TAMPERE UNIVERSITY OF TECHNOLOGY

Directed energy deposition – Advances in surfacing, remanufacturing & additive manufacturing

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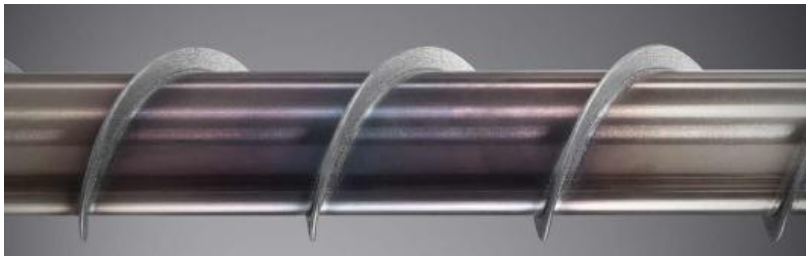
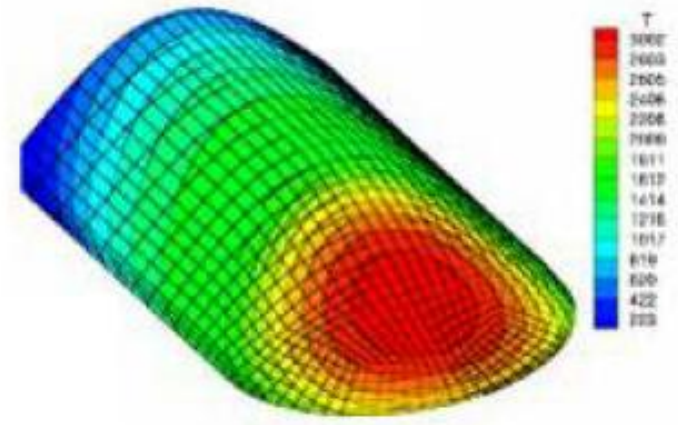
Outline

- Directed energy deposition (DED) (definition)
- Markets
- Laser methods:
  - o Powder
  - o Wire
  - o Strip
- Electron beam method
- Arc methods
- Applications





Directed energy deposition (DED)

- ISO/ASTM 52900:2016 ”Additive manufac-turing – General principles – Terminology”
  - o DED is AM process in which focused thermal energy (laser, EB, plasma-arc) is used to fuse materials by melting as they are being deposited
  - o The build surface can be an existing part onto which material is added (repairing)

Overview of AM processing principles for metallic materials

Type of material	Metallic		
State of fusion	Melted state	Solid + melted state	Solid state
Material feedstock	Filament / wire material	Powder material	Sheet material
Material distribution	Deposition nozzle	Powder bed	Sheet stack
Basic AM principle	Selective deposition of material to a substrate	Selective fusion of material in a powder bed	Fusion of stacked sheets
Source of fusion	Electron beam / Laser	Electron beam / Laser	Ultrasound
Process category	Directed Energy Deposition	Powder Bed Fusion	Sheet Lamination

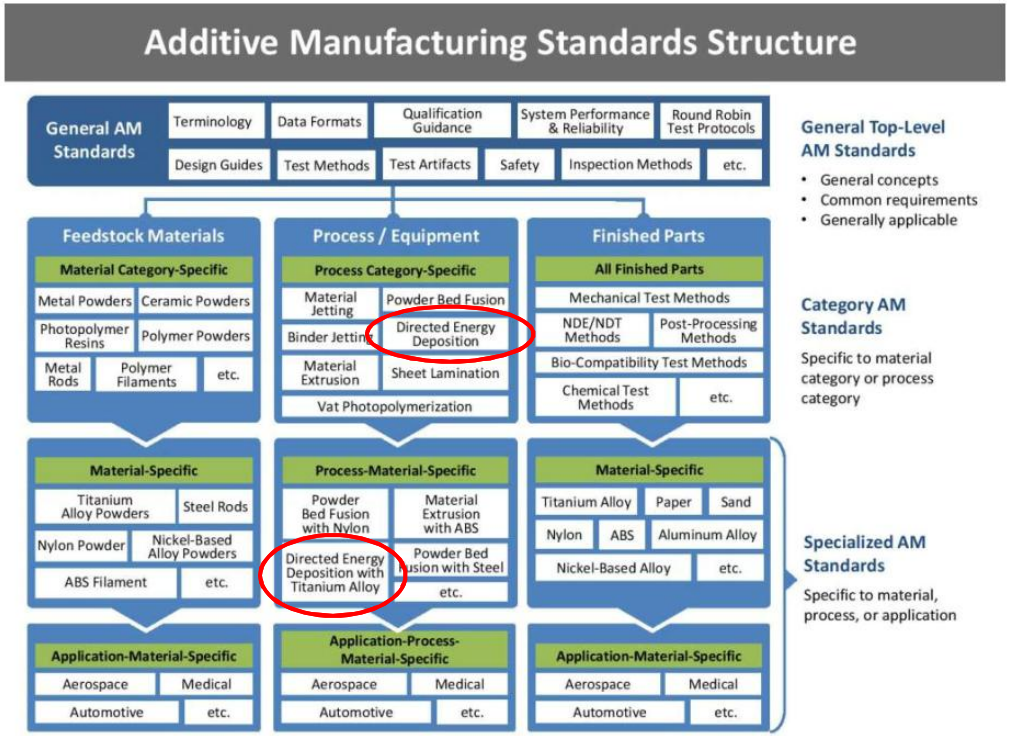
Powder bed fusion

Directed energy deposition

ISO/ASTM 52900:2016 ”Additive manufacturing – General principles – Terminology”

Directed energy deposition

- ASTM F3187 ”Guide for Directed Energy Deposition of Metals”, coming soon
  - Applications, DED system set-up, machine operation, documentation, work practices, system and process monitoring



ASTM INTERNATIONAL

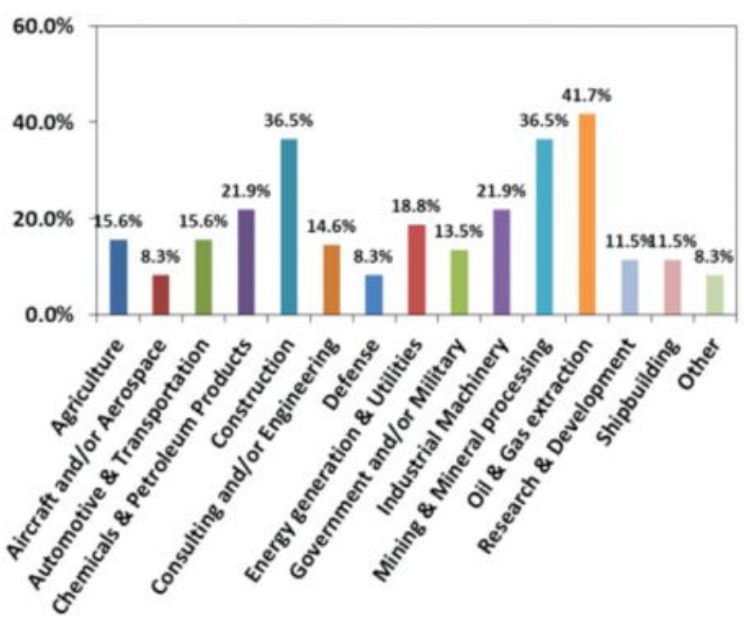
Weld surfacing

- § Composite solution (cheap substrate + more expensive weld alloy)
- § Sustainable
- § Material efficient

- Global cladding/overlay welding markets expected to rise from 3.8 to 7.6 billion USD in the next 3 years*

  * MesoCoat Inc.

Sectors that utilize welding & weld cladding in Canada (Wang et al. CWA Journal, Aug 2016)

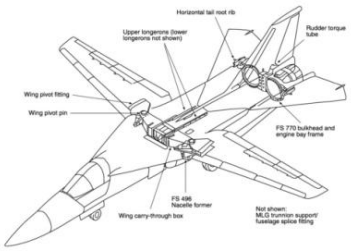


Remanufacturing markets

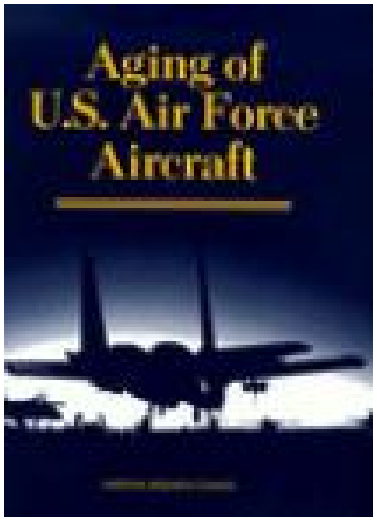
'Restoring used durable products to a "like new" condition'

- Remanufacturing machines is sustainable & green
- Essential part of circular economy
- Supported by EU Waste Directive and G7 Alliance
- Automotive industry remanufactures 35 million parts in Europe per year
- Caterpillar Inc.: Remanufacturing programme
- Repair of aircraft and ship components
- Steel mills, moulding & tooling, gear boxes etc.

3 500 Reman employees
100 Salvage engineers
6 000 different components
10% of typical CAT product can be remanufactured



Wing skins
Landing gear parts
Fuselage airframe
Engine blades

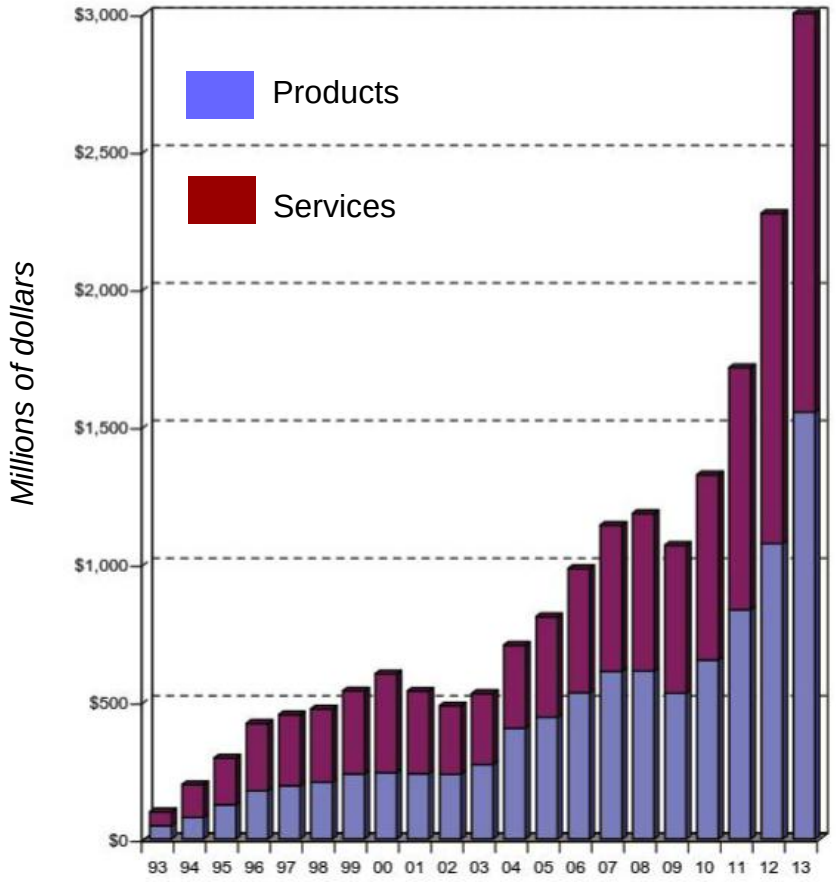


Liu ICALEO 2014, NRC report 1997

Schipull LAM 2011, The Engineer, Sep 2016

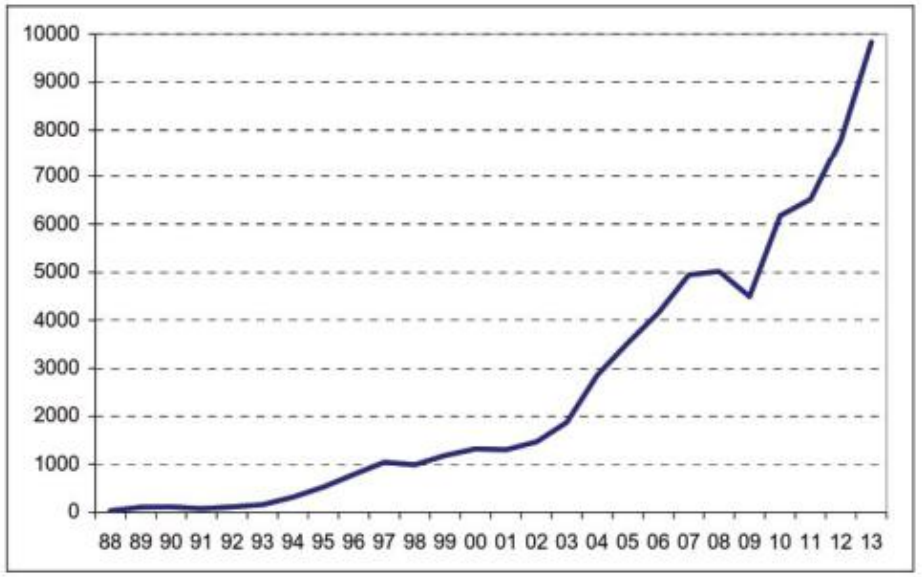
Additive manufacturing markets

Worldwide AM revenues



Wohlers Report 2014

Industrial unit system (> 5 000 USD) sales

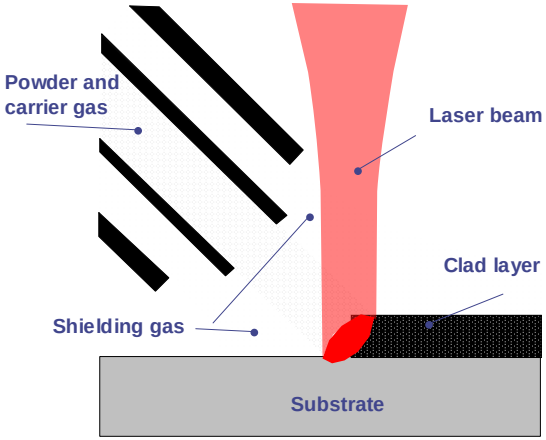


Source: Wohlers Associates, Inc.

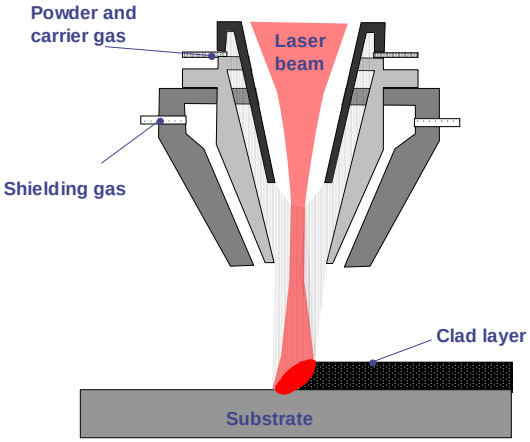
Out of 9 832 sold systems in year 2013, only 25 were directed energy deposition systems!!!

DED methods (laser)

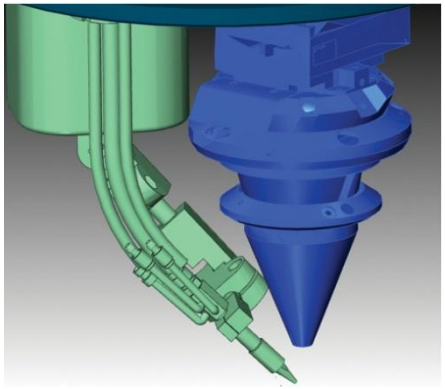
- Powder
- Wire
- Strip



Off-axis powder

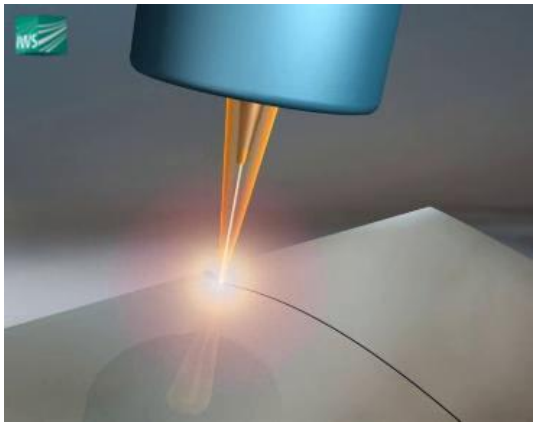


Coaxial powder

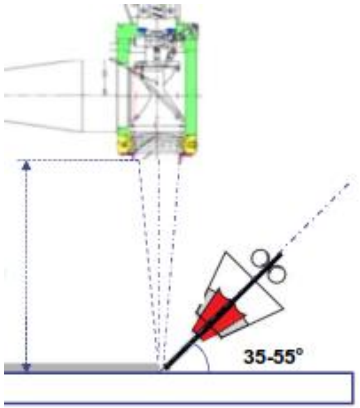


Off-axis cold- and hot-wire

Off-axis hot-wire (tandem)

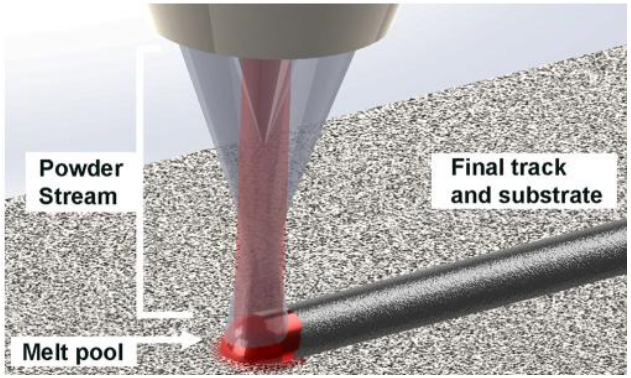


Coaxial cold- and hot-wire

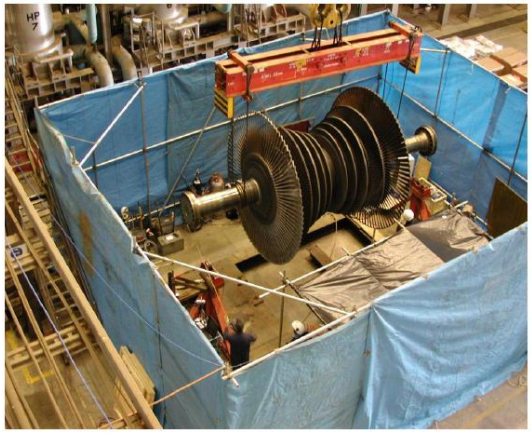


Off-axis strip

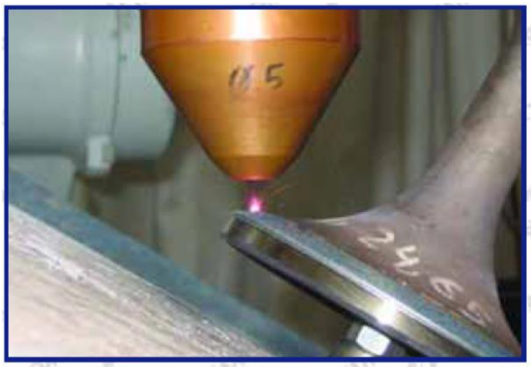
Industrial laser cladding & applications



1-step: coaxial powder



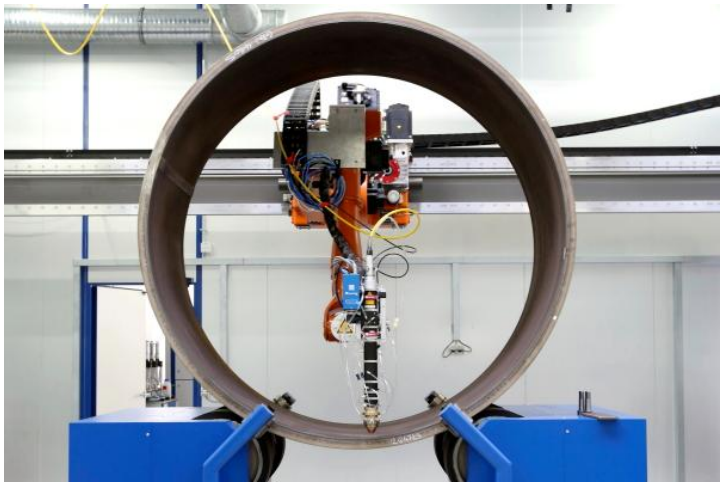
On-site cladding



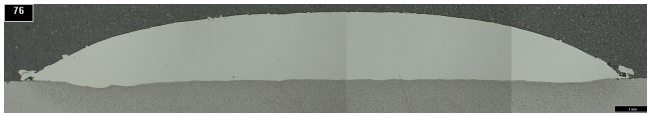
- Metallic and MMC coatings on metallic base materials
- Main benefits:
  - Fusion bond
  - Low dilution
  - Low distortion
- Industrial cladding with 3-6kW lasers & powder feedstock:
  - Low deposition rates (1-2 kg/h)
  - Low material efficiency (~70%)
- New components / Remanufacturing (50/50)

High power DED (laser, powder)

SPbSPU/TUT/Coax 11 IWS



15kW HPDL in Sheffield AMRC

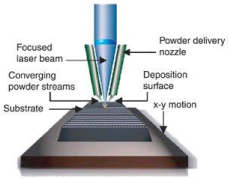


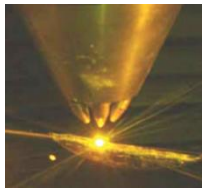
Inconel 625: 15 kW, 1 m/min, 15 kg/h (500 mm^3/s)

fimecc: Innovations and Network:
Novel product solutions: Trilaser

16kW laser cladding, LaserBond Ltd., Australia

Commercial DED devices (powder)





LENS 850-R (Optomec Inc.)

EasyCLAD (BeAM)

HC-254 (Huffman)

DMD 505 (DM3D Inc.)

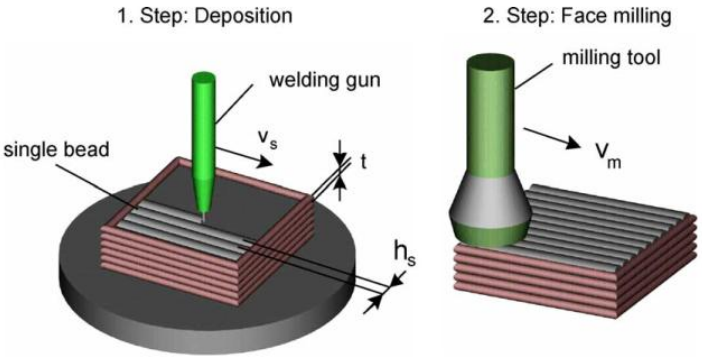
RPM's 557 (RPM Innovations Inc)

- 1 – 5 kW fiber, disc or diode laser
- 5-axis CNC machine
- Several powder hoppers
- Working volume 900 x 1500 x 900 mm^3
- Max component weight 200 – 300 kg
- Controlled atmosphere (O_2≤10ppm, H_2O<50ppm)
- Closed-loop process control
- Software to create tool path from 3D CAD data
- Powder is recycled
- Track width 0.5 – 5 mm
- Up to 50 mm^3/s
- 0.35 – 1.5 million USD

Hybrid (AM + subtractive)

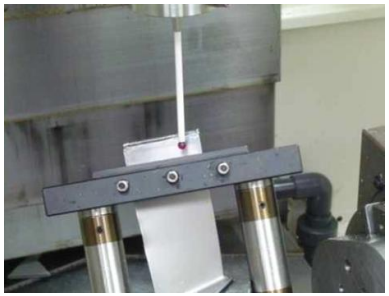
DMG Mori: Lasertec 65 3D

Optomec Lens + Fadal CNC mill

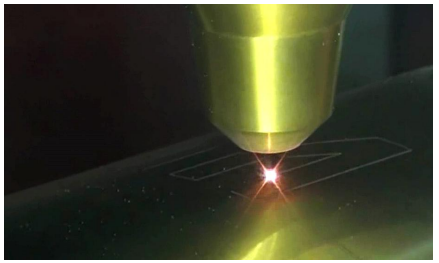


Mill + laser (automatic tool switch)

+



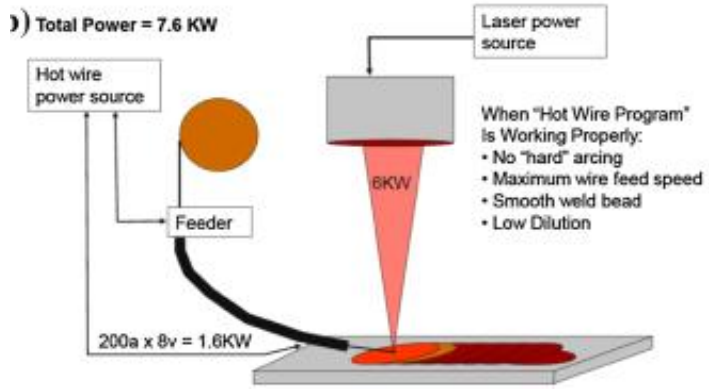
Inspection with touch probe



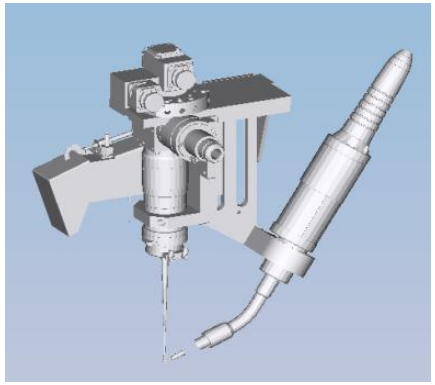
Laser microprocessing

Hybrid Manufacturing Technologies

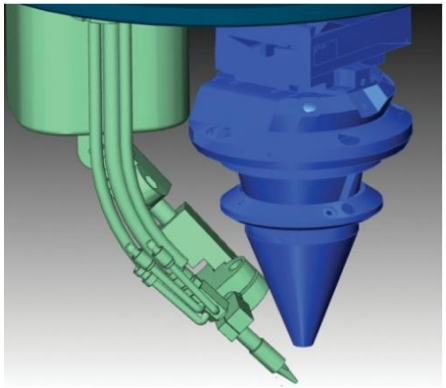
Laser wire cladding & additive manufacturing

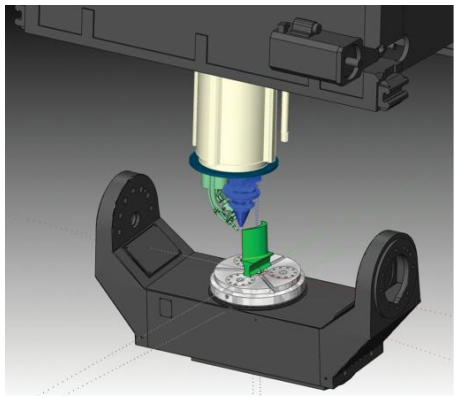


The Lincoln Electric Company, Cleveland



University West, Trollhättan



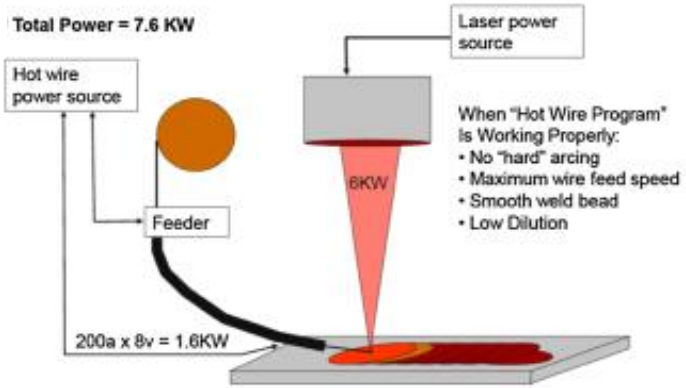


Fraunhofer IPT, Aachen

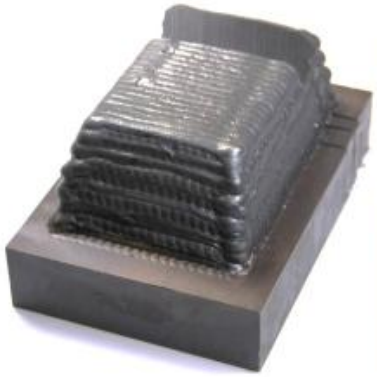
- Main benefits over powder:
  - Material efficient (100%)
  - Clean
  - Possible to heat by resistive heating
  - Chemically cleaner feedstock
  - Less contamination during processing (powders possess high specific surface areas)
  - Cheaper than powder
- Tubular wires more challenging

Laser hot-wire cladding & additive manufacturing

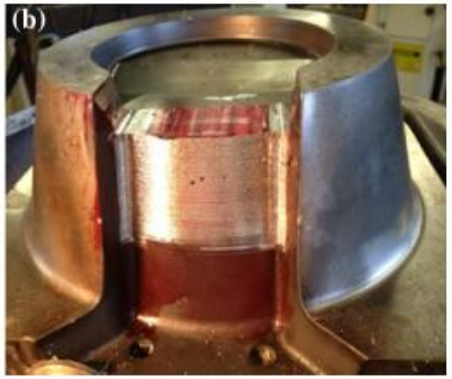
Kottman et al. JOM 67(3) 2015
Pangsrivinij, M.Sc. Thesis 2016



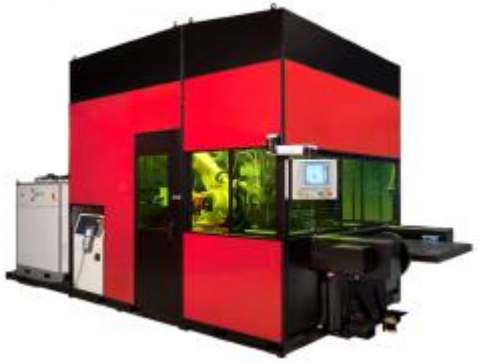
The Lincoln Electric Company, CWRU, Cleveland
15 kW fiber laser + Power Wave S500
Closed-loop control to optimize resistive heating & prevent arcing



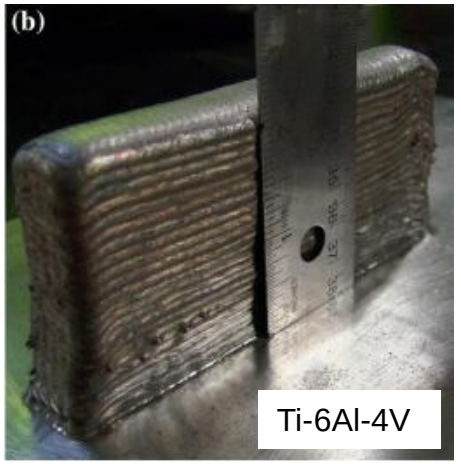
Maraging 250 steel test block on H13



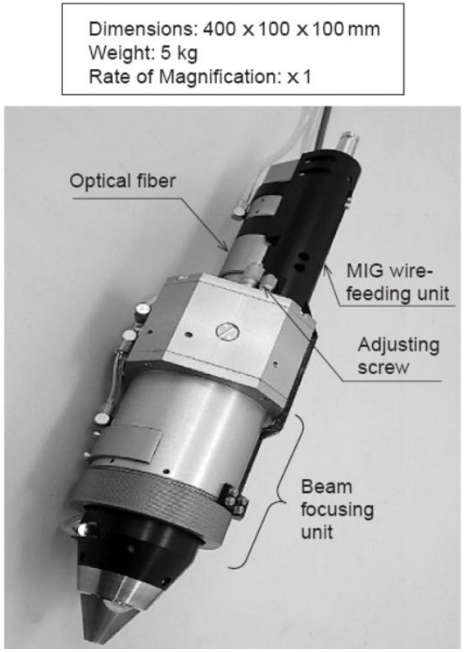
Die casting tool repaired with Maraging 250



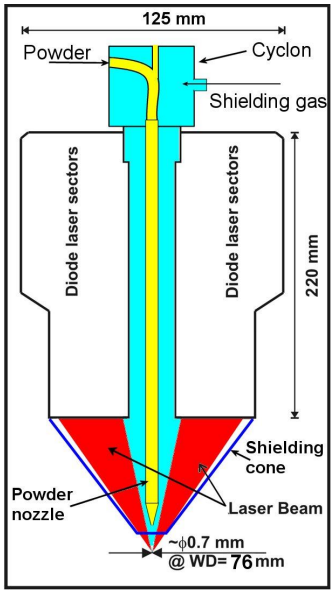
- Mild and high-alloy steels
- Tool steels
- Stainless steels (austenitic and martensitic)
- Nickel alloys (IN625 and IN622)
- Cobalt alloys (Co-6 and Co-21)
- Iron-based abrasion wear-resistant alloys (NanoSteel Company, Inc., Providence, RI)
- Titanium alloys (Ti-6Al-4V)
- Ni-WC and Fe-WC tubular wires



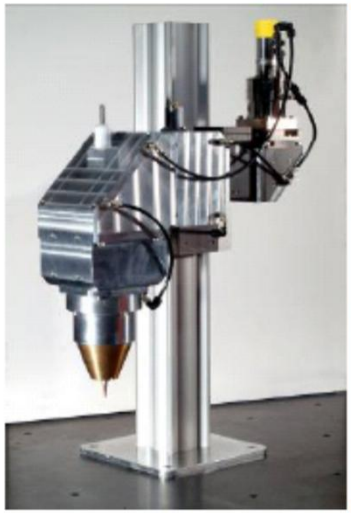
Coaxial wire laser cladding & additive manufacturing

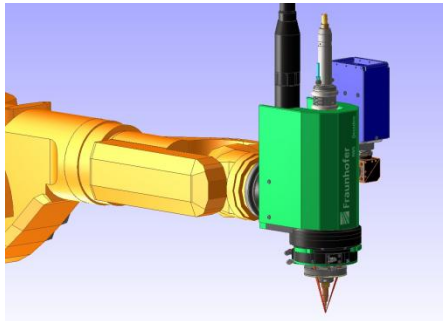


Mitsubishi

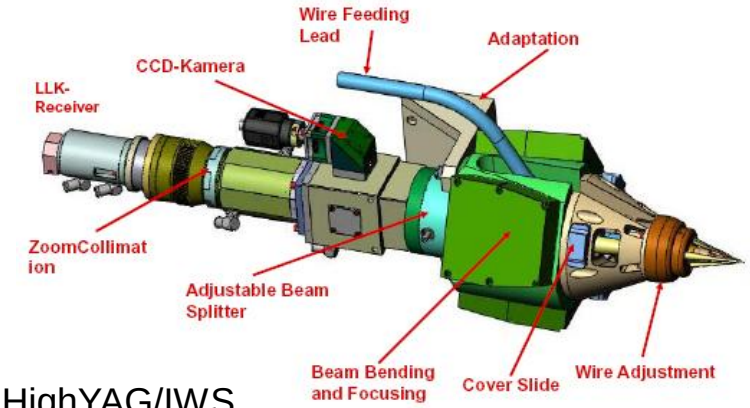


Cavipro





Fraunhofer IWS

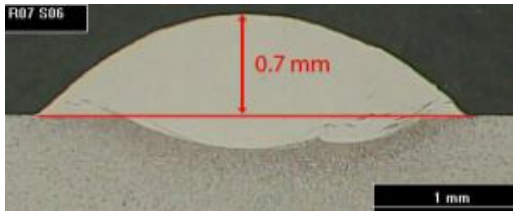


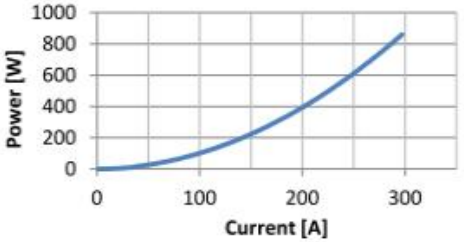
HighYAG/IWS

Coaxial hot-wire laser cladding & additive manufacturing

fimecc: Innovations and Network
Novel product solutions: Trilaser

Duplex: 3.5kW, 4m/min, 250A, 7V, 5kg/h (150 mm^3/s)

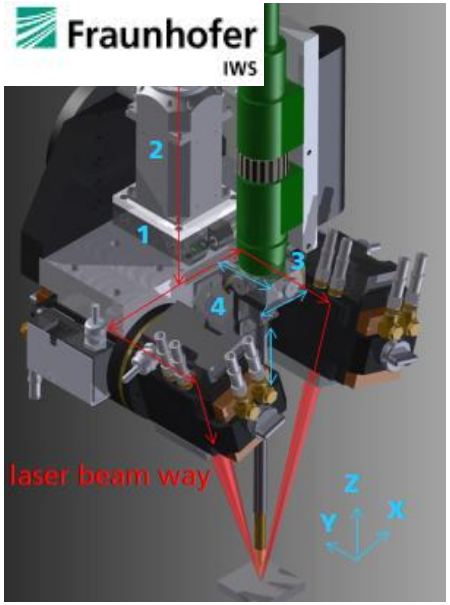




- Main benefits:
  - High process stability
  - Less parameters in wire alignment
  - Omni-directional
  - Increased productivity
  - Material efficient

Coaxial wire laser cladding & additive manufacturing

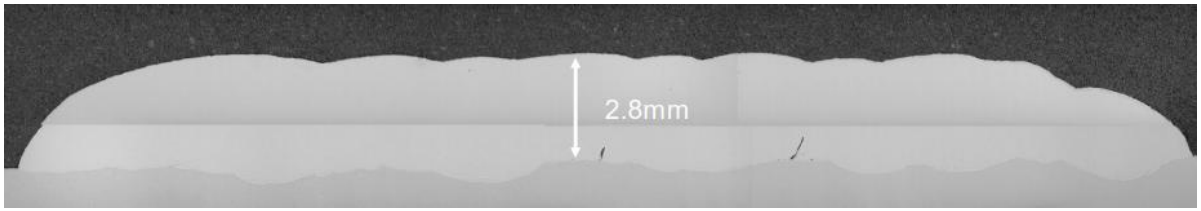
EUROPEAN COMMISSION



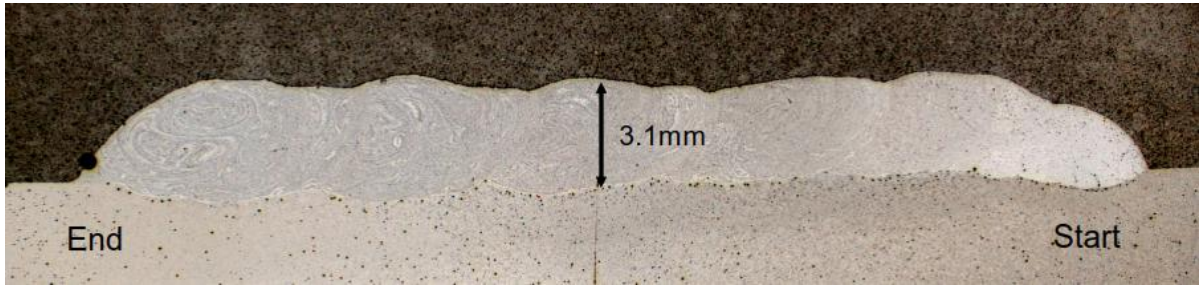
Laser cladding with thick wires, up to 10kW, Ø3.2mm wires, 10 kW Laserline HPDL

M-Era.Net: HiDEPO project

M-era.Net



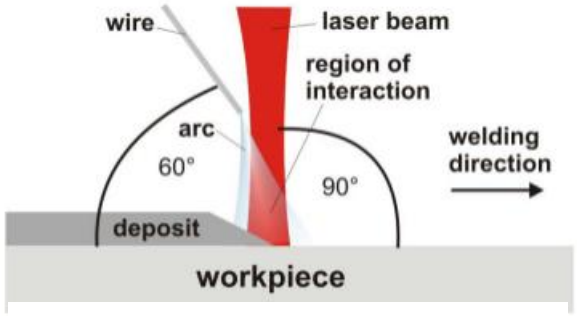
Inconel 625 Ø1.6mm solid wire,10 kW, 1600mm/min, 6.1kg/h



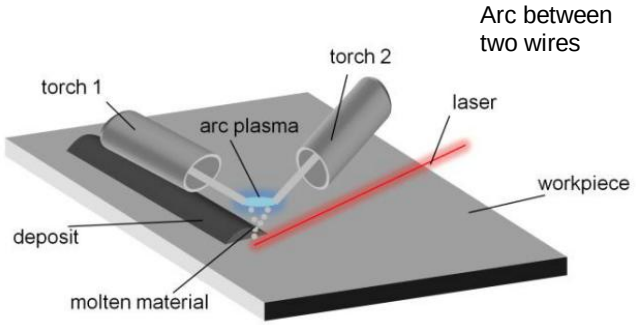
Sanicro 28 Ø1.6mm solid wire,10 kW, 2800mm/min, 5.5kg/h

Laser + arc hybrid cladding & additive manufacturing

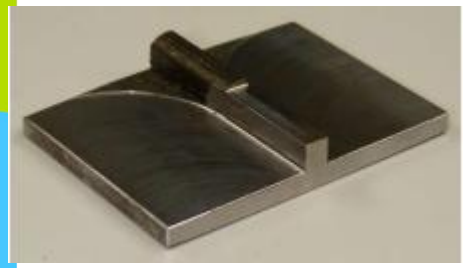
Barroi et al.

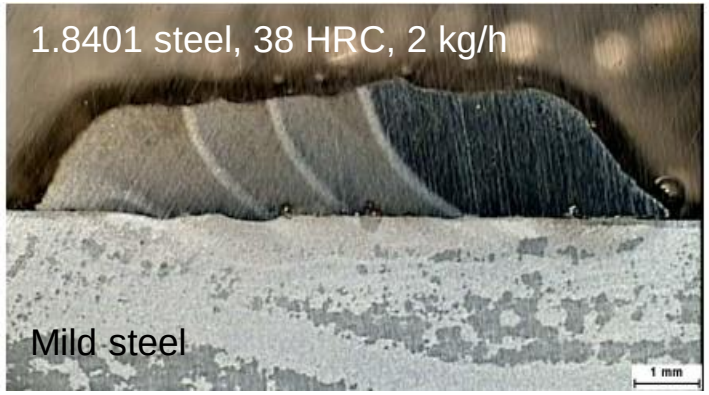


Laser + MIG/MAG, single wire

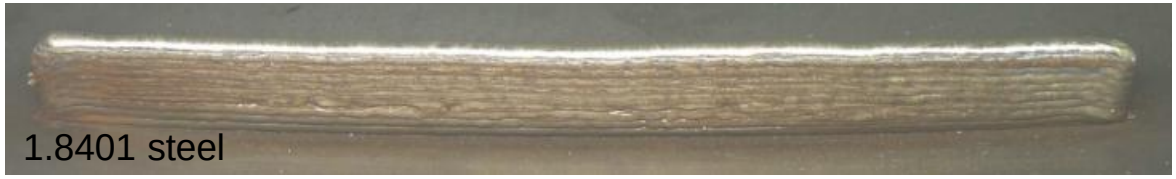


Twin wire 10kg/h





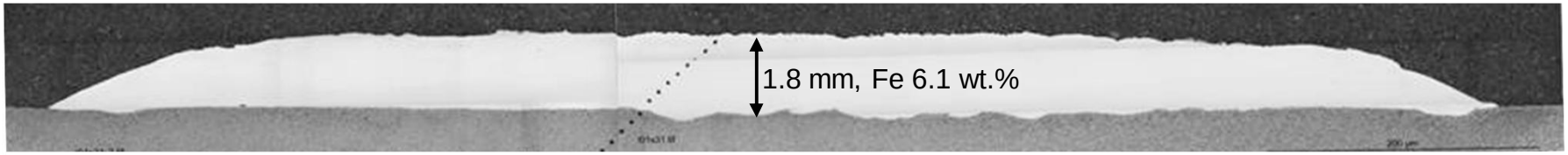
LZH
LASER ZENTRUM HANNOVER e.V.



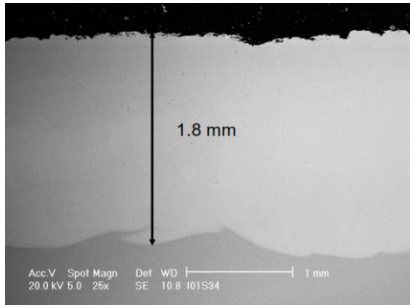
- Main benefits:
  - Low dilution
  - Low heat input
  - Increased productivity
  - Low power capacity laser source (<500W)
  - Stabilization & guidance of electrical arc by laser
  - More stable process

Laser strip cladding & additive manufacturing

EUROPEAN COMMISSION



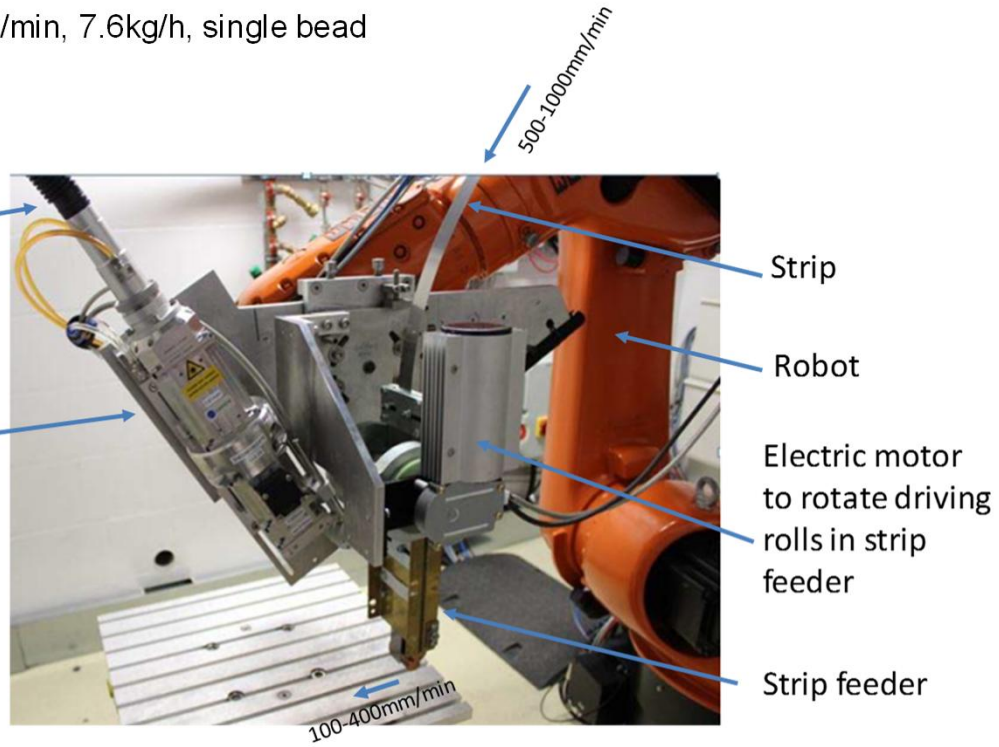
Inconel 625 30 x 0.5 mm^2 solid strip, 8.5kW, 300mm/min, 7.6kg/h, single bead



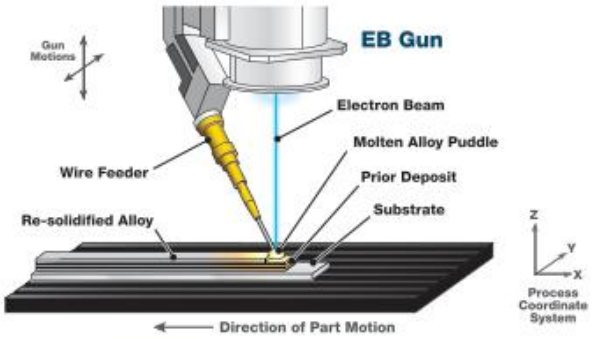
Laser cladding with strips, up to 20kW, 30 x 0.5 mm^2 strips, 20 kW Laserline HPDL

M-Era.Net: HiDEPO project

M-era.Net



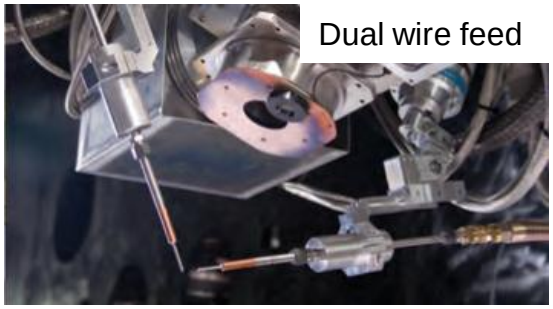
Electron beam + wire (Sciaky Inc.)



Sciaky's EBAM process provides high deposition rates for large-scale parts.

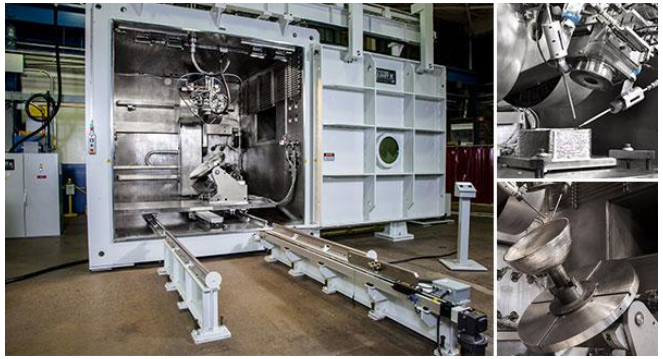
- Working space 5800x1200x1200 mm^3
- Deposition rate 3–9 kg/h
- Ti, Ta, Inconel, Stainless steels, Nb, W
- Closed loop process control
- Aerospace, automotive, agricultural, defense, nuclear, oil & gas

Ti6Al4V screw



Dual wire feed

Aerospace applications



Vacuum chamber

Build-up and repair of tooling & stamping dies

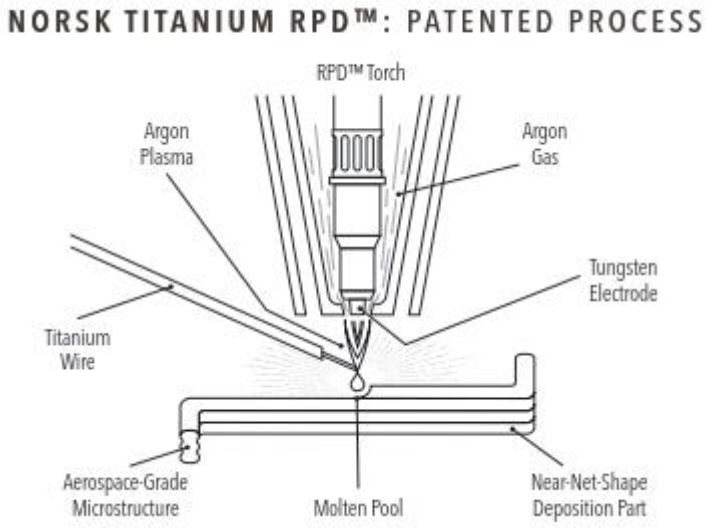
Rapid Plasma Deposition™ (Norsk Titanium AS)

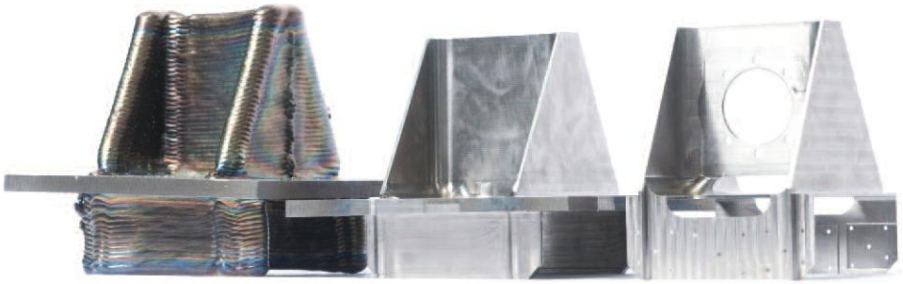
- Plasma-arc + wire (off-axis)
- Closed-loop process control
- Shielding box
- Working volume 1000x500x300mm^3
- Aerospace/aviation applications

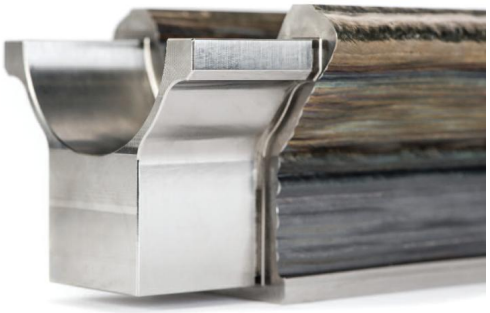
'Eliminating 50-75% of the costs when fabricating titanium components with arc-DED'

'1000 titanium parts in Boeing 787 that can be printed'

'200-lb. needed for 20-lb. part by subtractive manufacturing, 30-lb. needed by AM'



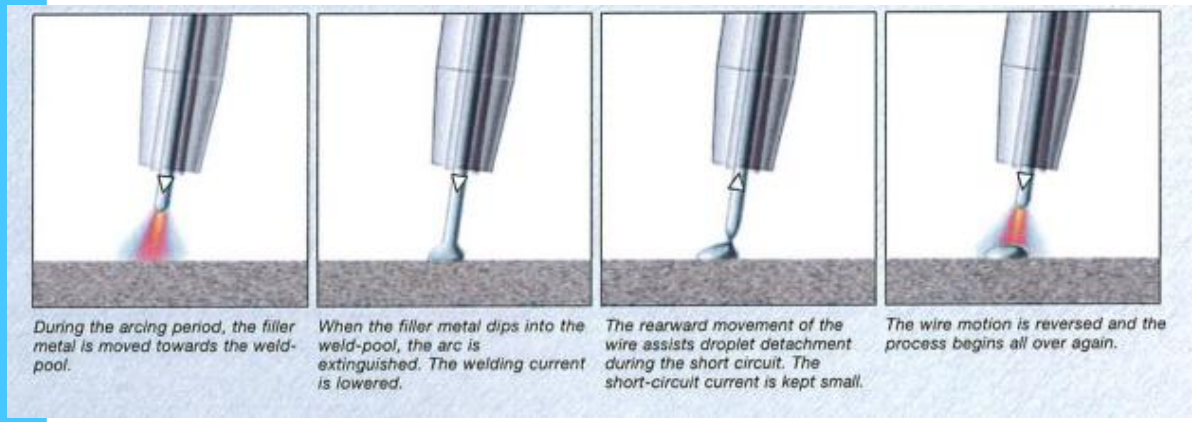




Cold metal transfer (CMT) cladding & additive manufacturing

- Advanced MIG/MAG
- High speed digital control
- Wire retracted at up to 140Hz
- Wire motion directly incorporated to electrical contol
- Max I = 280 A
- Solid wires up to Ø1.2mm
- Tubular wires up to Ø1.6mm

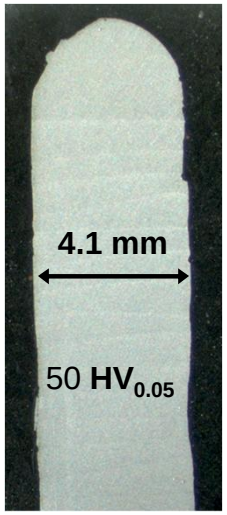
Single wire, ~5kg/h
Twin wire, ~10kg/h



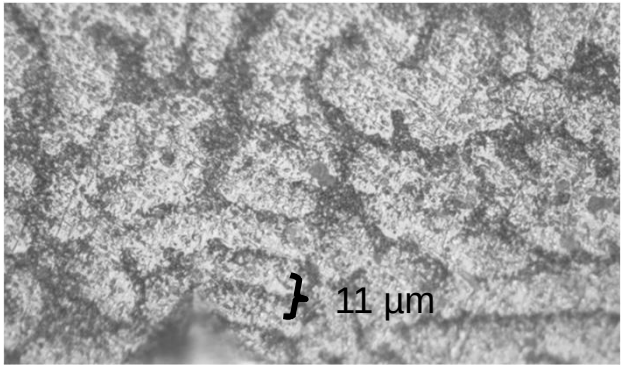
- Main benefits:
  - Low dilution
  - Low heat input
  - High productivity
  - Material efficient
  - Energy efficient (wall-plug, process)
  - Power by aggregate
  - On-site eligible
  - Low investments
  - No optical elements
  - Low safety precautions
  - Closed-loop process control???

Cold metal transfer (CMT) additive manufacturing

fimecc: Innovations and Network
Novel product solutions: Trilaser

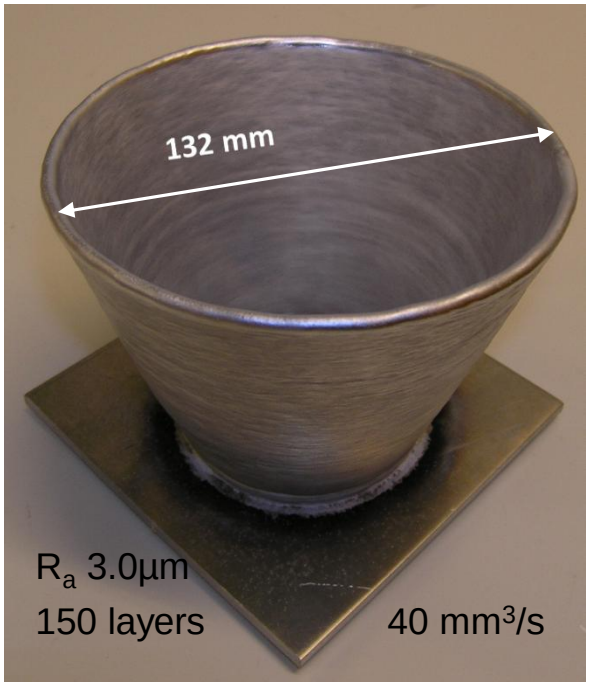


α-Al primary dendrite (light)

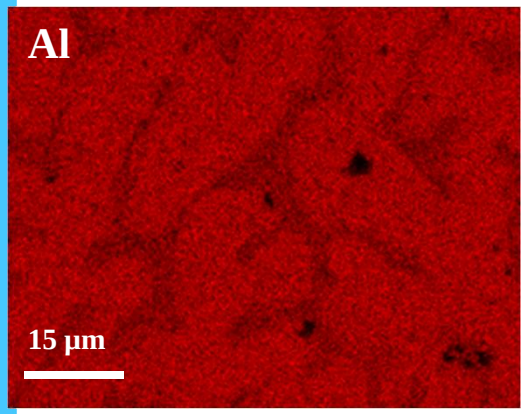


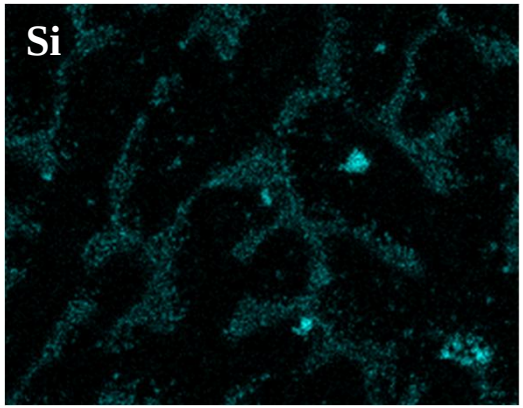
Al/Si eutectic (dark)

Transverse cross-section of AlSi5 build-up



Hypoeutectic AlSi5 (4043) by robot-guided CMT process

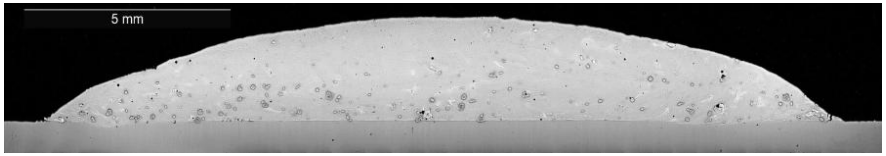




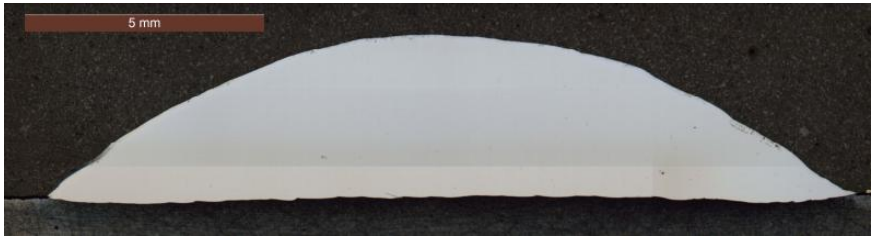
Elemental maps of Al and Si

CMT at TUT

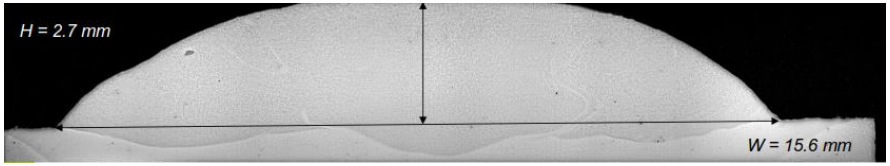
- Fronius CMT Advanced 4000R single wire
- ABB IRB 4600 robot (since April 2016)



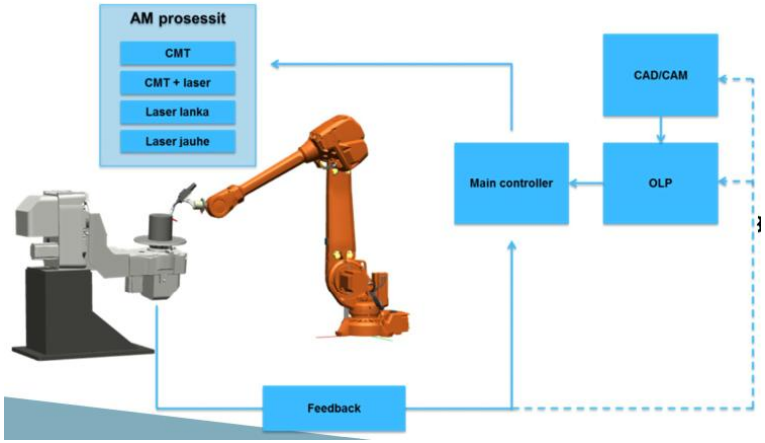
Stellite 12 (~500HV_1)

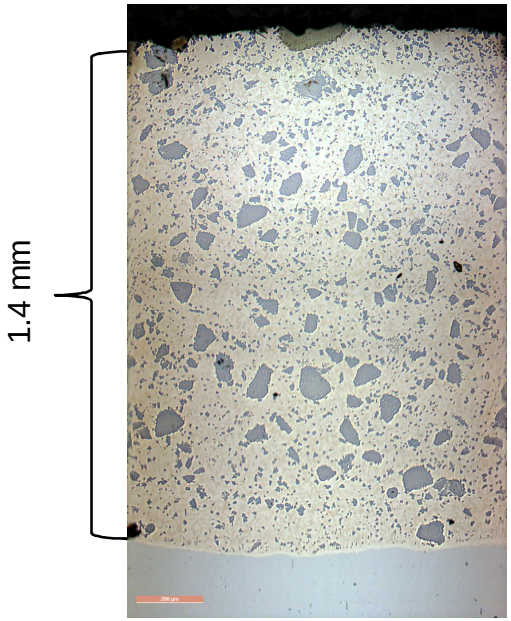


Incoloy 825 (Ø1.2mm, WFR 10.5m/min)



Austenitic martensitic VC tool steel (~800HV_1)



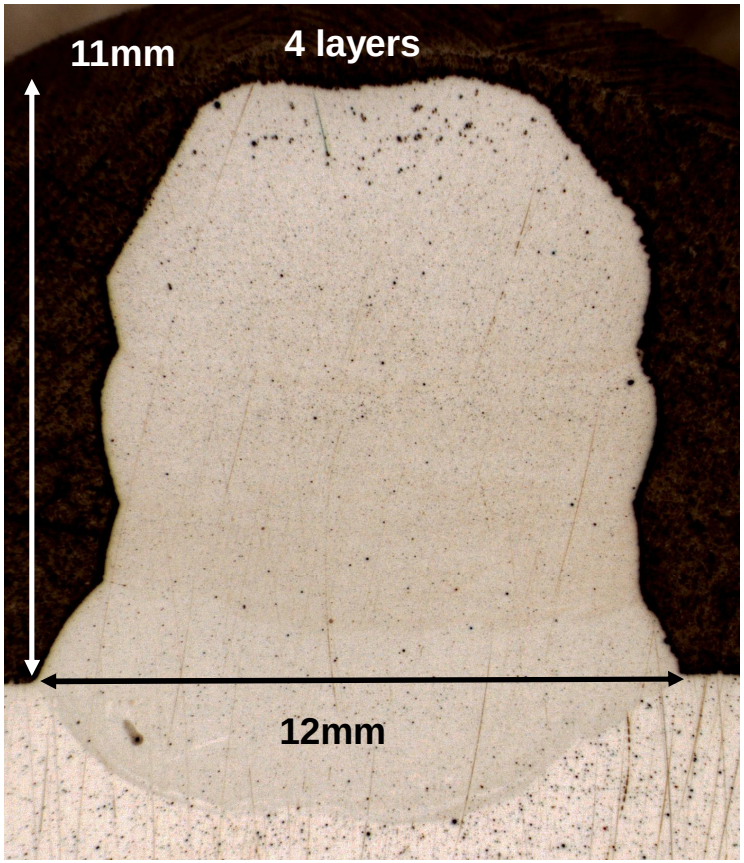


NIFD (WC/W_2C – NiCrBSi)

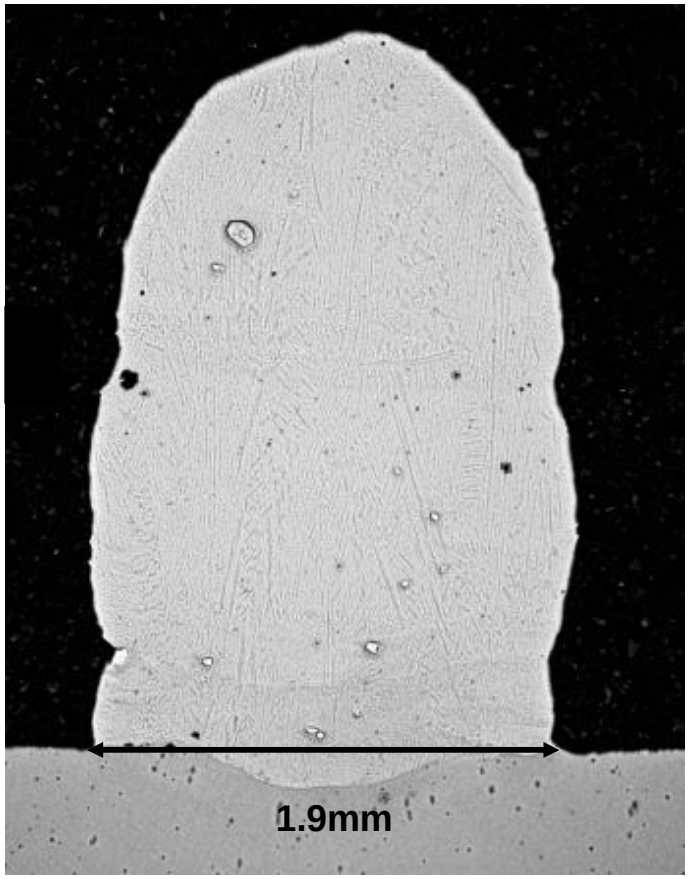
HARDNESS
480 $HV_{0.3}$ (clad: matrix)
2200 $HV_{0.3}$ (clad: carbide)

CMT at TUT

- Fronius CMT Advanced 4000R single wire
- ABB IRB 4600 robot (since April 2016)



Austenitic martensitic VC tool steel (~850HV_1)
Ø1.2mm, WFR 4.5-6.0m/min, weaving
Crack-free



Stellite 12 (~550HV_1)
Ø1.2mm, WFR 1.0m/min, stringer
Crack-free

Commercial Arc-DED devices

+1000K Arc metal deposition (Plus Mfg, USA)

- 2.5kg/h (upgrade to 20kg/h)
- Build volume 1200 x 900 x 600 mm^3
- Monitoring of part temperature
- Quenchant tank to cool the part

Value Arc MA5000-S1 (Mutoh Industries Ltd., Japan)

- ~250 000 USD
- Up to 140 mm^3/s
- Build volume 500 x 500 x 500 mm^3

Adaptive control for Arc-DED (Keystone Inc.)

- Closed-loop process controls needed to improve reproducibility and process consistency
- Control of build height (positioning sensor)
- Control and management of part temperature during an AM build (IR thermal monitoring)
- Monitoring the features of the melt pool during AM processing (melt pool size)
- Keystone developed sensors and control software that can be added to a welding robotic system and communicate with the robot's controller

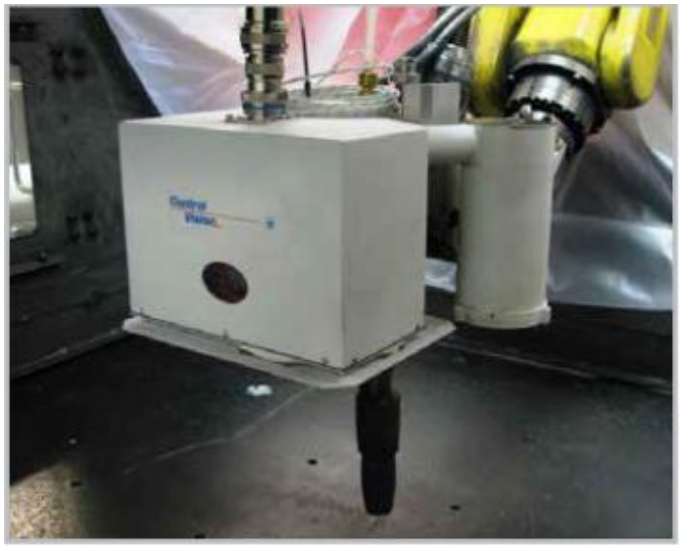
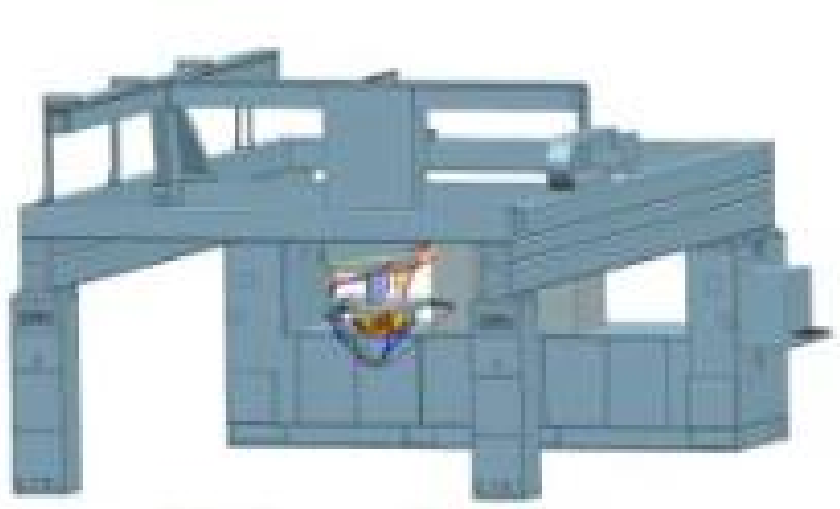


Figure 2. Keystone lightweight integrated sensor head mounted onto a robotic end arm

Trends in DED research

- *Development of large additive and subtractive manufacturing devices*



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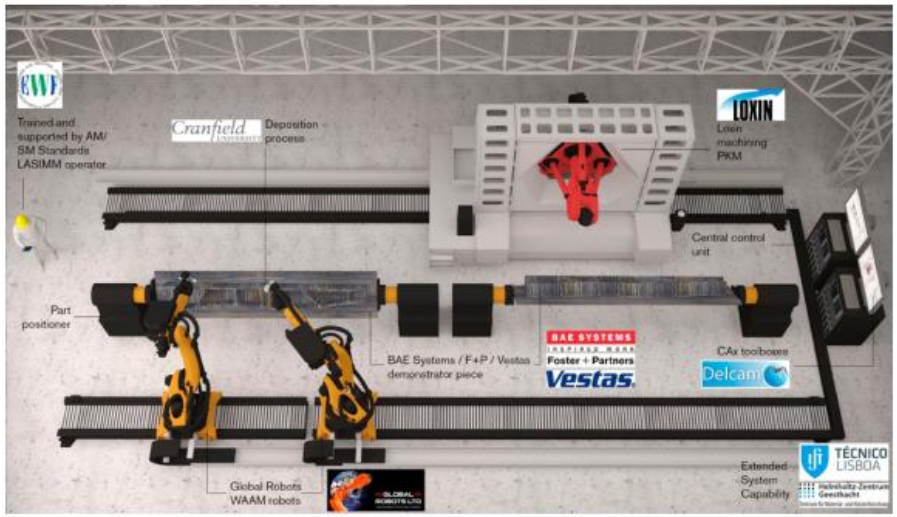

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Summary

- DED is AM process in which focused thermal energy (laser, EB, arc) is used to fuse materials by melting as they are being deposited
- Standardization is in progress
- DED is utilized in weld surfacing, remanufacturing and additive manufacturing
- Material feedstocks are powder, wire or strip
- Inexpensive metal-arc welding methods have experienced significant developments in recent years

THANK YOU FOR YOUR ATTENTION!