Wire arc additive manufacturing (WAAM) with a focus on tubular wires

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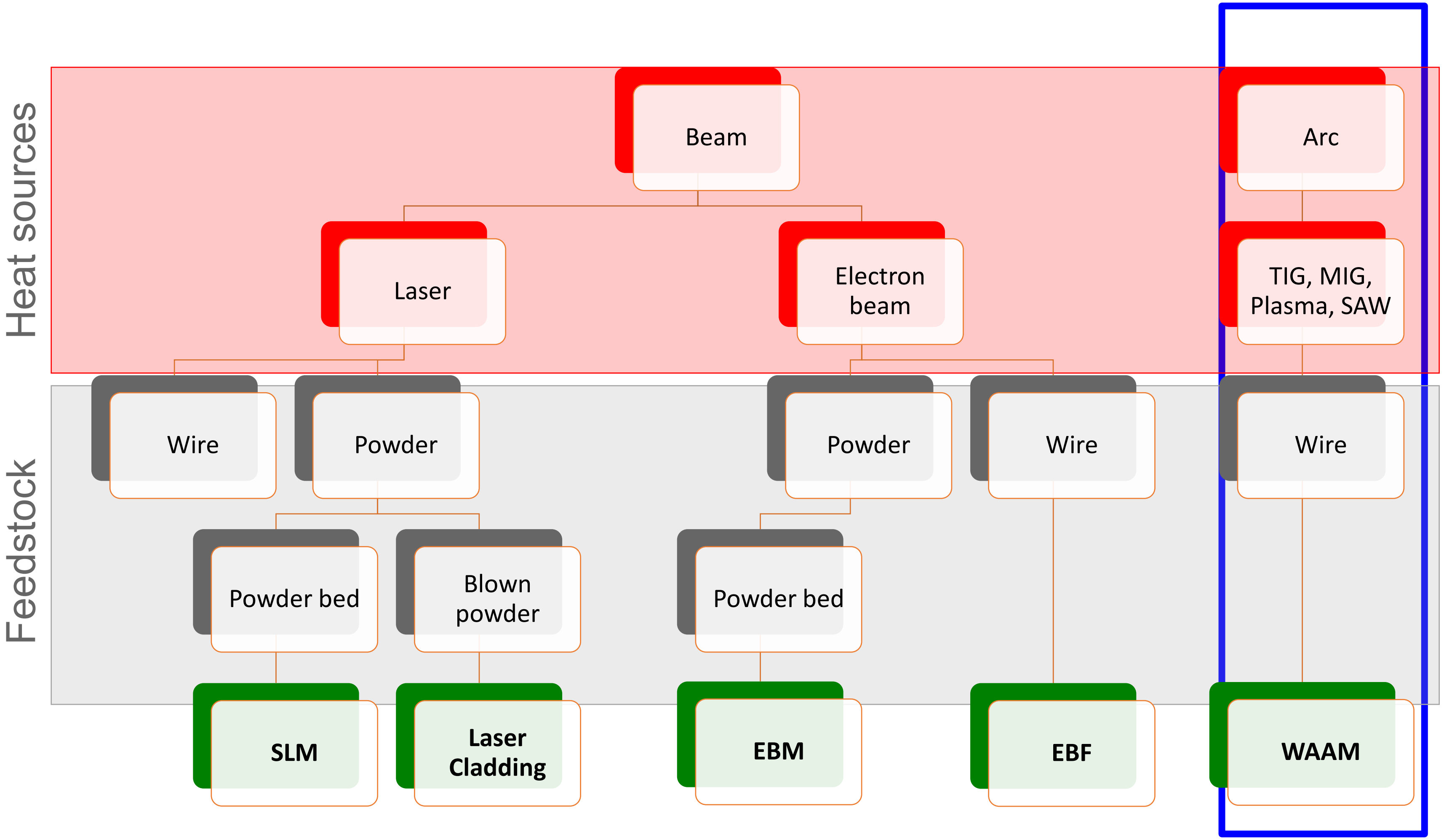
Global solutions. Solid performance.

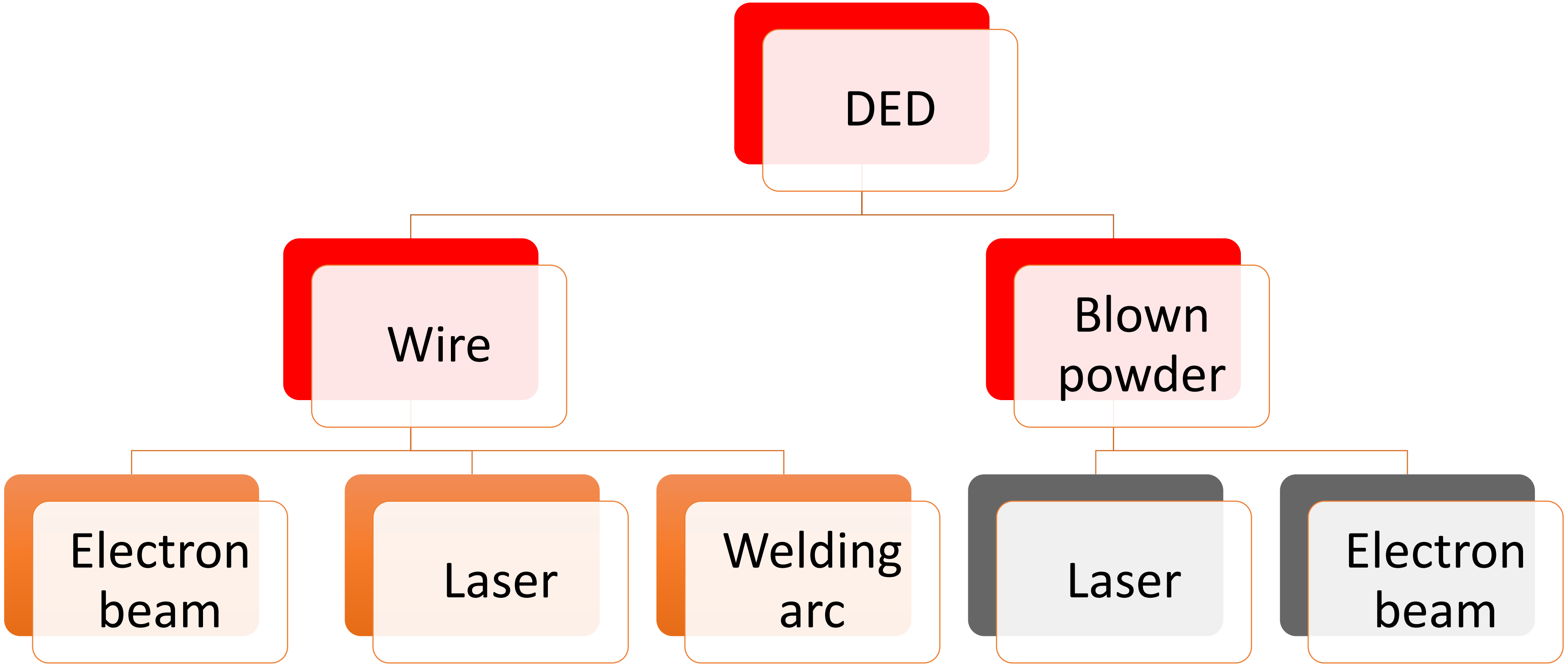
Agenda

- AM processes
- WAAM
- Wire vs powder
- Wire types and manufacturing
- Design of wires for AM
- AWS D20.1 and AIA recommended guidance
- Summary

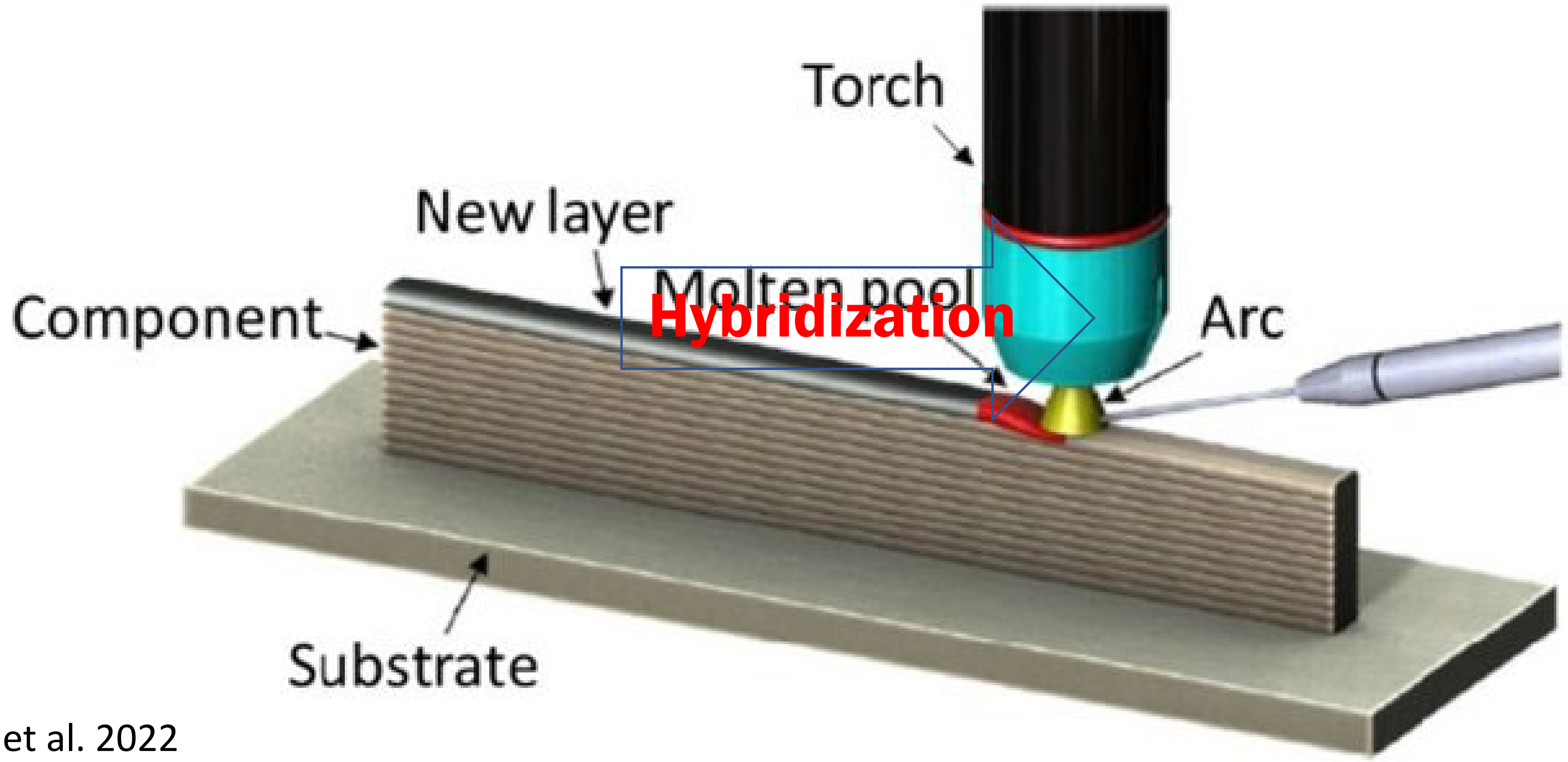
Additive Manufacturing Processes



Direct Energy Deposition

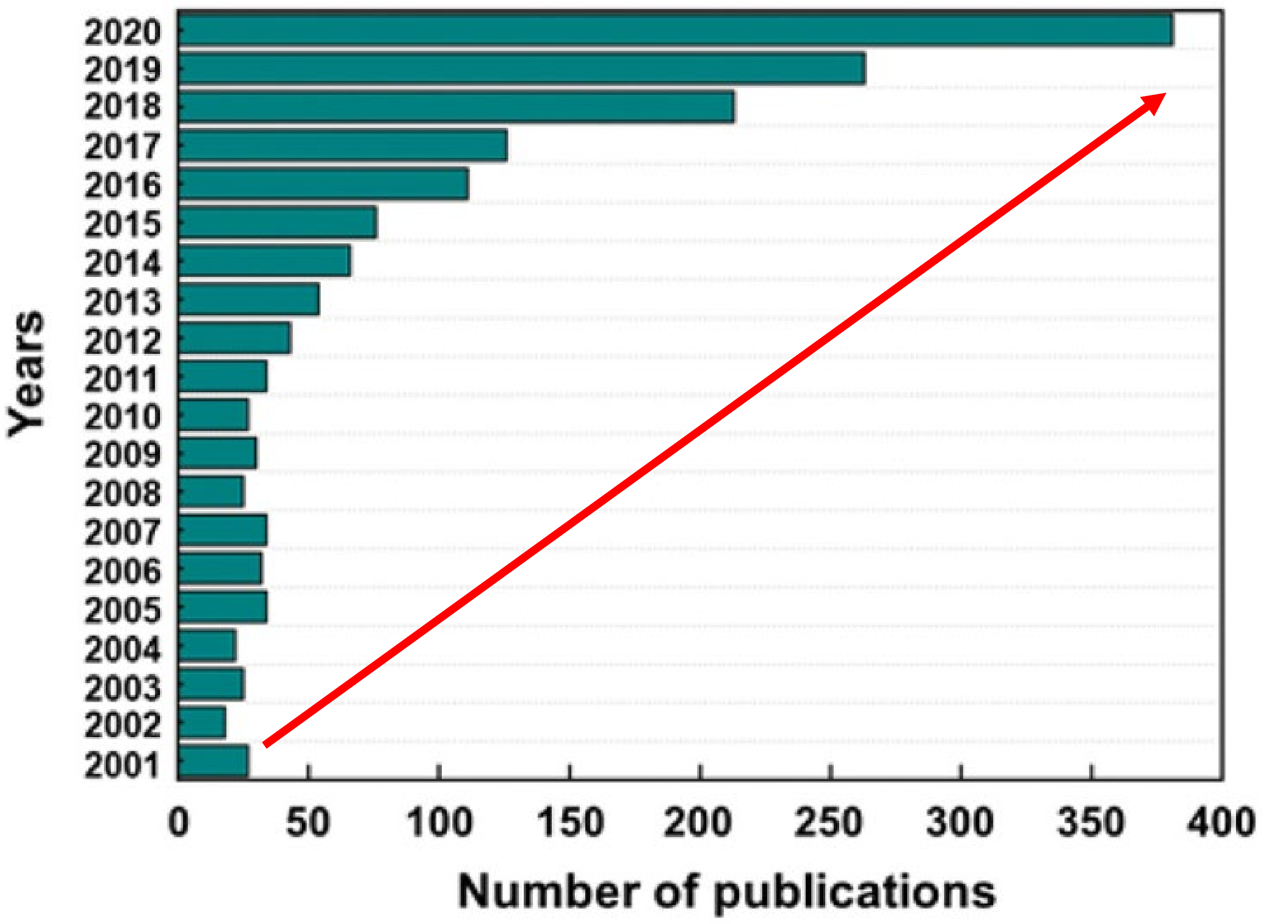


Wire Arc Additive Manufacturing



Kapil et al. 2022
Rodrigueset et al. 2019

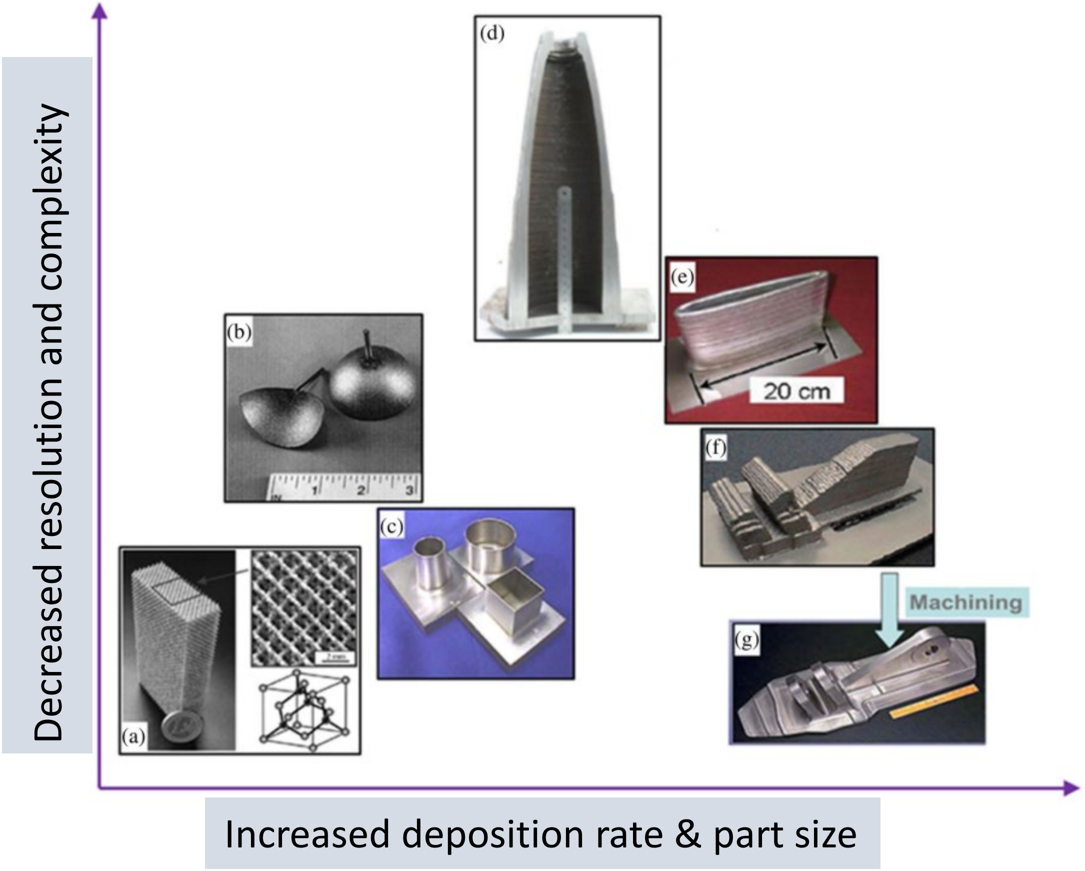
Research on WAAM+Ti on Science Direct



Zidong Lin et. al 2021

Wire vs Powder

- ✓ Wire more economical choice
- ✓ Higher deposition rate with wire
- ✓ Larger parts can be manufactured
- ✓ Higher material utilization (100%) compared to powder (40-60%)
- ✓ More complex parts with higher resolution by powder
- ✓ Powders pose a higher safety risk: higher flammability potential
- ✓ Inhalation concern using powder



Ding Lin et. al 2015

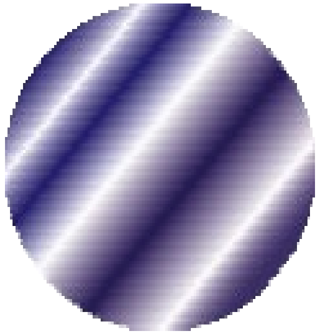
A WAAM example

The hooks are approx. 170 by 130 cm in size, a weight of 1,700kg, loading capacity of 350mt, usage of 90 kilometers of welding wire MF731B

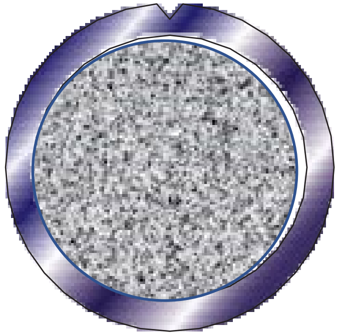
www.huismanequipment.com

Wire types

- ✓ **Solid wire:** not an option for all alloys

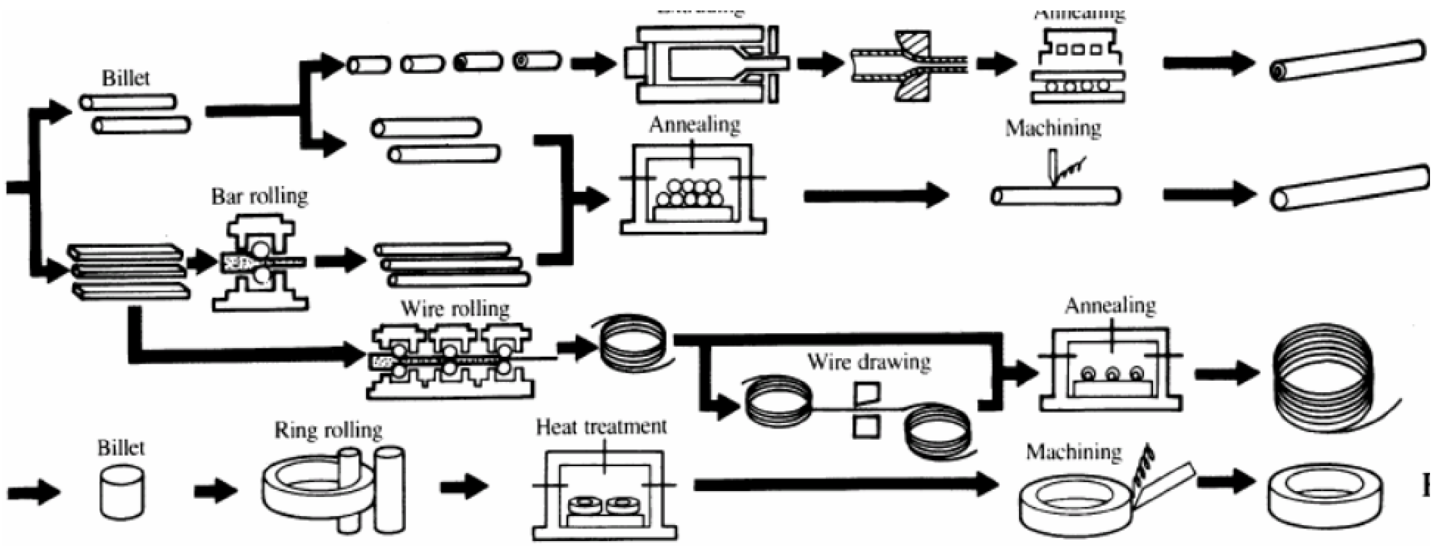


- ✓ **Tubular wires: metal cored wire (MCW), flux cored wire (FCW)**



Wire manufacturing

- ✓ Alloy dependable
- ✓ Cold rolling/forming
- ✓ Warm rolling/forming



Ti 6-4 Wire for AM

- Ti 6Al-4V: Do lots of cold draw / anneal
- Ti 6Al-4V: Warm rolling of Ti 6-4 wire controlled by acoustic emission monitoring (Hermith method)
- Ti 1Al-4V wire with Al cladding to give Ti 6Al-4V deposit
- Ti 1Al-4V wire with Al core to give Ti 6Al-4V deposit

ITW WELDING

Miller Elga

Wire manufacturing of Ti alloy: warm rolling

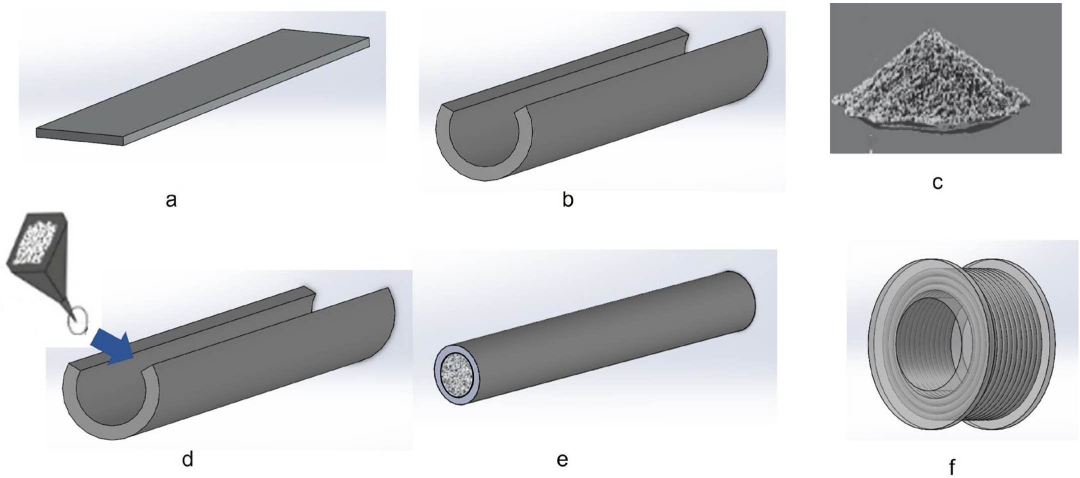
- The wire is heated up during the drawing process
- The material is more ductile, which increases the rate of the deformation
- Do not need to anneal the wire between the stages
- Strict control of the temperature and speed control with acoustic emission

Wire manufacturing of Ti alloy: Comparison to cold drawing

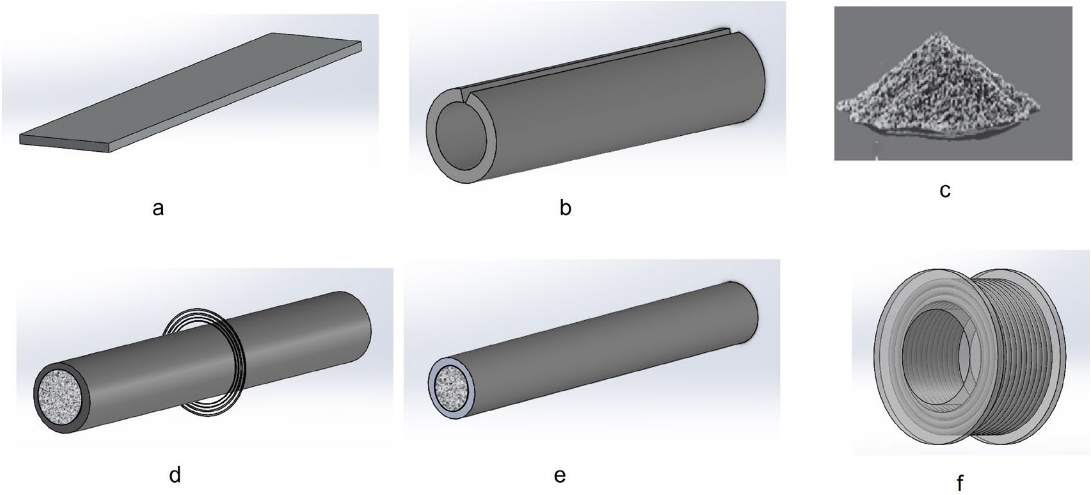
	Cold deformation	Warm deformation
Degree of deformation per one stage	Low (10-15%)	High (35-45%)
The number of production stages	Large (≥45)	Reduced (≤8)
Heat treatments	After each stage	No
Energy consumption	High level	Mid-level
Time of production	Long (up to 70 days for 1 ton)	Short (less than 4 days for 1 ton)
Production costs	High	Low

Tubular Wire manufacturing

Seamed tubular wire



Seamless tubular wire

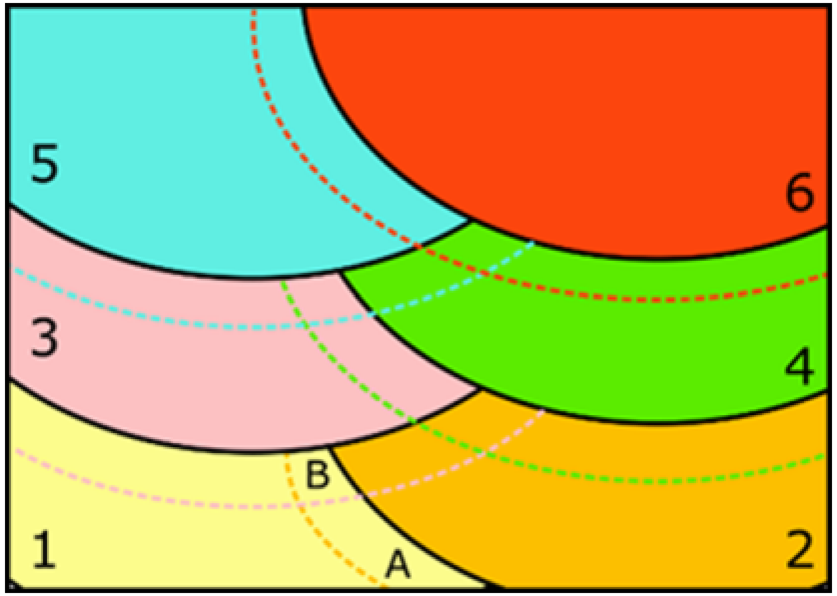


Why use tubular wires in AM

- **Higher flexibility in alloy design**
- **Better control of hydrogen → Seamless technology**
- **Higher deposition rate than solid wires**
- **Better penetration → Mitigating lack of fusion**
- **When the solid wire is not an option/limited choice: Stellite alloy, tool steels**
- **Silicon islands reduction**

Design of wires for AM

Use of fundamental knowledge generated by decades of research on welding



Welding vs Additive Manufacturing

Microstructural control during welding

- Manipulation of the heat source: pulsation or oscillation
- Nucleation particles into the melt pool
- Welding parameters
- External electromagnetic and ultrasonic stimuli

Welding vs Additive Manufacturing

Microstructure

- Large columnar grain formation along the build direction

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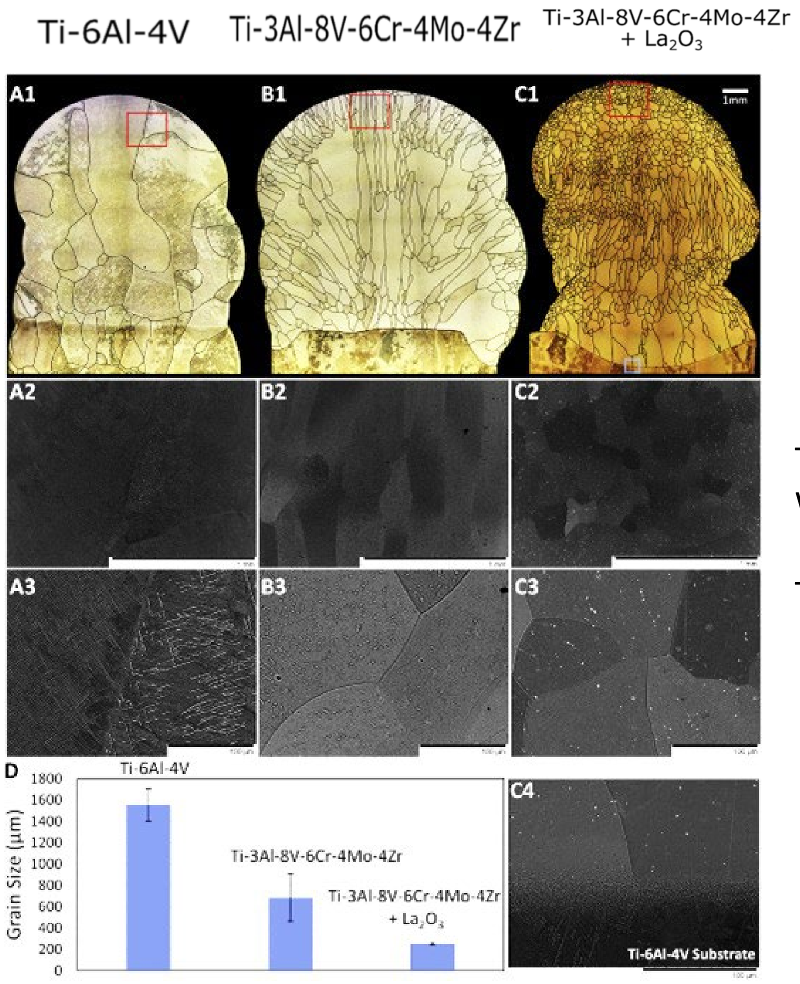
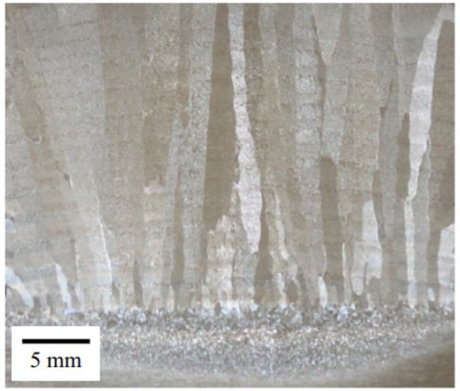
wires containing grain refining elements

↓

Grain size reduction and promotion of columnar to equiaxed transition



Bermingham et al. 2019



Texture in Ti6Al4V produced using WAAM

T. Debroy et al. 2018

Effect of different elements during fusion-based additive manufacturing

Alloy system	Element used	Effect
316L stainless steel	TiC	Grain refinement
Al-12Si (wt.%)	TiB_2	Grain refinement
AA 2024	Zr	Columnar to equiaxed transition; change in the thermal conductivity
AA 5083	Ti	Grain refinement; Columnar to equiaxed transition
AA 6061	AlTi5Bi1 (wt.%)	Grain refinement
AA 6061	AlSc2 (wt.%)	Grain refinement
AA 7075	ZrH_2	Grain refinement; columnar to equiaxed transition
Inconel 625	SiC	Hardness increase
Inconel 625	TiC	Hardness increase
Inconel 625	Al_2O_3	Decreased structural integrity of the part
Inconel 625	TiB_2	Grain refinement; increase of mechanical properties
Inconel 718	$WC\text{-}W_2C$	Grain refinement
Ti	Si	Grain refinement
Ti-6Al-4V	B	Grain refinement
Ti-6Al-4V	C	Grain refinement
Ti-6Al-4V	CaF_2	Increase the volume fraction of β phase
Ti-6Al-4V	Cr-Mo-Zr	Grain refinement; Columnar to equiaxed transition
Ti-6Al-4V	Cr-Mo-Zr + La_2O_3	Grain refinement; Columnar to equiaxed transition
Ti-6Al-4V	LaB_6	Grain refinement
Ti20V	B	Grain refinement
Ti12Mo	B	Grain refinement

Welding vs Additive Manufacturing

Application point of view

- ✓ Effect of dilution with the base metal

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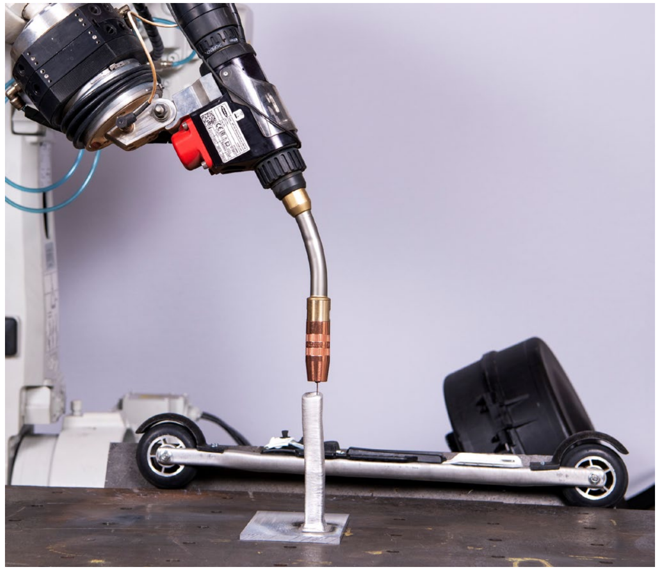
Wire composition similar to the target AM composition



A WAAM sample made at University West

ITW WELDING
Miller
Elga

Welding vs Additive Manufacturing

Inter-pass temperature

✓ **Higher heat build-up in AM compared to welding**

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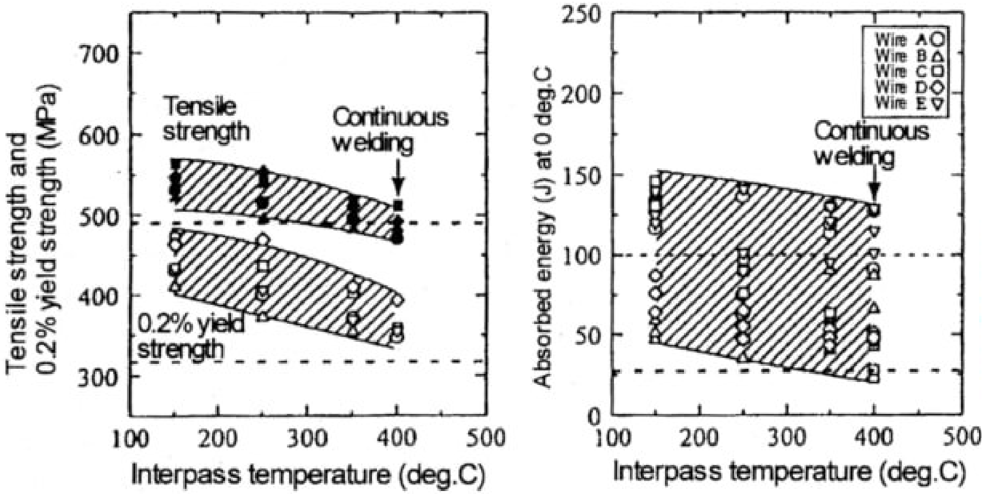
Modification of the wire composition



Eimer et al. 2021

Welding vs Additive Manufacturing

Porosity

✓ Absorption of nitrogen, oxygen, and hydrogen in the molten weld pool

⇩

Wire with less O2, N2 and H2

⇩

Seamless tubular wires

Welding vs Additive Manufacturing

Silicate formation

- Solid and MCW

⇩

Reduction and relocation of silicates

⇩

Metal cored wires

HIGHLIGHT project

Qualification of procedures, machines, and operators needed

AWS D20.1 Specification for fabrication of metal components using additive manufacturing

- Additive Manufacturing Procedure Specification (AMPS)
- Machine Qualification Record (MQR)
- Procedure Qualification Record (PQR)

Table 5.1
Inspection and Testing Requirements for Machine and Procedure Qualification

Test Method		Powder Bed Fusion			Directed Energy Deposition		
		Class A	Class B	Class C	Class A	Class B	Class C
Machine Qualification Standard Qualification Build(s)	Visual Examination	Yes	Yes	—	Yes	Yes	—
	Dimensional Inspection	Yes	Yes	—	Yes	Yes	—
	Radiographic Examination	Yes	Yes	—	Yes	Yes	—
	Density Testing	Yes	Yes	—	Yes	Yes	—
	Tension Tests	54	54	—	36	36	—
	Metallographic Examination	Yes	Yes	—	Yes	Yes	—
Procedure Qualification Preproduction Test Build(s)	Visual Examination	Yes	Yes	Yes	Yes	Yes	Yes
	Dimensional Inspection	Yes	Yes	Yes	Yes	Yes	Yes
	Penetrant Testing	Yes	Yes	—	Yes	Yes	—
	Radiographic Examination	Yes	Yes	—	Yes	Yes	—
	Density Testing	Yes	Yes	Yes	Yes	Yes	Yes
	Tension Tests (Witness Specimens)	3	1	—	—	—	—
	Tension Tests (Component)	3	3	—	3	3	—
	Metallographic Examination	Yes	Yes	Yes	Yes	Yes	Yes
	Chemical Analysis	Yes	Yes	—	Yes	Yes	—

AWS D20.1 Specification for fabrication of metal components using additive manufacturing

- Wire feedstock procurement
- Wire storage
- AM machines
- Employment of Heating to prevent moisture accumulation
- Feedstock Change Plan:

“ When the AM machine is used for more than one material type, the contractor shall establish a feedstock change plan that includes cleaning procedures adequate to remove contamination and a means of demonstrating that contamination does not exist from a previous build cycle of a different material type”

Content	AWS	ISO
Wire procurement and delivery condition	A5.01	14344
Wire sizes and packaging	A5.02	544
Specification for Ti alloy solid wires	A5.16	24034
Specification for Ni alloy solid wires	A5.14	18274
Type of inspection documents	-	10204
Specification for fabrication using AM	D20.1	-

Aerospace Industries Association (AIA)

Recommended Guidance for Certification of AM Component

Wire feedstock material specification requirements should include, but may not be limited to chemistry, melting practice, surface condition, including surface quality, size and tolerance, twist, fabrication method, lot definition, traceability requirements, packaging requirements, and wire-making process controls

Summary

- Wires produced for welding are used in the AM industry, sometimes with minor modifications.
- As AM technology is rapidly developing, it would not be surprising that specific modifications are required, especially in certain alloy systems and applications.
- The experience and knowledge gained in the development and manufacturing of welding wires can appropriately be translated into the AM to develop specifically designed AM wires.
- Depending on the application and alloy system, chemical composition modification of welding wires and wires with higher purity levels may be required to produce AM parts with optimum properties.
- Procurement, testing, delivery condition, and storage of AM wires require extra caution.