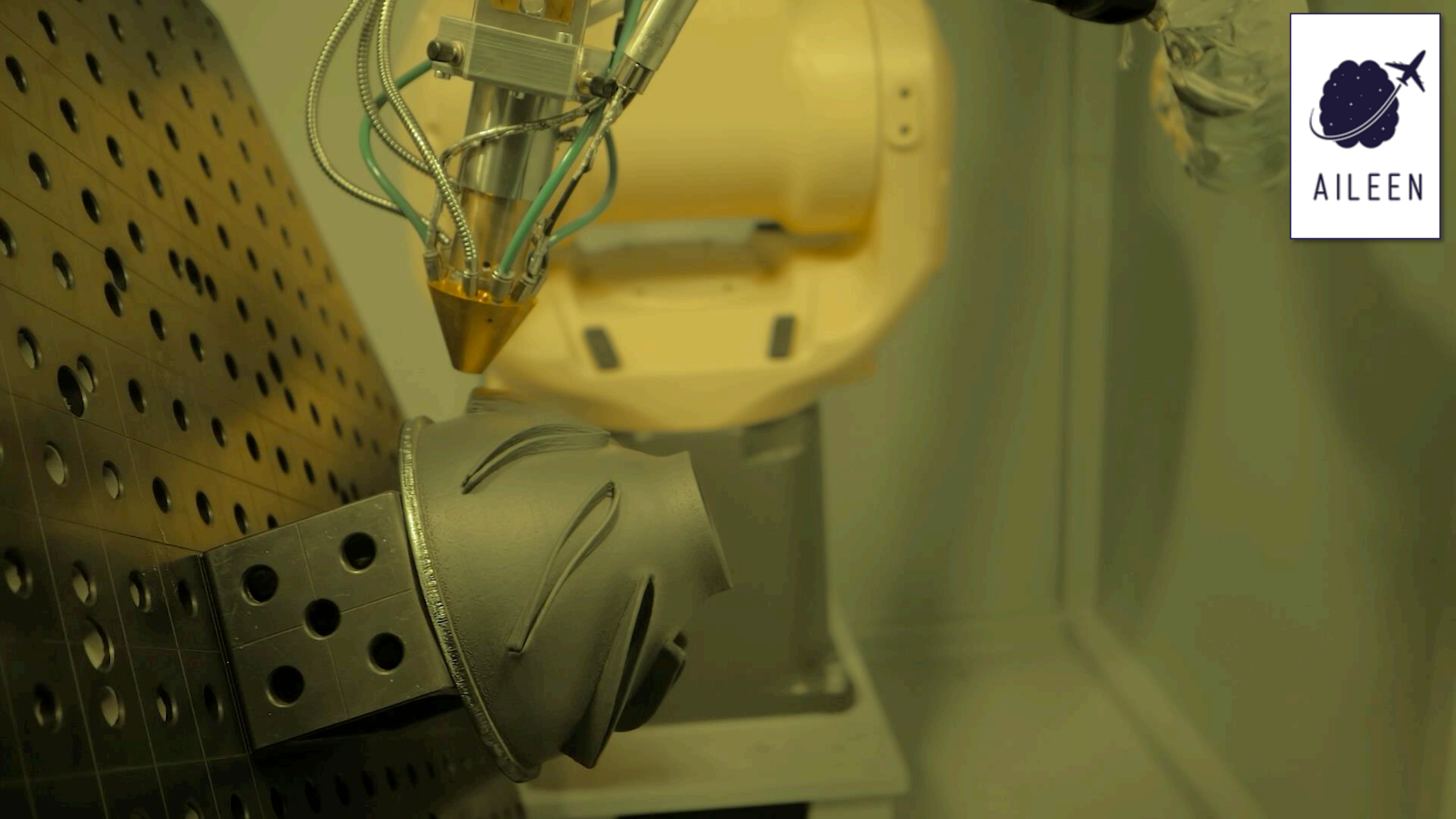
IDONIAL
TECHNOLOGY CENTRE



FAN 3D

**Brunel
University
London**

- Basics
- Overview of the Design Workflow for Metal AM DED
- DED Processes
 - Laser Beam
 - Friction Stir
 - Electron Beam
 - Electric Arc
- Benefits and Drawbacks



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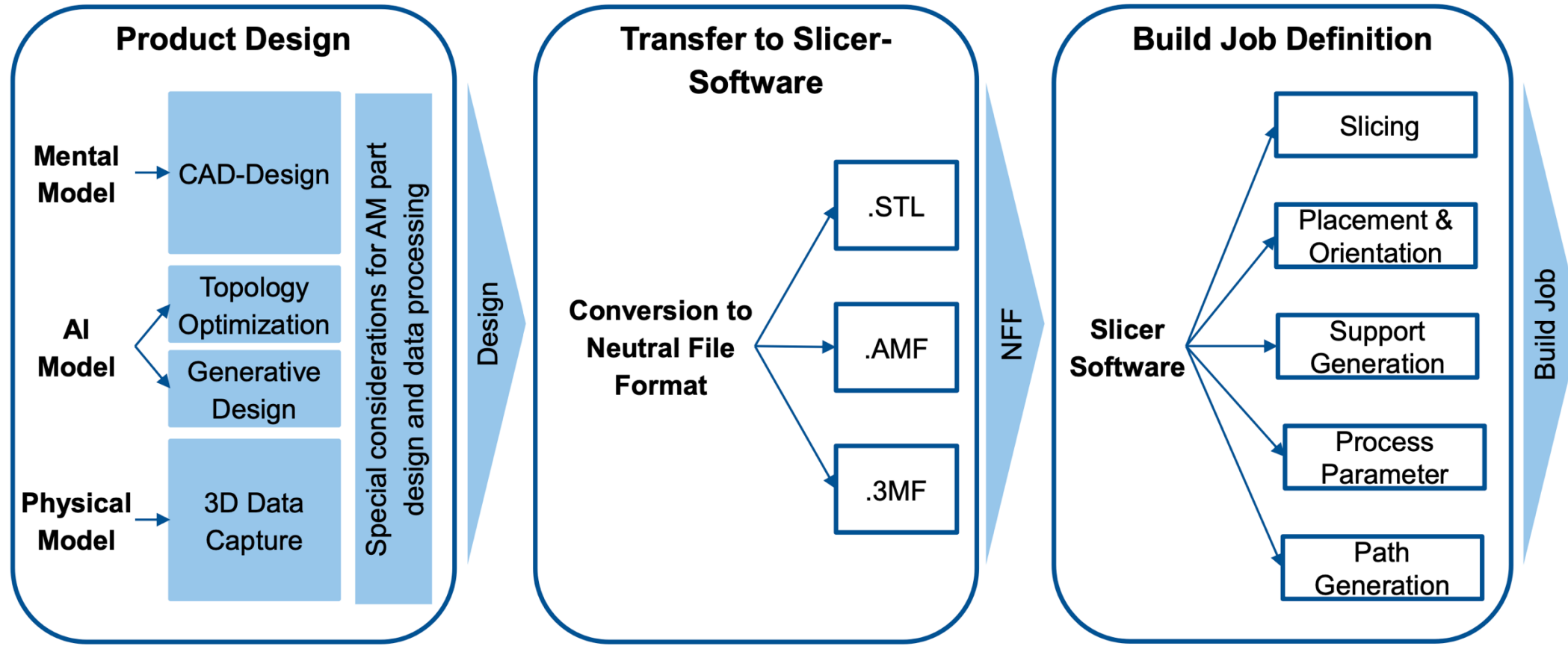
Directed Energy Deposition (DED) Processes



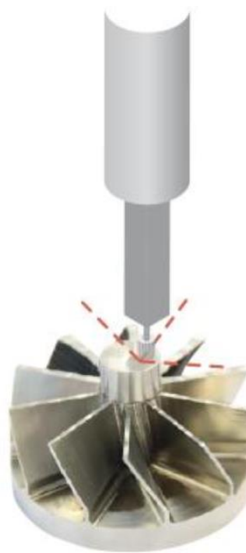
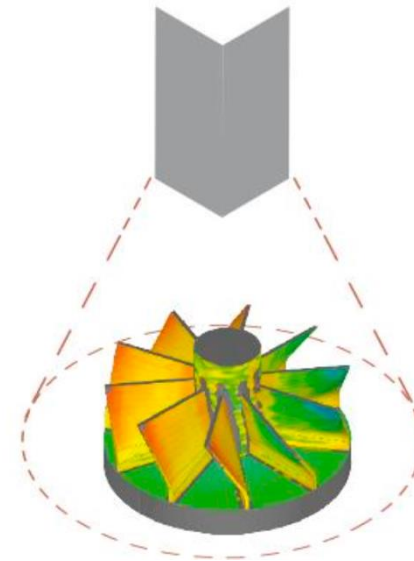
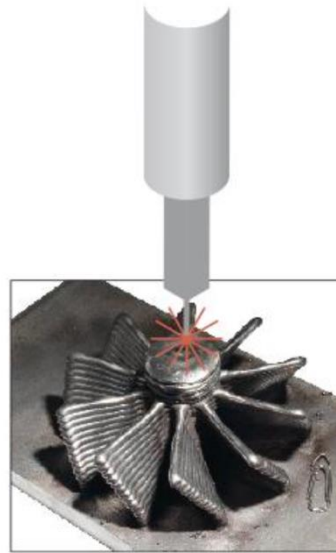
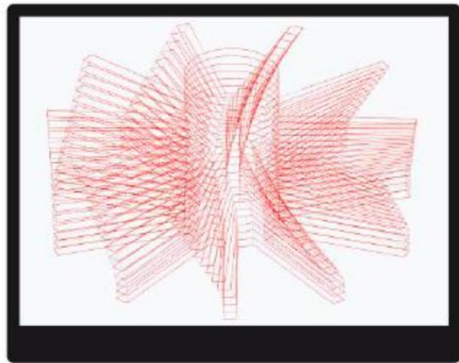
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Overview of the Design Workflow for Metal AM DED



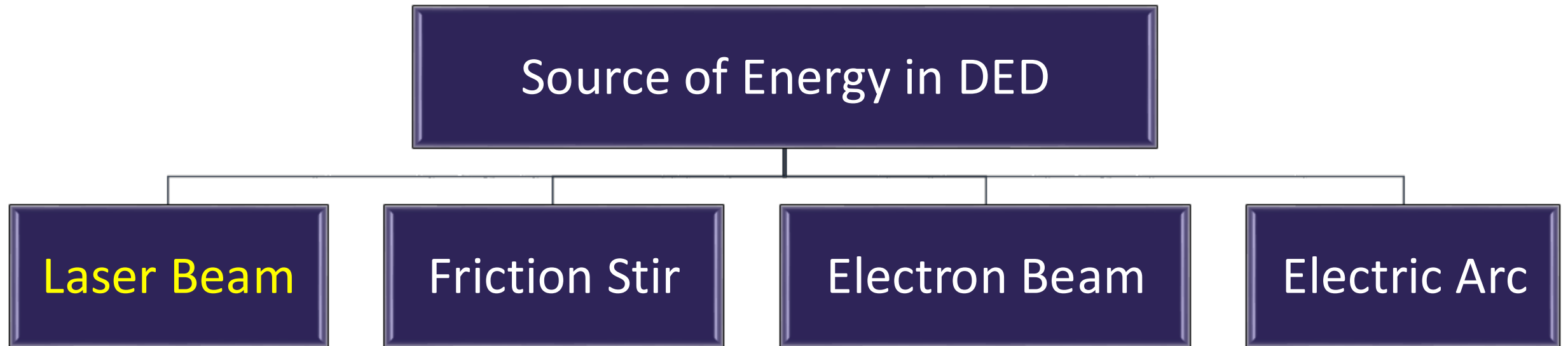
Overview of the Design Workflow for Metal AM DED



Introduction to DED



- Parts are fabricated by **melting** and **deposition** of material from **powder** or **wire** feedstock.
- Mostly used with **metal powders**
 - Metal Deposition
- **Energy** focused into a **narrow region**
- NOT used to melt a material that is pre-laid in a powder bed
- Used to melt materials as they are being deposited (similar to?)



Introduction to DED

- Focused heat source
 - Laser
 - Electron beam
 - Plasma arc
- Complex 3-dimensional geometry requires either **support** material or a **multi-axis** deposition head.
- Dense products
- High surface roughness

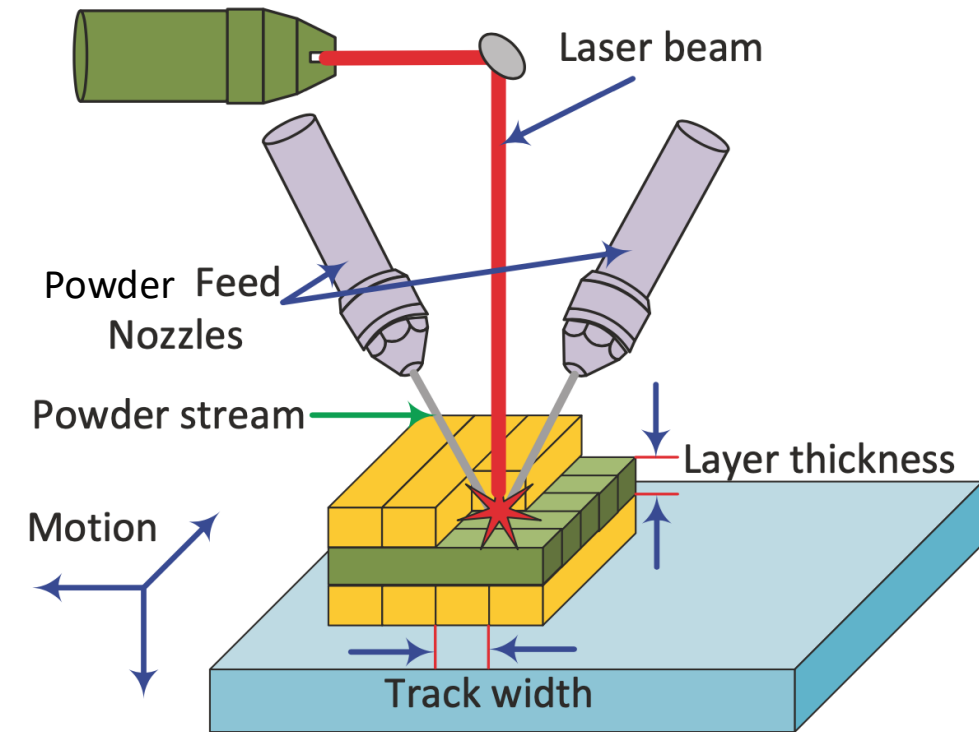


Fig. 10.1 Schematic of a typical beam deposition process [1]

- Laser Engineered Net Shaping (LENS), Directed Light Fabrication (DLF), Direct Metal Deposition (DMD), **Direct Metal Tooling (DMT)**, 3D Laser Cladding, Laser Generation, Laser-Based Metal Deposition (LBMD), Laser Freeform Fabrication (LFF), Laser Direct Casting, LaserCast , Laser Consolidation, LasForm
- Differences in
 - Laser power, laser spot size, laser type, powder delivery method, inert gas delivery method, feedback control scheme, and/or the type of motion control

Introduction to DED

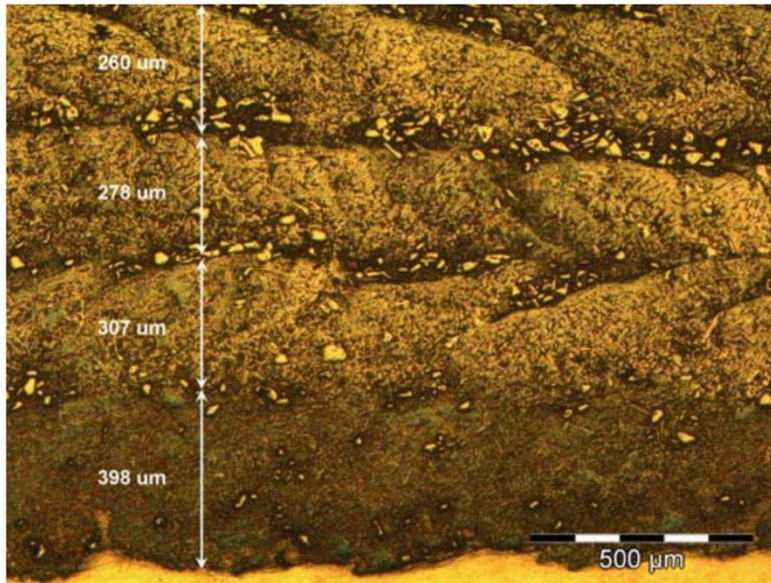


Fig.10.2 LENS-deposited Ti/TiC metal matrix composite structure(4 layers on top of a Ti substrate) [1]

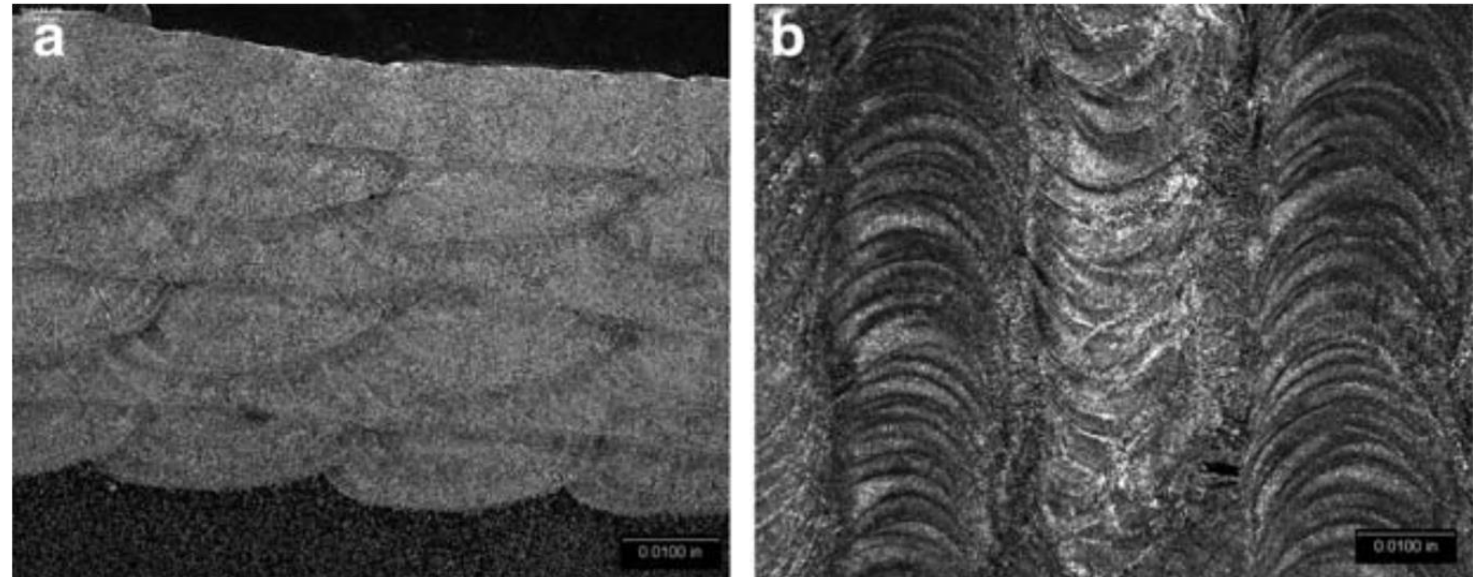


Fig. 10.3 CoCrMo deposit on CoCrMo: **(a)** side view (every other layer is deposited perpendicular to the previous layer using a 0,90,0 pattern); and **(b)** top view of deposit [1]

– Laser-Based Metal Deposition (LBMD)

- Most common type
- Substrate used
 - Flat plate
 - Existing part
- Deposition head
 - Laser optics
 - Powder nozzles
 - Inert gas tubing
 - Sensors



- **Kinetic energy** of powders is **greater** than the effect of **gravity**.
 - Non-vertical deposition is effective.
 - Multi-axis deposition head motion
 - Depending on the desired geometries, the optimum design of a LBMD apparatus changes.
- **Laser** generates a small **molten pool** (0.25–1 mm in diameter and 0.1–0.5 mm in depth) on the substrate as powder is injected into the pool.
- The powder is melted as it enters the pool and solidifies as the laser beam moves away.

Non-vertical Deposition



DED Process Description



- Small molten pool & rapid traverse speed
 - High cooling rates
 - Large thermal gradients
- Depending on the material
 - Unique solidification grain structures
 - Non-equilibrium grain structures
- At lower cooling rates, the grain features grow and look more like cast grain structures.
- 25% overlap
- 0.25–0.5 mm layer thickness

Material Delivery – Powder Feeding



- Available metal and ceramic powders
- **Excess powder** used
- **Recycling** necessary
- E_c , energy density of the beam must be above a critical amount to form a melt pool on the substrate.
- Height and volume of the deposit melt pool depend on
 - Melt pool location with respect to the focal plane, scan rate, laser power, powder flow rate, and surface morphology

Material Delivery – Powder Feeding

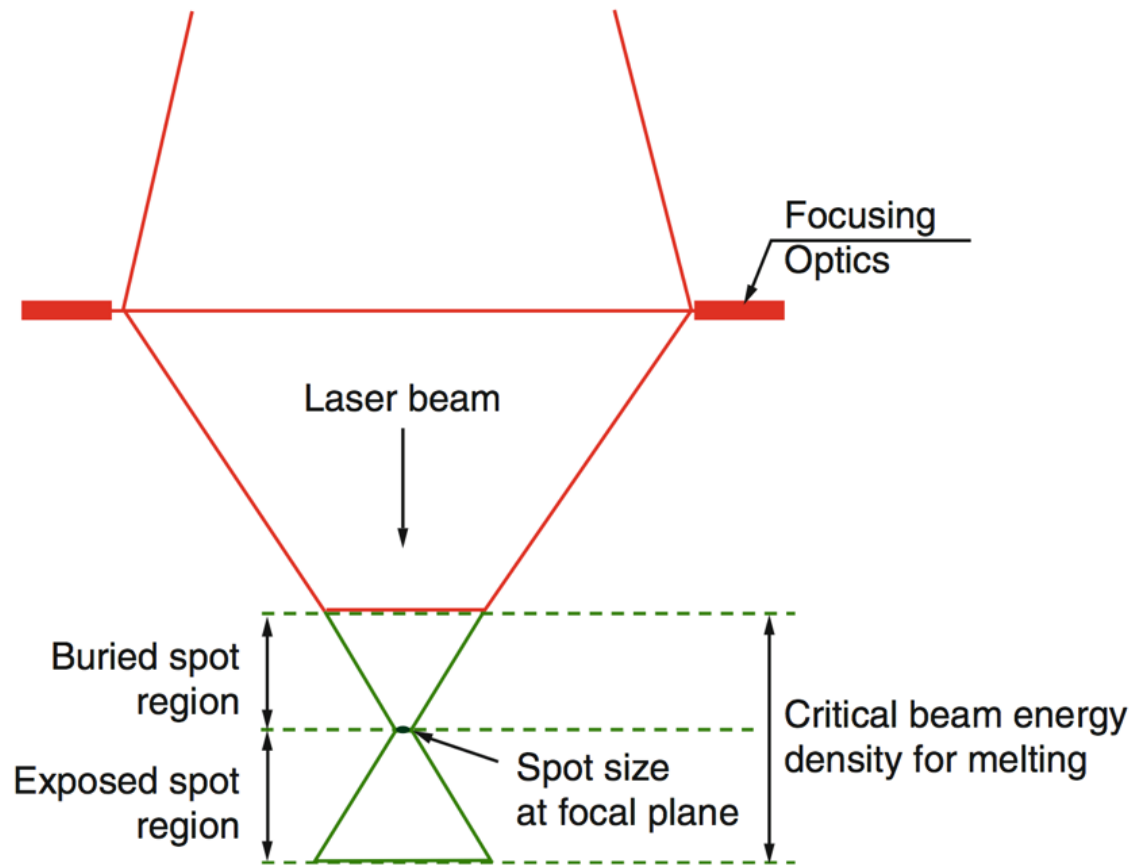


Fig. 10.4 Schematic illustrating laser optics and energy density terminology for beam deposition [1]

Material Delivery – Powder Feeding



- When **parameters** are **not set properly**,
 - Layers may be thinner
 - No deposition after some number of layers
- When the first layer is formed on a substrate, the laser **focal plane** is typically **buried** below the surface of the substrate approximately 1 mm.
- **Powder** is typically **fed** by **first fluidizing** a container of powder material (by bubbling up a gas through the powder and/or applying ultrasonic vibration) and **then** using a pressure drop to **transfer** the fluidized powder from the container to the laser head through tubing.

Material Delivery – Powder Feeding

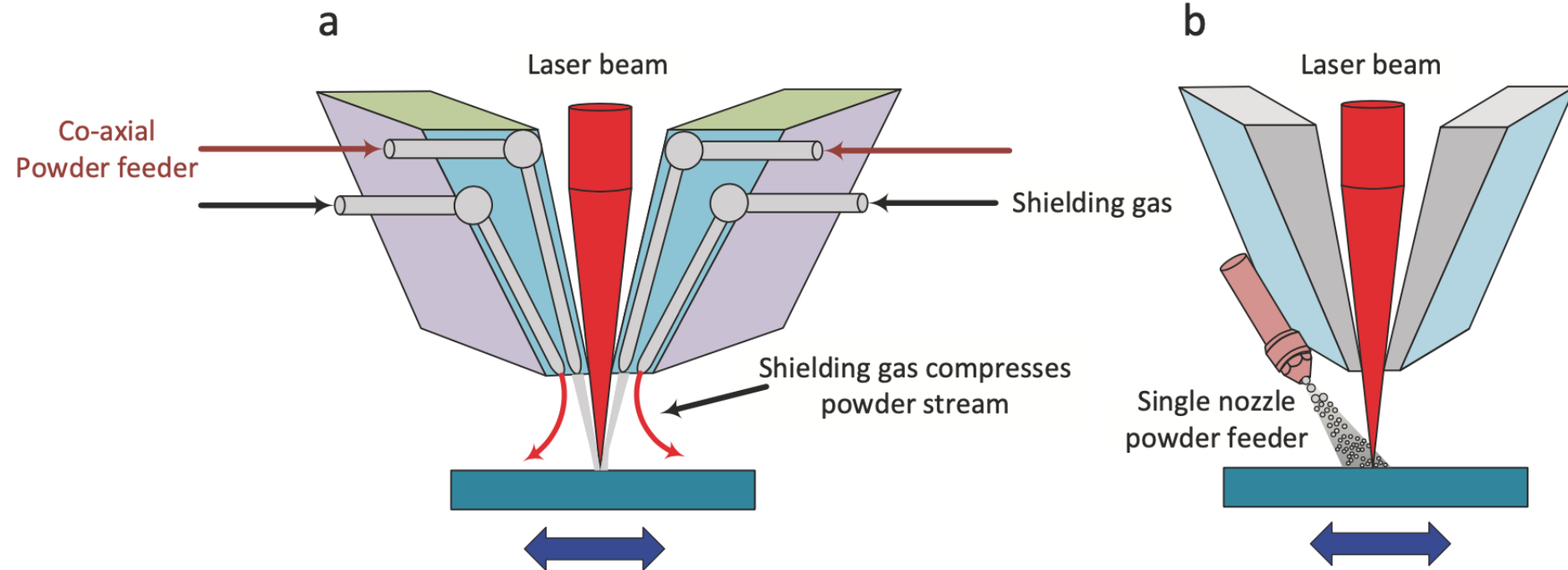


Fig. 10.5 Illustration of powder nozzle configurations:

a) co-axial nozzle feeding

b) single-nozzle feeding [1]

Material Delivery – Powder Feeding



- Co-axial feeding
 - Higher capture efficiency of powder
 - Focusing shielding gas can protect the melt pool from oxidation
- Single-nozzle
 - Apparatus simplicity
 - Better powder capture efficiency than 4-nozzle feeding
 - Ability to deposit material into tight locations
- 4-nozzle
 - More consistency in build height

Material Delivery – Wire Feeding



- The **volume** of the **deposit** is **always equal** to the volume of the **wire** that has been fed.
- **100%** feedstock capture efficiency
- Effective for
 - Simple geometries
 - Coating of surfaces
 - Porous structures
- Feeding systems are determined according to the desired deposit geometries.

Powder Feeding vs. Wire Feeding



Powder-Based DED

- Large variety of available materials
- Contactless process
- Possibility of using two or more powders simultaneously
- Lower material efficiency due to overspray
- Safety requirements and health protection
- Encapsulated system requirement

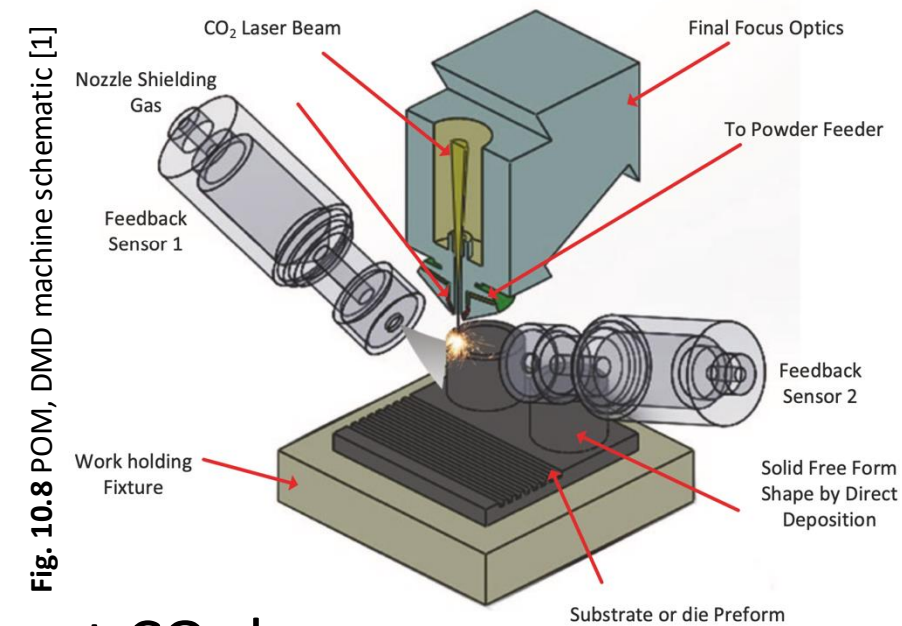
Wire-Based DED

- High material efficiency
- No contamination of machines
- Easier system integration and machine retrofit
- Limited range of materials and alloys
- Complicated process requiring contact while deposition

- First commercialized in 1997 (LENS)
- Process materials in an enclosed inert gas chamber
- 4-nozzle feeder
- Flexible, any powder can be processed.
- Systems for **monitoring build height** and melt pool area can be used to **dynamically change** process **parameters** to maintain constant deposit characteristics (closed loop systems)

DED Systems

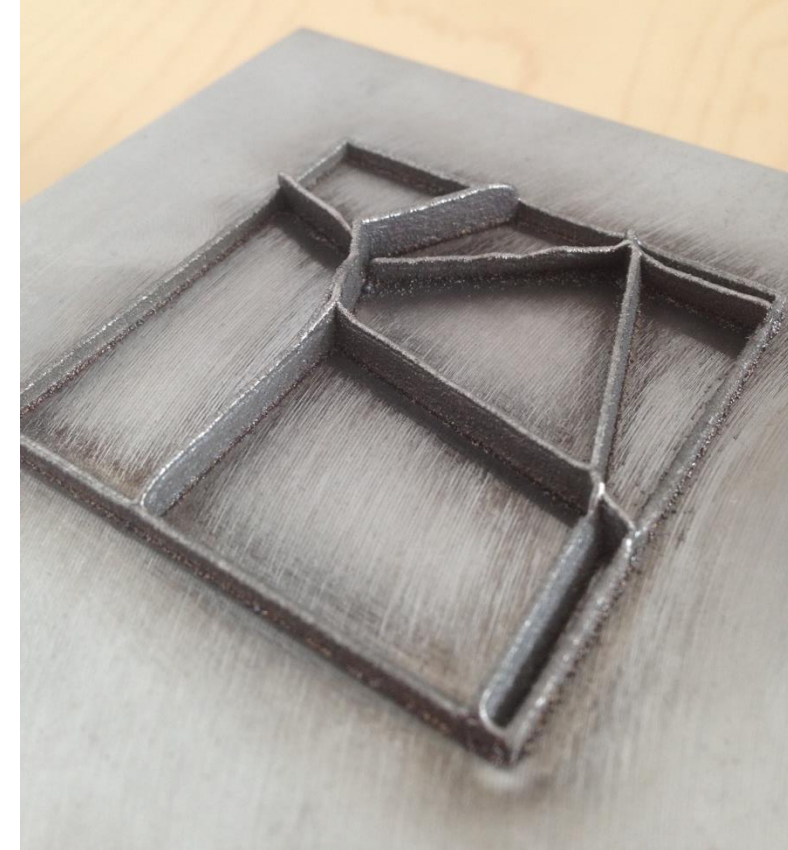
- POM, USA
- 5-axis, co-axial feeding
- Shielding gas
- Closed-loop control system
 - CCD cameras
 - Size of the weld pool
 - Parameters adjusted: powder flow rate, deposition velocity and laser power
- CO₂ laser, absorptivity of most materials is much less at CO₂ laser wavelengths
 - Larger heat affected zone



DED Systems - Closed-loop control system



<http://www.insstek.de/wp-content/uploads/2015/01/insstek-Druckvorgang.jpg>



DED Systems

- AeroMet, USA
- Larger parts
- 18 kW CO₂ laser
- Rib on plate structures
- Decreased manufacturing time for larger parts
- Less precision
- Larger heat affected zone



Fig. 10.9 AeroMet System [1]



Fig. 10.10 Electronics Housing in 316SS

- SLA, FFF, and SLS machines are sold with **optimized parameters**.
- For the DED systems, **users** should **optimize** the parameters according to the material and application.
 - Track scan spacing
 - **Powder feed rate**
 - **Laser traverse speed**
 - **Laser power**
 - Laser spot size

- **Scan patterns**
 - Different orientations at consecutive layers
 - To minimize residual stress build-up
- **Hatch spacing** is set to obtain overlaps
- **Layer thickness** should be less than the melt pool depth
- To control **deposit thickness**, travel speed can be dynamically changed based upon sensor feedback.

Typical Materials and Microstructure



- Metallic and ceramic powders which are stable in molten pool can be used.
- Metals with high **reflectivities** and thermal **conductivities** are **difficult** to process.
- **Weldable** materials are **easier** to process.
- **Ceramics** are more **difficult** to process
 - Ceramic or metal **matrix** composite
- **Gradient** material combinations

Typical Materials and Microstructure

Ti-6-4

Ti-22-23

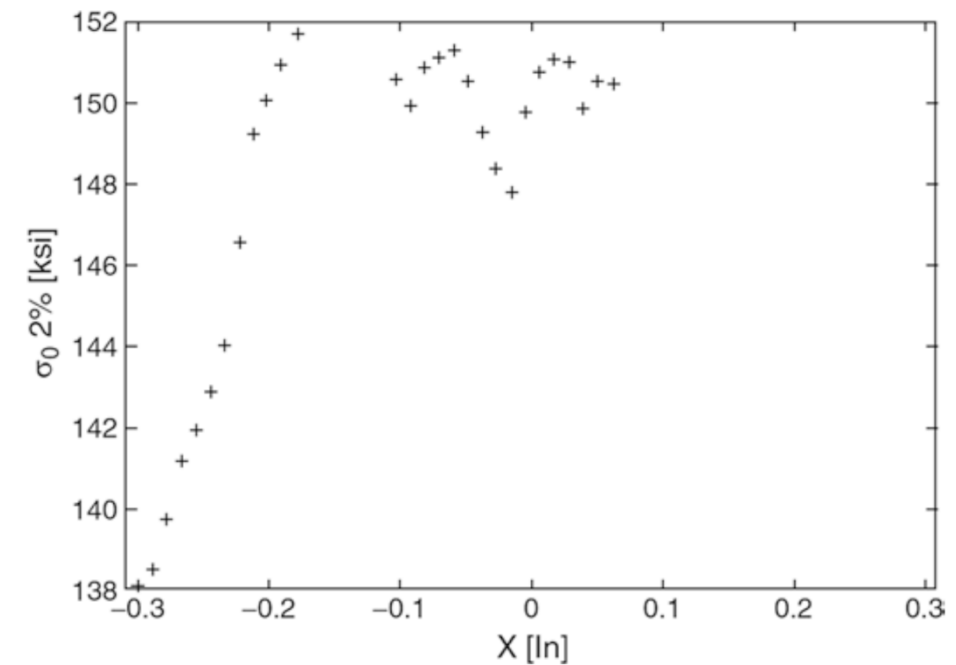
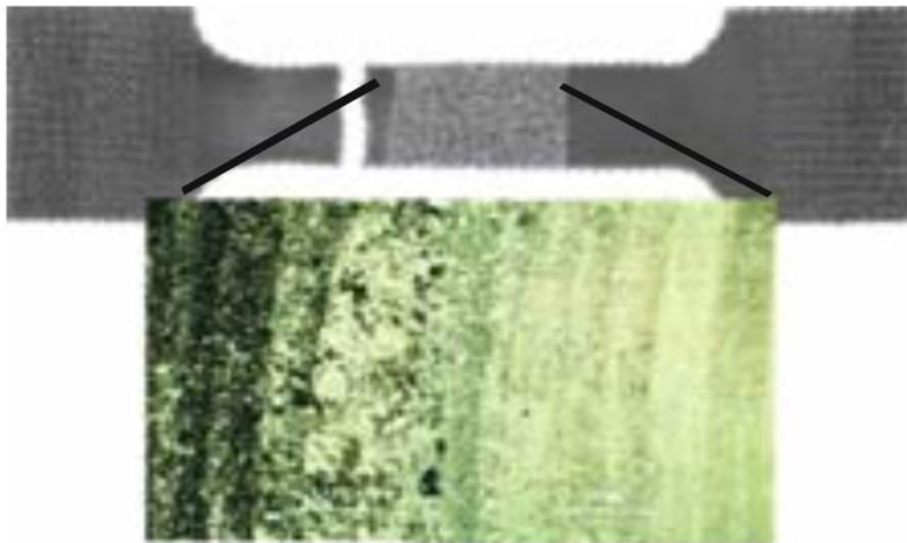


Fig. 10.20 Smooth transition between a 100% Ti-6-4- and 100% Ti-22-23 alloy in the gage section of a tensile bar. The transition region is shown at higher magnification [1]

Typical Materials and Microstructure



- **Advantages of high solidification** cooling rates
 - **Suppression of diffusion** controlled solid-state phase transformations
 - **Formation of supersaturated** solutions and non-equilibrium phases
 - **Formation** of extremely **fine microstructures** with dramatically reduced elemental segregation
 - **Formation** of **very fine** secondary phase particles
- The **thermal history** can be **different** at each point in a part, leading to phase transformations and a variety of microstructures.

no visible porosity

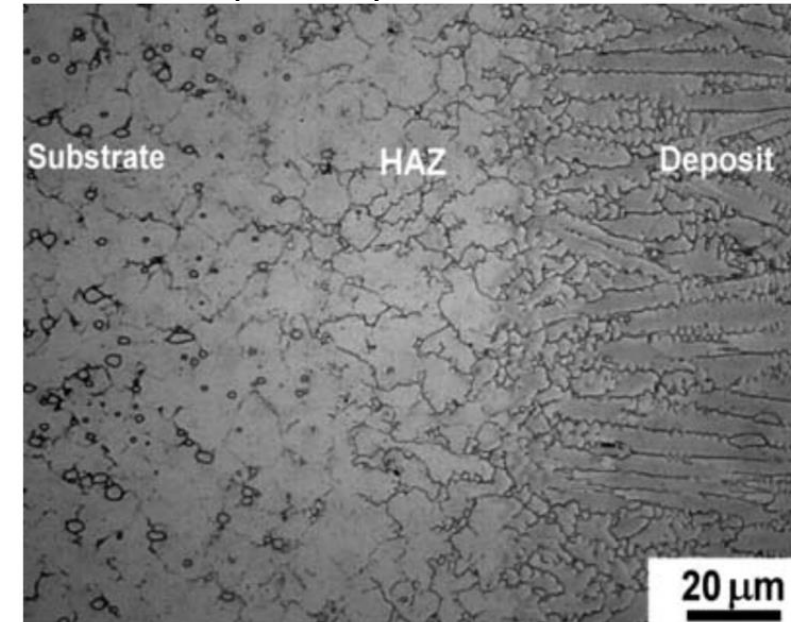


Fig. 10.22 CoCrMo LENS deposit on a wrought CoCrMo substrate of the same composition (deposit occurred from the right of the picture) [1]

Typical Materials and Microstructure

- **Residual stresses** due to solidification
 - **Cracks** during or after the fabrication
- Significant **problem** when dealing with metallurgically **incompatible dissimilar material** combinations.
- Thin **interlayers** are utilized to overcome this issue.
- **Superior** yield and tensile strengths because of their fine grain structure
- **Worse** ductility

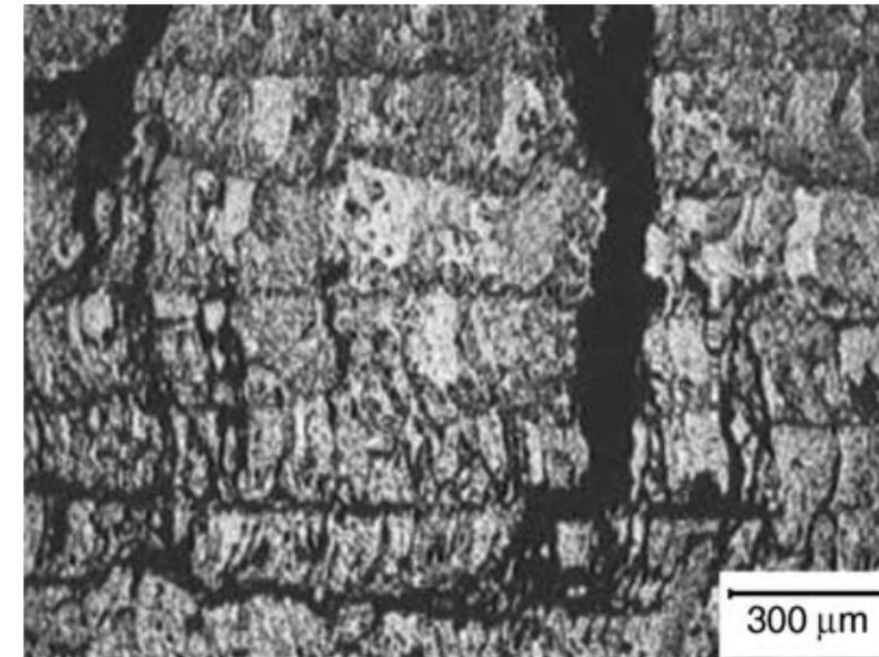
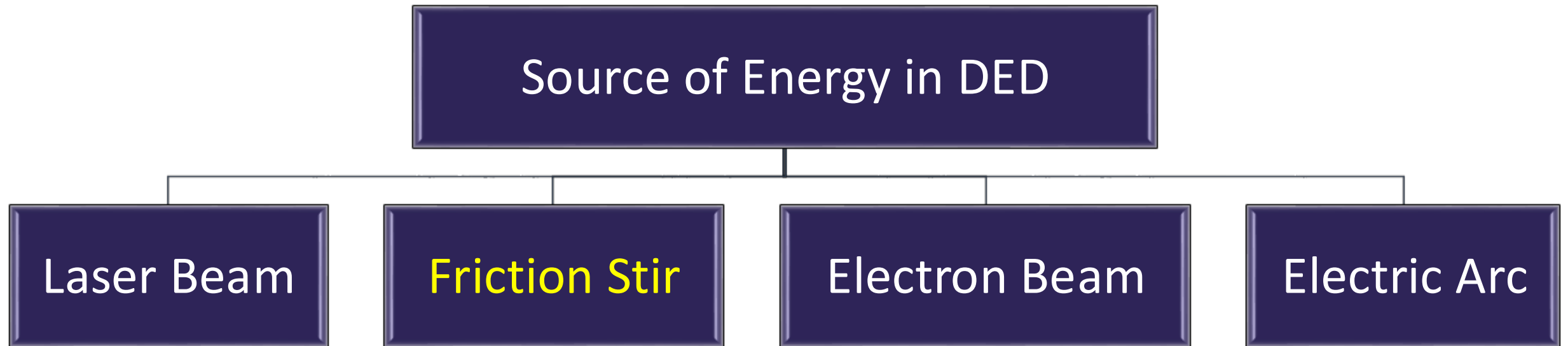


Fig. 10.23 Cracks in a TiC LENS deposit due to residual stresses [1]

Processing–Structure–Properties Relationships



- Cast microstructures
- Solidification microstructure depends on **local** solidification **conditions**
 - Solidification rate
 - Temperature gradient at the solid/liquid interface
- By calculating these variables, the microstructure can be predicted based upon calibrated solidification maps.



Friction Stir Additive Manufacturing (FSAM)



- Commercialized by MELD Manufacturing
- **Solid-state process** which works below the melting temperature
- **Not technically** a DED process
- More **similar** to DED than other AM techniques
- **Plastically deforms** or softens metal feedstock while simultaneously depositing that feedstock in a layer-wise fashion
- Performed in **open atmosphere**

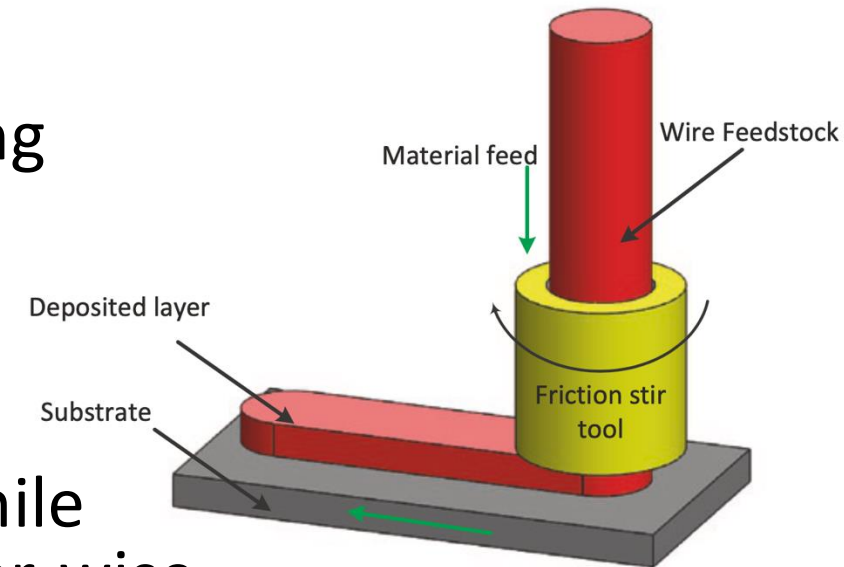


Fig. 10.18 Schematic of FSAM [1]

<https://www.youtube.com/@meldmanufacturing325>

Friction Stir Additive Manufacturing (FSAM)



- Process **un-weldable** materials
- **Low** processing **temperatures**
 - **Low residual** stresses
 - **High density** with significantly low process energy
 - **Less** chance of thermally induced **porosity**
- **Lower demand** for expensive and time-consuming **post-processes**
- Produces small grains, thus **improving mechanical properties** such as hardness, corrosion, and wear resistance as well as tensile strength

Friction Stir Additive Manufacturing (FSAM)

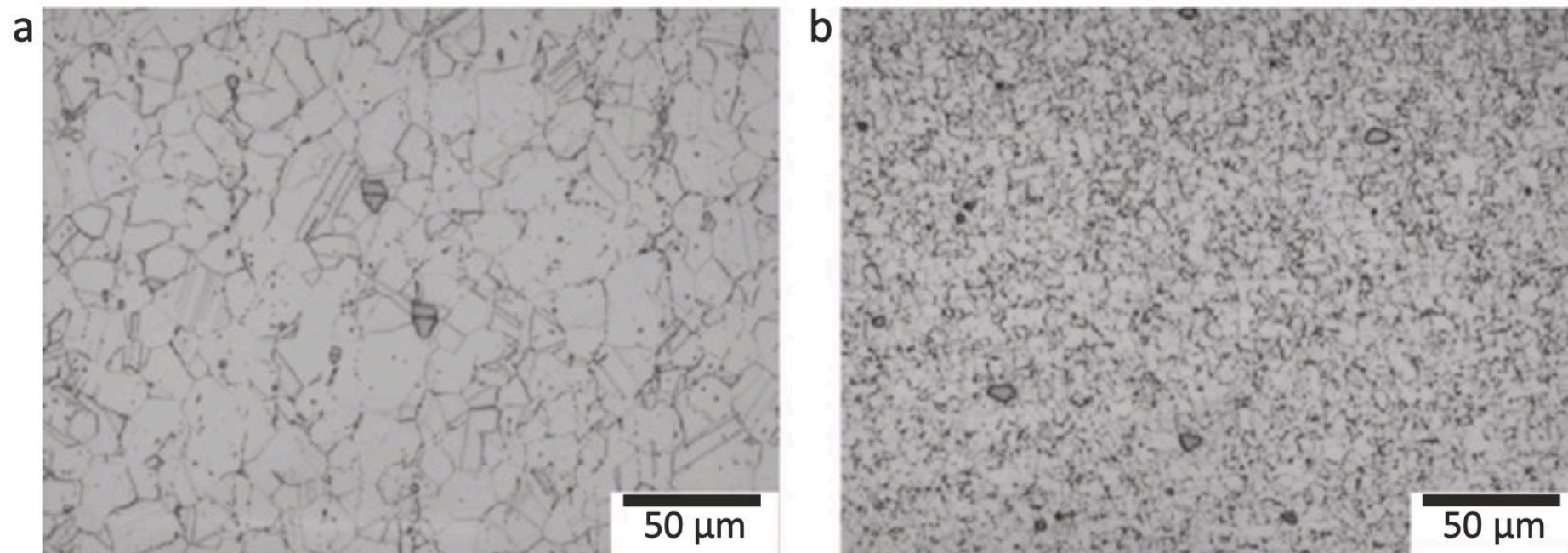
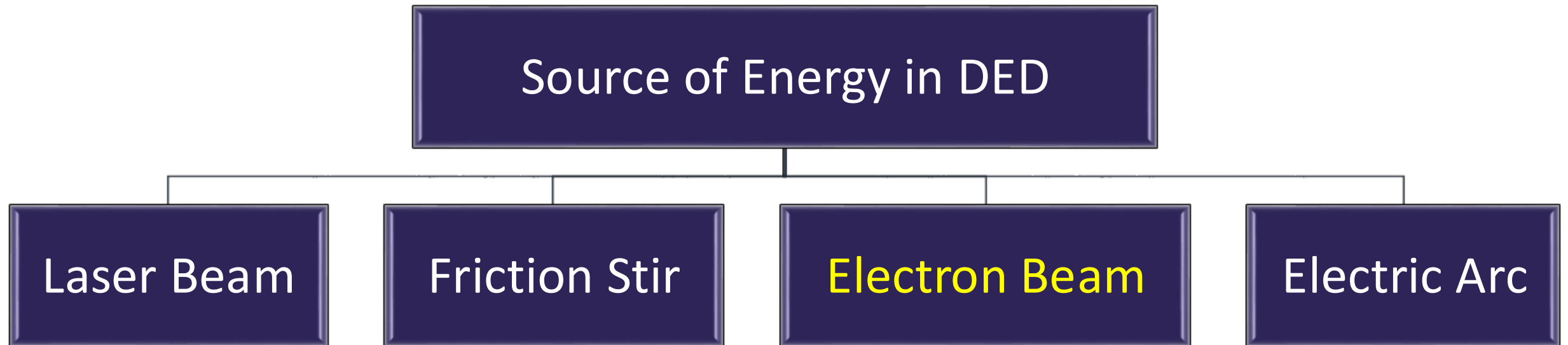


Fig. 10.19 Microstructure of Inconel 625 (a) before and (b) after FSAM [1]



Electron Beam Based Metal Deposition Processes

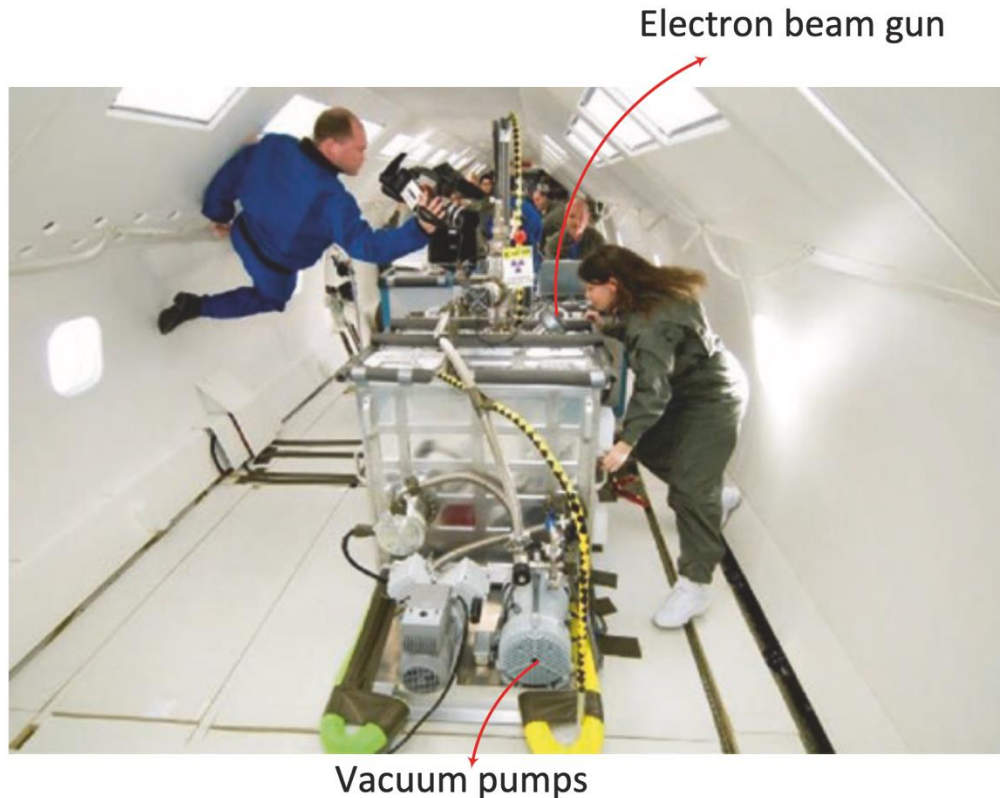


Fig. 10.12 NASA engineers test the EBF³ system during a parabolic flight in 2007 [1]

- NASA's Langley Research Center
 - 2007
 - Electron Beam Freeform Fabrication (EBF³)
 - Rapid deposition under high current flows or better accuracy using slower deposition rates
 - Wire feeding is preferred. **Why?**
- Post-processing and surface treatment
- Sciaky

<http://www.sciaky.com/additive-manufacturing/applications-industries>

Electron Beam Based Metal Deposition Processes

- Almost 100% efficiency in feedstock consumption
- 95% efficiency in power usage
- Highly reflective materials (Al, Cu, etc.)
- High production rate of 2500 cm³/hr
- Used to produce Ti parts for vertical tails of the F-35

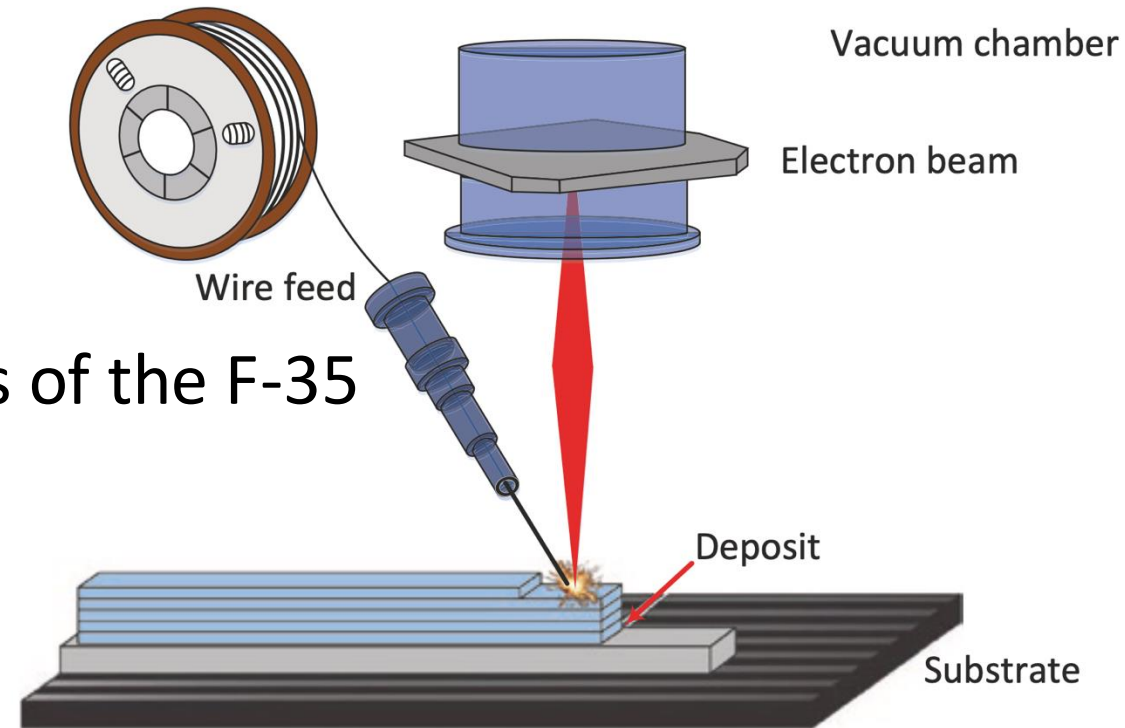
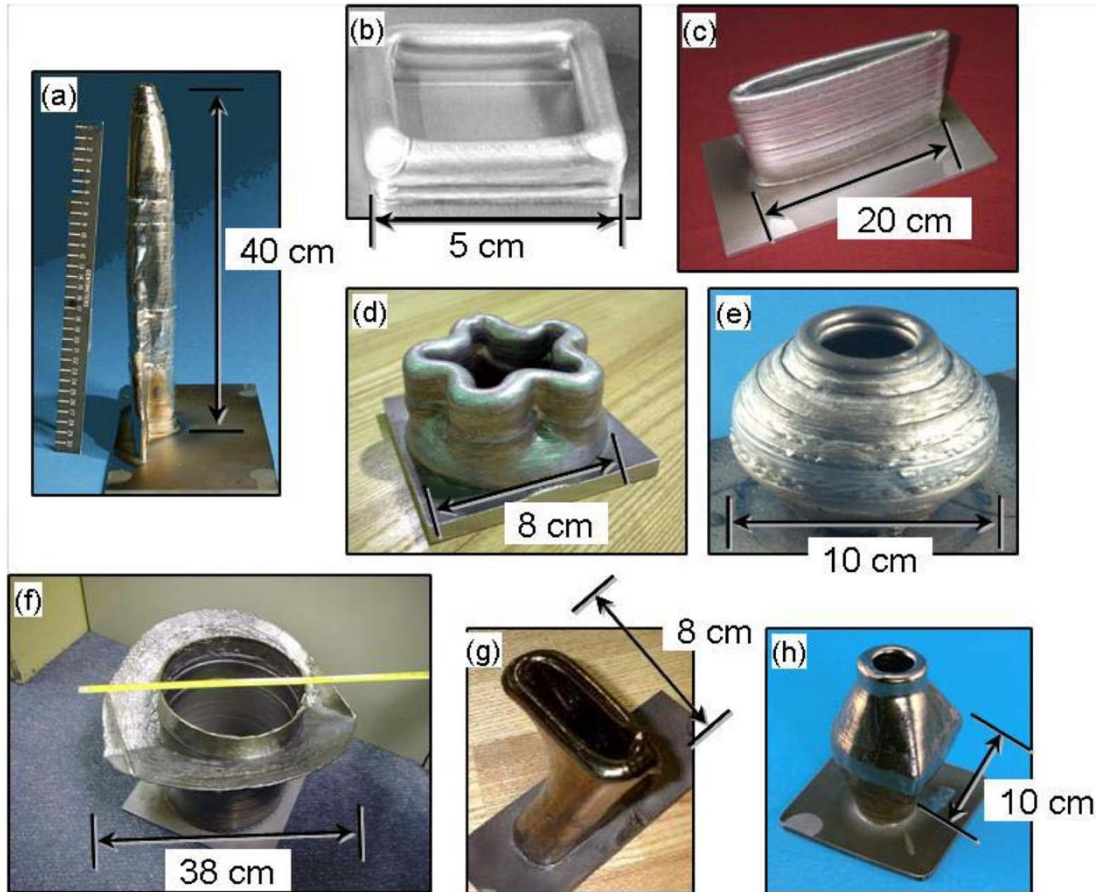


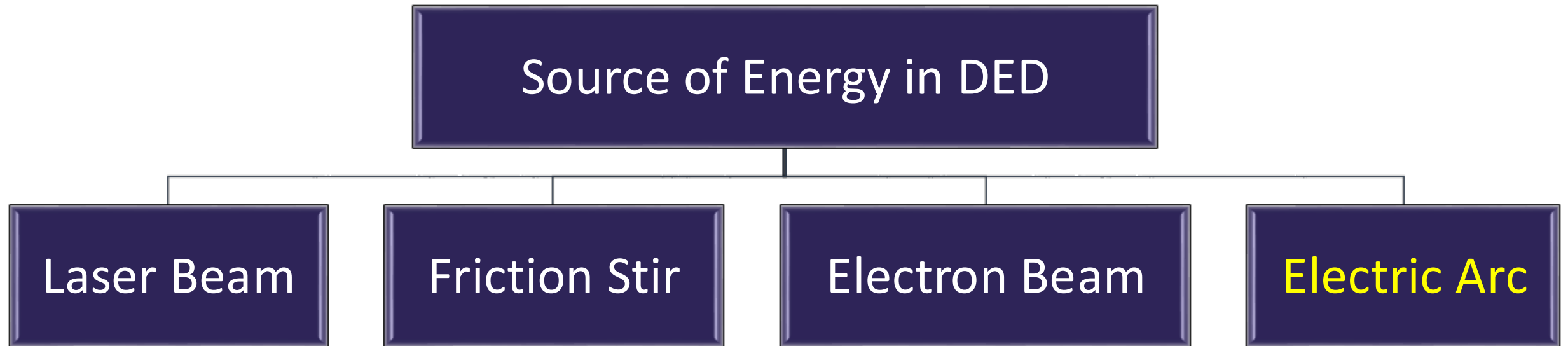
Fig. 10.15 Schematic of EBF³ components [1]

Electron Beam Based Metal Deposition Processes



- Examples of parts
 - a) Ti-6-4 wind tunnel model
 - b) 2219 Al square box
 - c) 2219 Al airfoil
 - d) 2219 Al mixer nozzle
 - e) 2219 Al converging diverging nozzle
 - f) Ti-6-4 guy wire fitting
 - g) Ti-6-4 inlet duct
 - h) Ti-6-4 truss node with flat attachment surface.

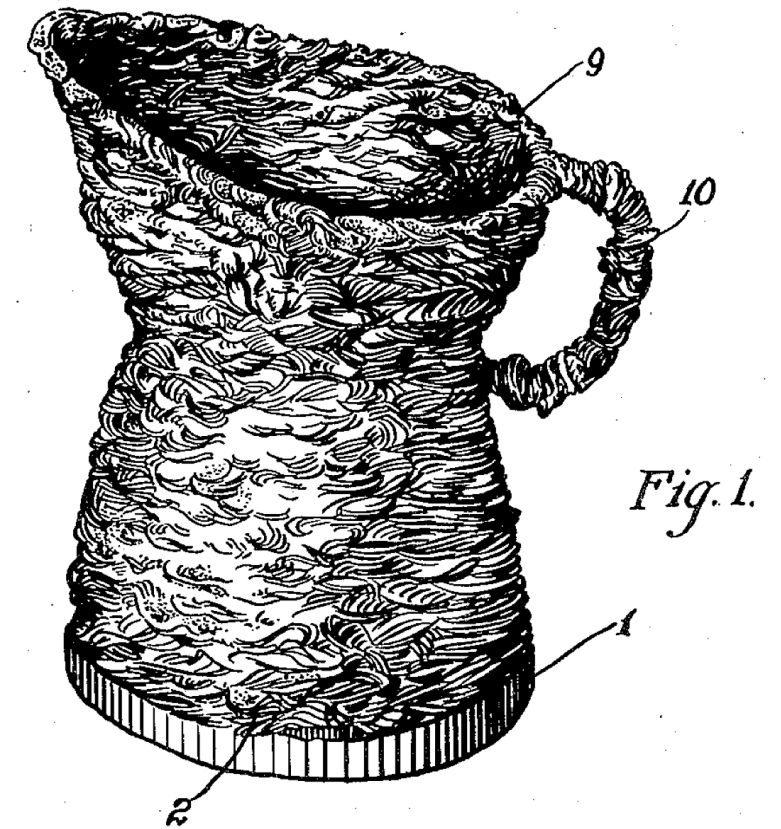
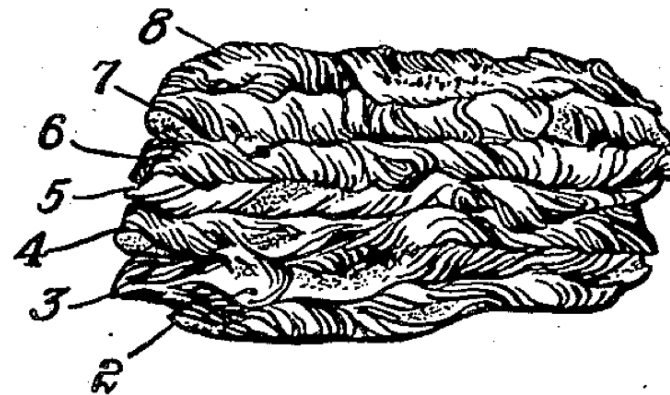
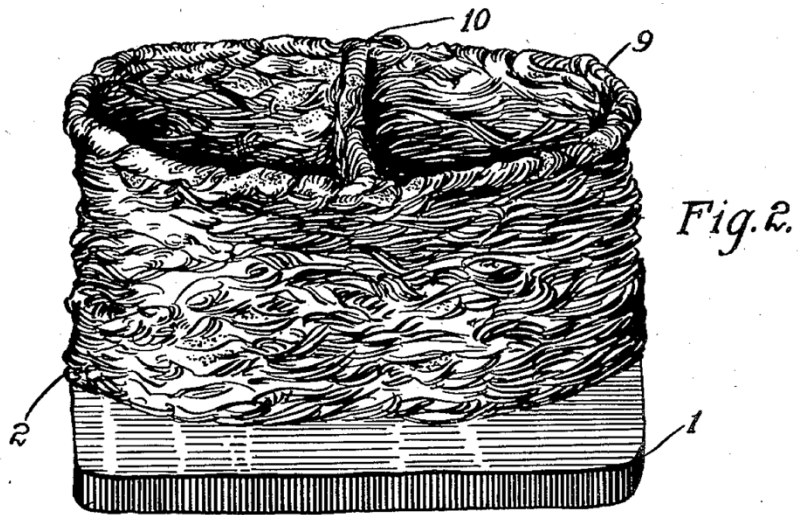
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Wire Arc Additive Manufacturing (WAAM)

– Method of Making Decorative Articles

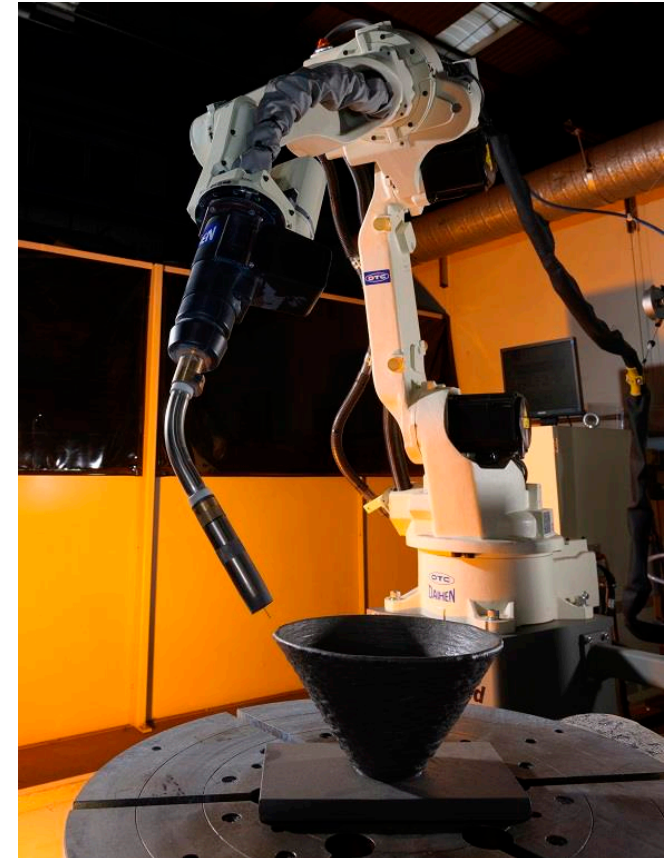
- April 14, 1925
- Ralph Baker



Wire Arc Additive Manufacturing (WAAM)

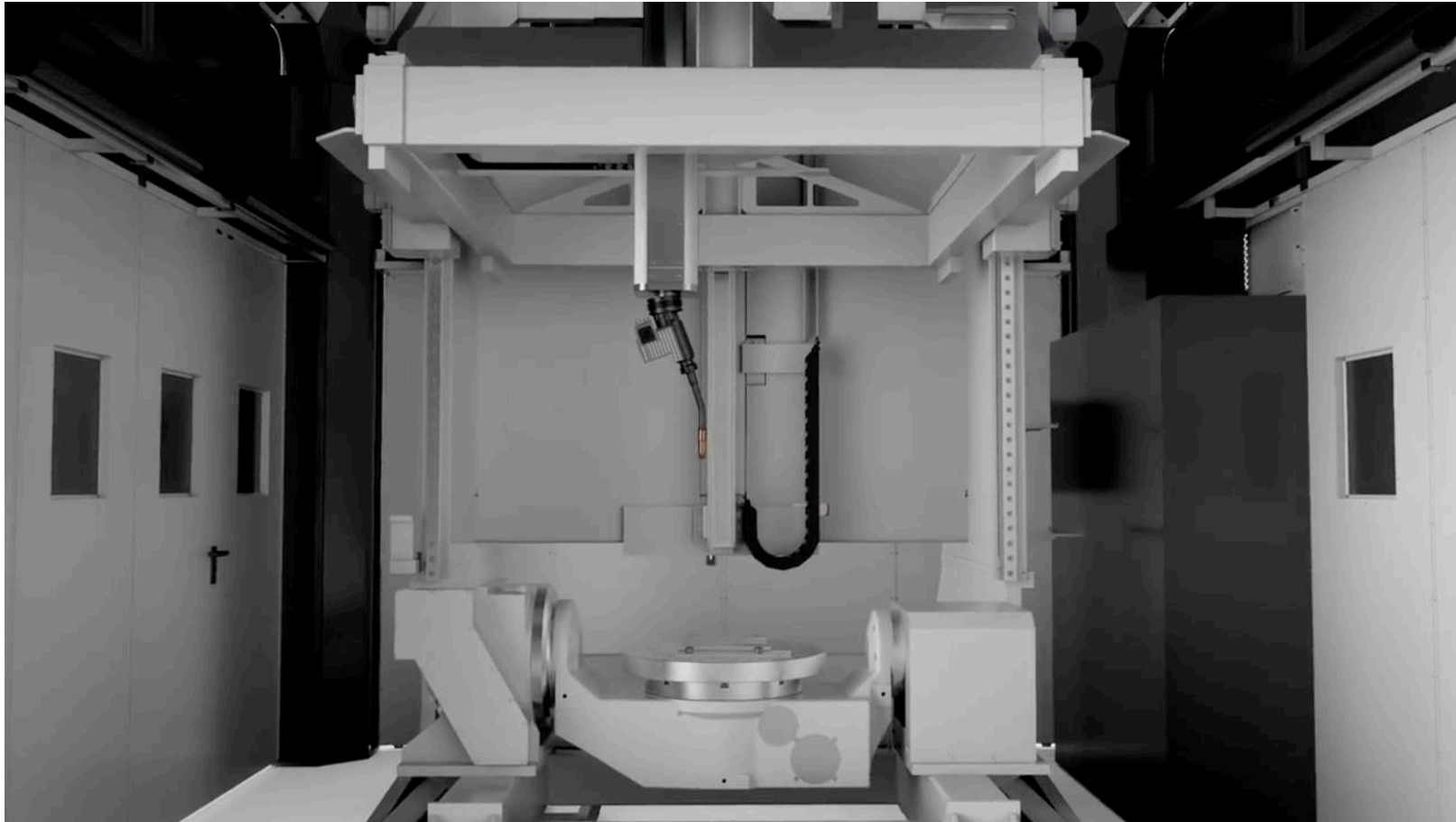


- Gas Tungsten Arc Welding (**GTAW**)
- Gas Metal Arc Welding (**GMAW**)
- **Cost and lead time reduction** for medium-to-large scale engineering components of medium complexity
- **Not a net-shape** or fully automated process
- **Machining** to achieve geometrical or surface finish requirements



<https://www.twi-global.com/image-library/JK137-figure1.jpg>

Wire Arc Additive Manufacturing (WAAM)



Wire Arc Additive Manufacturing (WAAM)



Gross Weight	300 kg	22,5 kg
Buy-to-Fly	20:1	1,5:1
Material Loss	285 kg	7,5 kg
Semi-finished Product Costs	€20.000	€2.500
Lead Time	Weeks - Months	Days

Hybrid DED Systems



<https://youtu.be/ruTo9hIYQGw>

Post Processing for DED



- Highly used in metal AM methods
 - **Tailor** mechanical properties
 - **Reduce** residual stresses
- Selection of post-processing method **depends** on
 - Target material
 - Manufacturing method
 - Working temperature
 - Heat treatment conditions
- **Heat treatment** improves **strength** and enable **grain refinement**.

- **Fully-dense** parts with highly **controllable microstructural** features
- **Functionally graded** components with composition variations in the X, Y and Z directions
- Producing **directionally solidified** and **single crystal structures**
- **Repairing** and **refurbishing** defective and service damaged high-technology components such as turbine blades
- DED can be used to deposit thin layers of dense, corrosion resistant and **wear resistant** metals on components to improve their performance and lifetime
- **Tensile properties** can be **equivalent** to or sometimes **better** than traditionally processed materials.

DED Benefits



- **Higher deposition rates** compared to Powder Bed Fusion systems
- Suitable for **large parts**
- Net shape or near-net shape
- **Greater design freedom** with multi-axis DED systems
- High **TRL**
- Reduction in **lead-time**
- Reduced **waste**
- Manufacturing in **zero-gravity** environment

DED Drawbacks



- Poor resolution and surface finish
- Shrinkage: residual stress and deformation may occur due to local temperature differences.
- Slower build speed for powder-based systems
- Cannot produce as complex of structures as PBF processes
 - Support structures
 - Multi-axis heads
- Post-processing
- Finishing operations required
- More detailed process planning

References



- 1) Gibson, Ian, et al. *Additive manufacturing technologies*. Vol. 17. Cham, Switzerland: Springer, 2021.
- 2) Prof. Dr.-Ing. Katrin Wudy, Data Preparation and Design in AM, TUM, 2024.
- 3) Prof. Dr. Peter Mayr, Directed Energy Deposition, TUM, 2024.



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Design of Metal AM Parts for Aerospace & Defense – DED

Design for DED

Prof. Dr. Ulaş Yaman

Welding Technology and NDT Center

Middle East Technical University



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Outline



- Design for Manufacture
- Design for Additive Manufacturing
- Design for Directed Energy Deposition
 - Things to consider
 - Examples
 - Related Standards

Design for Manufacture (DfM)



- **Designers** should **tailor** their **designs** to **eliminate** manufacturing **difficulties** and **minimize** manufacturing, assembly, and logistics **costs**.
- Practice of designing products to **reduce**, and hopefully **minimize**, manufacturing and assembly **difficulties** and **costs**
- Requires **extensive knowledge** of
 - manufacturing and assembly processes
 - supplier capabilities
 - material behaviors
- Although it is conceptually simple, it can be difficult and time-consuming to apply.

Design for Manufacture (DfM)



- DfM efforts
 - Industry practices, including reorganization of product development using integrated product teams, concurrent engineering
 - Collections of DfM rules and practices
 - University research in DfM methods, tools, and environments

Elimination of Conventional DfM Constraints



- Additive Manufacturing **reduces** the **burden** on organizations to have integrated product development teams that spend large amounts of time resolving constraints and conflicts.
- Designers must **learn** far **fewer** manufacturing **constraints**.
- Designers have much **greater** design **freedom**.
- In AM, designers have **difficulties** in thinking about **products** in **unconventional** ways.

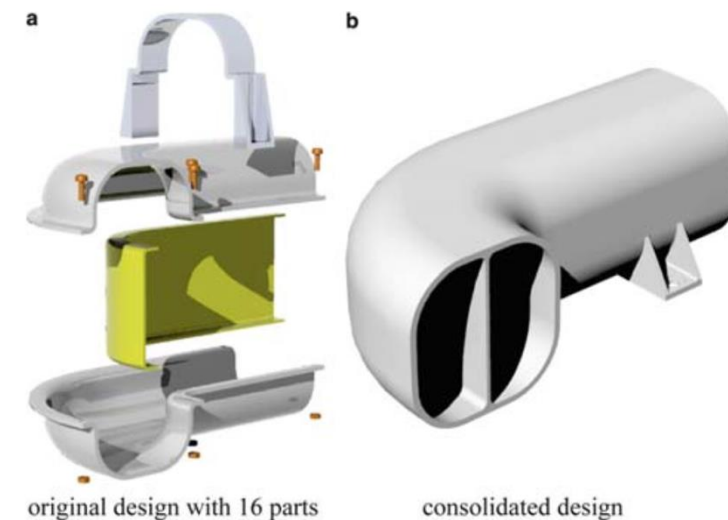


Fig. 17.2 Aircraft duct example [1]

Design for Additive Manufacturing (DfAM)



- Objective
 - **Maximize** product **performance** through the synthesis of
 - shapes,
 - sizes,
 - hierarchical structures,
 - material compositions,
 - subject to the **capabilities** of **AM** technologies

Design for Directed Energy Deposition (DfDED)



– Consider

- Function
- Customer requirements
- Mechanical loads
- Energy source
- Process resolution
- Degrees of freedom
- System configuration
- Multi-axis deposition
- Support structures
- Substrate/build platform position
- Work holding and fixturing
- Build orientation
- Bead geometry
- Geometric features

– Consider

- Feedstock materials
- Substrate materials/thickness
- Microstructures
- Distortion
- Stress management
- Surface quality
- Mechanical properties
- Dimensional accuracy
- Post-processing
- Assembly
- Non-destructive Testing (NDT)
- Cost
- Sustainability

Function



- What is the main purpose of the part?
- What are the requirements?
 - High temperature
 - Low temperature
 - Fatigue
 - etc.
- What are the loads?

System



- Which type of energy source is used?
- How many degrees of freedom the system has?
- How is the system configured?
- Does the system have multi-axis deposition capabilities?
- What is the minimum feature size?

Platform	Energy Source	Environment	Feedstock
Robot	Laser Beam	Inert Gas	Powder
Robot – Rotary Table – Rail	Electron Beam	Vacuum	Wire
3 or 5-axis Machine Tool	Electric Arc	Active Gas	
Gantry	Friction Stir	Open	

[2]

System



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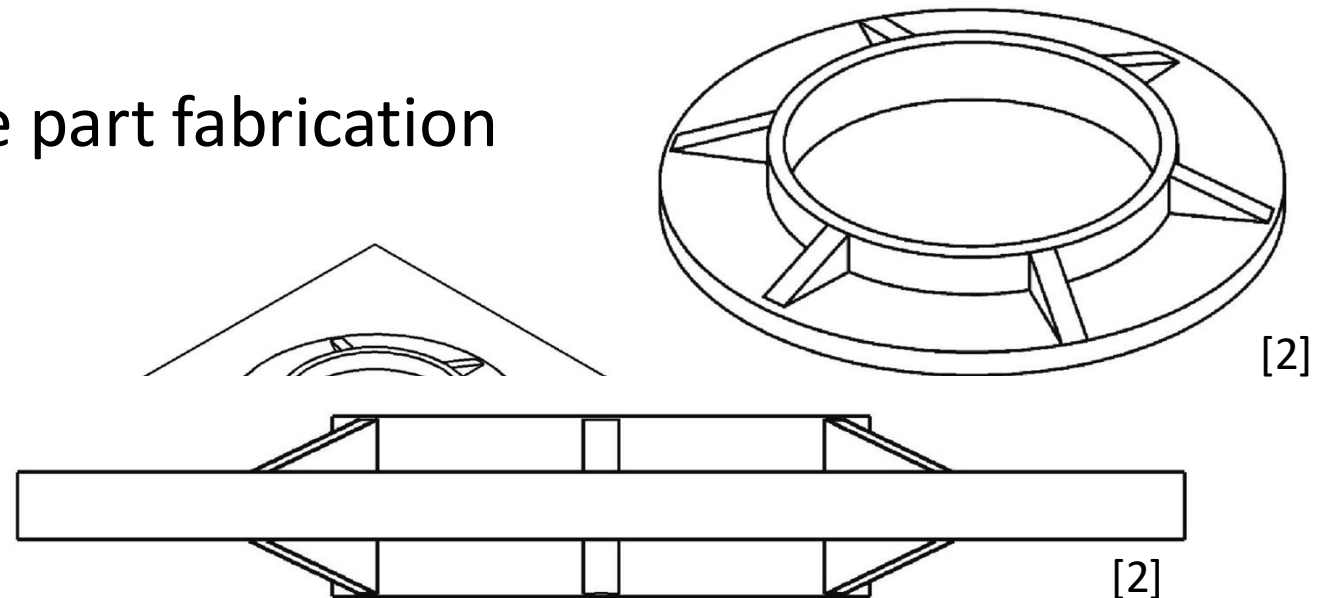
Process	Build Volume	Detail Resolution	Deposition Rate	Coupling Efficiency	Potential for Contamination
Laser Directed Energy Deposition					
Electron Beam Directed Energy Deposition					
Arc Plasma Directed Energy Deposition					
Lower					Higher
This table is intended as a general guide. Variations in individual systems and process advancements may affect the characteristics of each process.					

[3]

Build Options and Variations



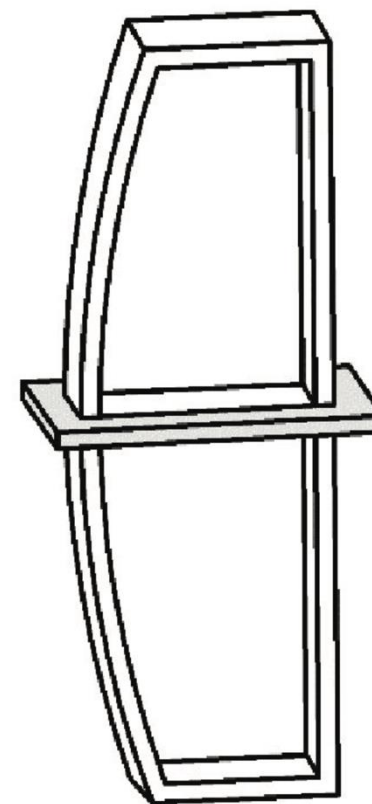
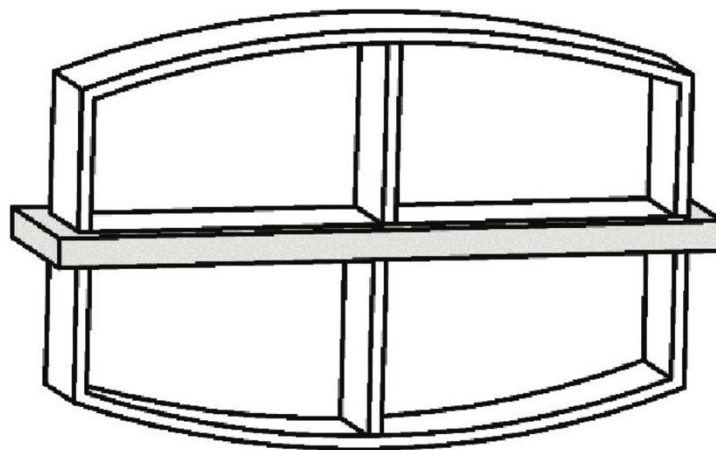
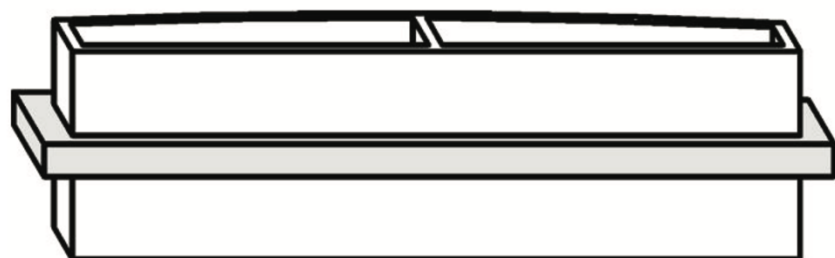
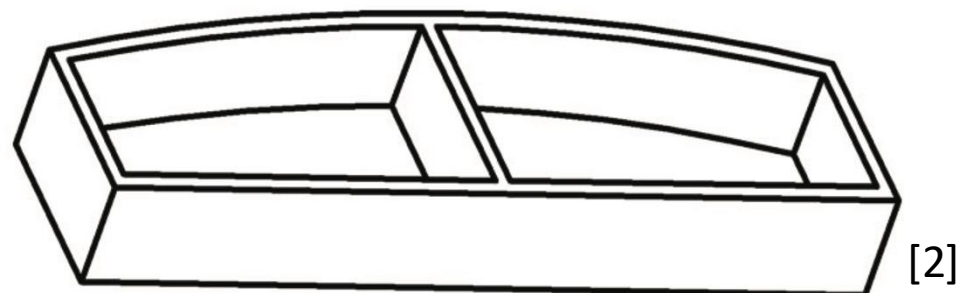
- Building features on existing parts, surface modifications, or repair
 - Limited build options
 - Part should be oriented and fixtured in a manner that facilitates efficient metal deposition.
- For net-shape or near-net-shape part fabrication
 - Many build options
 - Cylindrical flange part
 - Part parallel to the substrate
 - Incorporate substrate into the part
 - Symmetric build



Build Options and Variations

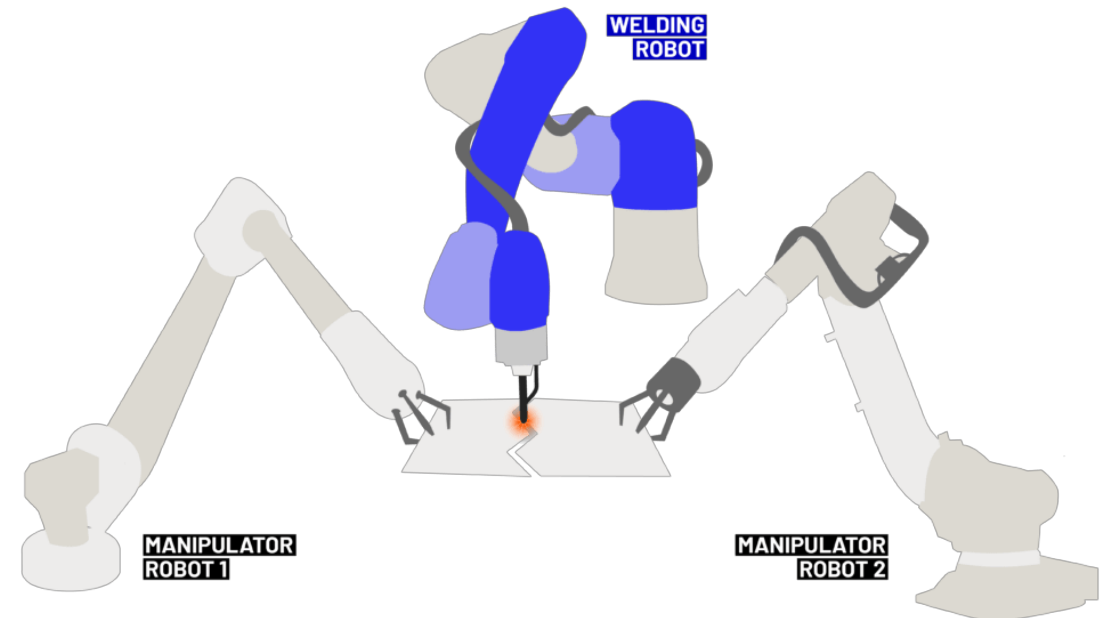
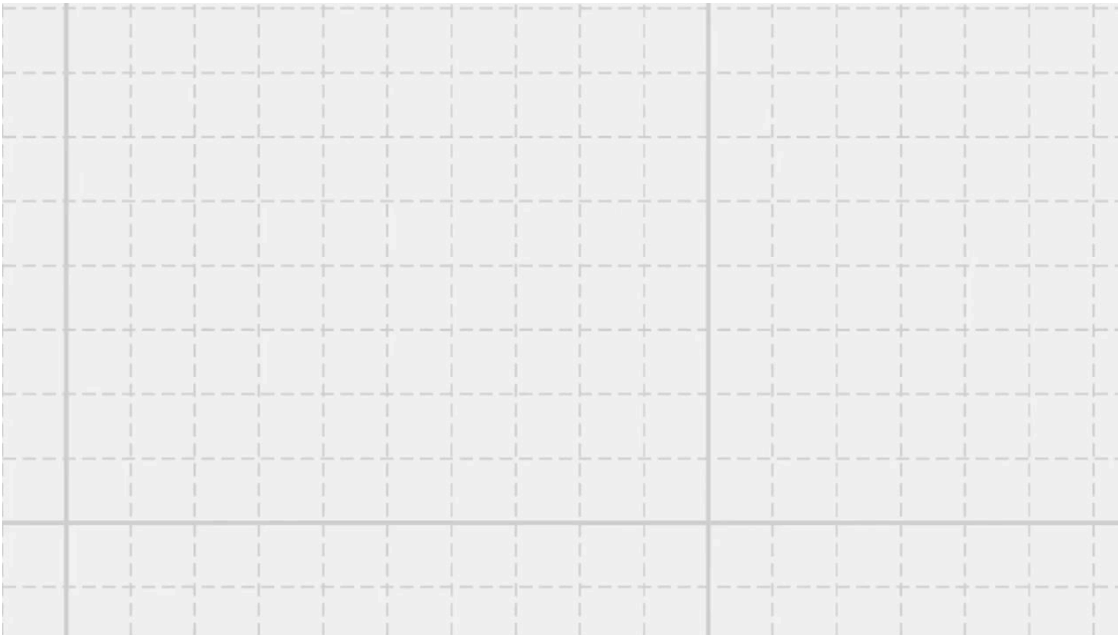


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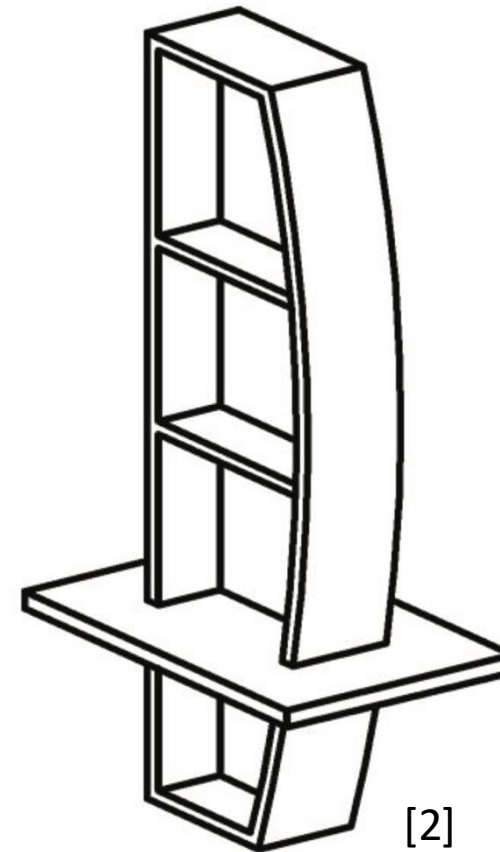
Build Options and Variations

- COROB Project <https://corob-project.eu>
 - flexible, cooperative and intelligent multi-robotic solution for arc welding-based manufacturing processes



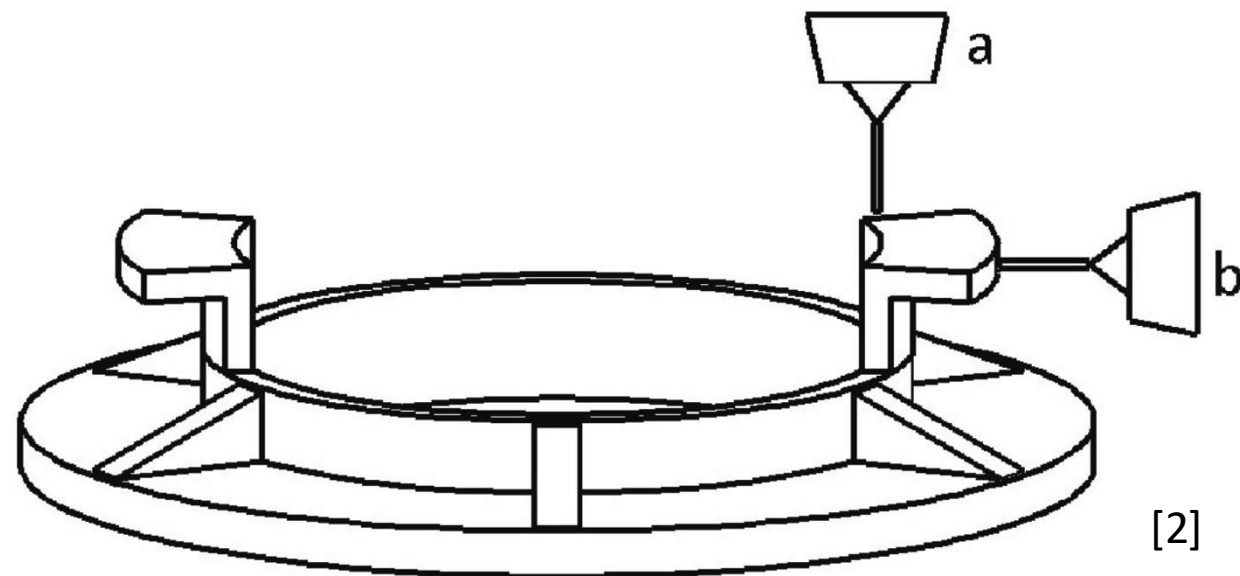
Build Options and Variations

- Asymmetric build configurations
 - Care needs to be taken to minimize distortion



Avoidance of Overhangs

- Sacrificial support structures
- Reorientation



Material, Economic and Time Efficiency

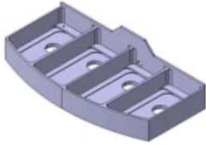
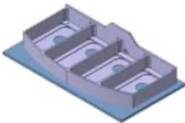
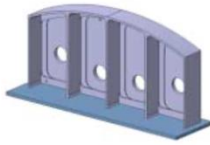
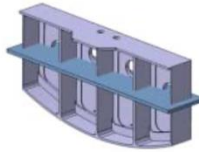
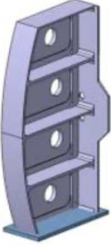


– Efficiency in terms of waste material, time and cost

- Build orientation
- Substrate location
- Build sequence

– Buy-to-fly ratio

– For higher material efficiency, heat source size should be larger than powder or wire diameter

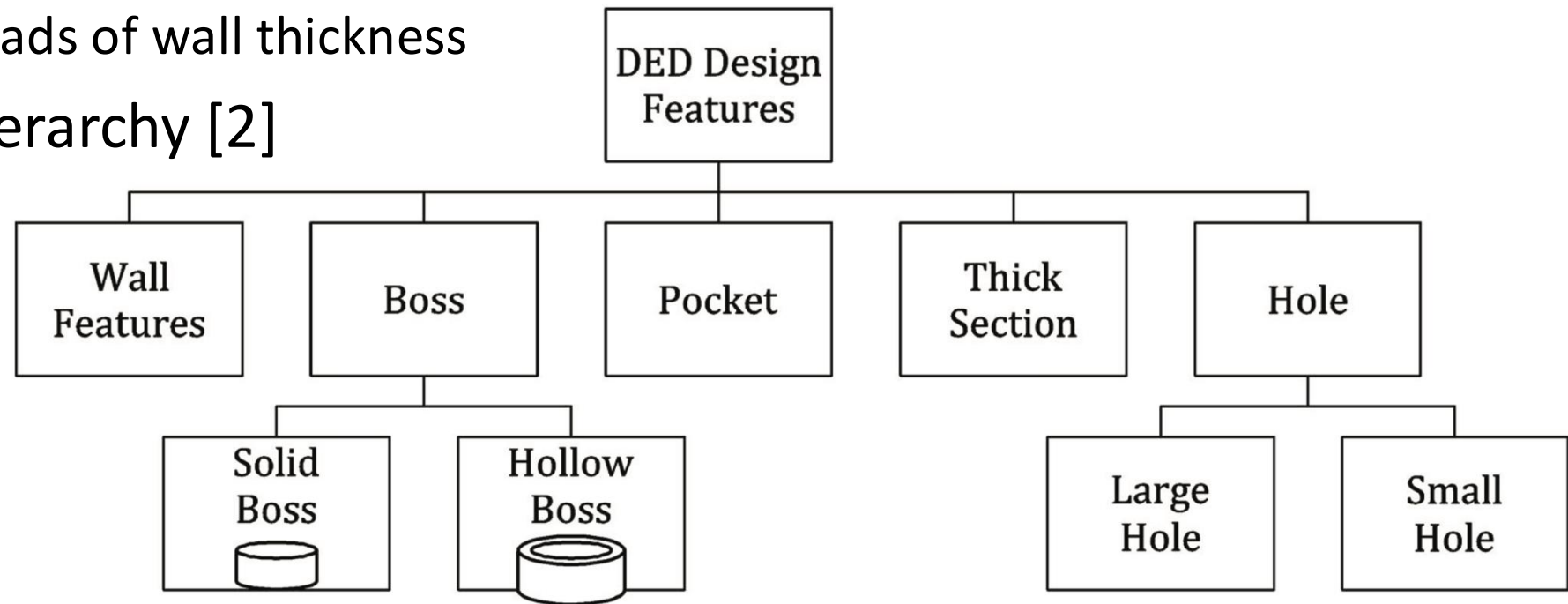
	Build Option 1	Build Option 2	Build Option 3	Build Option 4	Build Option 5
					
Buy to Fly WAAM	1.2	1.2	1.2	1.1	1.1
Substrate Mass (kg)	6.3	3.2	2.5	1.2	1.0
Deposited Material Mass (kg)	5.2	8.5	9.4	9.2	9.3
Waste Material from Substrate (kg)	1.9	2.0	2.2	1.0	0.7
Number of Build Operations	1	2	2	2	2
No. of Double Sided Build Operations	0	0	1	1	0
Total Build Operations	1	2	3	3	2
Mass Above Substrate (kg)	9.6	9.6	4.4	4.8	9.6
Mass Below Substrate (kg)	0.0	0.0	5.4	4.8	0.0

[4]

Design Feature Types



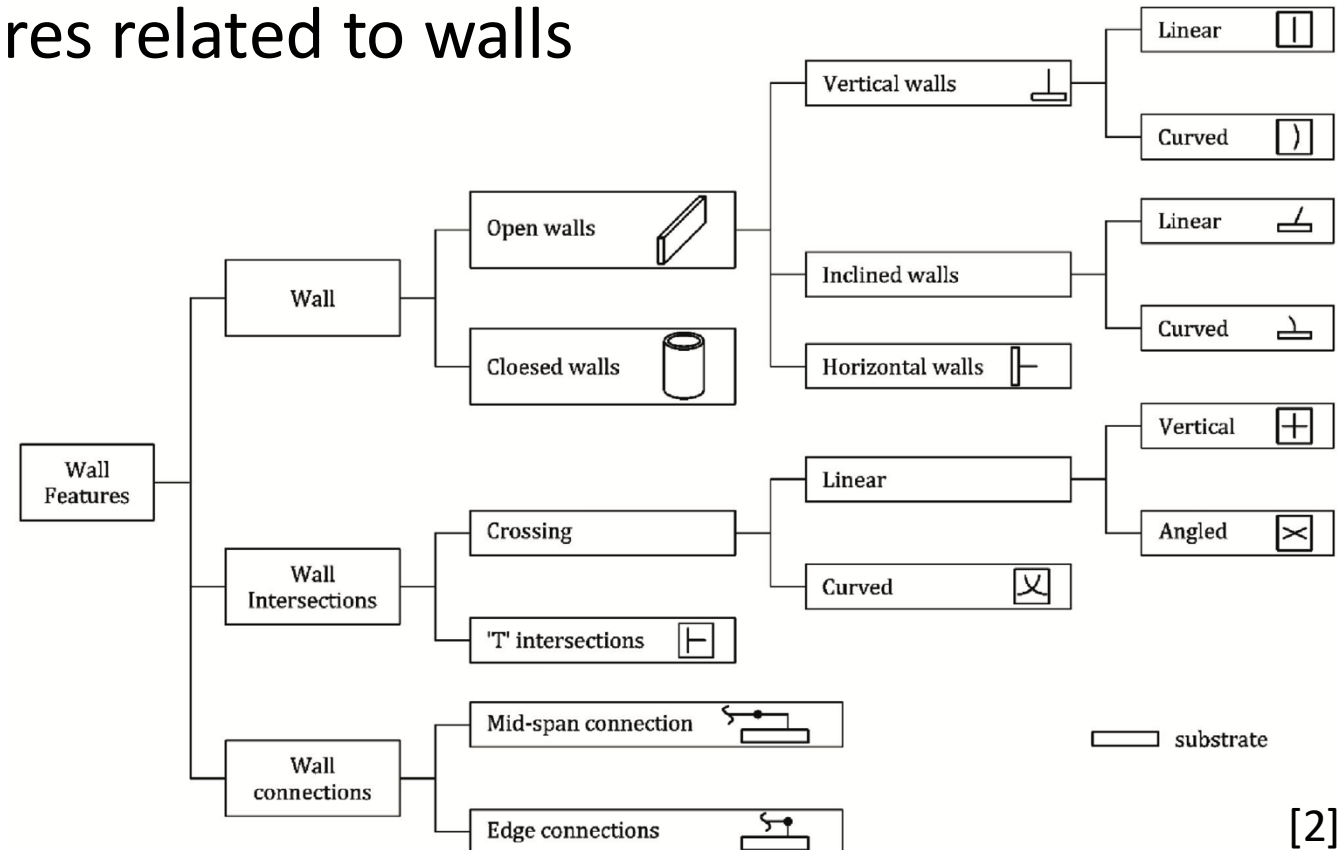
- Most design features can be considered as some type of wall.
 - High-aspect ratio geometric region
 - One or several beads of wall thickness
- Design feature hierarchy [2]



Wall Features



- Example hierarchy of features related to walls



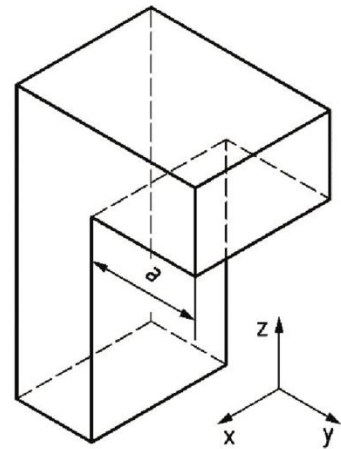
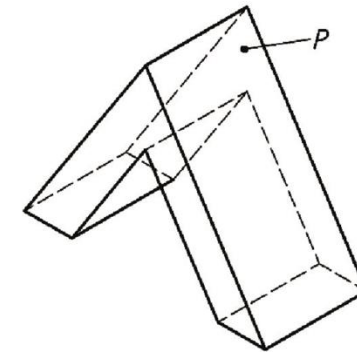
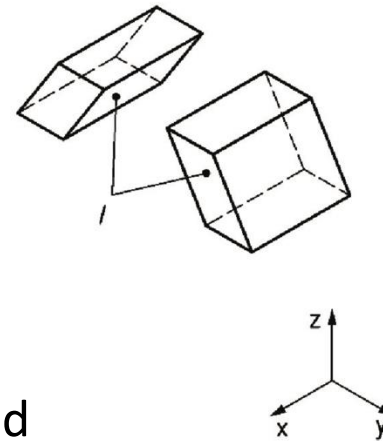
[2]

Manufacturing Features and Effects



– Manufacturing effects represent part geometric characteristics emerging due to the process

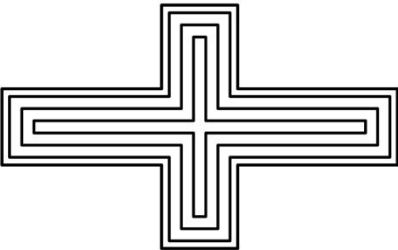
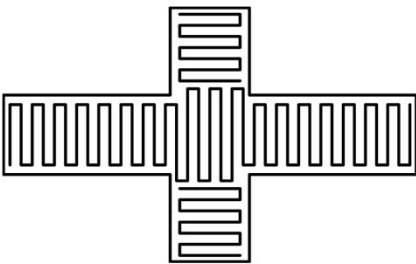
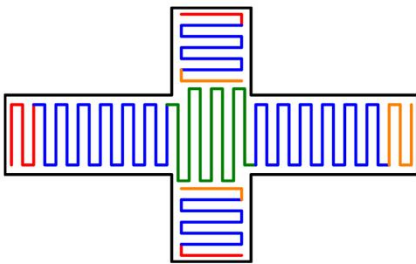
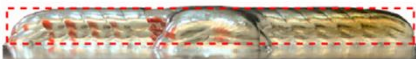
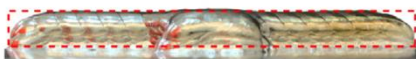
- Overhangs
 - Some of them cannot be manufactured.
 - The head or the substrate may be tilted.
 - Heat input should be controlled
- Islands
 - Connection at the upcoming layers
- Wall Intersections
 - Twice the amount of the metal deposited



[2]

Manufacturing Features and Effects



	Tool path based on adaptive path planning [9]		MPP (segmentation only)	MPP (segmentation + zones)
Tool paths	 (a)		 (f)	 (i)
Plan view results	 (b)	 (d)	 (g)	 (j)
Side view	 (c)	 (e)	 (h)	 (k)

[6]

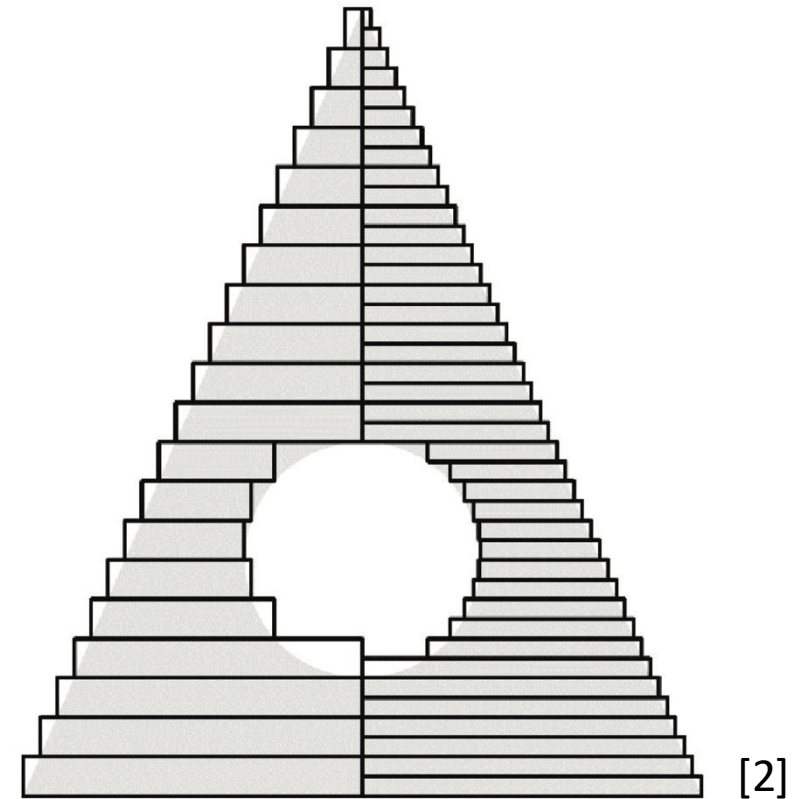
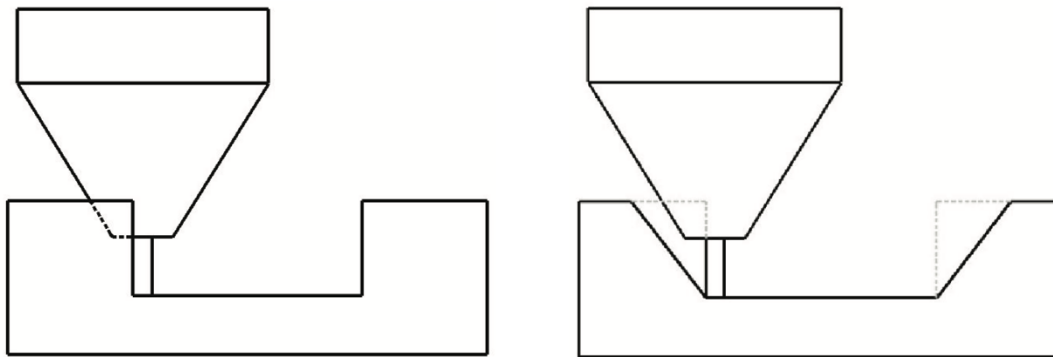
Manufacturing Features and Effects

– Stair-step Effect

- Trade-off
- Adaptive slicing

– Accessibility

- Deposition axis normal to the surface



Design Guidelines for DED

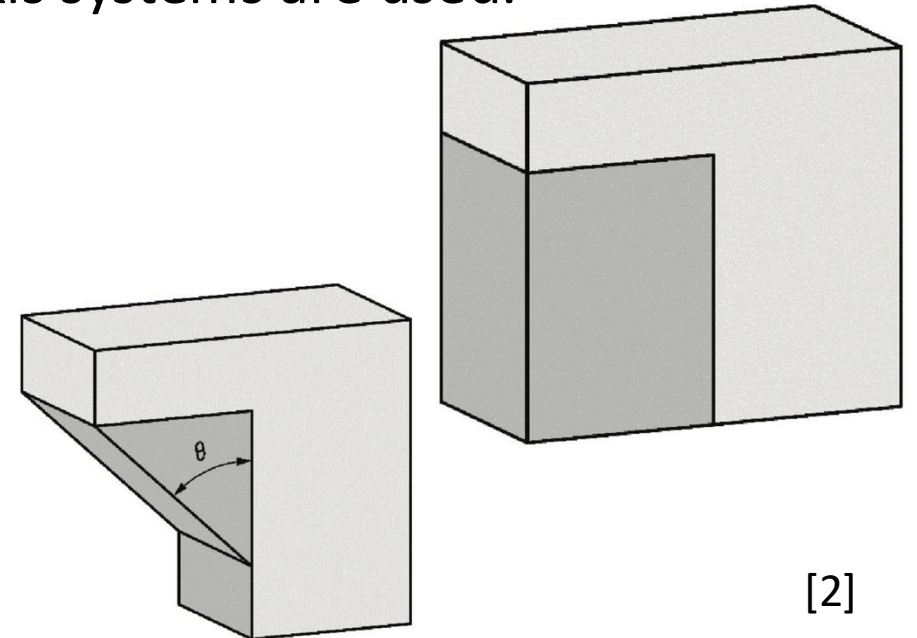


- **Flexibility** of DED processes offer **opportunities** for manufacturing of **unique products** with **properties** that cannot be realized with other manufacturing technologies.
- Part **repair** and **remanufacturing**
 - Fabrication of rib and boss features on large forged products
 - DED reduces lead-times for such larger products.
 - Eliminates the use of forging dies.
- **Limited** part **optimization**
- **Manufacturing trials** of part features

Design Guidelines for DED

– Support structures

- **Not often** used
- Overhang features should be supported when 3-axis systems are used.
 - Gussets
 - Solid walls
 - Ceramics or other materials may also be used.
- Not necessary for 5-axis and robotic DED systems



[2]

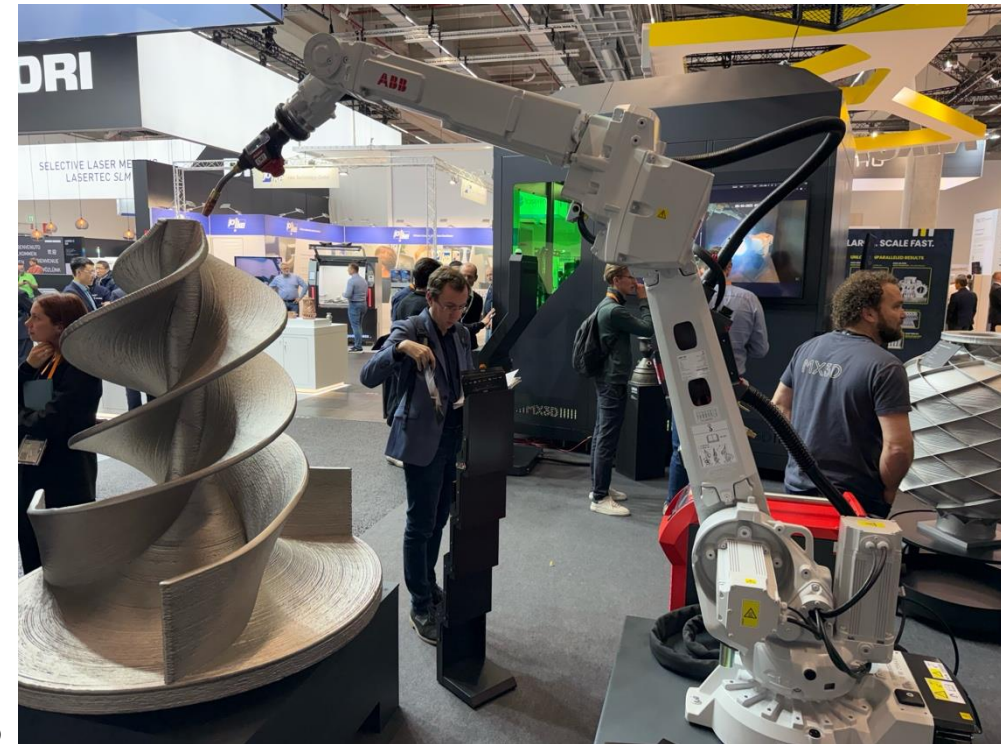
Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



- Important steps in DED **process planning**
- Affects
 - Build time
 - Build complexity
 - Buy-to-fly ratio
 - Support structures
 - Mechanical properties
 - Distortion

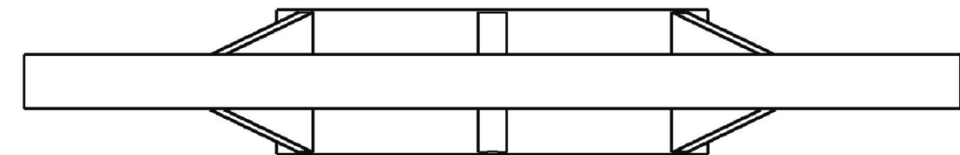
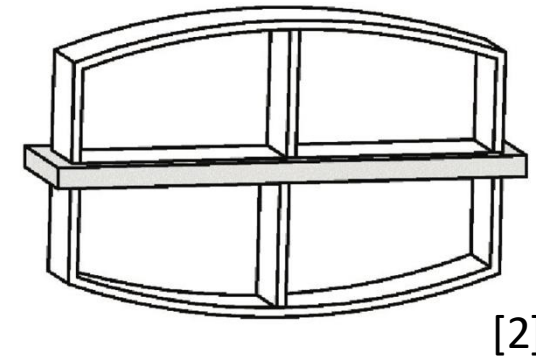
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Design Guidelines for DED Build Orientation



- **Longer** straight **beads** result in more **distortion**.
 - Tall narrow builds result in less distortion.
 - Difficult process control due to heat dissipation
- **Oriented** builds may **not** need **support** structures.
- **Symmetrical** builds **balance residual** stresses and reduce distortion.
- **Non-symmetrical** builds on **both sides** of the substrate may be performed.



Design Guidelines for DED Substrate / Build Platform Position



- **Substrate** may be **embedded** into the part.
 - Reduced build time and simpler deposition
- **Substrate aligned** with a **planar wall** of the part
 - Reduced build time
 - Distortion problems
- **Substrate aligned** with the **central planar wall** of the part
 - Symmetrical build
 - Less material deposition
 - Complicated double-sided build

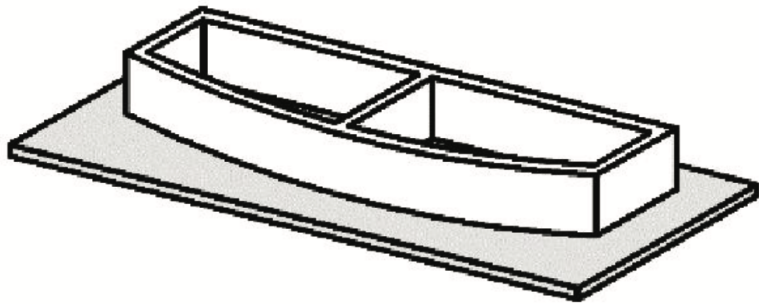
Design Guidelines for DED Substrate / Build Platform Position



- **Substrate** at the **center** of the part
 - Symmetrical build
 - More material deposition, longer build time
 - Higher buy-to-fly ratio
- **Heat dissipation** affected by
 - Substrate orientation
 - Thickness
 - Alignment with flat walls
- Heat dissipation affects **distortion**.

Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



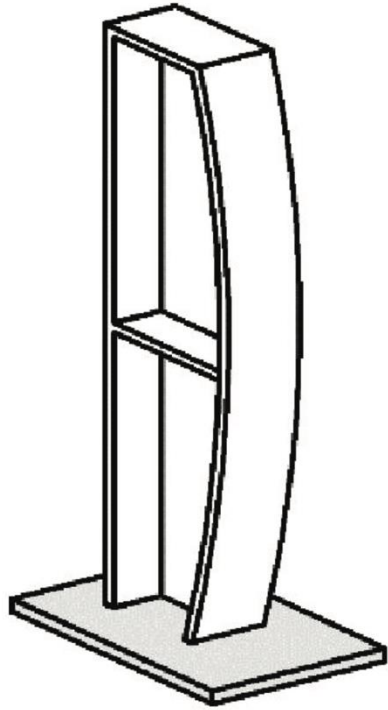
Low-wide build on planar outer wall

- + Maximizes substrate volume in part
- + Less material deposited, so shorter build time
- + No overhanging features
- + Efficient use of build volume in machine
- Higher BTF ratio due to large substrate area required for work-holding
- Higher risk of distortion than other orientations due to long straight beads

[2]

Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



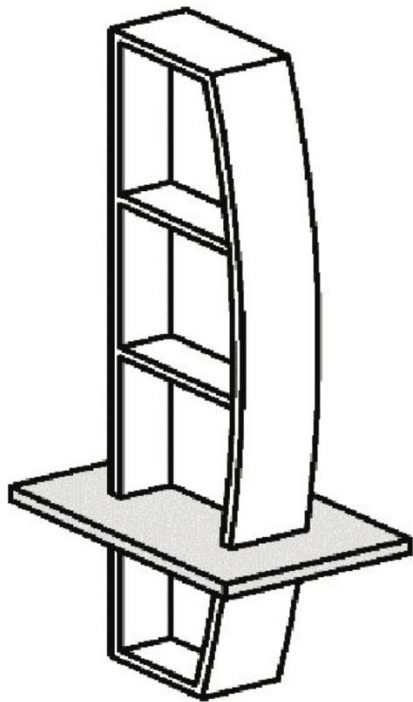
Tall narrow build on planar outer wall

- + Lower BTF ratio due to smaller substrate area required for work-holding
- + Lower risk of distortion compared to low-wide build
- Overhanging features increase build complexity
- Can cause problems with heat dissipation
- Depositing more material, therefore increased build time
- Can be difficult to maintain a consistent build without closed-loop control

[2]

Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



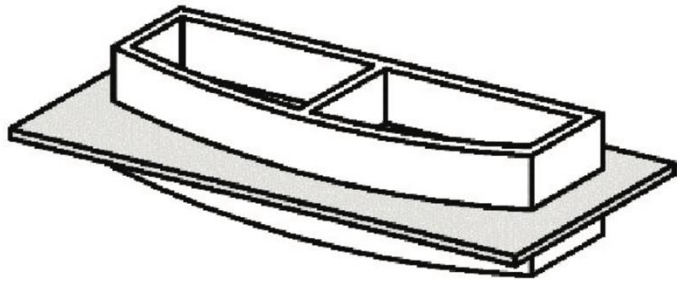
Symmetrical build

- + Balanced residual stresses during build reduces the risk of distortion
- More complex double-sided deposition, so requires a rotary table or more manual operations
- Overhanging features increase build complexity

[2]

Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



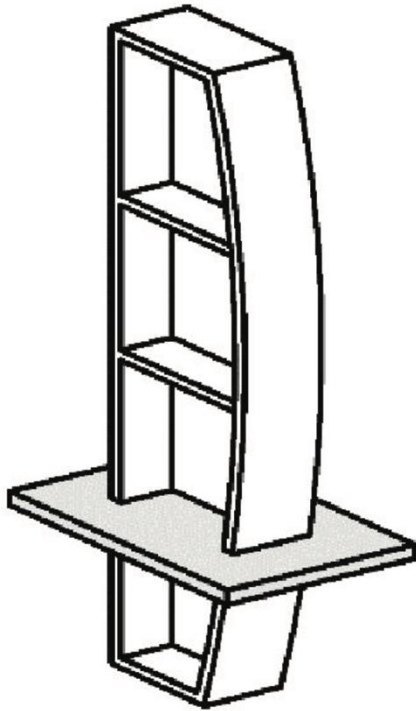
Symmetrical back-to-back build

- + Balanced residual stresses during build reduces the risk of distortion
- + Maximizes substrate volume in part
- + Less material deposited, so shorter build time
- + No overhanging features
- More complex double-sided deposition
- Higher BTF ratio due to large substrate area required for work-holding
- Additional manufacturing operation to separate parts after build

[2]

Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



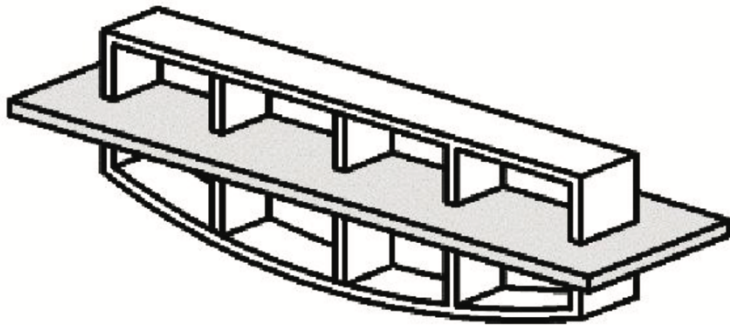
Build on planar internal wall (not on plane of symmetry)

- + Efficient use of substrate
- + Partially symmetrical build
- Unbalanced build in upper layers of part
- Overhanging features increase build complexity

[2]

Design Guidelines for DED

Build Orientation and Substrate / Build Platform Position



Substrate at centre of part (not aligned with internal wall)

- + Partially symmetrical build, reduces risk of distortion
- Larger volume of material deposited than other build options, hence longer build time
- More waste material in substrate
- Overhanging features increase build complexity

[2]

Design Guidelines for DED Multi-axis Deposition

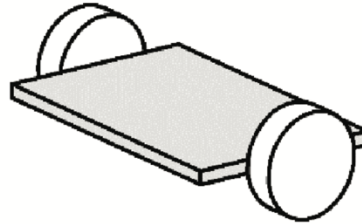
- Commonly performed with the **part** mounted onto a **rotary table**
- Parts can be built **symmetrically** if the rotary table can tilt 360°.
- **Reorientation** to eliminate the need for **support** structures.



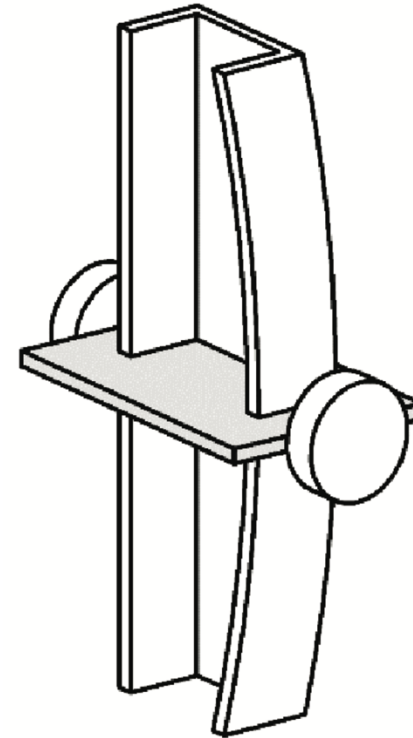
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Design Guidelines for DED Multi-axis Deposition

1. Position substrate on rotary table



2. Build vertical walls of part using two-sided deposition, build alternate layers on opposite sides of the substrate, and rotate the part between each layer

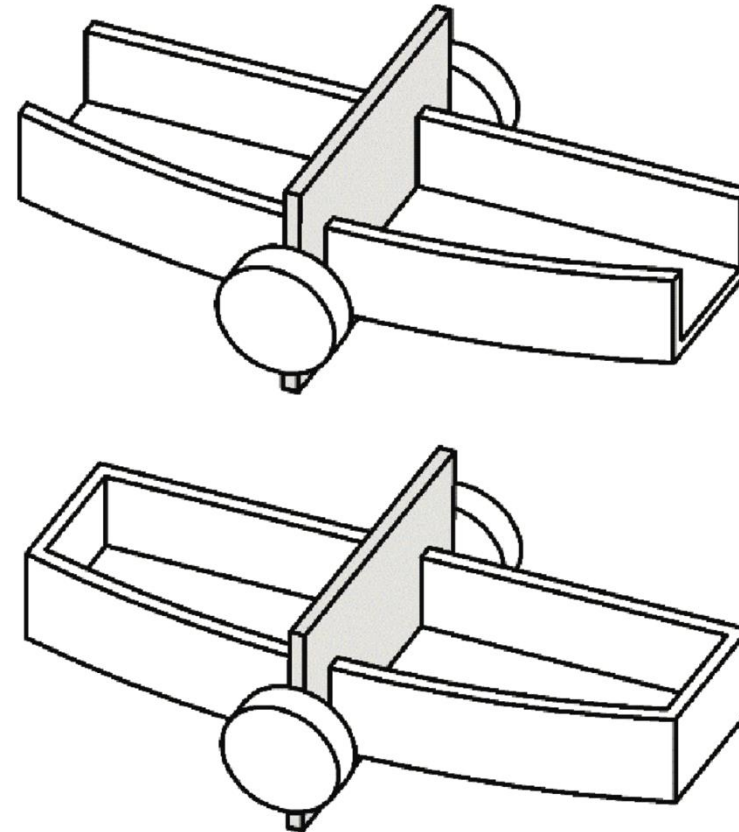


[2]

Design Guidelines for DED Multi-axis Deposition

3. Reorient the part to build end walls

4. Build end walls using single-sided deposition



[2]

Design Guidelines for DED Substrate Thickness



– Trade-off

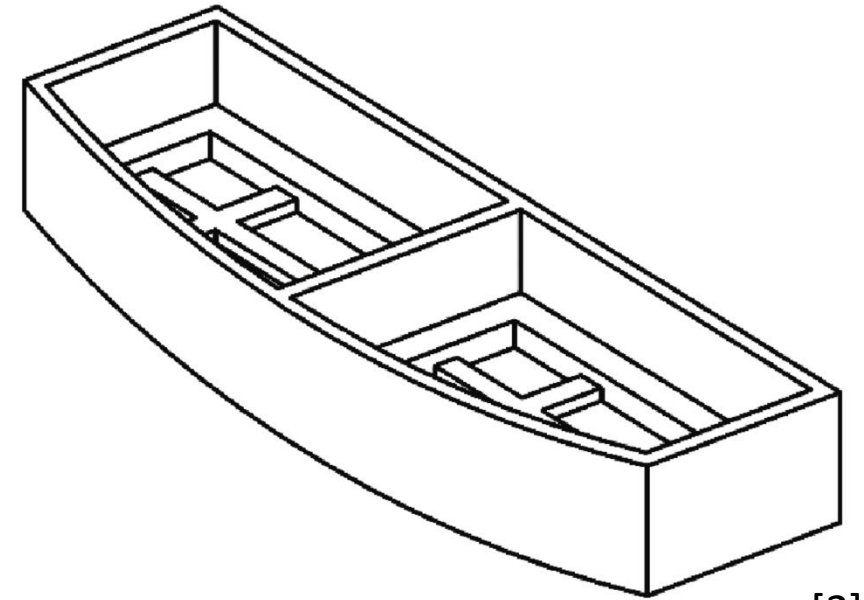
- Build complexity
- Build time
- Buy-to-fly ratio

– Thinner Substrate

- Less material removal during post-machining
- Increased build complexity
- Distortion and buckling

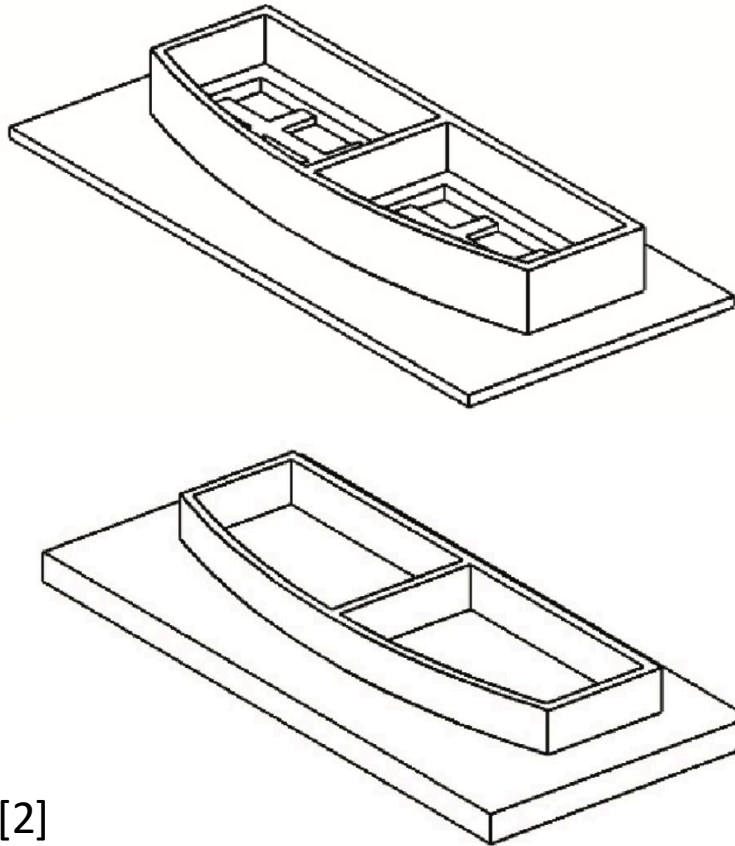
– Thicker Substrate

- Less build complexity
- More material removal in post-machining



[2]

Design Guidelines for DED Substrate Thickness



[2]

Thin substrate

- + Lower BTF ratio
- More complex build
- Higher risk of distortion and buckling of substrate

Thick substrate

- + Simpler build
- + Lower risk of distortion and buckling of substrate
- Higher BTF ratio
- More post-machining operations required

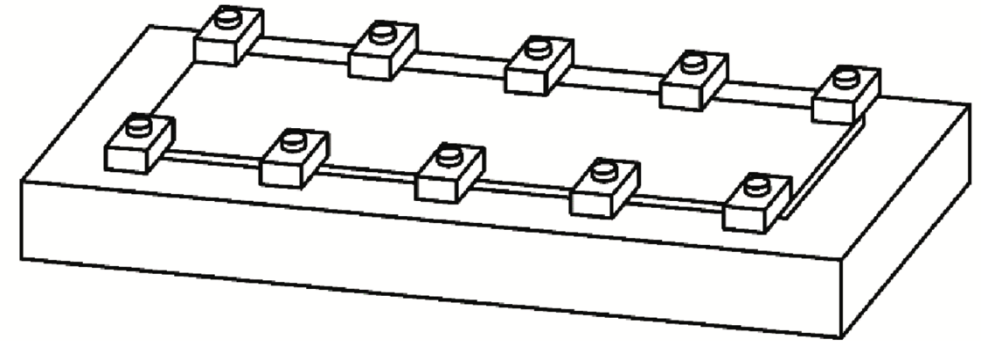
Design Guidelines for DED Distortion



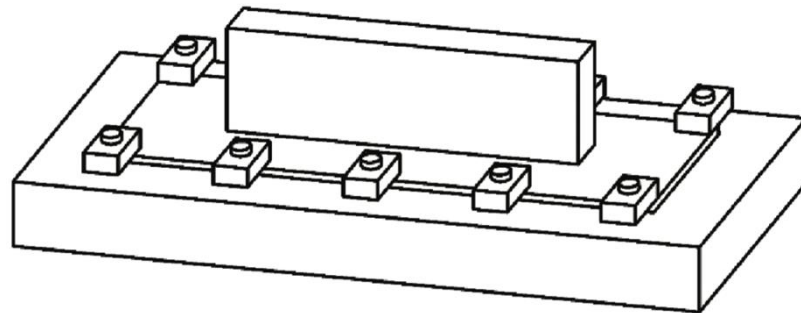
- Following **guidelines** should be considered to **avoid distortion**.
 - Design and optimize **build orientation**
 - Design and optimize the **tool path** to **distribute heat**
 - **Constant interlayer temperature** to minimize temperature differences
 - **Adaptable process parameters** according to the geometry of the part
 - **Pre-heating** of the substrate
 - **Fixturing** and **clamping** of the substrate

Design Guidelines for DED Work Holding and Fixturing

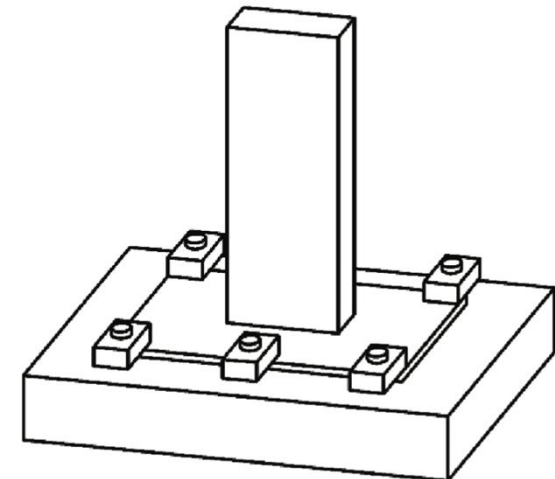
- **Clamps**
 - Prevent part distortion
- **Tool path planning** should be considered.
 - Collision
 - Dry runs to ensure no collision
- **Trade-off**
 - Fixturing
 - Distortion
 - Build time



[2]



a)



b)

Design Guidelines for DED

Design Considerations



- **Small features** should be **post-machined**.
 - Negative features
 - Holes, slots
 - Positive features
 - Ribs, tabs, bosses

Design Guidelines for DED

Design Considerations



– Cavities

- Good for partially enclosed cavities
- Avoid using completely closed cavities although technically possible
 - For 3-axis systems: overhang capabilities determine manufacturability
 - For 5-axis systems: accessibility determines manufacturability
 - Powder-fed systems: Completely enclosed cavities can entrap powder.
 - Post-machining is sometimes impossible.

Design Guidelines for DED

Design Considerations



– Slots and Grooves

- Minimum size related to the process resolution, controlled by melt pool size
- Slots or grooves in non-vertical walls can cause overhangs. How is it solved?

– Wall Thicknesses

- Minimum wall thickness depends on the melt pool width.
 - It may be modified using the process variables.
- Thick walls
 - Multiple beads
 - Oscillated deposition path.

Design Guidelines for DED

Design Considerations



– Holes

- Manufacturability depends on the **orientation** of the hole's **central axis**. **Why?**
- **Smaller** holes usually obtained with **post-machining**.
- For the 5-axis systems, **collision checks** should be performed.

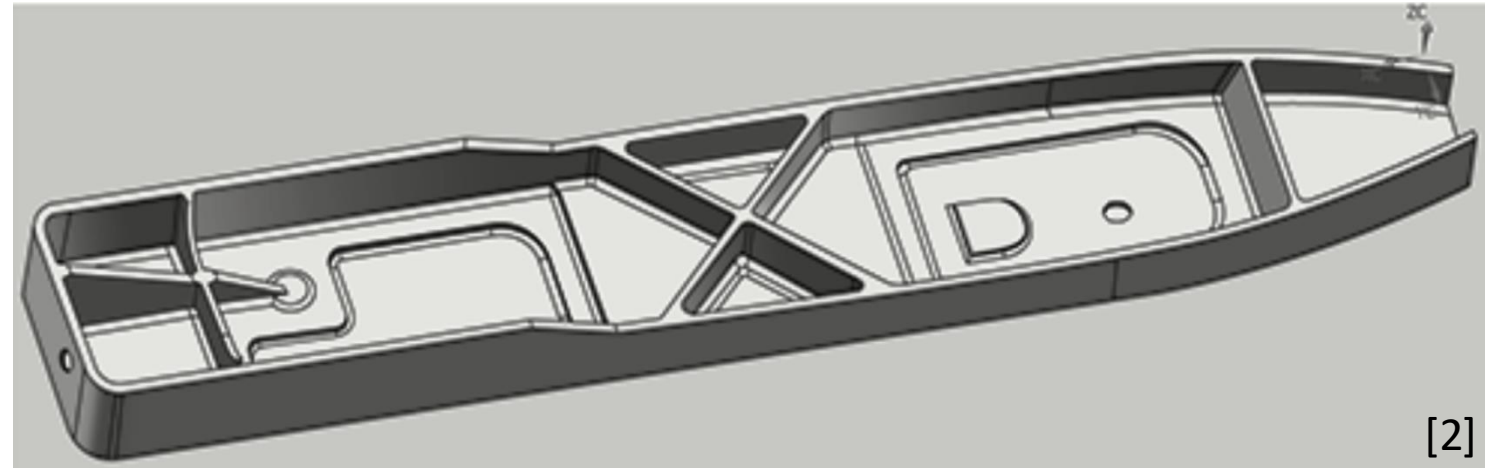
– Inspectability

- Some features may **limit** inspection **angles** and inspection **probe access**.
- Depending on the inspection technique, **material** must be **added** to ensure **inspectability**.

Examples – Thin-Walled Part

– GKN Aerospace

- Vertical walls
 - Slanted walls
 - Walls with varying height
 - Wall crossings
 - Pockets
 - Bosses
 - Holes
- Wire-fed, laser DED
 - 1219 mm of length
 - 6.35 mm of wall thickness



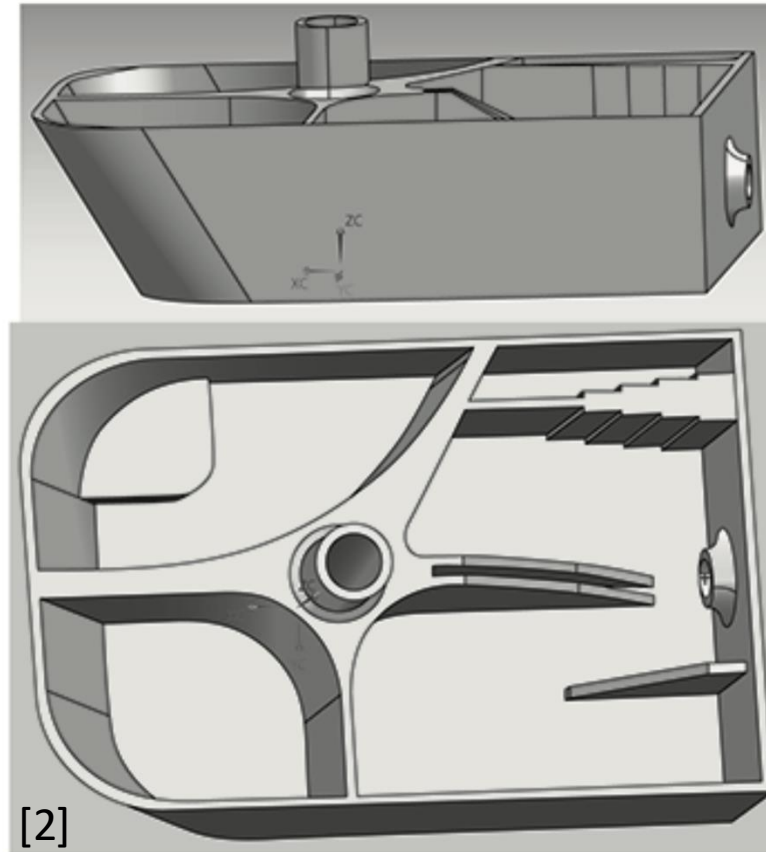
<https://www.gknaerospace.com/news-insights/news/gkn-aerospace-northrop-grumman-collaboration-achieves-additive-manufacturing-milestone/>

Examples – Benchmarking Part

– GKN Aerospace

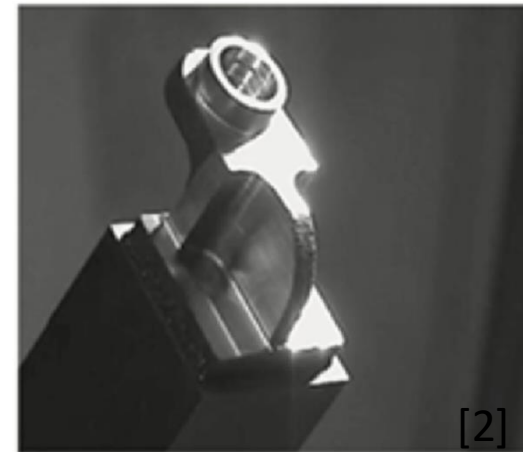
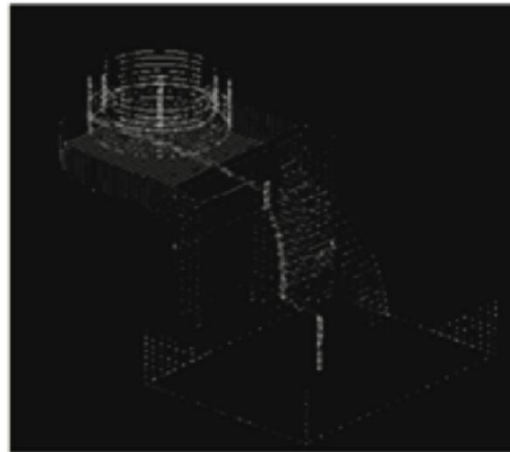
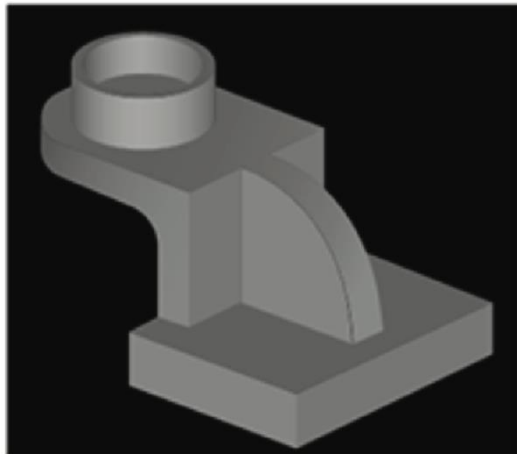
- laser powder-fed
- laser wire
- electron beam wire
- plasma wire
- arc wire

– 412 mm of length



Examples – Multiple Build Directions

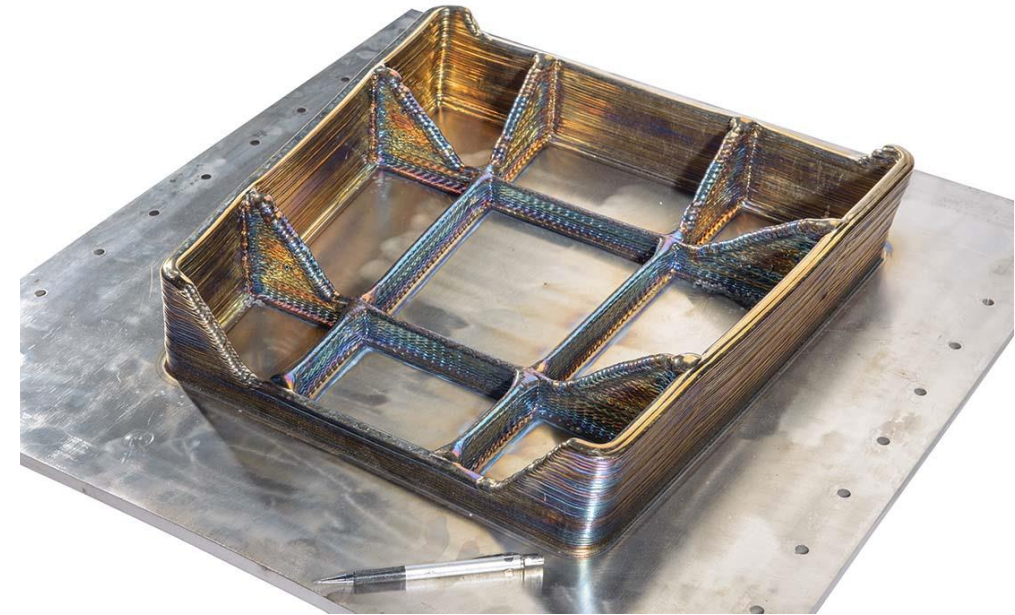
- **Missouri University of Science & Technology**
- The **decomposition** into **sub-components** should be done in such a way that each is **built** upon a prior **sub-component**.
- **Centroidal** axis method



Examples – Landing Gear Rib Part



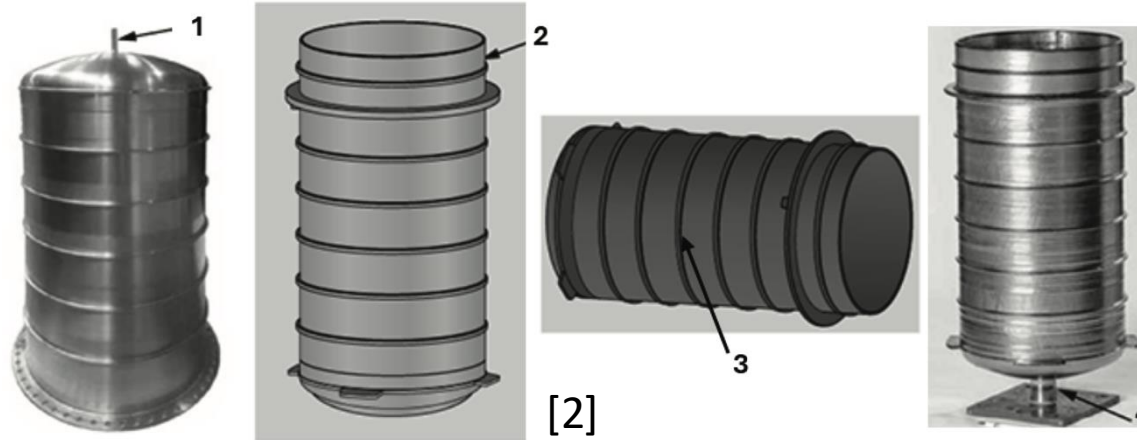
- **Cranfield University**
- Plasma based wire arc DED
- Ti-6Al-4V
- Built by Cranfield for Bombardier
- Final mass of 20 kg
- 500 mm of length
- Buy-to-fly ratio decreased to 2.3 from 12
- Symmetric build approach



<https://www.waam3d.com/case-studies/landing-gear-rib>

Examples – Pressure Vessel

- **Cranfield University**
- Pressure vessel for space exploration
- 1000 mm of height
- 8,5 kg
- 2 mm of machining stock
- Spiral tool path



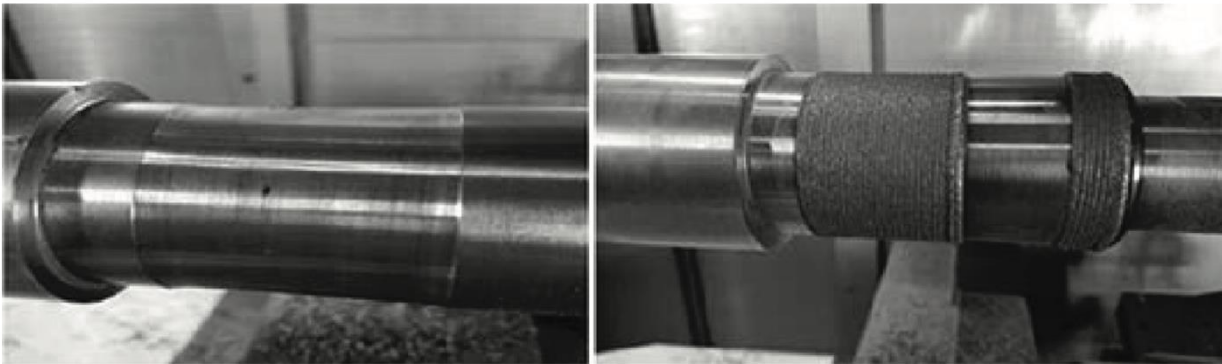
<https://www.cranfield.ac.uk/press/news-2019/titanium-pressure-vessel-for-space-exploration-built-successfully-using-the-waam-process>



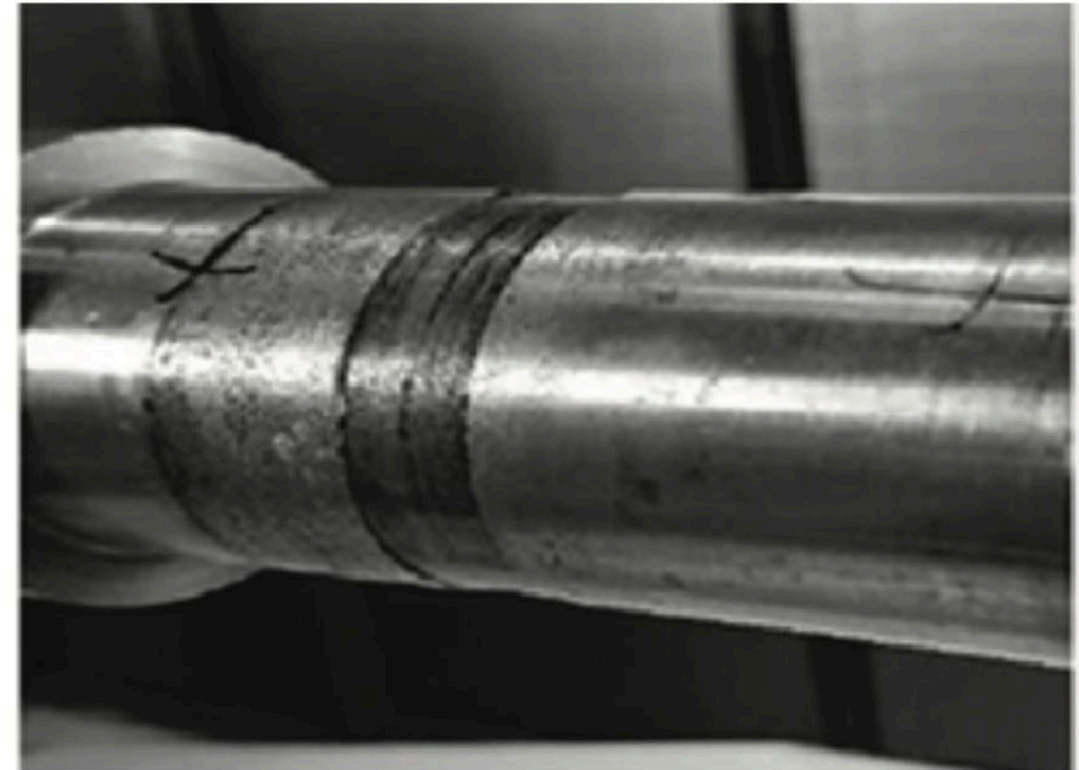
Formnext 2023

Example – Shaft Repair

- **Boeing**
- 787 mm of length
- Stainless steel powder
- Powder size of $44\text{ }\mu\text{m}$ to $177\text{ }\mu\text{m}$



[2]



Example – Blade Repair



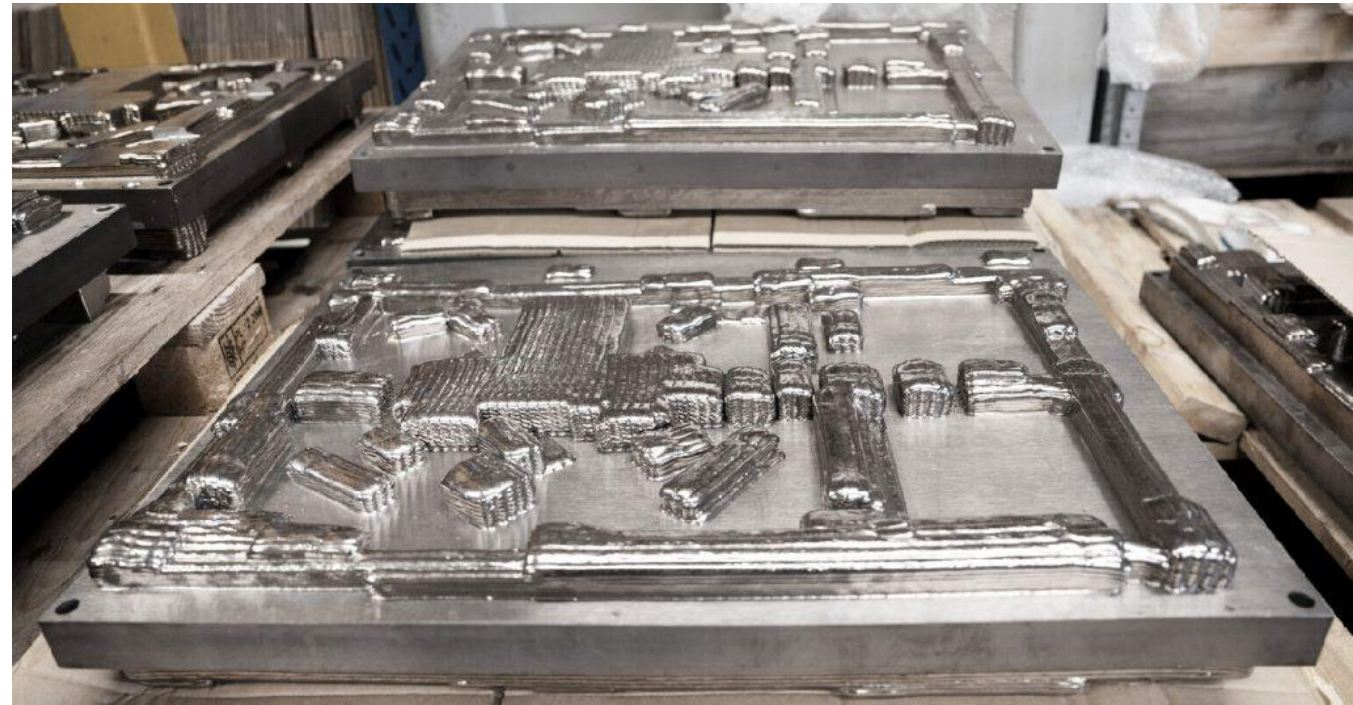
- Erosion and corrosion protection
- Stellite 6 Powders
- 17-4PH
- Laser-powder DED
- Three layers
- 0.3 mm of layer thickness



Example – Silicon Wafer Carrier Tray



- **Norsk Titanium**
- Plasma based wire arc DED
- Ti-6Al-4V
- 700 mm of length
- Saved 105 kg of Titanium



<https://www.metal-am.com/articles/fly-by-wire-how-additive-manufacturing-took-to-the-skies-with-norsk-titanium/>

Example – Commercial Aerostructure Support Bracket



- **Norsk Titanium**
- Serial manufacturing
- An aft galley part for the Boeing 787 Dreamliner
- Plasma based wire arc DED
- Ti-6Al-4V
- 330 mm of length
- Buy-to-fly ratio decreased to 10 from 27



<https://www.metal-am.com/articles/fly-by-wire-how-additive-manufacturing-took-to-the-skies-with-norsk-titanium/>

References

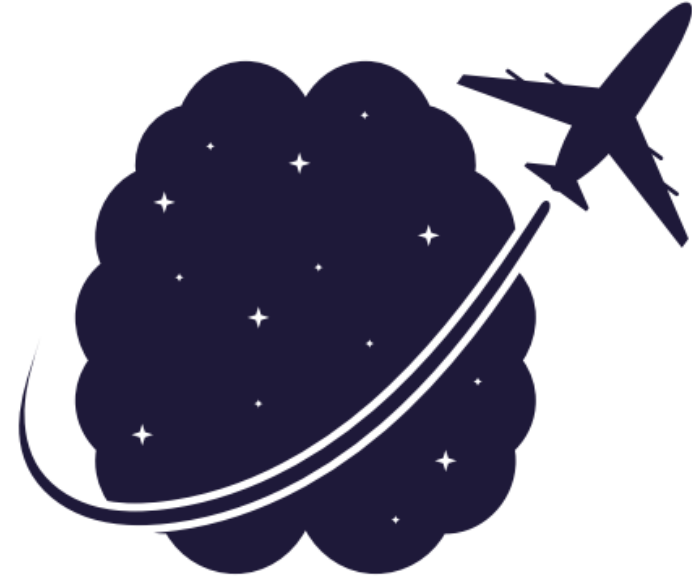


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- 3) ASTM F3187
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- 5) Michel, Florent, et al. "A modular path planning solution for Wire+ Arc Additive Manufacturing." *Robotics and Computer-Integrated Manufacturing* 60 (2019): 1-11.
- 6) Michel, Florent, et al. "A modular path planning solution for Wire+ Arc Additive Manufacturing." *Robotics and Computer-Integrated Manufacturing* 60 (2019): 1-11.



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Design of Metal AM Parts for Aerospace & Defense – DED

Standards
Design Documentation
Digital Thread
Future Opportunities & Challenges

Prof. Dr. Ulaş Yaman

Welding Technology and NDT Center

Middle East Technical University



CenSec
CENTER FOR DEFENSE, SPACE & SECURITY



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AKADEMIE**

**ASTURIAS HUB
DEFENSA**



IDONIAL
TECHNOLOGY CENTRE



FAN 3D

**Brunel
University
London**

- Standards Relevant to Design for DED
 - ISO/ASTM 52910:2017(E): Standard Guidelines for DfAM
 - ISO/ASTM DIS 52922: AM—Design—DED of Metals
- Design Documentation to Comply with Standards/Traceability
 - AWS D20.1/D20.1 M:2019
 - ISO-ASTM PWI 52969
- Maintaining the Digital Thread
- Future Opportunities & Challenges

Standards Relevant to Design for DED



- ISO/ASTM 52910:2017(E): Standard Guidelines for DfAM

ISO/ASTM 52910:2017(E)



**Standard Guidelines for
Design for Additive Manufacturing**

Standards Relevant to Design for DED



– ISO/ASTM DIS 52922: AM—Design—DED of Metals



**DRAFT
International
Standard**

**ISO/ASTM DIS
52922**

**Additive manufacturing — Design
— Directed energy deposition of
metals**

*Fabrication additive — Conception — Dépôt de matière sous
énergie concentrée de métal*

ICS: 25.030

ISO/TC 261

Secretariat: DIN

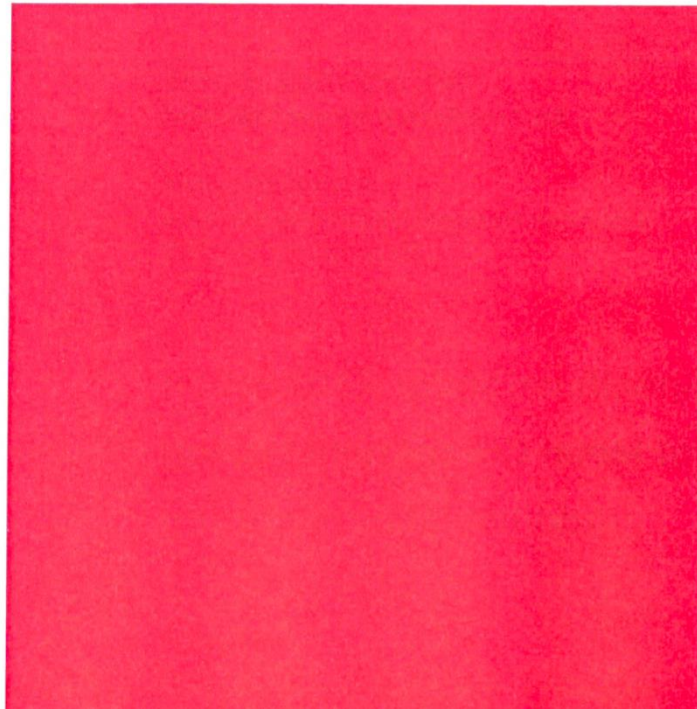
Voting begins on:
2025-09-12

Voting terminates on:
2025-12-05

Design Documentation to Comply with Standards/Traceability



– AWS D20.1/D20.1 M:2019



AWS D20.1/D20.1M:2019
An American National Standard

**Specification for
Fabrication of
Metal Components
using Additive
Manufacturing**

Design Documentation to Comply with Standards/Traceability



– ISO-ASTM PWI 52969



ISO/TC 44/SC 5 N 887

ISO/TC 44/SC 5 "Testing and inspection of welds"

Secretariat: **AFNOR**

Committee manager: **Augier de Cremiers Flavie Mme**

ISO/TC 261/JG 59 - NP Ballot on ISO-ASTM PWI 52969 -Additive manufacturing for metals - Non-destructive testing and evaluation - Imperfections classification in DED parts-

Maintaining the Digital Thread



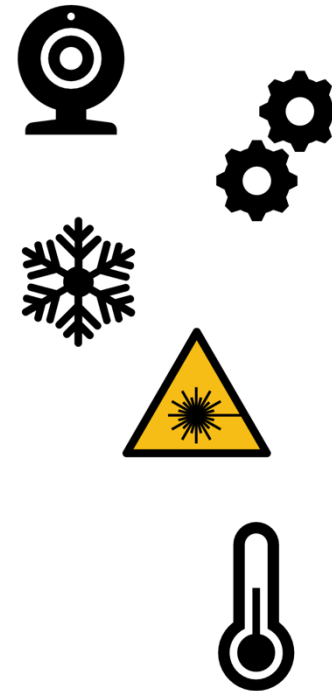
- Design and Modeling (CAD/CAM)
- Simulation and Process Planning
- **In-Process Monitoring and Data Capture**
 - Recording of sensor data of process parameters
 - Image and video recordings
 - Maintenance of checklists
 - Permanent archiving
- Hybrid Manufacturing and Post-Processing
- Closing the Loop: Feedback to Design



<https://youtu.be/L3CkzQQFZXs?si=0Yb3bt6ou7kfhWI9>

Maintaining the Digital Thread

- Monitoring is well established in laser-based processes.
- Monitoring of
 - Position of all axes
 - Laser power
 - Scan speed
 - Powder feed rate
 - Molten pool dimensions
 - Cooling system
 - Temperature, pressure
 - Gas flow

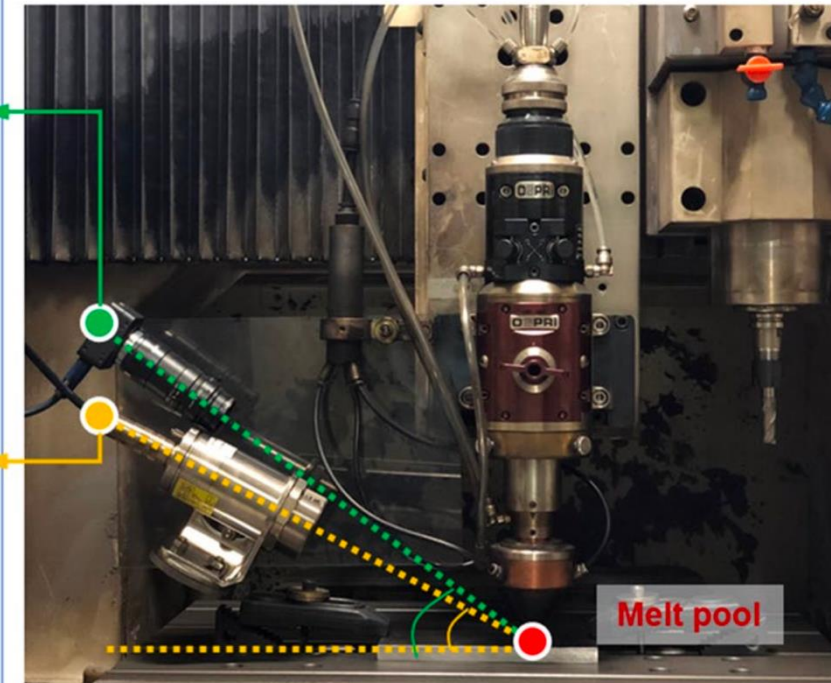


Maintaining the Digital Thread

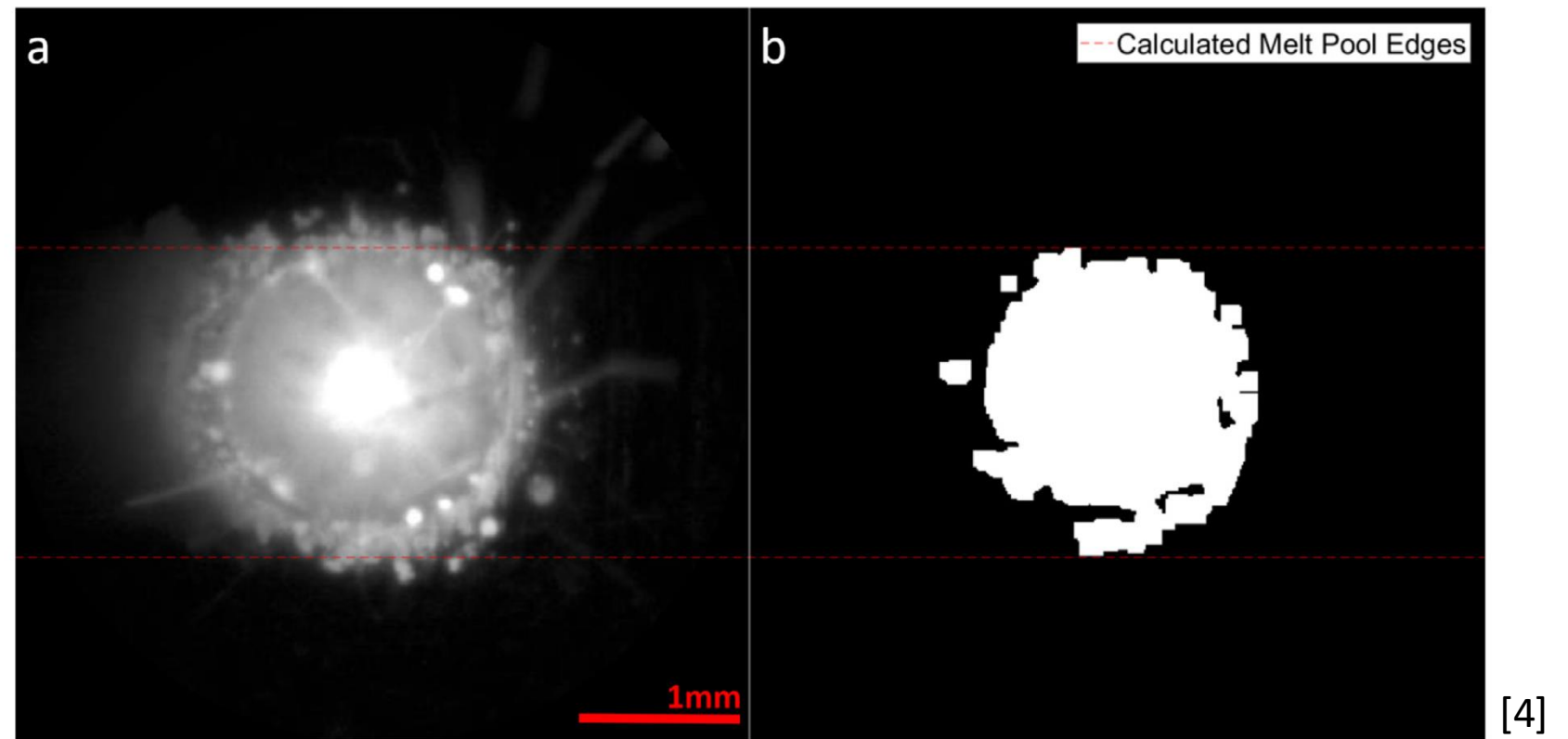
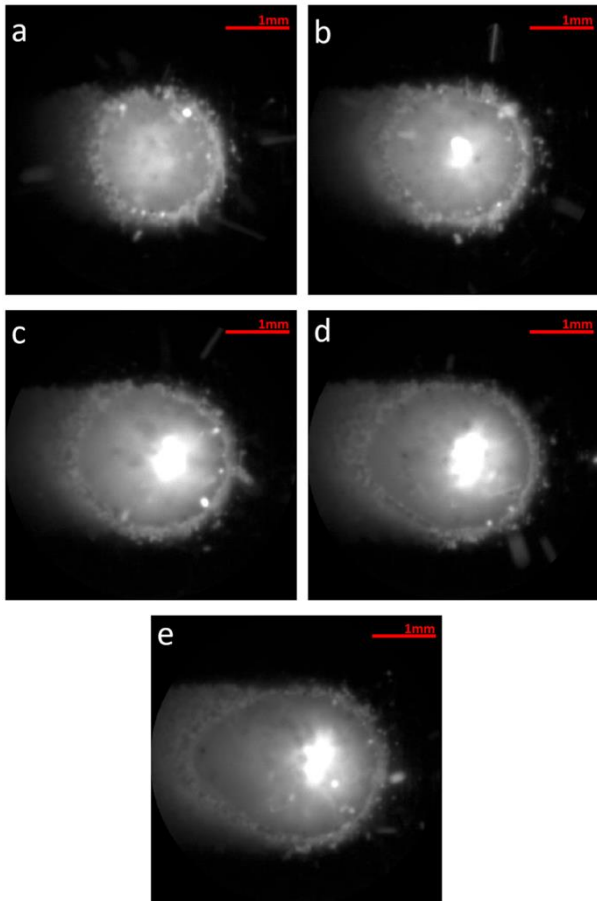
– Melt Pool Monitoring

- Temperature intensity
- Size
- Shape
- Temperature profile
- Detection of process lights in one of two colors
- Signal processed quickly (FPGA)
- Qualitative statements about melt pool dynamics and temperatures

[3]



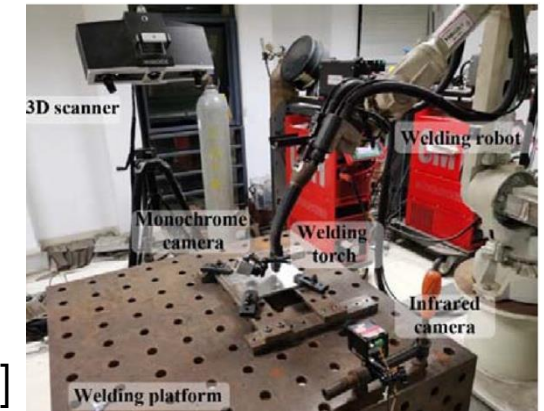
Maintaining the Digital Thread



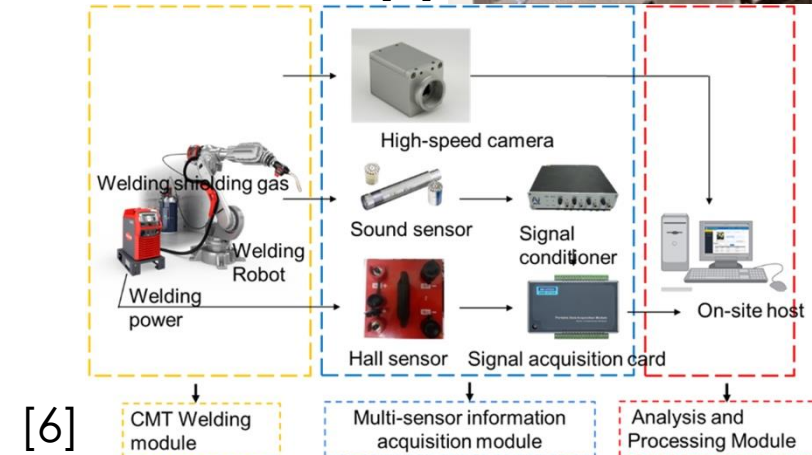
[4]

Maintaining the Digital Thread

- **3D scanner, monochrome and infrared cameras**
 - Comprehensive information; reduces the effect of strong light, splash, or noise; reliable and accurate
- **Hall sensor, sound sensor, high-speed camera**
 - Comprehensive data collection; improved abnormality detection through the whole process; enhanced reliability



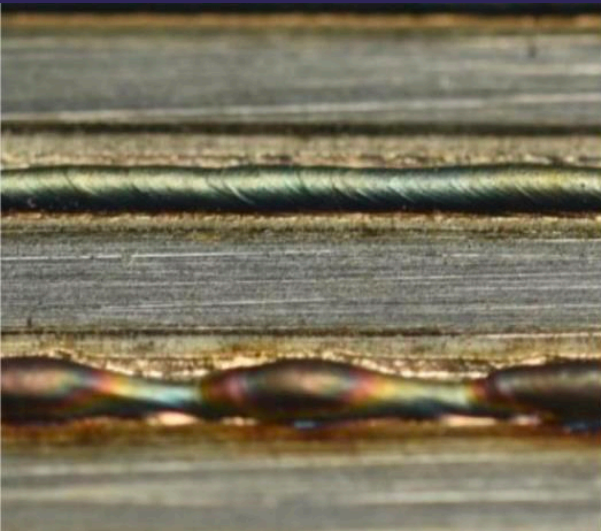
[5]



Challenges



Repeatability



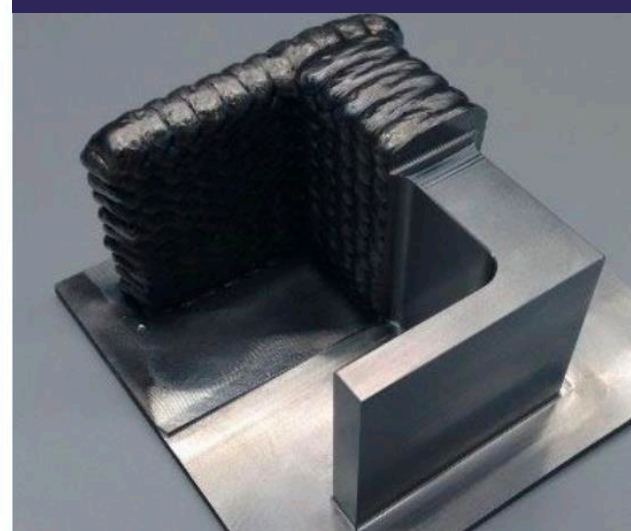
Fraunhofer IPT

Stability



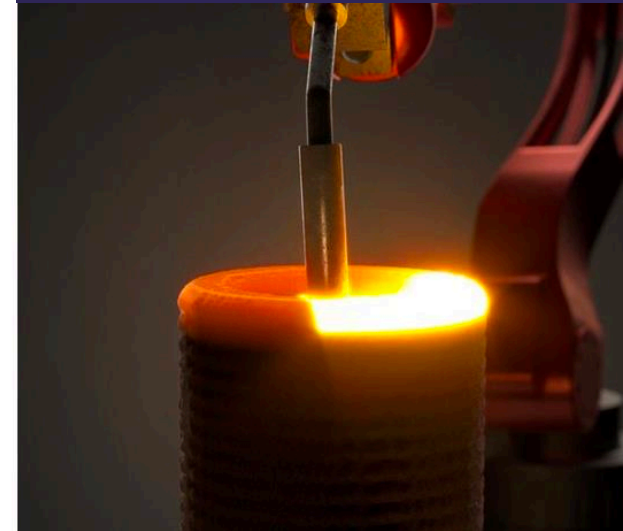
Fraunhofer IPT

Accuracy & Surface Finish



Lortek

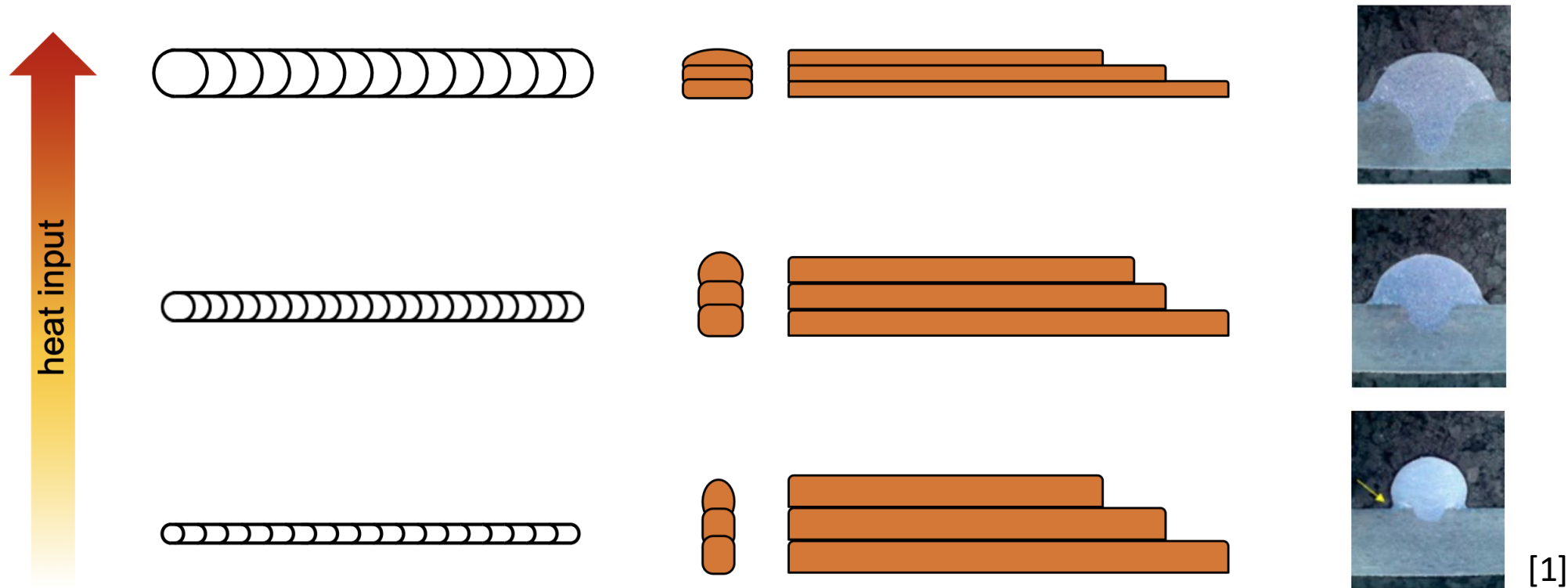
Thermal Impacts



Vallourec

Challenges

Effect of Heat Input on Geometry

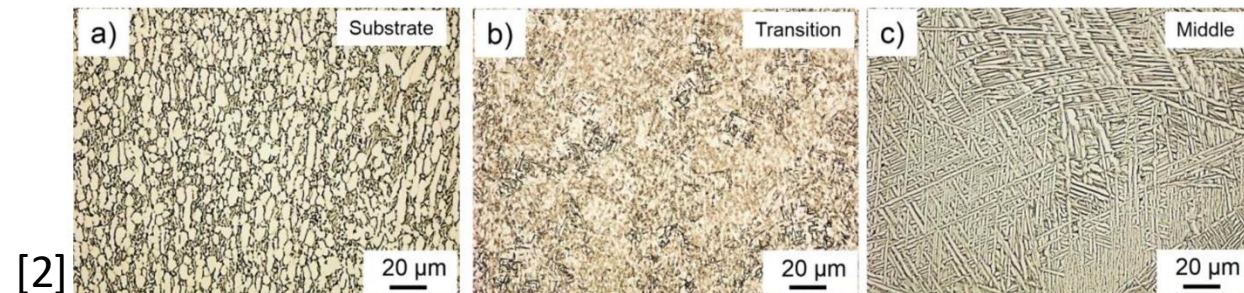
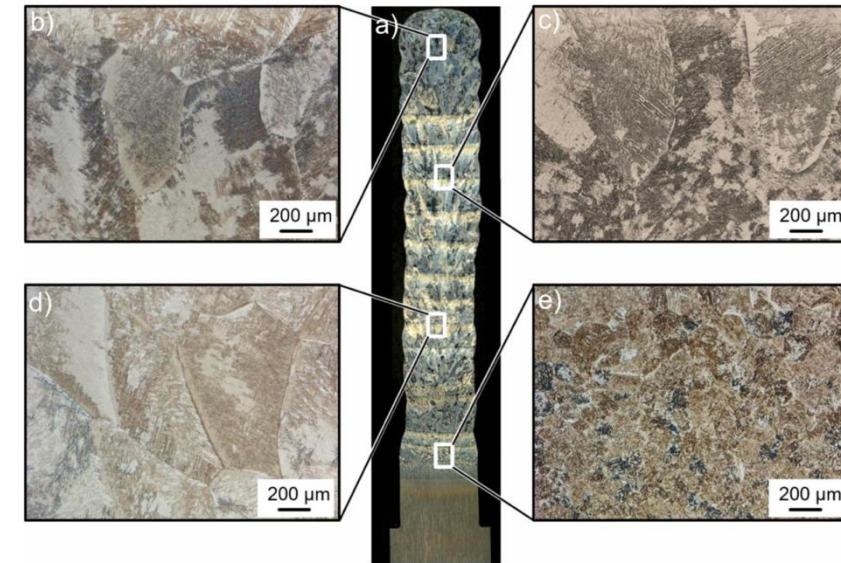


Challenges

Effect of Heat Input on Microstructure and Grain Structure



- Hybrid structure out of Ti-6Al-4V
- First layers welded with higher heat input
 - compensate higher heat dissipation and pre-heating of substrate
- Oscillating welding path
- Cooling time between deposition of each layer: 130 s



Future Opportunities



- Functionally Graded and Multi-Material Structures
- Large-Scale Structural Repair and Remanufacturing
- Sustainability and the Circular Economy
- Hybrid and Intelligent Manufacturing
- Specialized Industry Applications

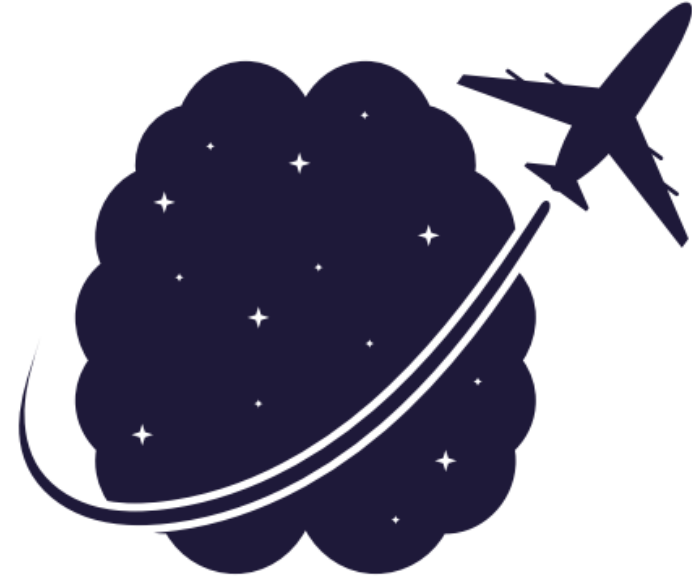
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