Wire + Arc Additive Manufacturing

by

Hanadi Salem, Professor
Materials & Manufacturing
Mechanical Engineering, AUC

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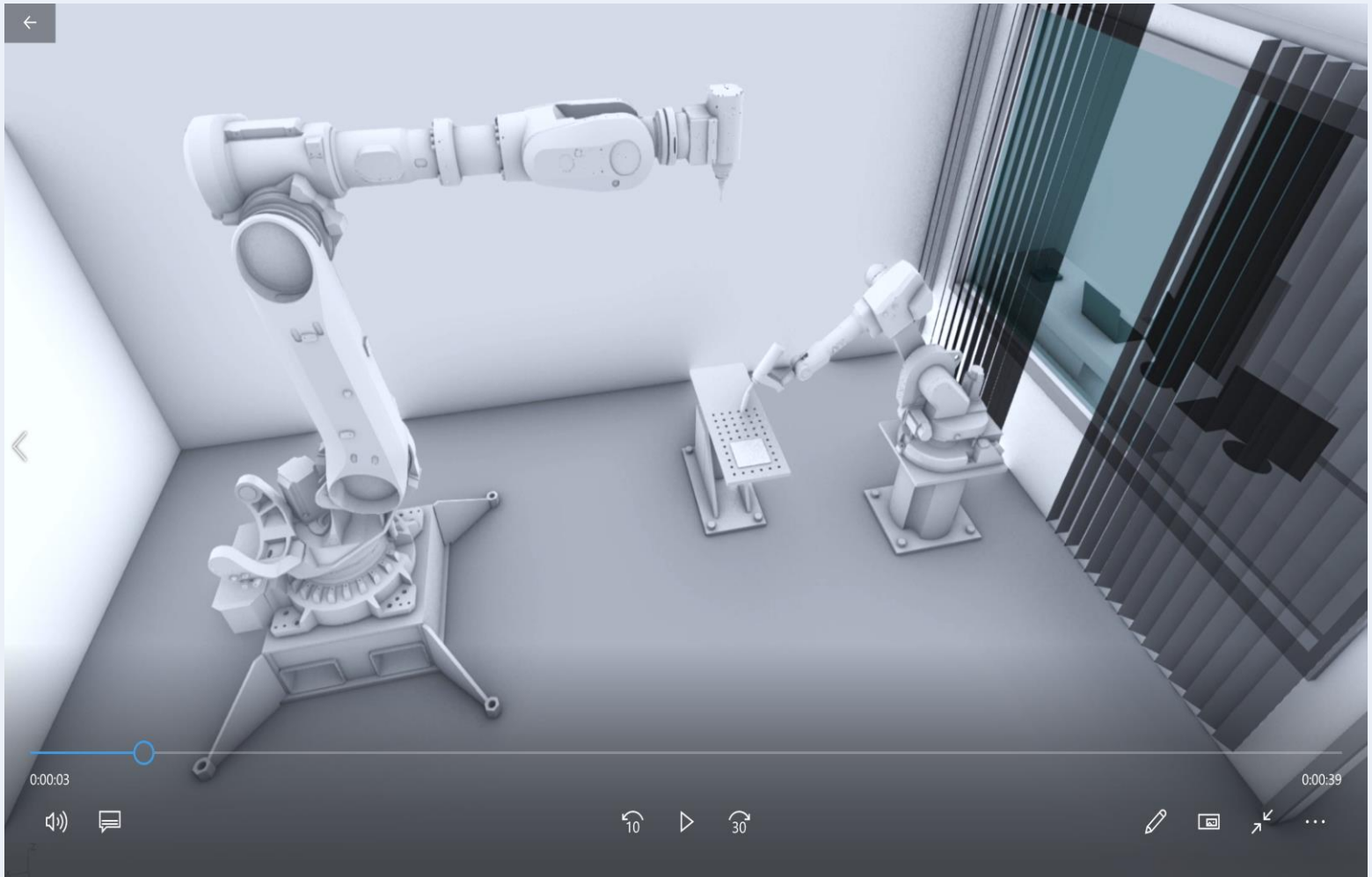
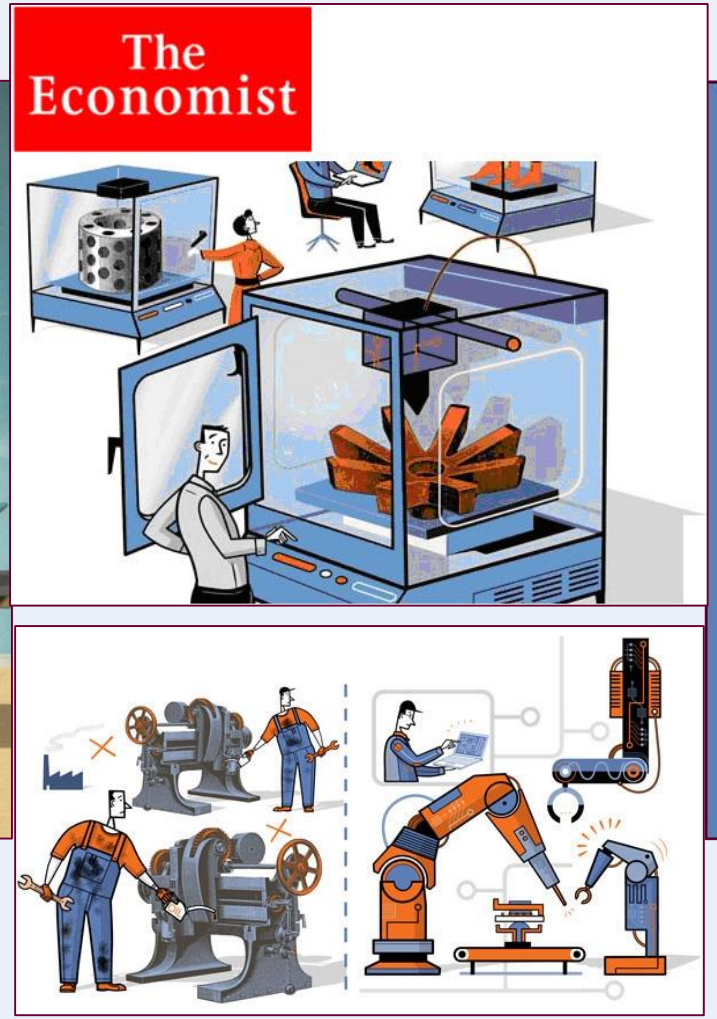
Outline

The American University in Cairo

Wire Arc Additive Manufacturing Robotic System at AUC



3D Printing
3rd-4th Industrial Revolution Transition



What is Additive Manufacturing?

- Bottom-up Process of joining materials to produce objects starting from 3D model data, Layer by layer, Opposite to subtractive manufacturing methodologies (m/c)

Advantages and benefits which include:

- 3D CAD drawing of a component to a shape to be converted directly into physical part,
- Reduction in design constraints,
- Reduction in complex assembly,
- Increases design flexibility,
- Near net shapes, and efficient material utilization,
- Lower pollution (green process),
- Reduction in time-to-market needs and hence
- Production at a relatively lower cost than traditional manufacturing

E-Manufacturing
Freedom Fabrication
Generative Manufacturing
Additive layer Manufacturing
Additive Manufacturing
Constructive Manufacturing
Direct Digital Manufacturing
Additive Fabrication

INDUSTRIES USING AM

- Automotive

Worldwide Auto Production (2017)
74 million

Various web sources

INDUSTRIES USING AM

•Other transportation Vehicles

Various web sources

INDUSTRIES USING AM

- Aerospace

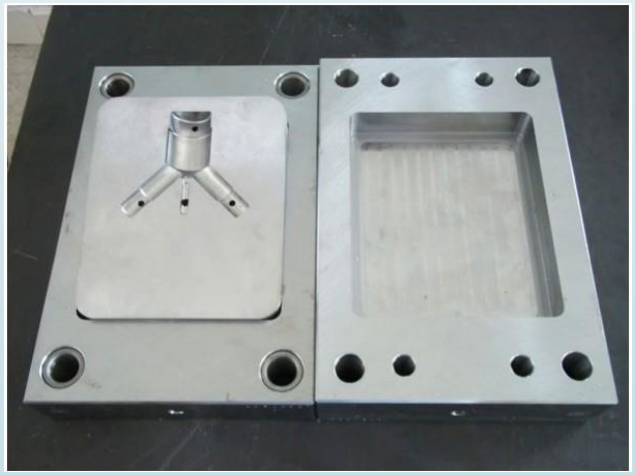
Boeing 747 total orders and sales to Q1 2018:
1554 (~32/yr)

Various web sources

Industries Using AM

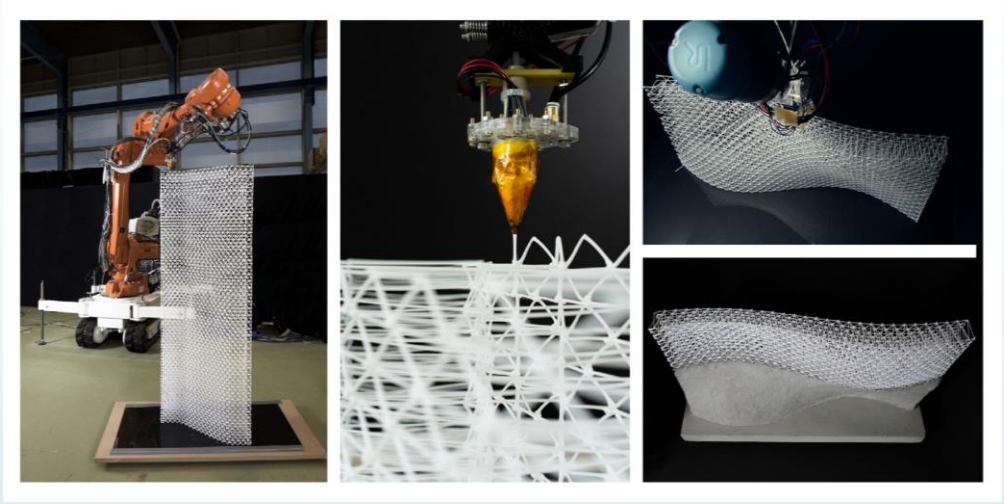
- Tooling Dies & Molds

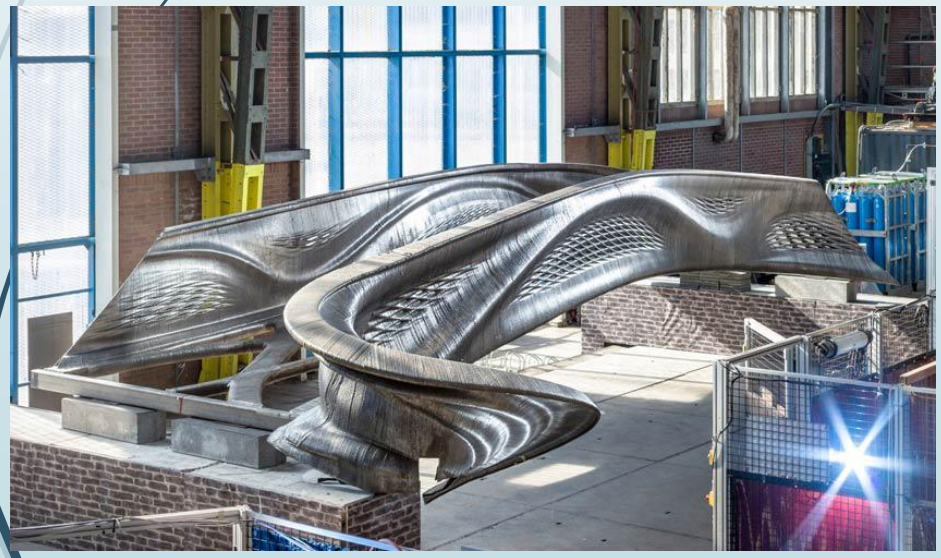
Various web sources



INDUSTRIES USING AM

- Construction
- Architecture



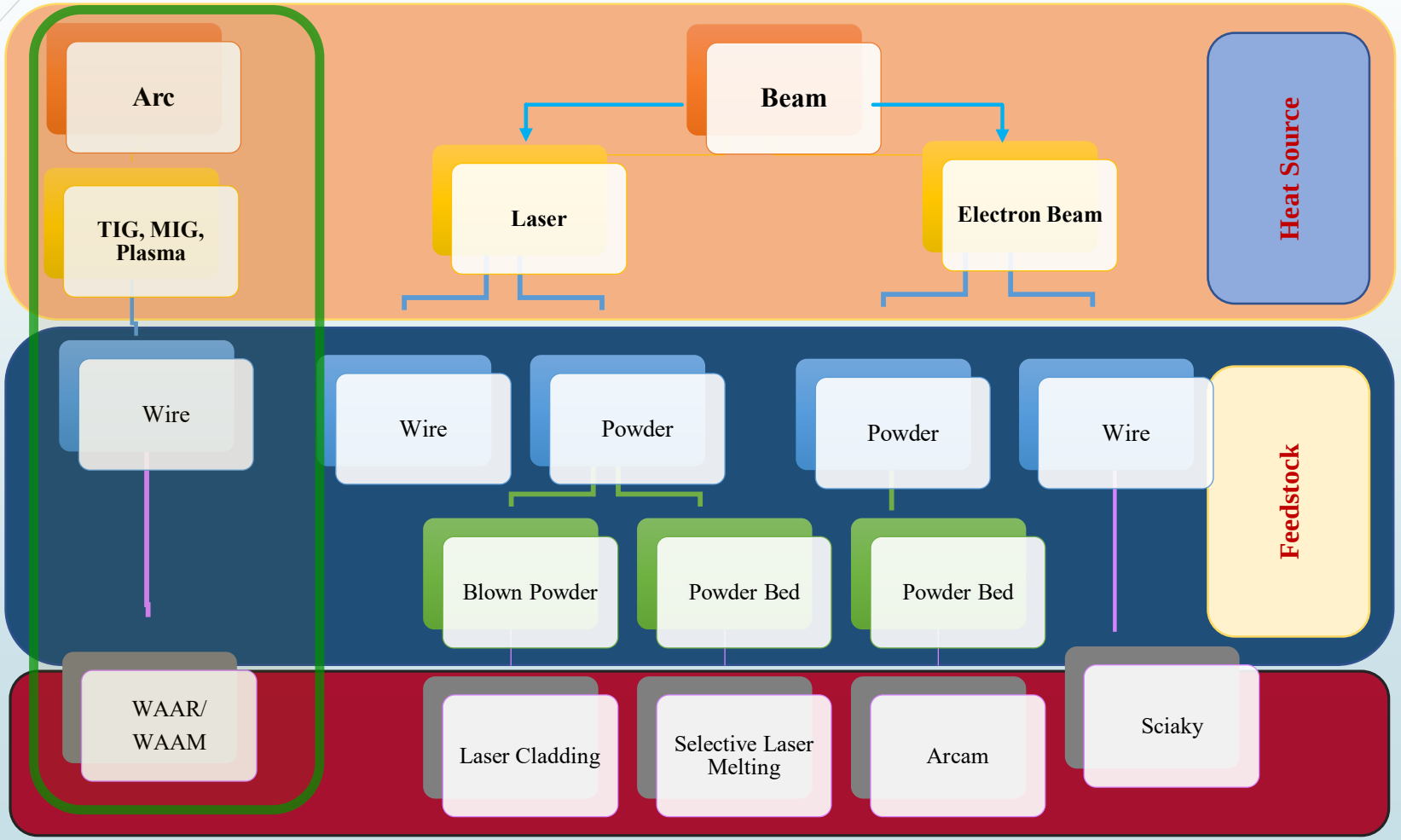


3D printed steel bridge by MX3D finally ready
https://www.3dnatives.com/en/3d-printed-steel-bridge260420184/

https://www.google.com/search?q=WAAM+for+architecture&source=lnms&tbm=isch&sa=X&ved=2ahUKEwiQj4Du5-LoAhUPzYUKHU6ZBt0Q_AUoAXoECAsQAw&biw=772&bih=563&dpr=3#imgrc=RDdLB0cHeMAx9M

Metal Additive Manufacturing Technology

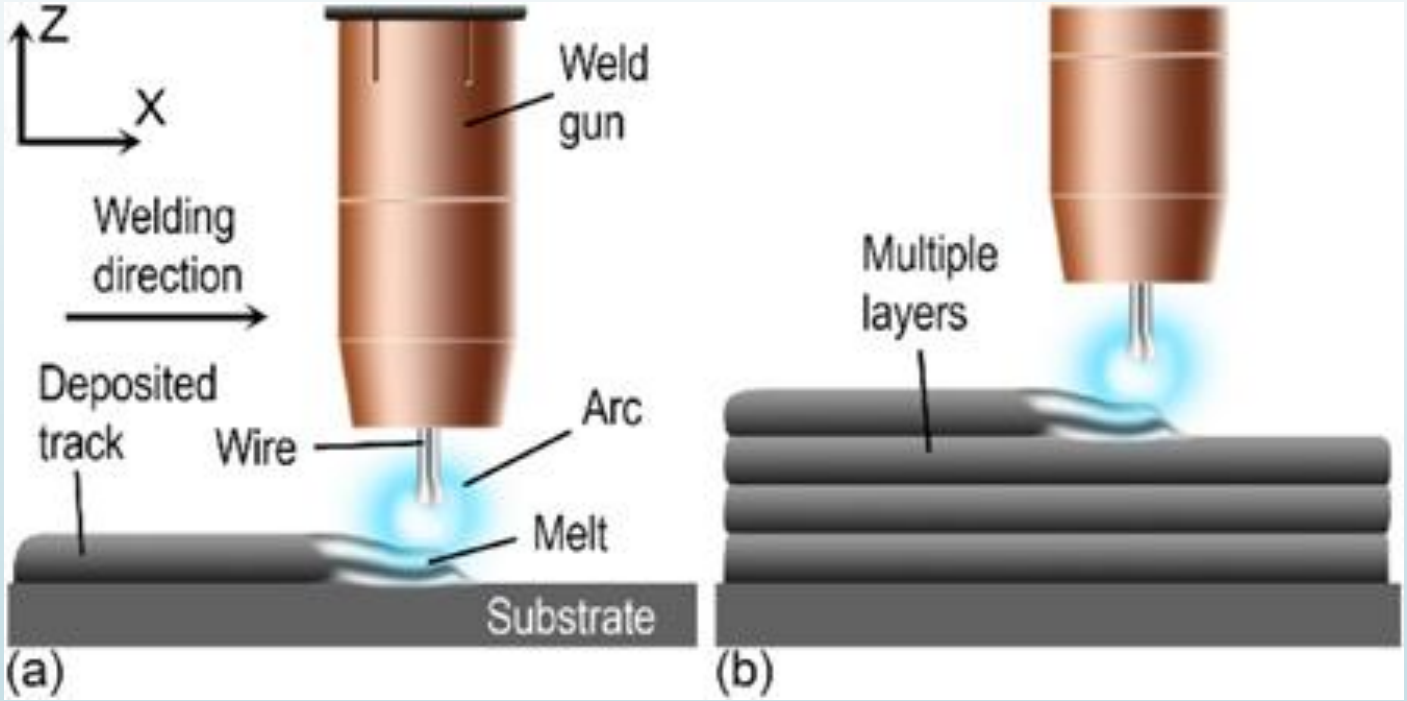
Metal Additive Manufacturing: Classification



A flow chart classifying AM in terms of the materials feed stock, energy source, build volume

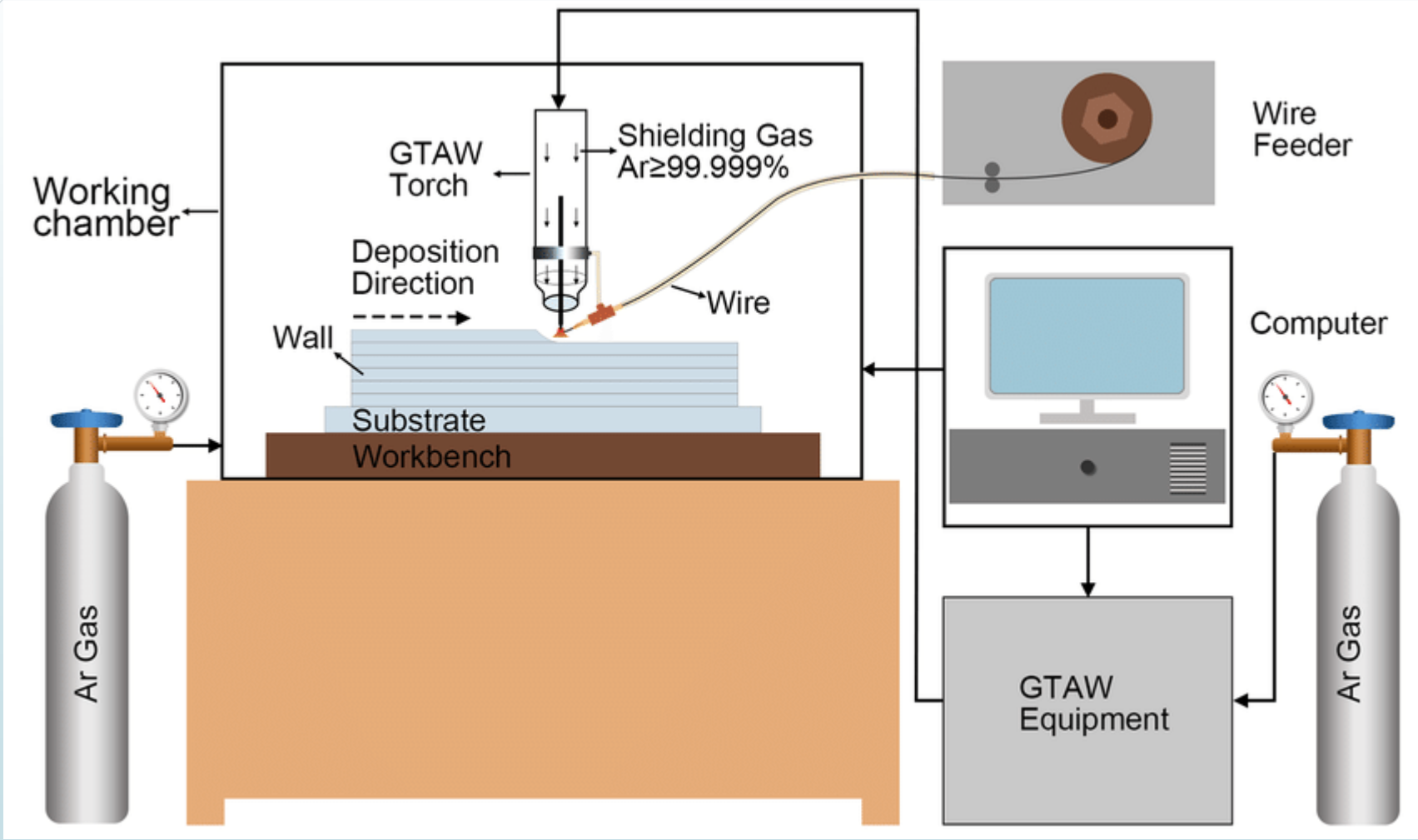
[Cranfield].

Wire Feed Additive Manufacturing



https://www.researchgate.net/publication/293491378_The_effectiveness_of_combining_rolling_deformation_with_Wire-Arc_Additive_Manufacture_on_b-grain_refinement_and_texture_modification_in_Ti-6Al-4V/figures?lo=1

Wire Feed Additive Manufacturing



https://www.researchgate.net/publication/310820827_Wire_Arc_Additive_Manufacturing_of_AZ31_Magnesium_Alloy_Grain_Refinement_by_Adjusting_Pulse_Frequency/figures?lo=1&utm_source=google&utm_medium=organic

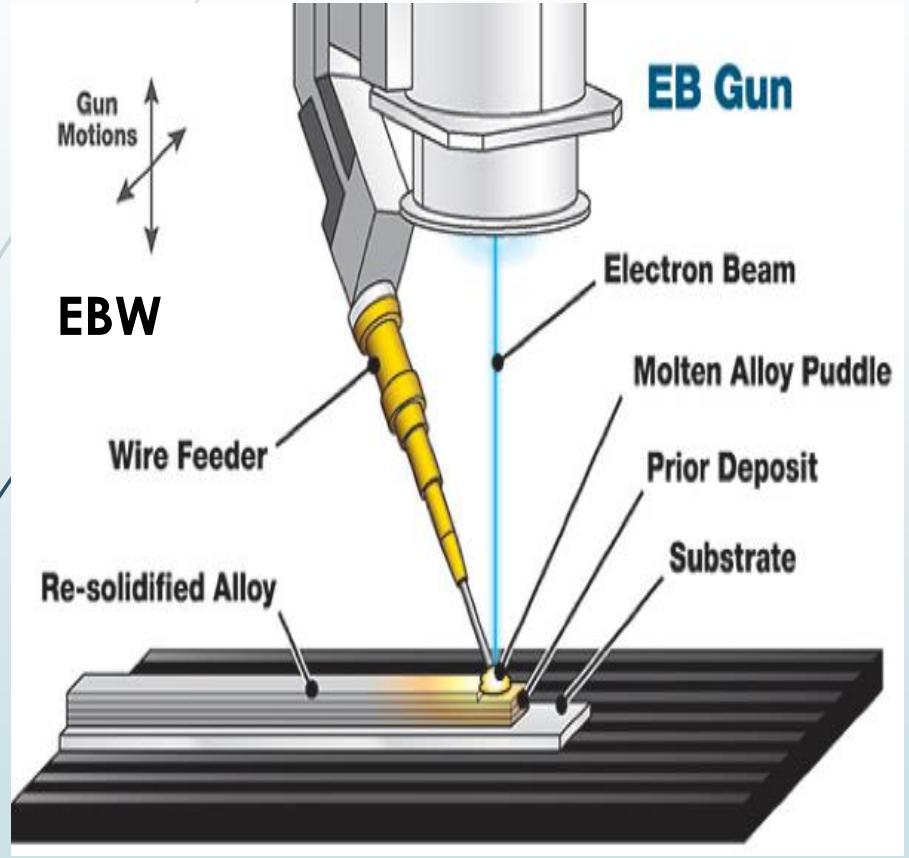
Wire Additive Manufacturing

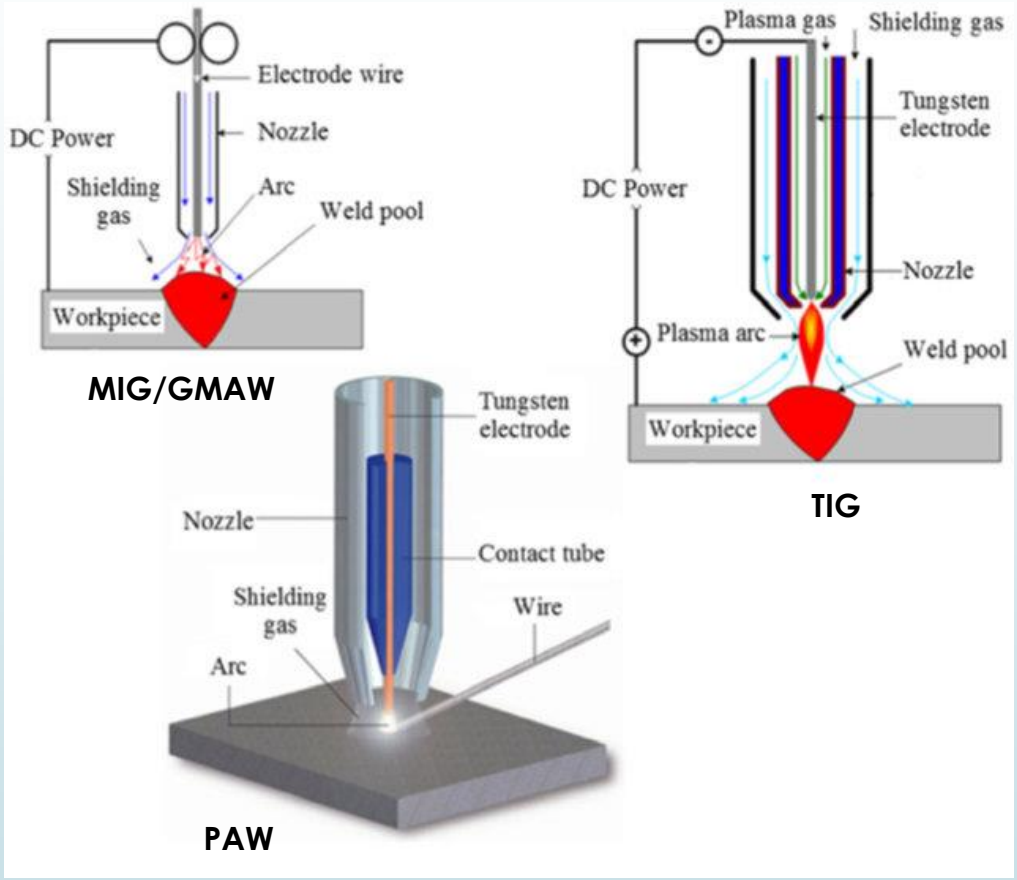
- New wire and arc welding based technologies
- Provides new routes to manufacture ready-to-use large metal parts.
- with very high deposition rates
- Specific deposition cost (dependent upon BTF):
- – Ti: US$ 380/kg
- – Al: US$ 26/kg
- – Mild steel: US$ 32/Kg

- BTF: is Buy-to-Fly ratio used for evaluation of the weight of the raw material divided by the weight of the final component

Examples of Manufactured aircraft parts by WAAM Truss work part, conjunction part, Engine part (steel & Cupper) and landing Gear Rib

Types of Wire Feed Energy Sources



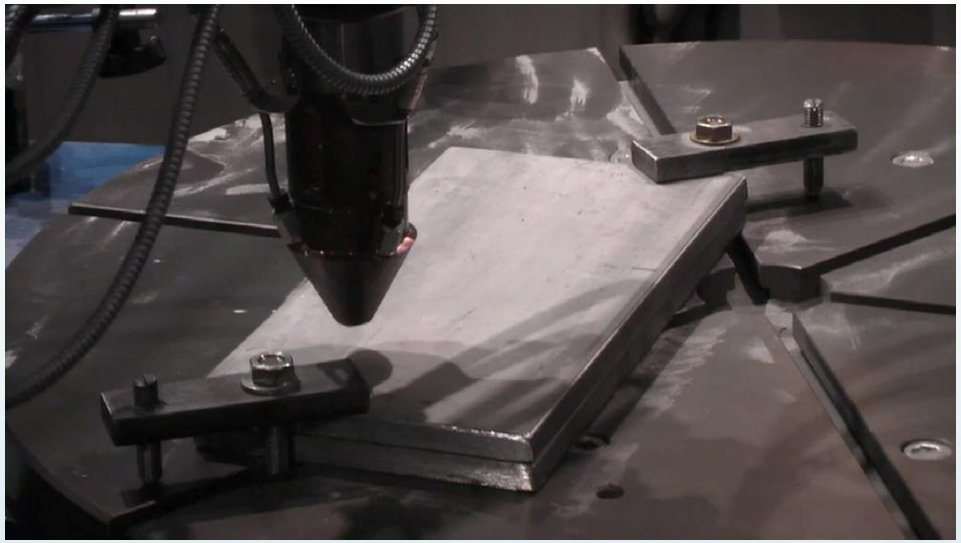


- Schematics of WAAM Systems

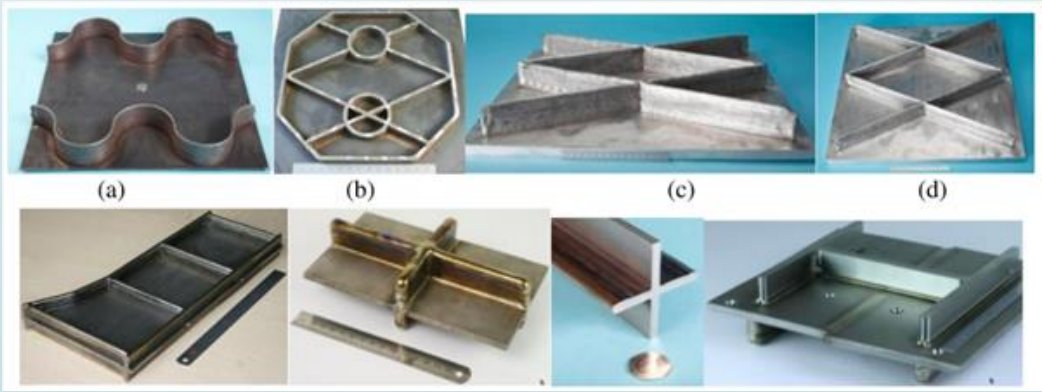
https://www.researchgate.net/publication/332886203_Review_of_Wire_Arc_Additive_Manufacturing_for_3D_Metal_Printing/figures?lo=1

WAAM Advantages

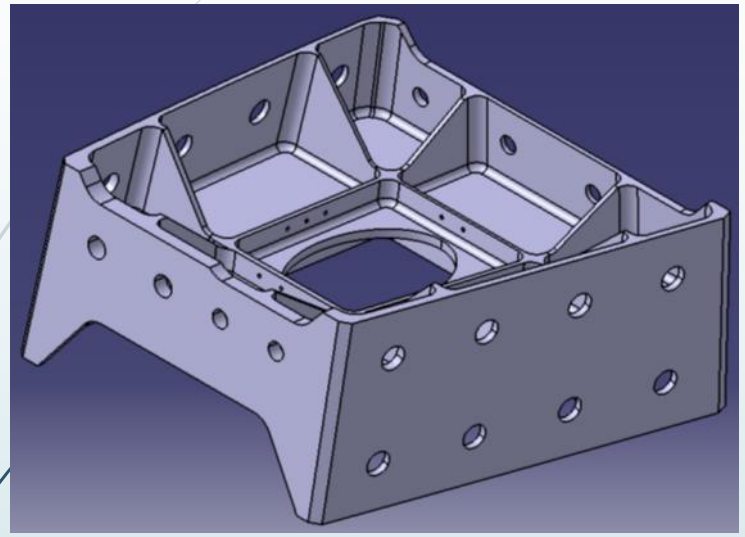
- Repair vs. Replace
- Local low cost solution
- Application to worn-out aviation parts
- Weldable and non-weldable alloys
- Load-bearing and non-load bearing parts
- Straight near net shapes
- Thin and thick walled crossovers
- Build rates: 0.5 - 4 kg/hour
- Unlimited building volume
- 100% dense parts with no defects
- No material supply issues – aerospace grade wires

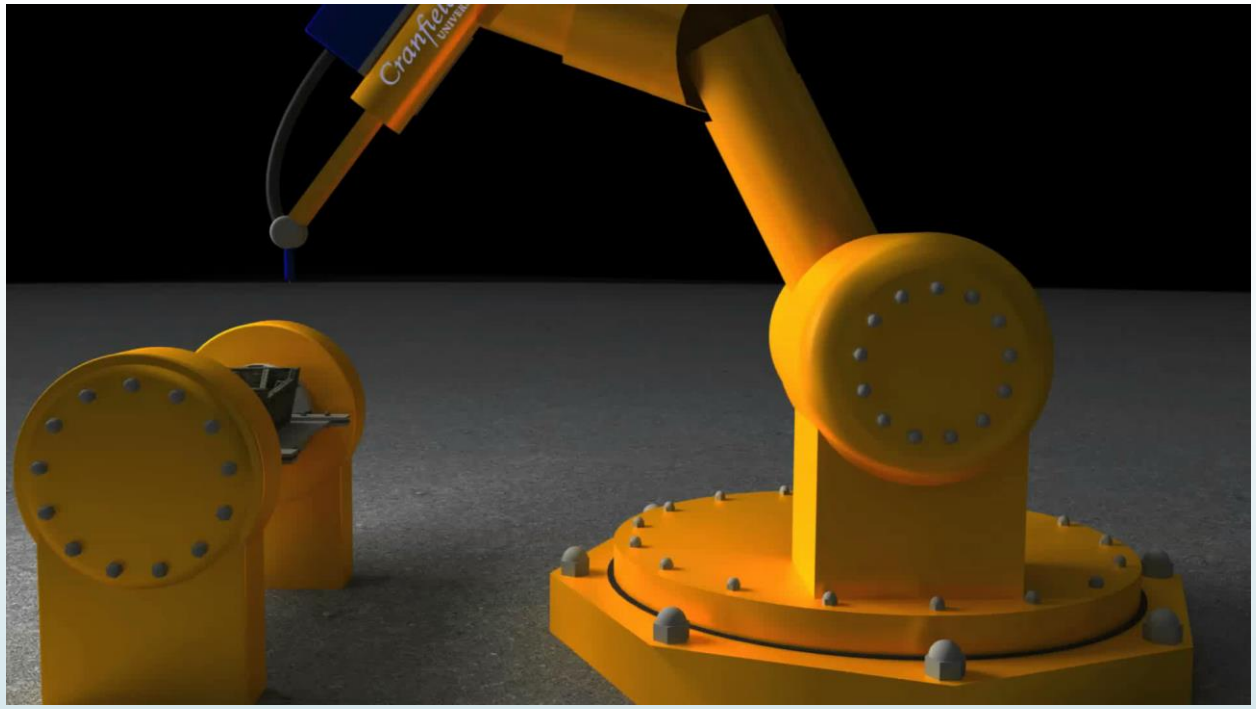


Media 1 – Laser Deposition



WAAM: Landing Gear Rib (Ti & Steel)





WAAM vs. Machining

Manufacturing Options	Mass (Kg)	BTF	Cost (US$ K)	Cost Reduction
Conventional M/C	20	12	20.25	-
WAAM	20	2.3	6.25	69%

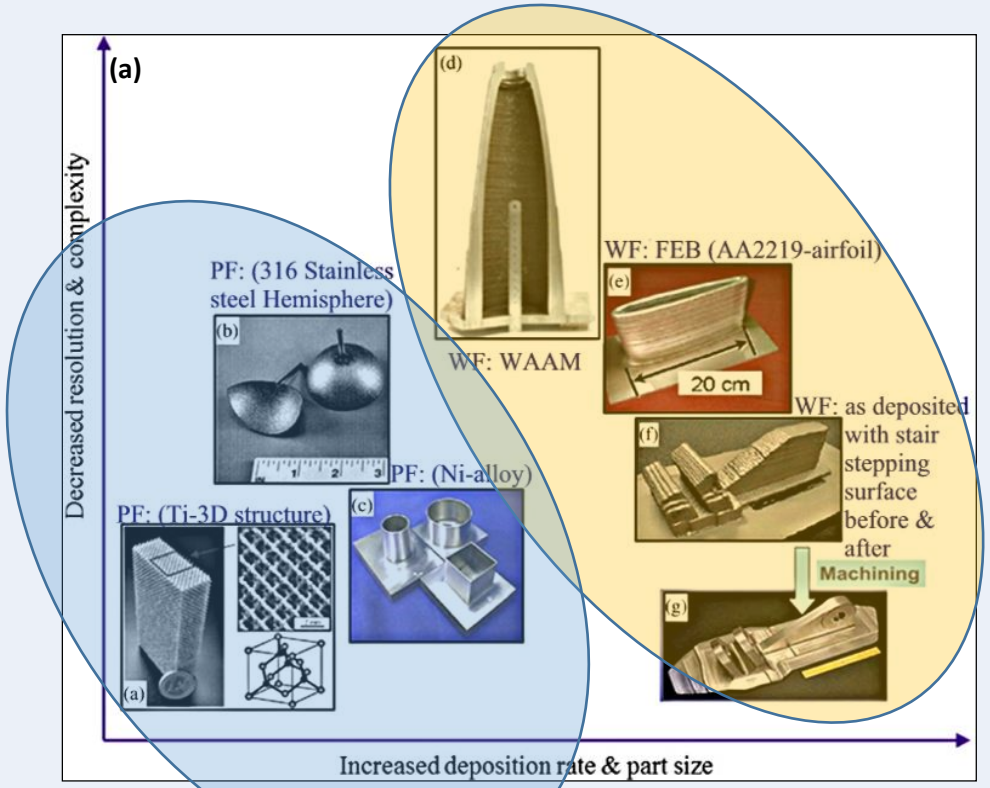
Ti-Alloy

Manufacturing Options	Mass (Kg)	BTF	Cost (US$ K)	Cost Reduction
Conventional M/C	36	12	2	-
WAAM	36	2.3	0.875	55%

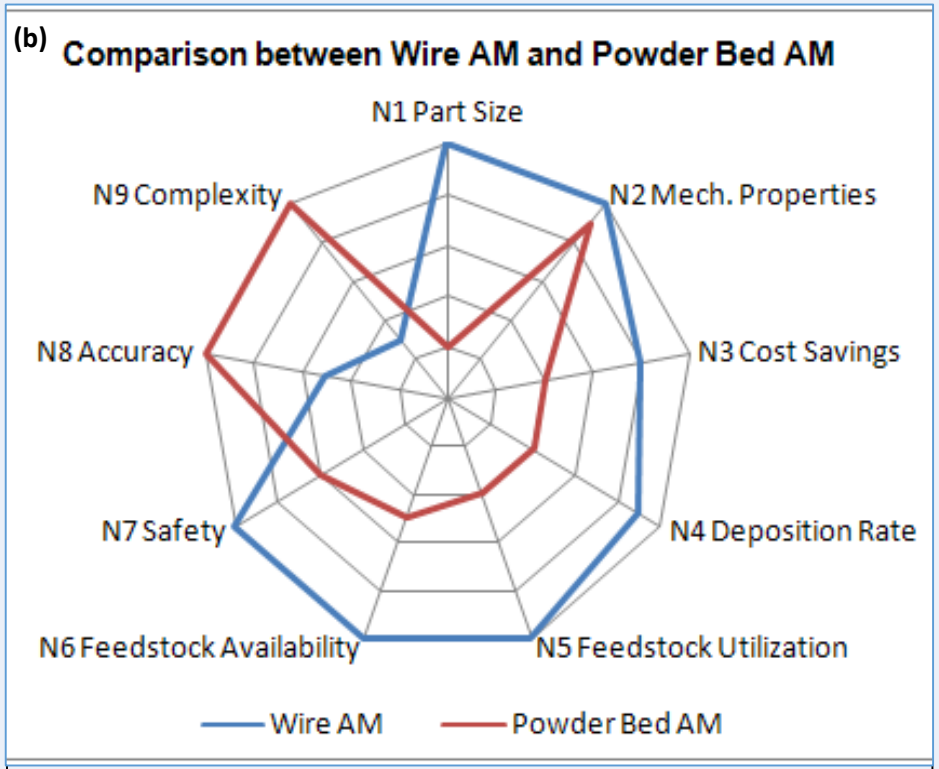
Steel

Powder Feed Vs. Wire Feed AM Systems

The American University in Cairo



Variation of part resolution and complexity with the deposition rate and part size for the PF and WF systems AM technologies [*Wire Additive review*]



Wire AM is a very promising technology for producing medium-to-large components with high complexity at a much cheaper cost compared to powder bed AM

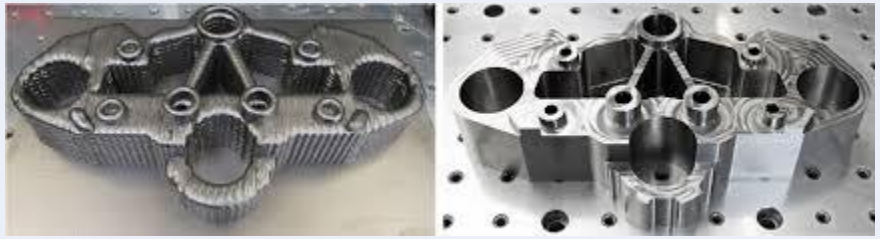
Wire Feed AM Advantages

The American University in Cairo

- Repair vs. Replace
- Local low cost solution
- Application to worn-out parts
- Weldable and non-weldable alloys
- Load-bearing and non-load bearing parts

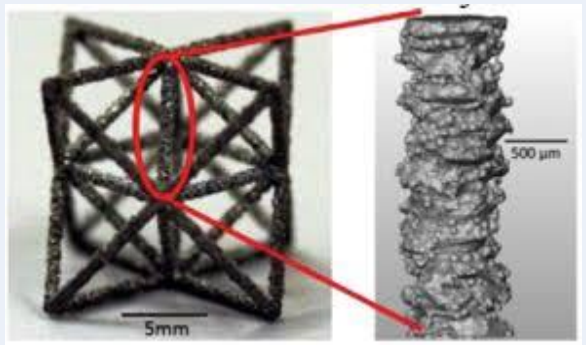
- Straight near net shapes
- Thin and thick walled crossovers
- Building rates: 0.5 - 4 kg/hr
- Unlimited building volume
- Dense parts with no defects

- No material supply issues –grade wires



https://www.google.com/search?q=Wire+Arc+Additive+Manufacturing+products&source=lnms&tbm=isch&sa=X&ved=0ahUKEwiuiYv88IziAhWQohQKHc4_A1QQ_AUIDigB&biw=1536&bih=706#imgrc=qdsZNwpywbF6LM:

https://www.imagicasa.be/en/blog/13508/obsessed-with-3d-printin



https://cargocollective.com/chrisborgc/ROBOTIC-WIRE-ARC-ADDITIVE-MANUFACTURING

Wire Arc Additive Manufacturing Distribution Worldwide

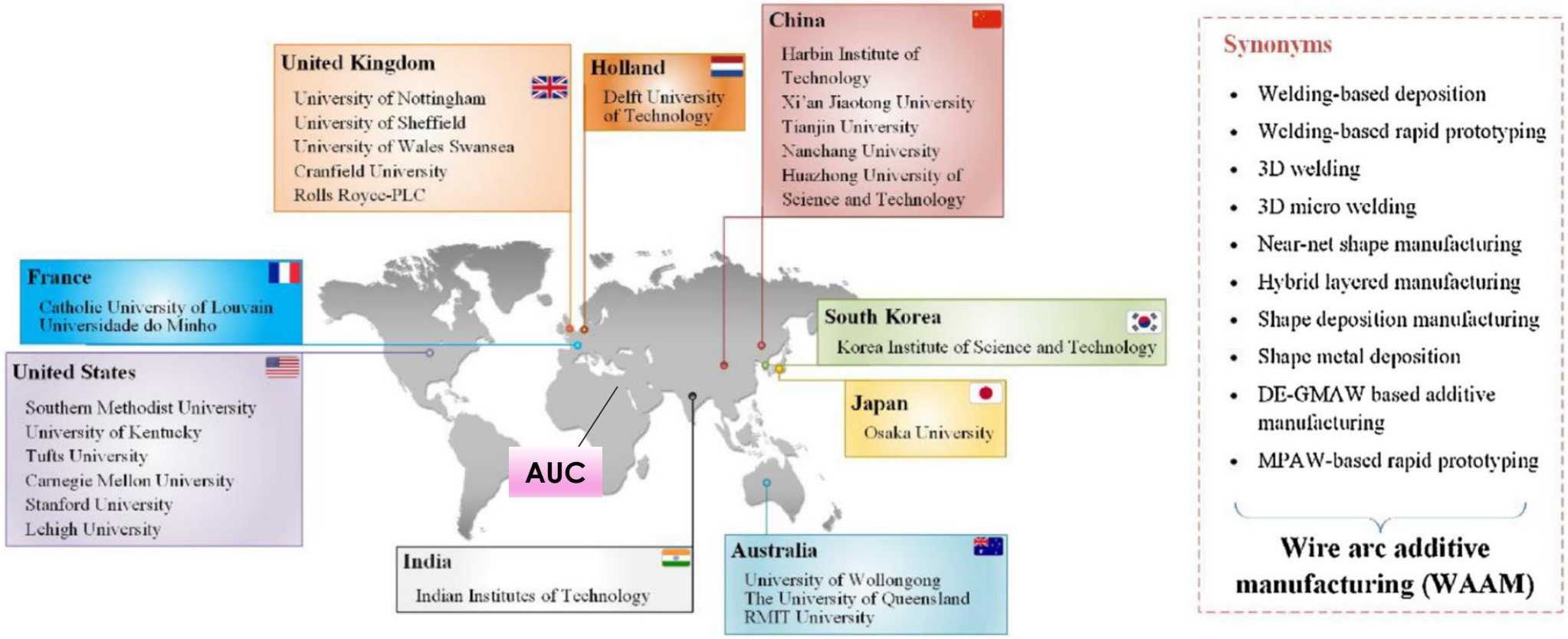
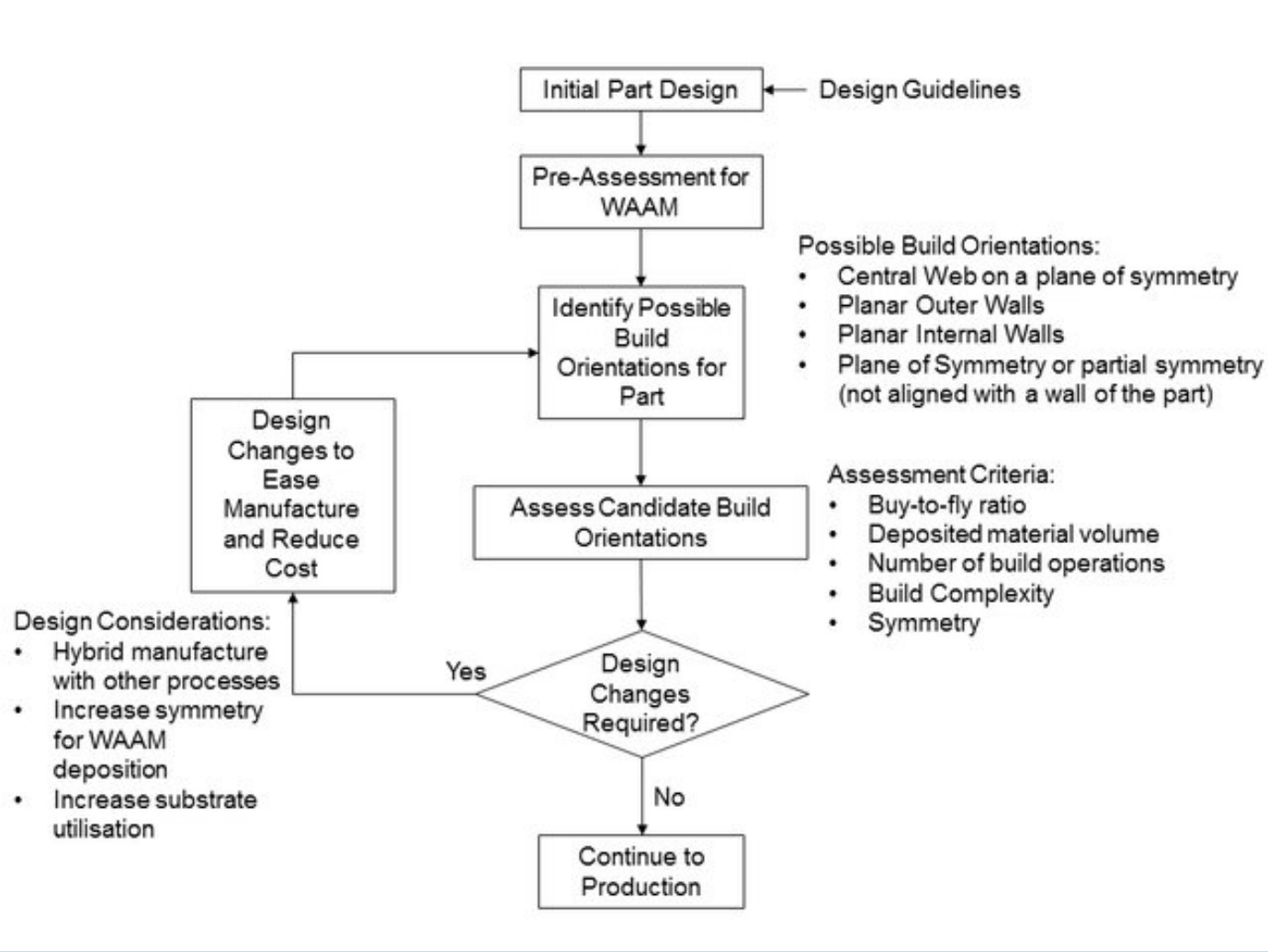


Fig. 1. The distribution of main WAAM research groups.

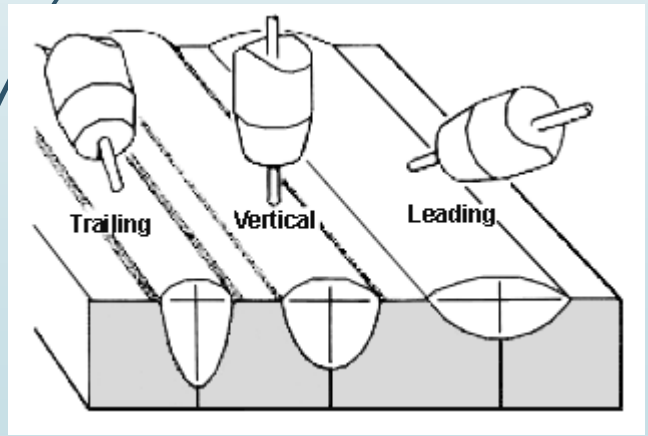
WAAM Process Design

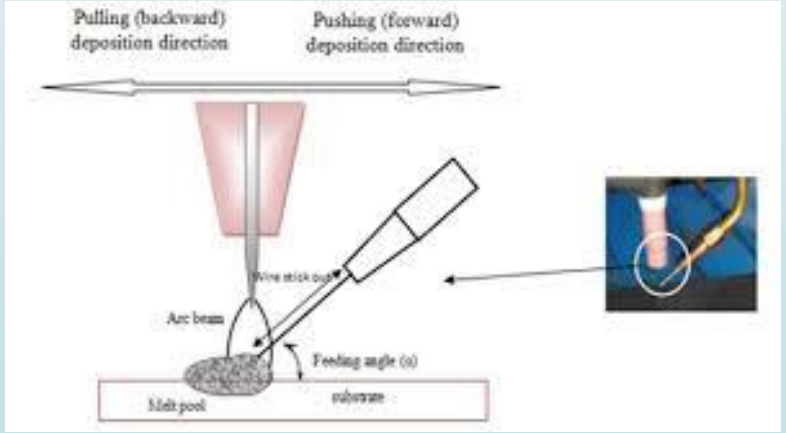


Design for Wire + Arc Additive Manufacture: design rules and build orientation selection
https://www.researchgate.net/publication/319215130

WAAM Process Parameters

- Wire Material Selection
- Robot Manipulation Parameters:
  - Working Angle
  - Travel Angle
  - Waiting time





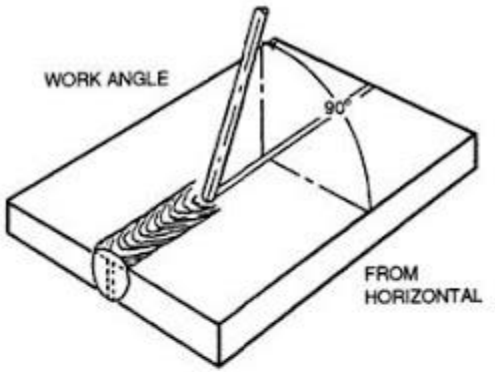


Figure 7-15.—Work angle.

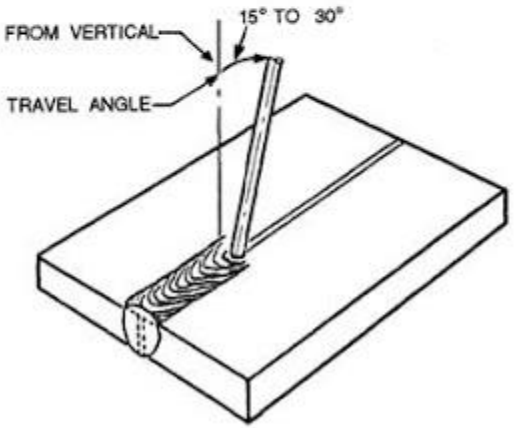


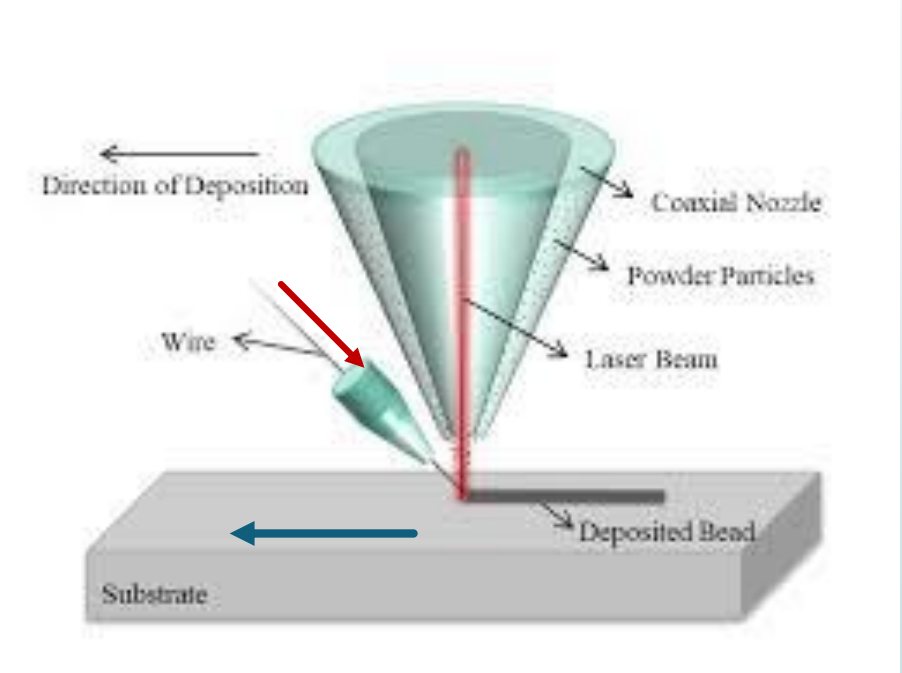
Figure 7-16.—Travel angle.

https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-the-effect-of-electrode-angle-in-sa-submerged-arc-welding

Manipulation using Robot Studio for Building of the Parts

WAAM Processing Parameters

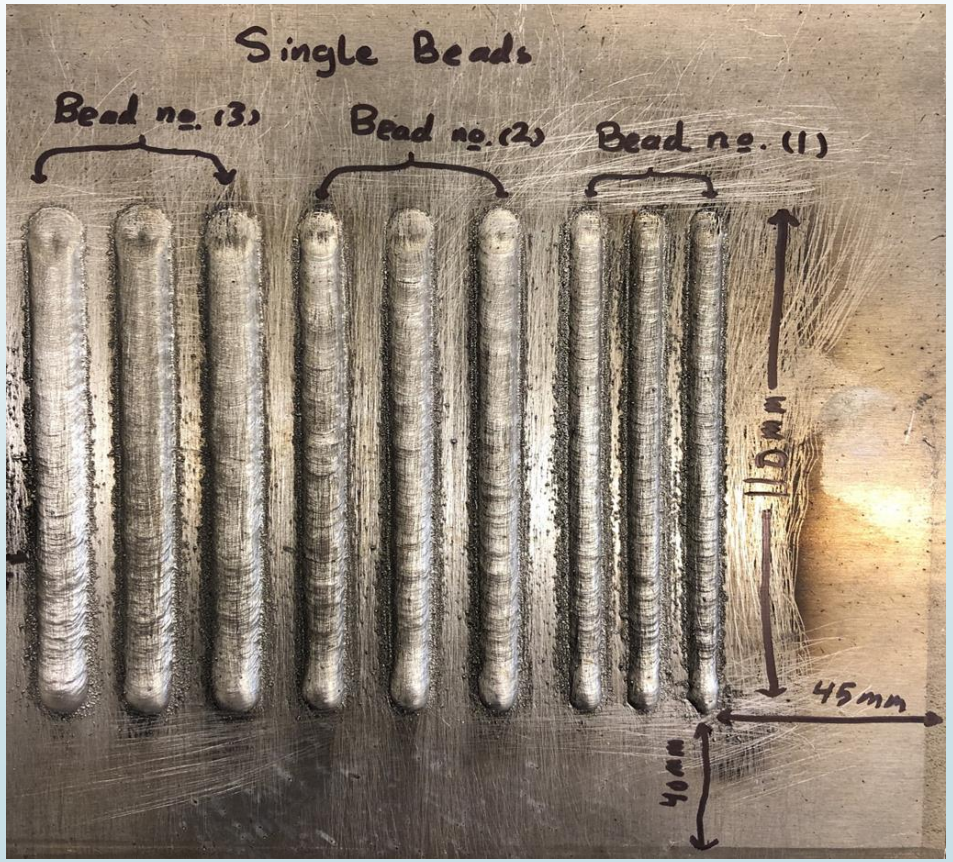
- Deposition Parameters:
  - Wire Feed Speed
  - Travel Speed
  - Voltage
  - Waiting time



http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-92242017000400466

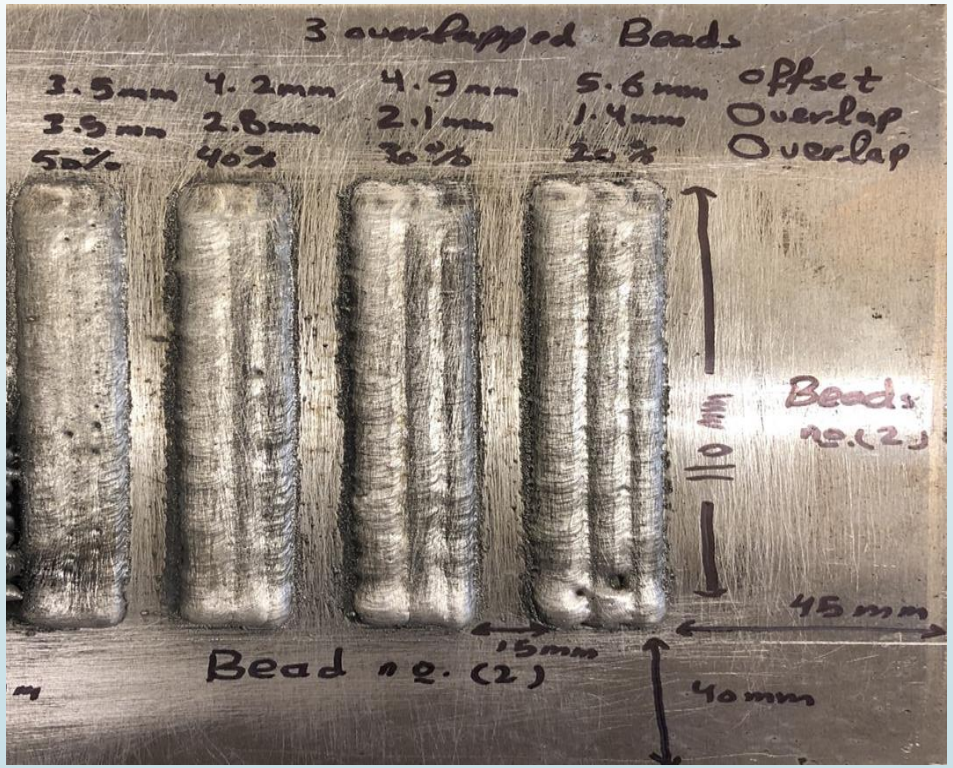
Bead's Geometry & Tool Path

- **Bead Geometry:**
  - Bead width and Height, which controlled by deposition parameters



Bead's Geometry & Tool Path

- **Bead Geometry:**
  - Overlapping Distance: % of the bead's width used to determine the beads overlapping distance



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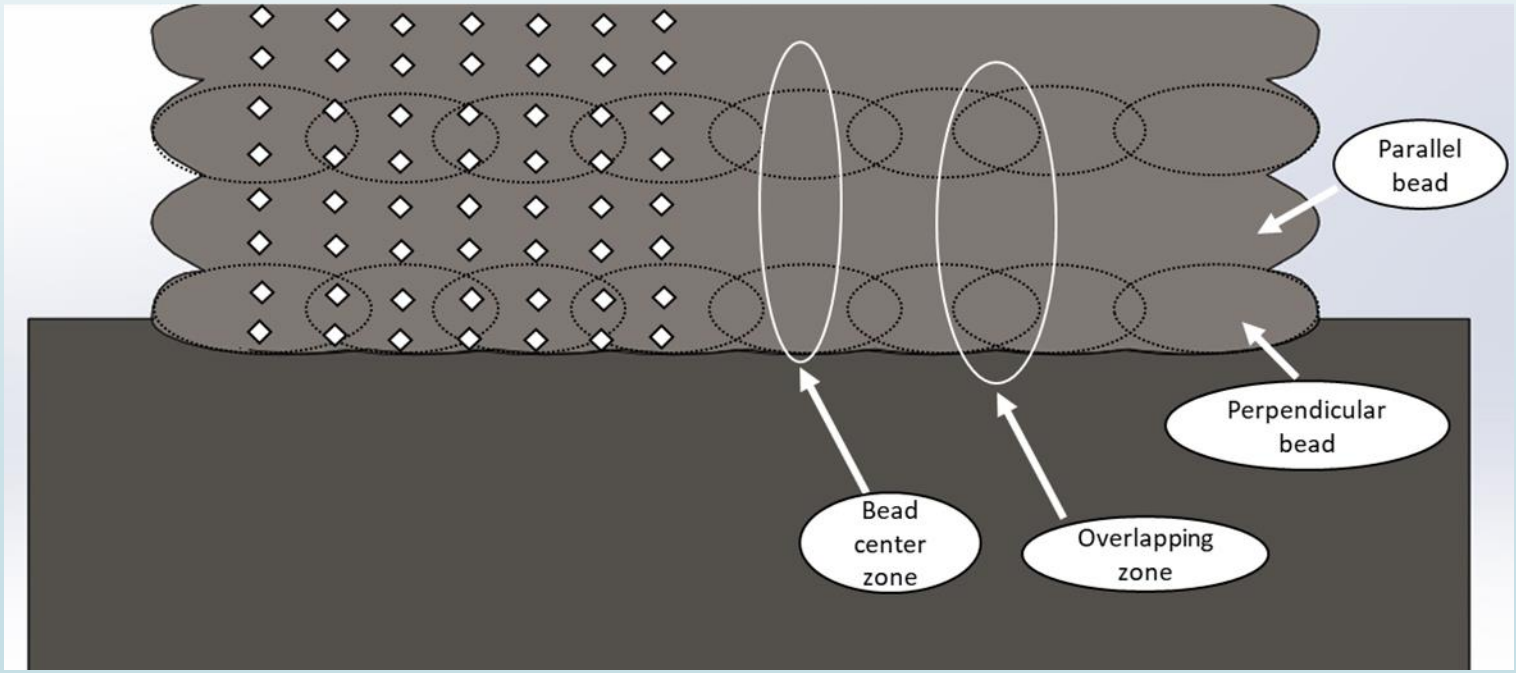


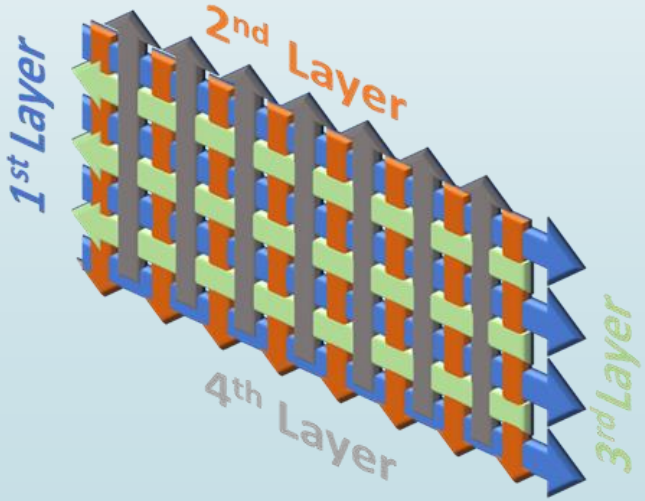
Bead Width (5 mm) Increased % overlapping (30-50%)

Increased Bead width

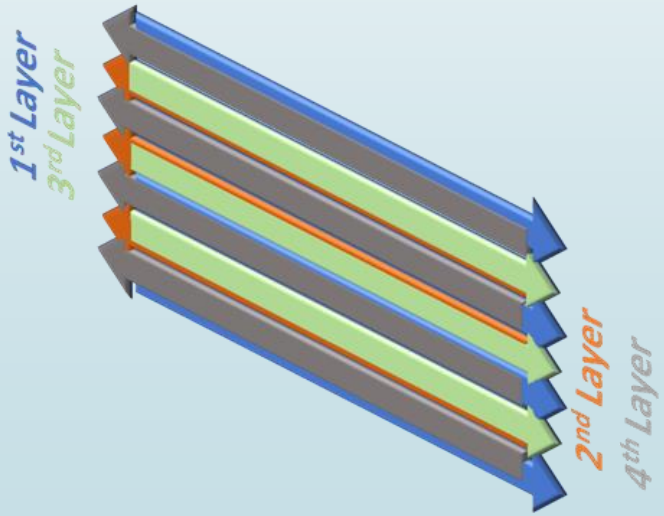
Bead Width (9 mm) Increased % overlapping (30-50%)

Bead's Geometry & Tool Path

- **Tool Path:**
- Building of the part can take several paths between layers along the building direction
  - Parallel
  - Orthogonal
  - Alternate deposition



Alternate/Orthogonal

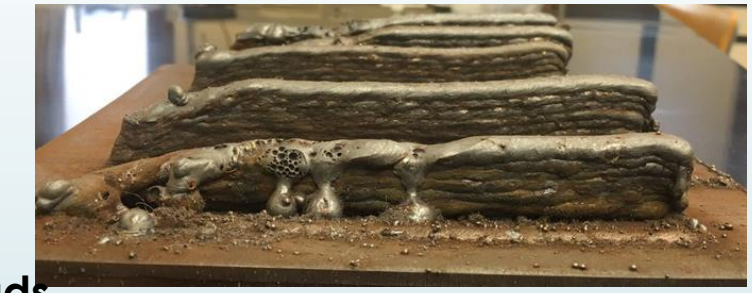


Alternate/Parallel

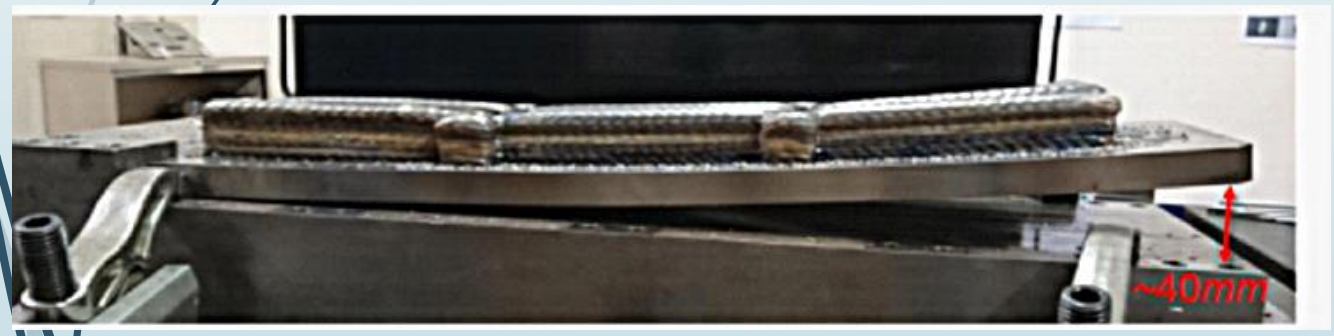
Challenges to WAAM/R

Distortion & Residual Stresses: Shrinkage and uneven cooling rates during Wire Deposition

Irregular Beads



Shape Distortion



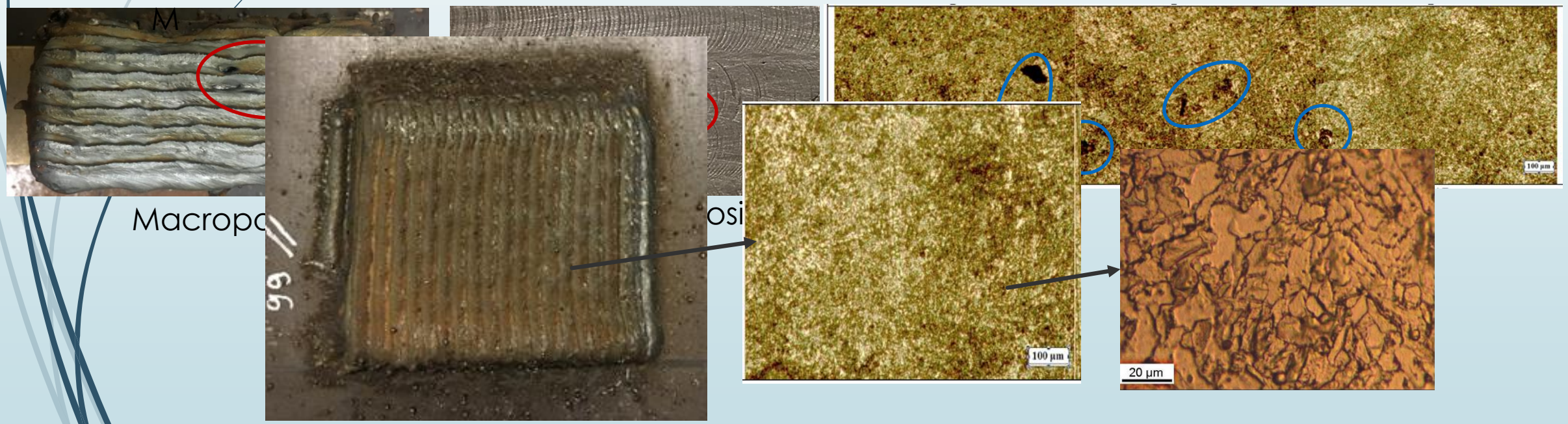
Uniform Beads

Energy Input: Voltage, current, wire feed speed, ambient temperature,
Protecting Gas flow rate control

Challenges to WAAM/R

Structure Integrity and **Mechanical Properties**

Macro, Mesos & Microstructural evolution control



WAAM/R Project @ AUC

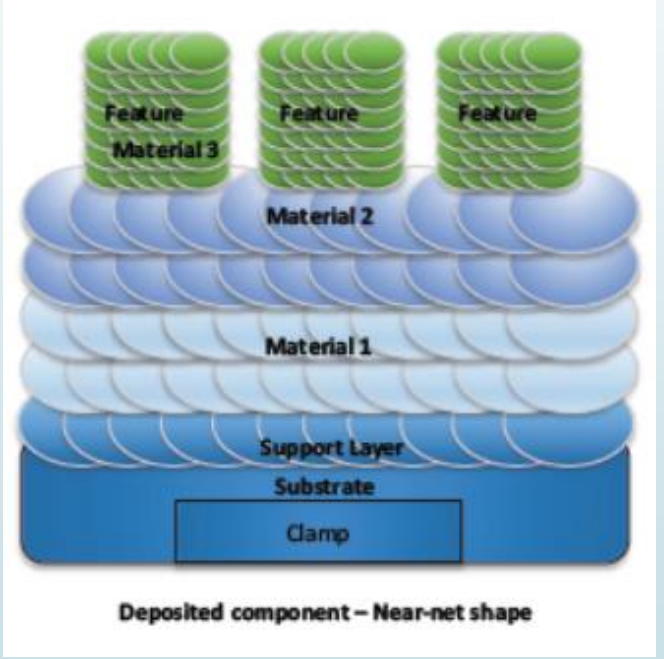
Integrated WAAM/R System

I. Deposition (Additive)

Wire Material Selection (Grade wire)

Wire Material Design:

- Single Material (pre-designed)
- Multilayer materials
- Composite
- Insitue Alloying
  - multiple wire feeders
  - wire + Powder feeders



Integrated WAAM/R System: Multi-Sensor

II. Process Design: Real-time monitoring System

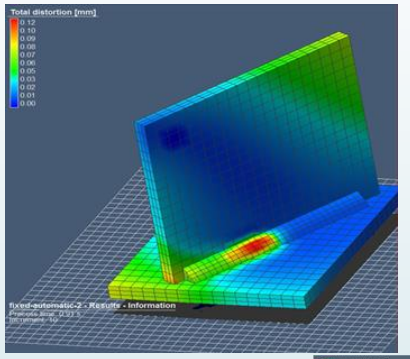
Oxygen Level
Gas Flow Rate

Voltage & Current
Wire Feed Rate
Head Travel speed

Energy input

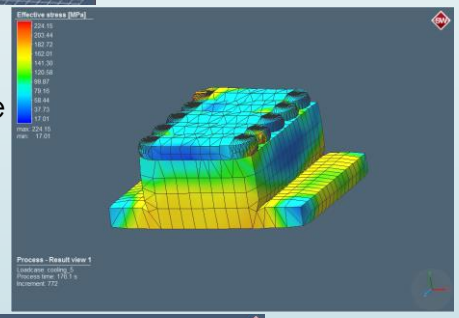
Positioner (bead height & Geometry control)
Laser Profiler

Modeling & Simulation

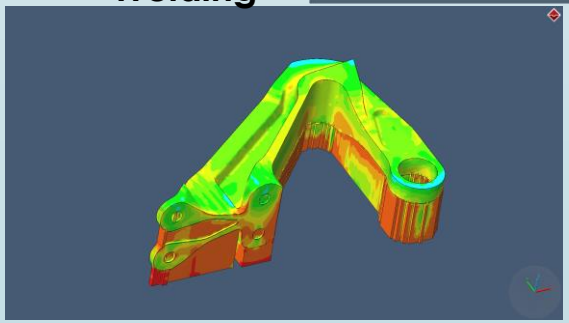


WAAM Single Bead wall

WAAR Multiple Beads Layer



SIMUFACT Welding



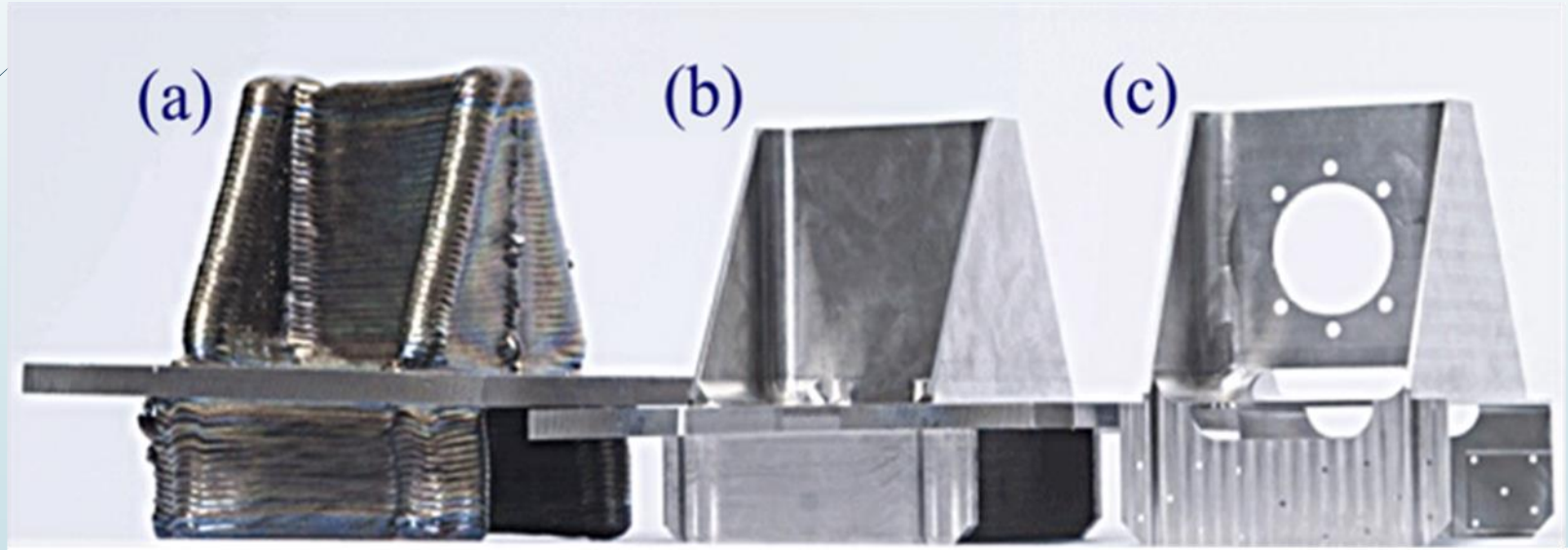
AM Component

SIMUFACT Additive Manufacturing

simufact
Simulating Manufacturing
MSC Software Company

Integrated WAAM/R System: Multi-Sensor

III. Surface Finish (Subtractive)



WAAM processed Aircraft part passing through three stages (a) Wire deposited section, (b) Machine sculpted, and (c) final finished part. http://www.norsktitanium.com/

Integrated Additive/Subtractive: Final Finish

CNC

Robot Controled System

Integrated Additive/Subtractive: Final Finish

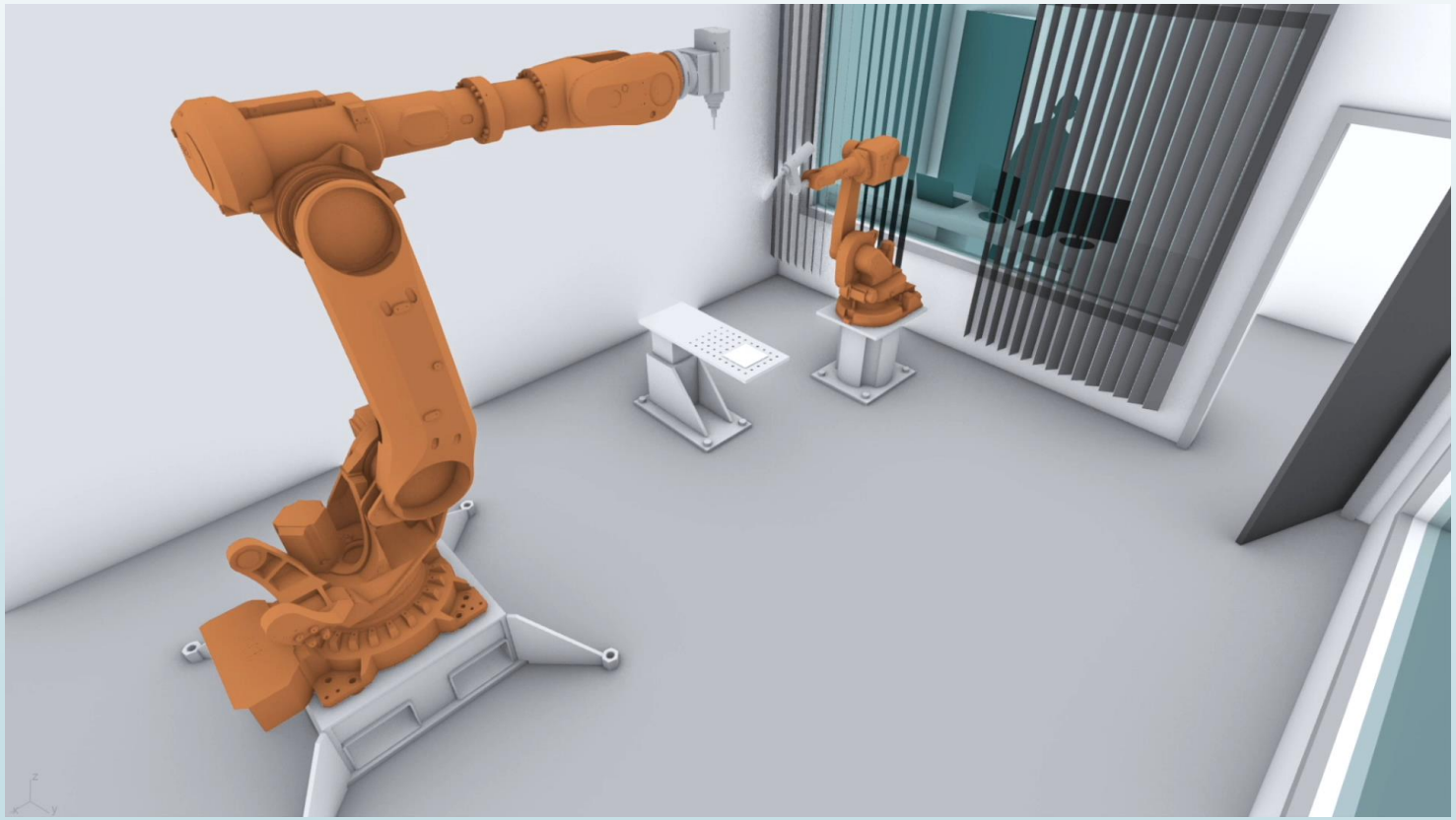
Metal 3D Printing Tools for CNC Hybrid AM/Machines

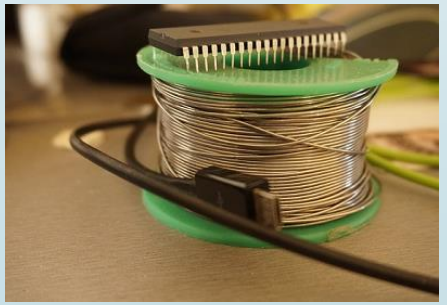
AUC From Conventional To Smart

The American University in Cairo

Additive/Subtractive Integrated Robotic System

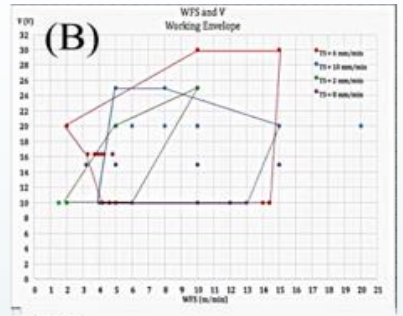
Additive Manufacturing Centennial Lab (AMCL)

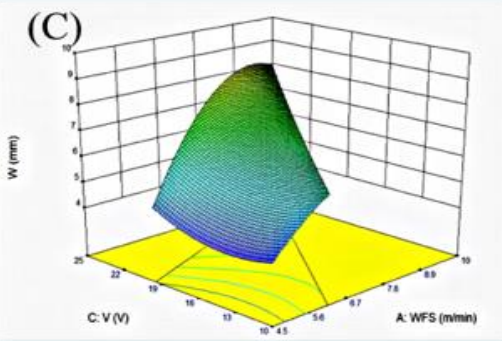


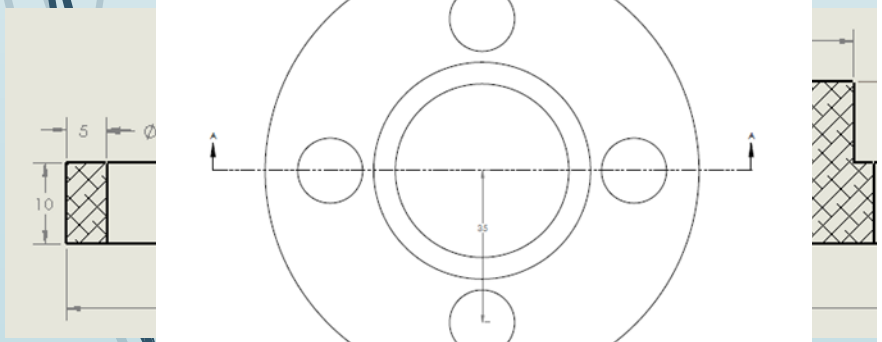


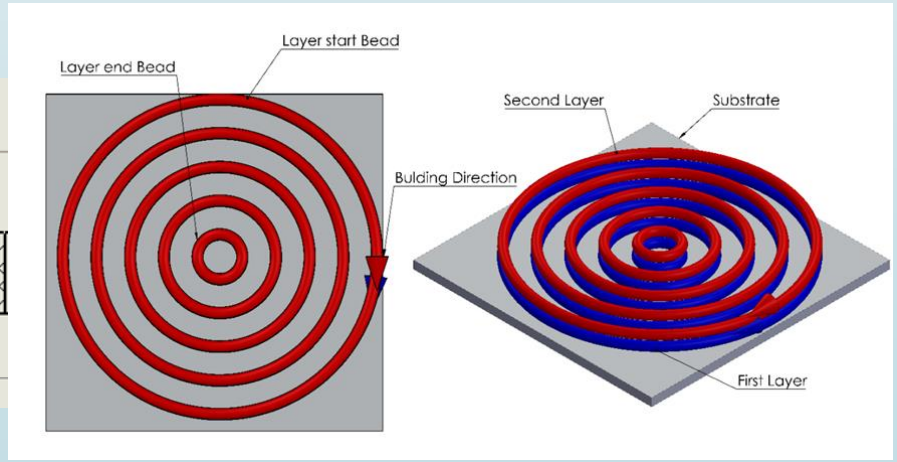
WAAM Process design and optimization, example (1) @AMCL

- Part Selection (Eng. Drawing)
- Material Selection (wire alloy)
- Process window development
- Development of the Bead overlapping Model
- Prismatic Block Manufacturing
- Mechanical & Structural Integrity Analysis
- Al-Flange Manufacturing (Additive/Subtractive)









WAAM Process design and optimization, example (1) @AMCL

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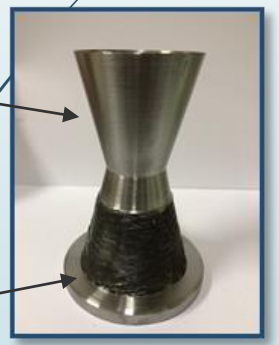
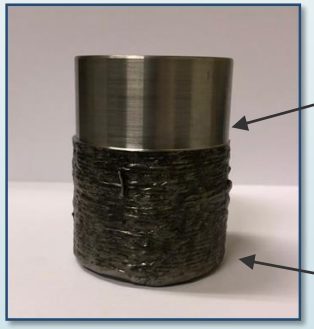
Steel & Al-Flange

Surface Finished

As-WAAM-ed

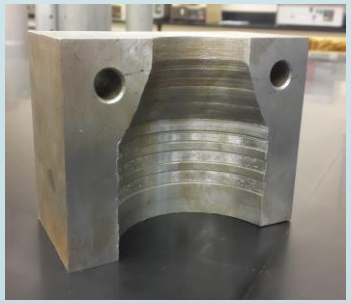




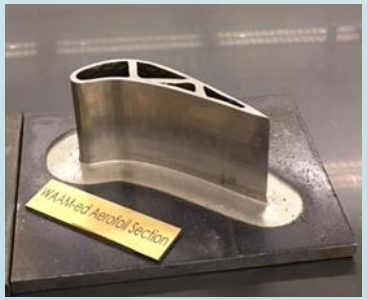
Surface Finished

As-WAAM-ed

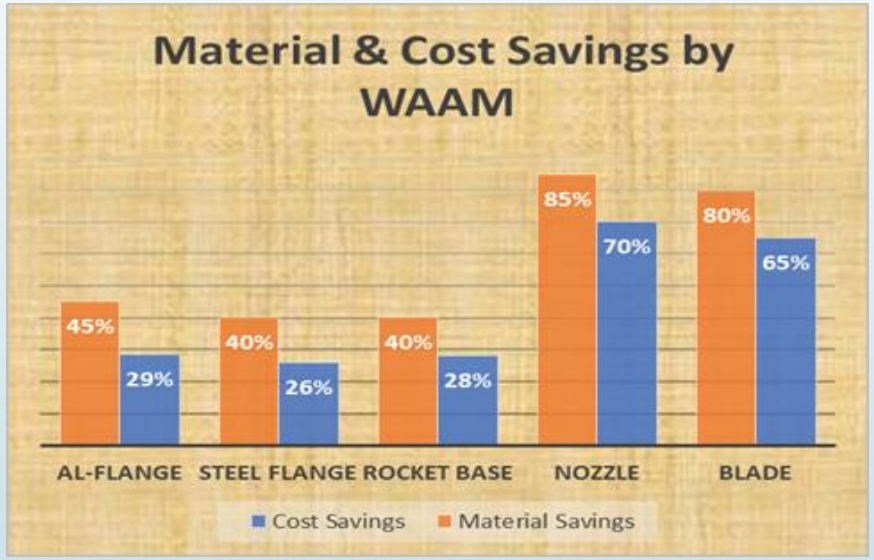
Nozzle and thin walled Sections



Molds & Dies



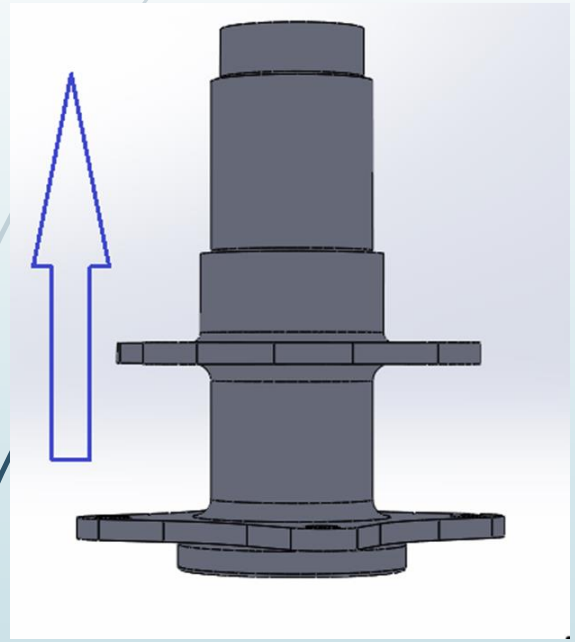
Turbine Blades

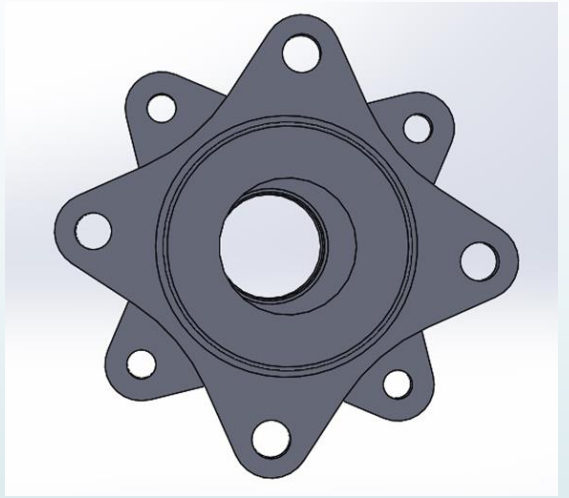


WAAM parts @ AUC

WAAM-ed Race Car Spindle: Challenging Product

The American University in Cairo

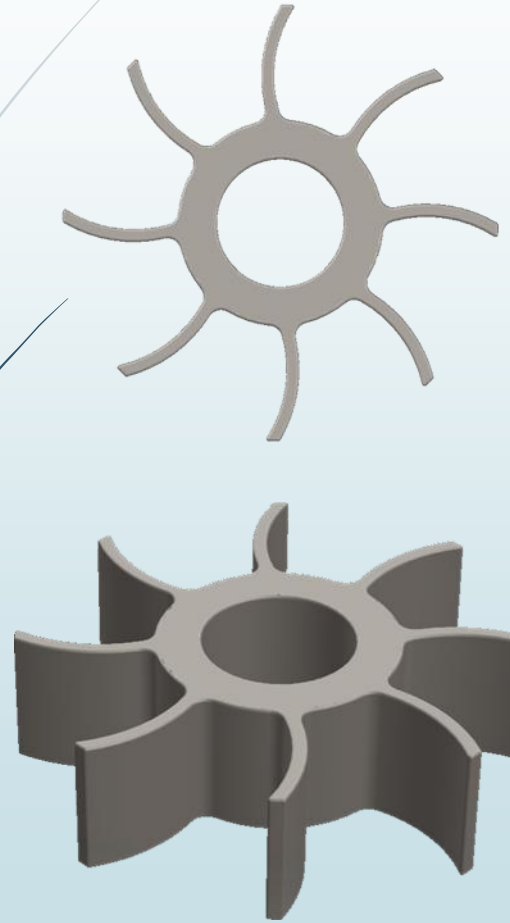




Material Savings: 87%
Cost Savings: 58%

WAAM parts @ AUC

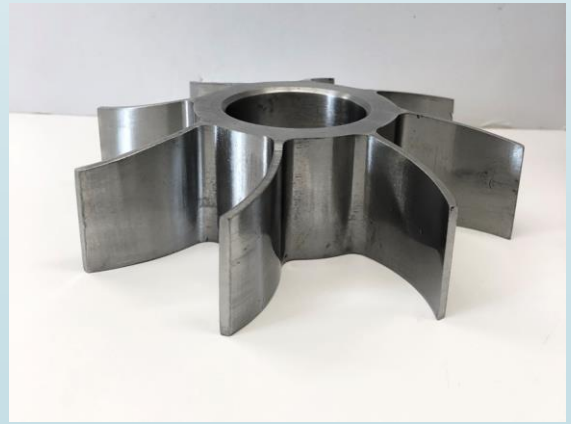
WAAM-ed Gear/Fan: Challenging Product



Step 1: Generating paths from CAD files/Slicing

Step 2: as-WAAM-ed

Step 3: Post Surface Finish



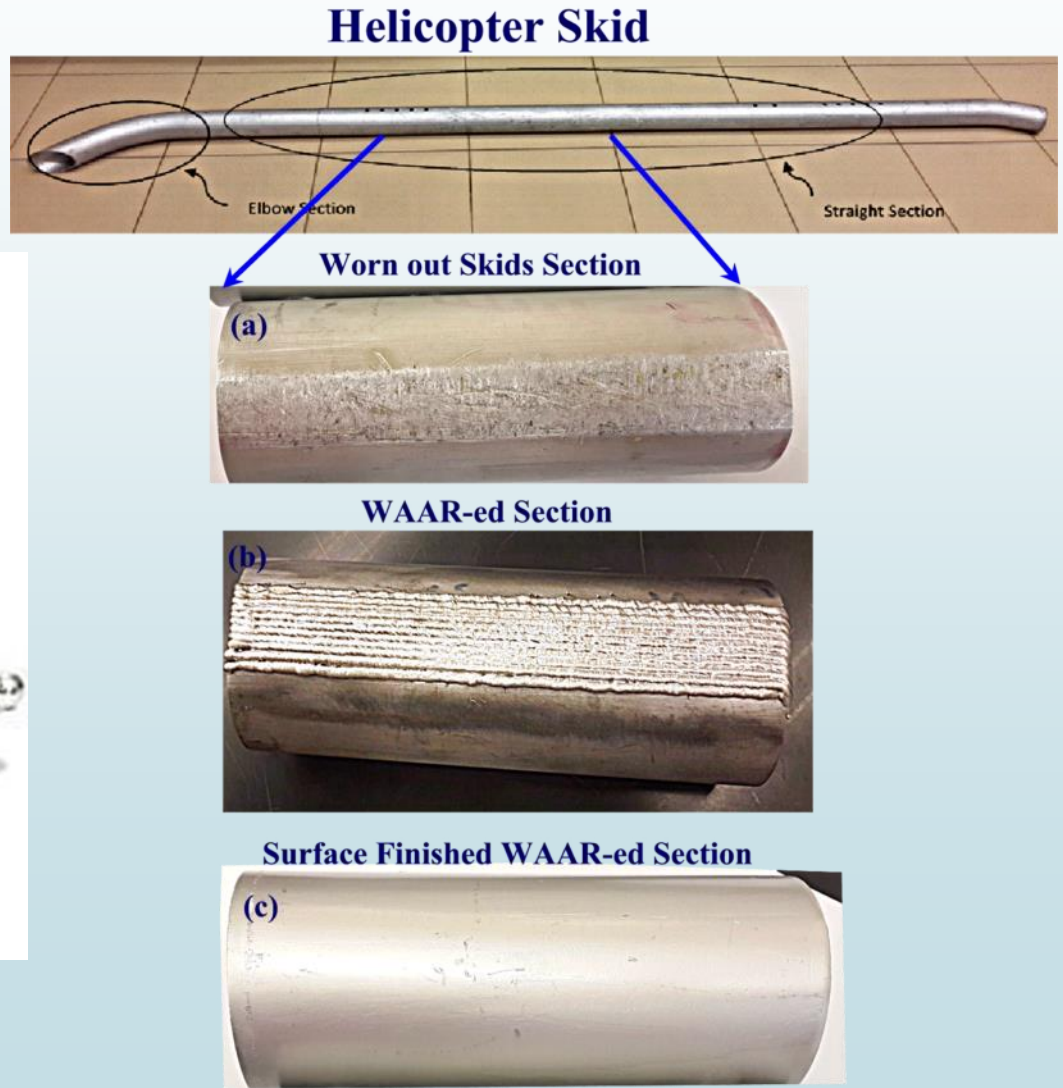
Step 4: Post separation from substrate

WAAR: Repair of challenging parts
Worn out Helicopter Skids (Case 1) @ AMCL

The American University in Cairo

AA2024 Helicopter Skids, 2.6m long, 3.5mm tube wall thickness
Egyptian Air Force Central Workshop
Worn out length 1.3m and reduced thickness of 2.3mm

Al- Wires: 4xxx and 2xxx series



WAAR: Repair of challenging parts
Worn out Helicopter Skids @ AMCL

Repair (WAAR) Strategy

- **Wire Material Selection**

Wire Alloy	Properties	Concerns
5356 (reported)	Least recommended	
4145 (investigated)	High ease of weld*, High strength of welded joint, High corrosion resistance, Sustains high service temperatures	Low ductility
2319 (ordered)	High strength of welded joint, High corrosion resistance, Sustains high service temperatures	Low ease of weld

Wire Arc Additive Repair (WAAR) Strategy

- **Process Design**
  - Manipulation parameter
  - Deposition Parameters
  - Tool Path
- Surface Machining for repair
- Depositions
- Surface Finish
- Evaluation for Validation
  - Tensile Testing
  - Bending Test
  - Mesostructure
  - Microstructure

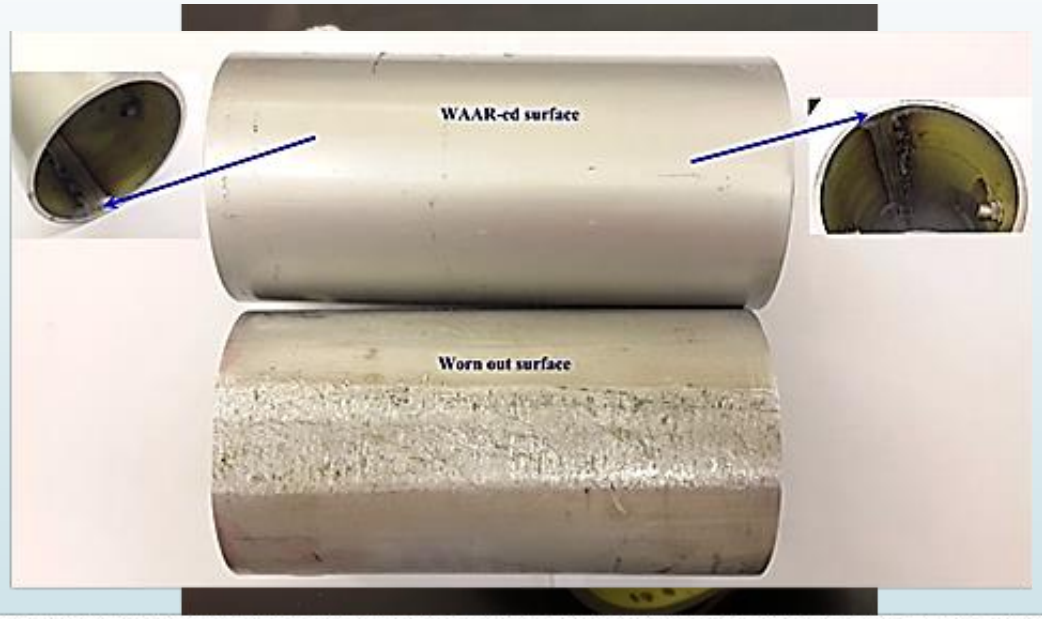
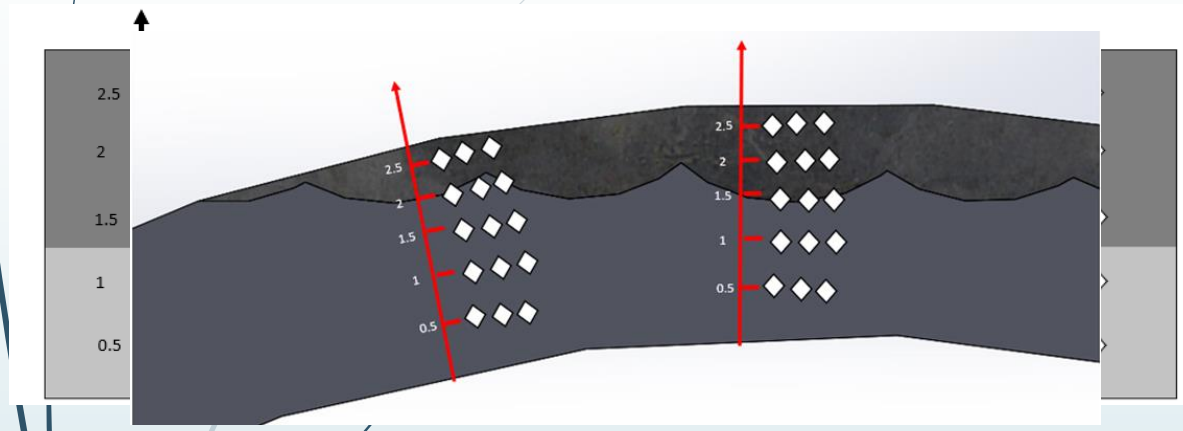


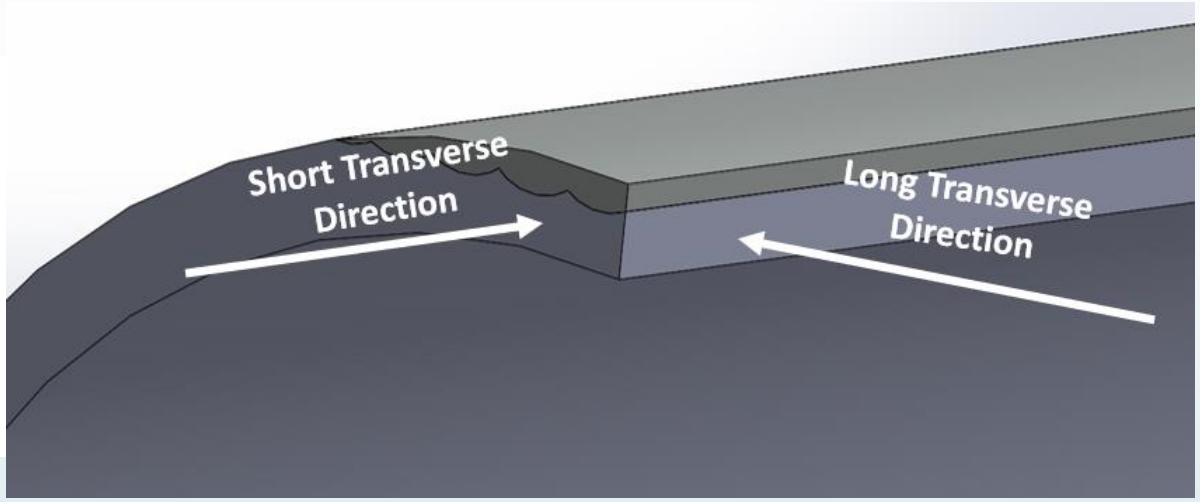
Fig. 15 Shows Pictures for the As-received Worn-out Skids and the WAAR-ed Section Post Surface Finishing along the Longitudinal Direction of the Tube and Pictures on the Right and the Left Showing Evidence for the Repair as Indicated by the Darkened Area on the Inner Walls of the Tube

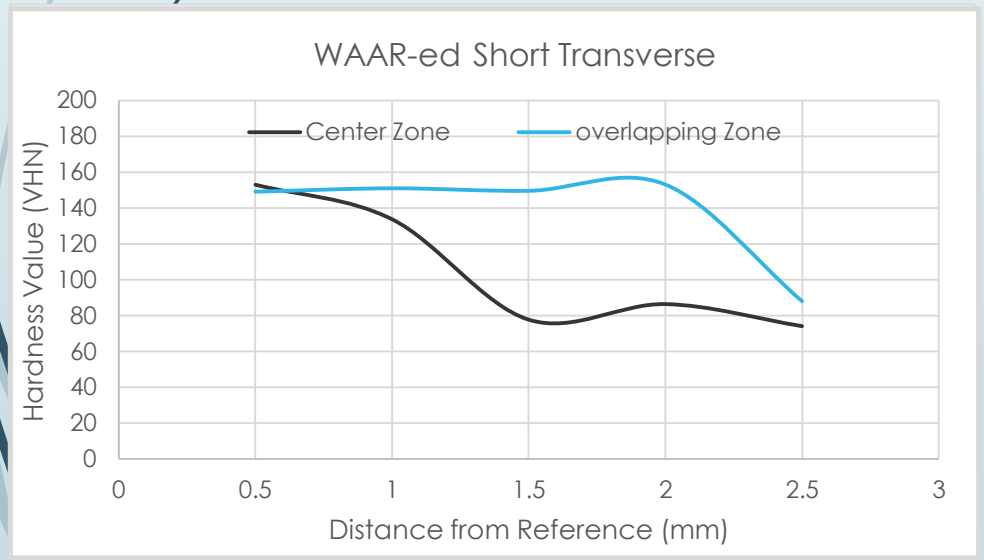
Mechanical properties :

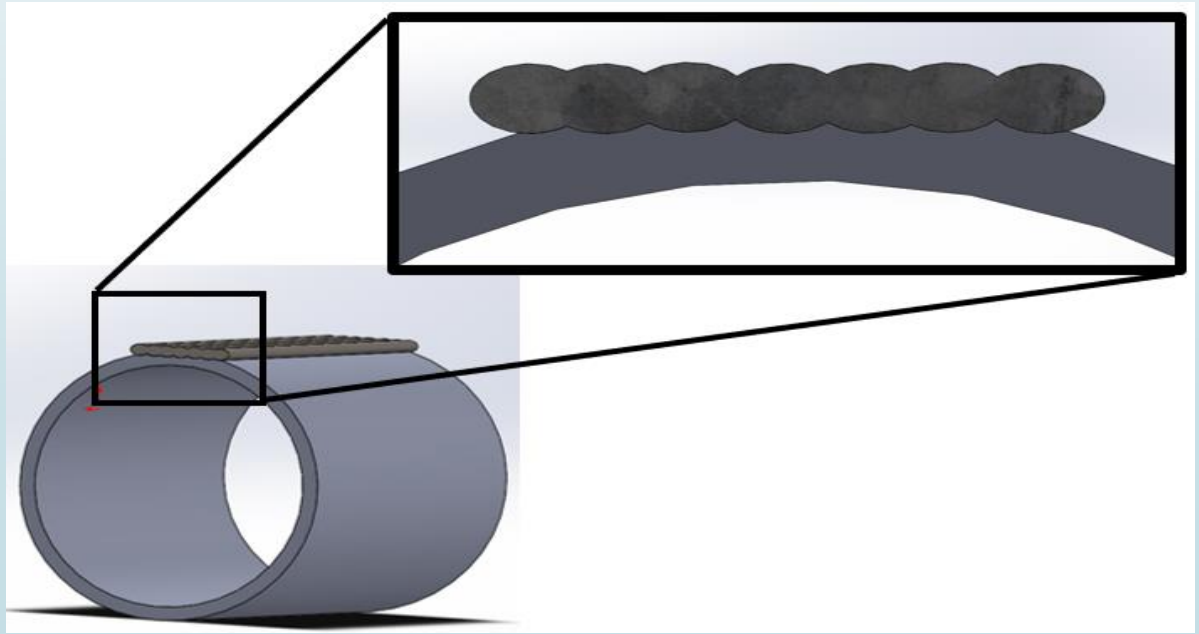
Condition	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation %	Bending Strength (MPa)	Hardness VHN (ST, LT)
AR-Skid AA2024 T6	215.6	460	76.86	3.9	700	160, 164
WAARed AA 5356	91.3	404	85	3.5	455	145, 134
WAARed AA4043	109	273.8	75.5	2	525	139, 108
AA5356 Wire	131	269	-	17	-	
AA4043 Wire	124	186	-	8	-	

Hardness (VHN): AA4043









Repair of Worn-out & corroded C130 Engine Base Spare Part (Case 2)

- Stage A: Evaluation of the status of the as received C130 engine base section. This includes visual inspection, 3D scanning, alloy composition determination, and mechanical properties
- Stage B: Strategies for the repair procedure of the part
- Stage C: Implantation of the repair process
- Stage D: Mechanical properties characterization of the repaired sides C130 engine base compared to the as received

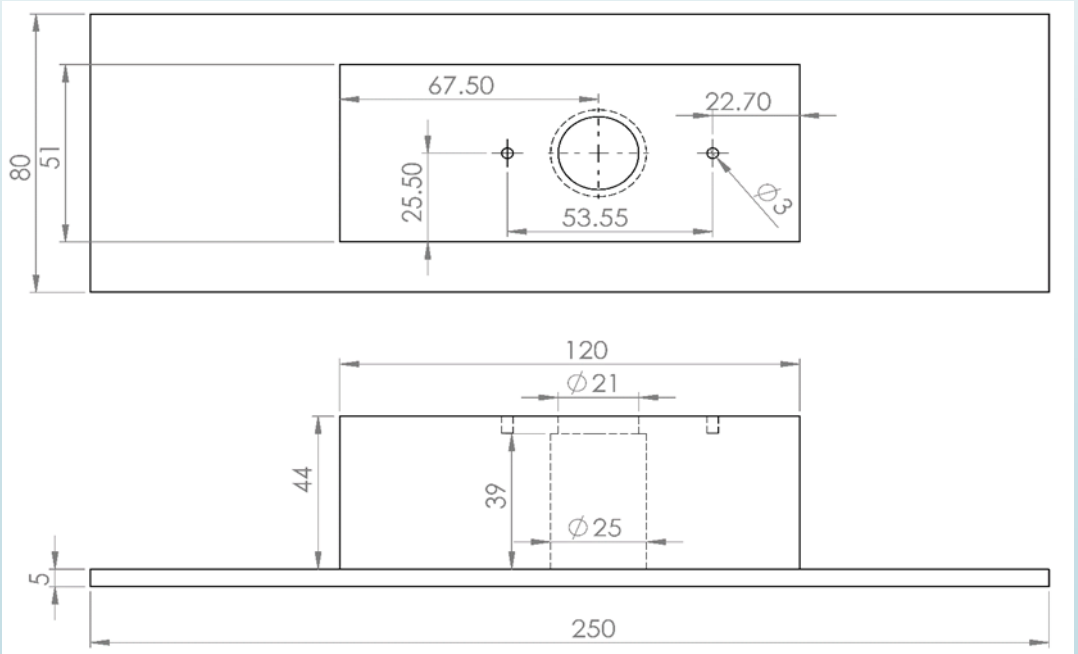
Fig. 9-1: As received C-130 Engine Base from the Air Force Central Workshop

As Received Part Assessment and Dimensioning

Chemical Composition for the as received C130 engine base

Element	Elements analyzed, %												
	C	Mn	Si	P	S	Ni	Cr	Cu	Mo	V	Ti	Al	B
%	0.228	0.714	0.043	0.012	0.080	0.025	0.036	0.013	0.013	0.003	0.000	0.001	0.0016

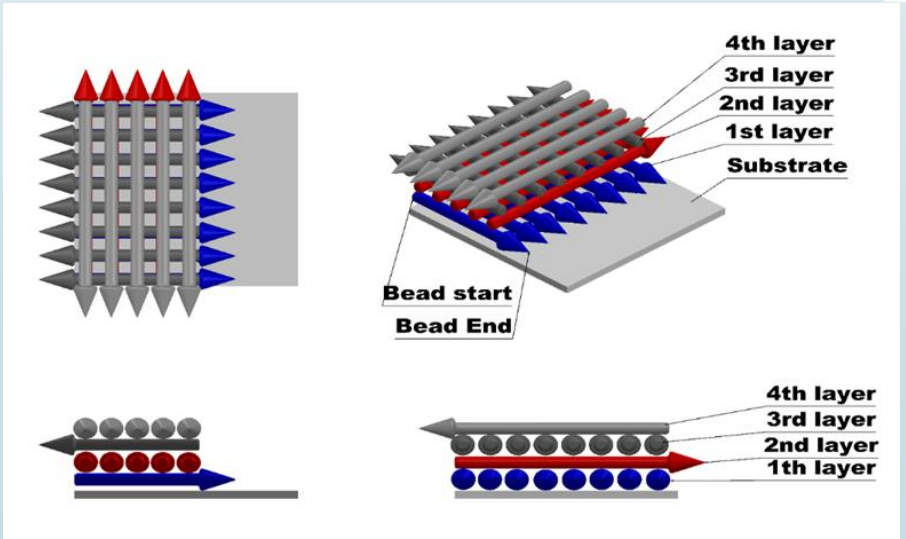
- **Regeneration of the Part Engineering Drawing:**
- 3D-Scanning: to facilitate
  - accurate surface profiling
  - The part accurate dimensions
  - The relative holes location and dimensions.
  - Surface defects location and dimensions.



Stage B: Strategies for the repair procedure of the part

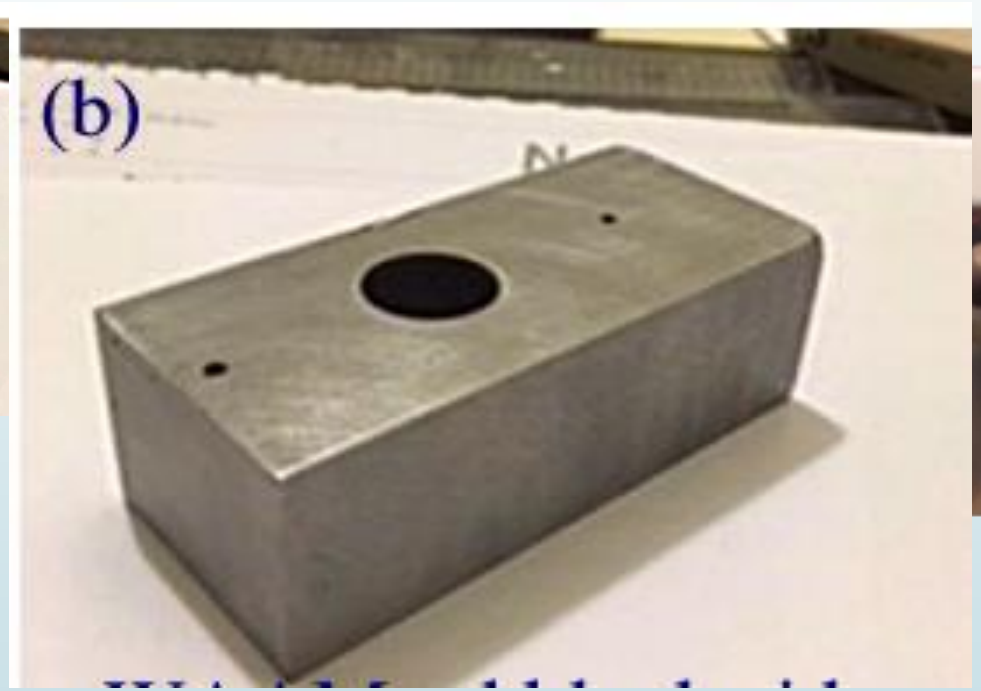
- Step 1: Damage assessment
- Step 2: Repair zones selection
- Step 3: Setting deposition strategy

Repair Zone selection



Stage C: Implantation of the repair process and Properties evaluation

- Unrepaired block sides post grinding



- Repaired surfaces WAAM+ Finished

- WAAM-ed Surface

WAAM/R: Project Team

The American University in Cairo

Dr. H. G. Salem (PI)
Prof, of Material Science & Materials, AUC
Project Management
Materials Design, Materials testing & structure characterization

Dr. M. Attallah
Egyptian Expert
Prof. of Advanced Materials Processing, Birmingham University.
Transfer of know-how

Dr. A. Nassef
Co-PI
Prof. of Design, modeling and Optimization, AUC
Process optimization

Eng. M. Bakr
Operations Manager, AUC
M.Sc. Mechanical Engineering Cairo University
Design & Manufacturing Expert
Technical Liaison with industrial Sector & Technical Support including,

Eng. A. Elsokaty (RA),
BSC of Metallurgical and Materials Engineering (2017), faculty of Petroleum and Mining Engineering, Suez University.
WAAM system Operation Eng.

Eng. S. Sadek (RA)
BSc., Manufacturing, Eng. Ain Shams Univ. (2018)
MENG-MSc graduate student at AUC
Material Characterization

Eng. O. Gadalla (RA),
BSc. of Mechanical Engineering, Mechanical Design and Production dpt. Cairo Univ. (2018).
Robot Studio, Modeling & Simulation

H. Shaarawy (RA),
MENG Senior student,
3D scanning