Cold Metal Transfer – a novel method for additive manufacturing and to produce cost-effective high-quality coatings

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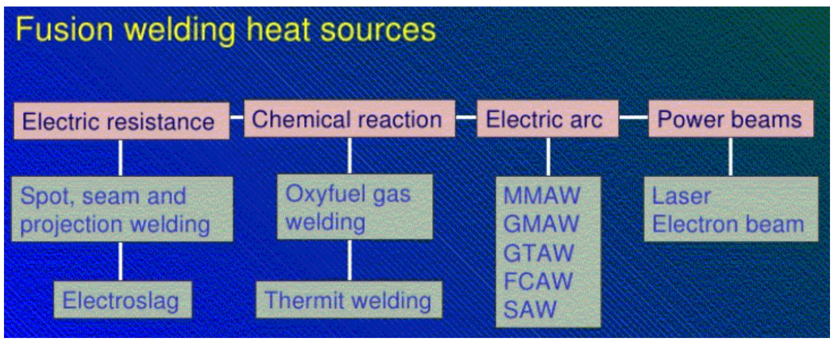
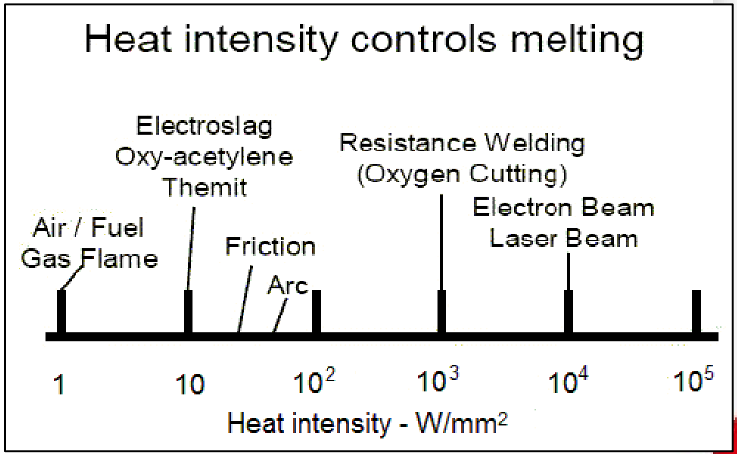
Contents

Welding processes



Classification of Fusion Welding Processes [Parab]

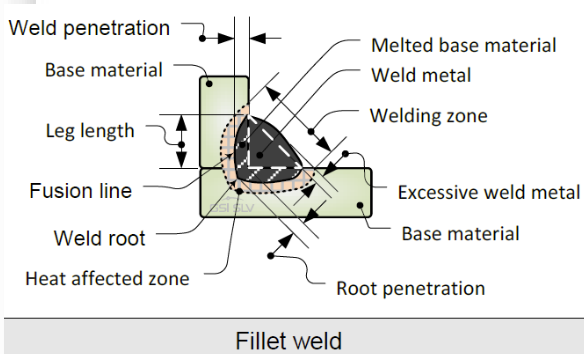


Power densities of welding heat sources [Parab]

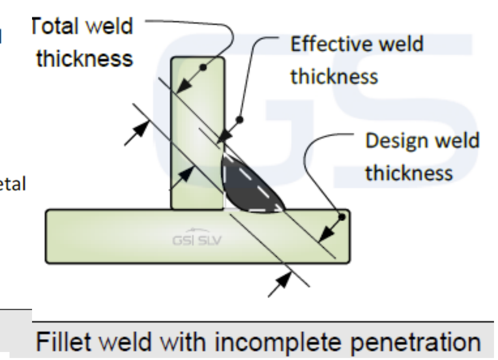
- 10 W/mm^2 melts most metals
- $10^4 – 10^5$ W/mm^2 vaporises most metals
- $10 – 10^4$ W/cm^2 typical for fusion welding

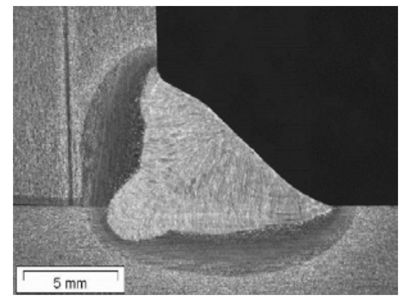
Fusion welding

- On fusion welding, penetration is of essence.
- Welds with poor penetration (or lack of fusion) can cause the whole structure to collapse.

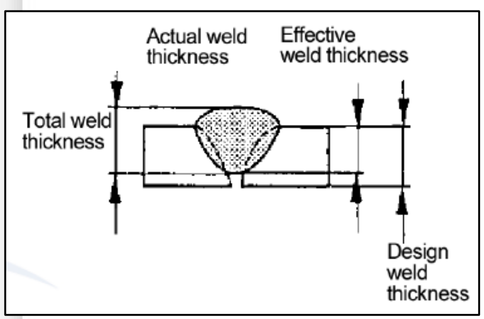


Fillet weld, dimensions [HG3]

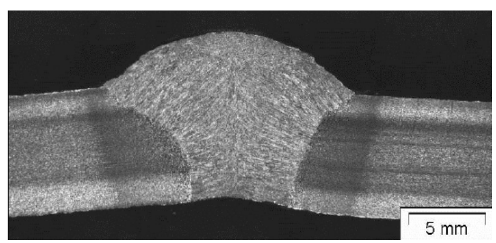




Fillet weld, actual cross section [HG2]



Butt weld, dimensions [HG3]

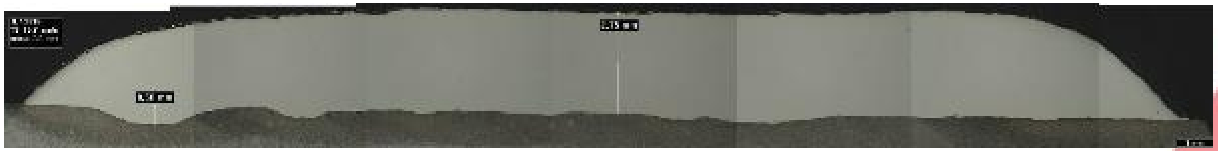


Butt weld, actual cross section [HG2]

Fusion welding vs. overlay welding (cladding)

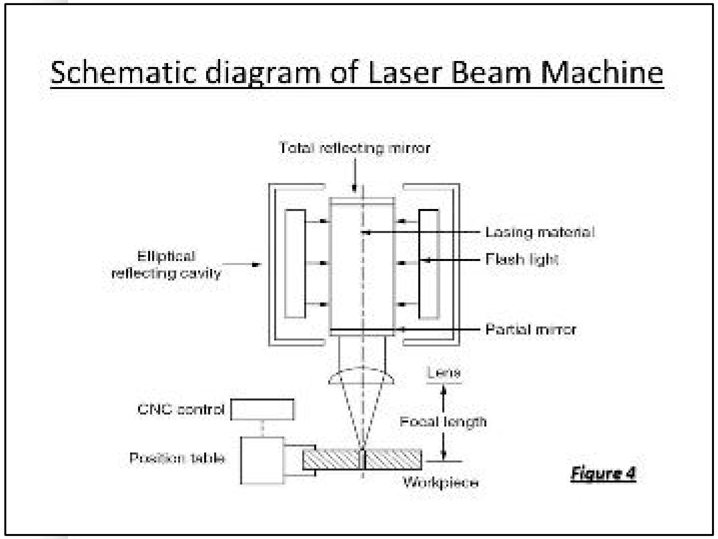
- On overlay welding, penetration should be avoided (without lack of fusion).
- Penetration dilutes the weld-deposit chemistry and potentially decrease its resulting wear and corrosion resistance properties

Overlay welding with CMT. martensitic steel. Cross section. Excessive penetration (~1 mm) and dilution – poor properties, hot cracking. Thickness ~2 mm.

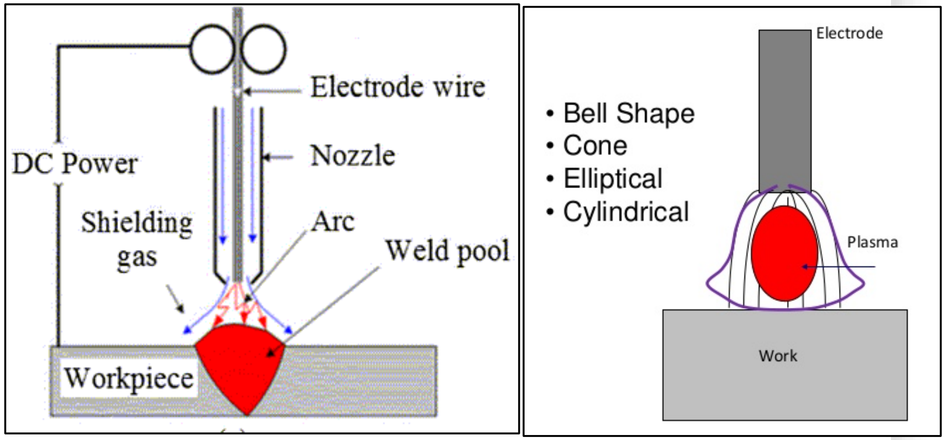


Overlay welding with CMT. Inconel 625. Cross section. Some penetration (~0,5 mm) on the first and second bead – good properties. Thickness: 2,7 mm.

Welding processes – laser vs. electric arc



Schematic of laser materials processing [Johns]



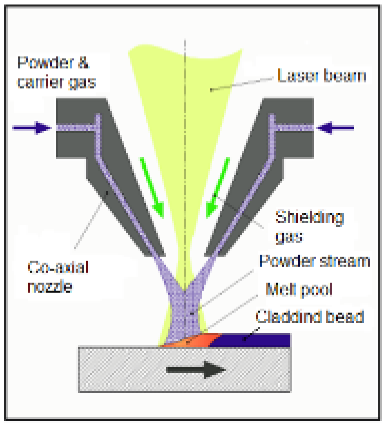
Schematic of arc welding (MIG/MAG) and Electric arc [Ding, Pau

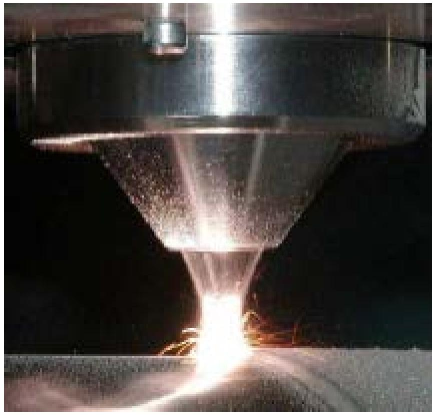
Laser:
+ Best focusability – large energy density – cutting and deep penetration welding
- Expensive
- Need of precise positioning

Electric arc:
+ Cheap
- Poor focusability – no cutting (except plasma), low penetration on welding
- No need of precise positioning

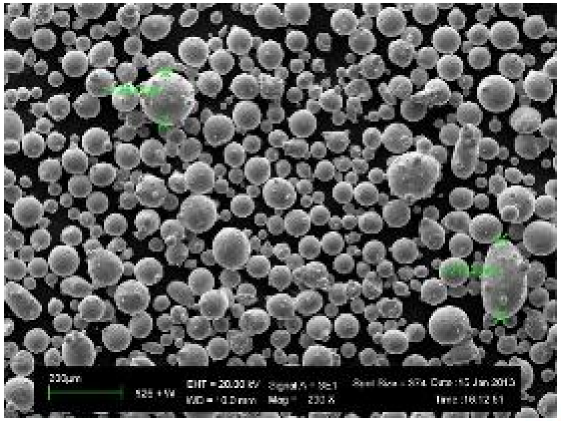
Processes – laser cladding

- Powder with a particle size ~50 – 150 µm is blown coaxially through the nozzle to the substrate laser beam.
- Laser beam melts powder and thin layer of substrate material.
- Typical cladding rate is 2 kg /h.





Laser cladding process

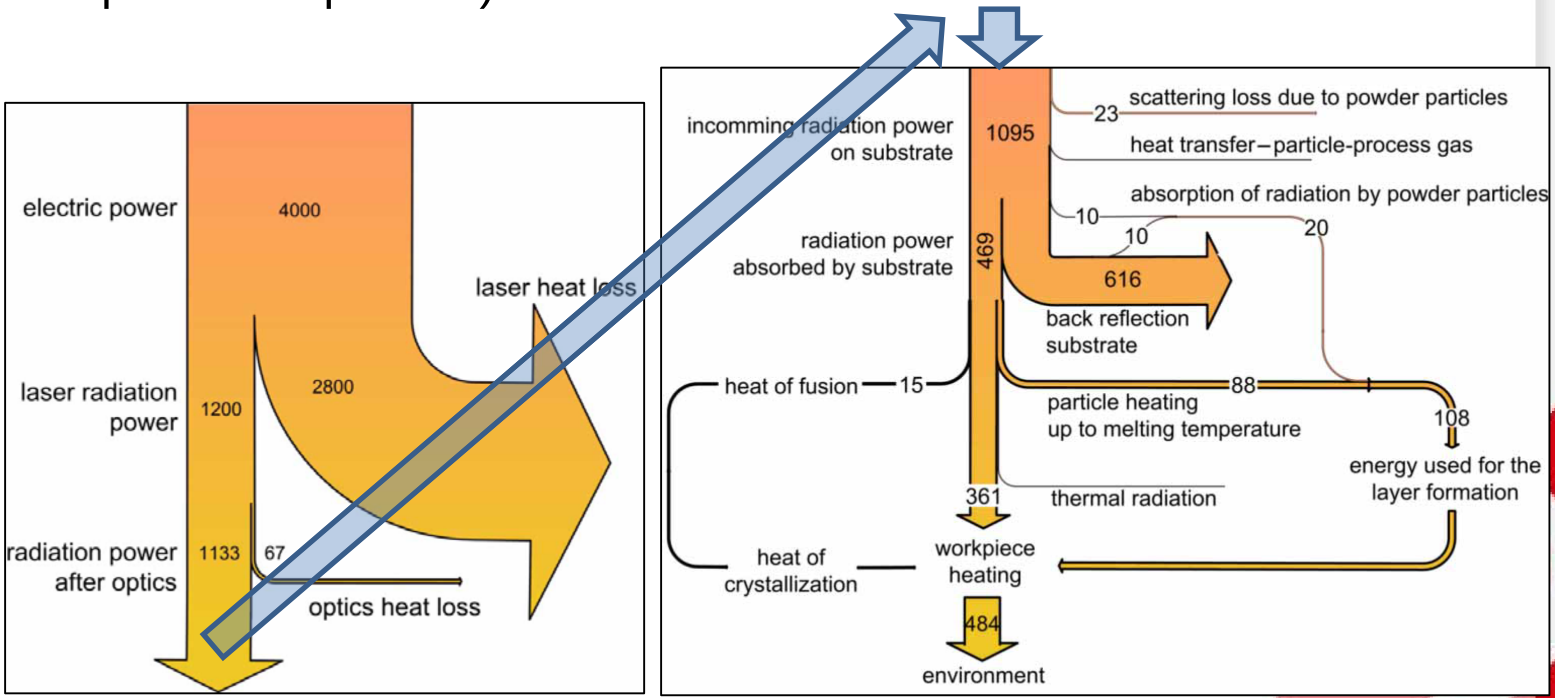


Laser cladding powder

Inconel 625 laser cladding. Cross section. Very low penetration and dilution. Thickness: ~1,5 mm

Laser process – energy efficiency

Around 10% of total energy usage ends up to heat the material on laser cladding process (4000 W electric power → 469 W to heat workpiece and powder)



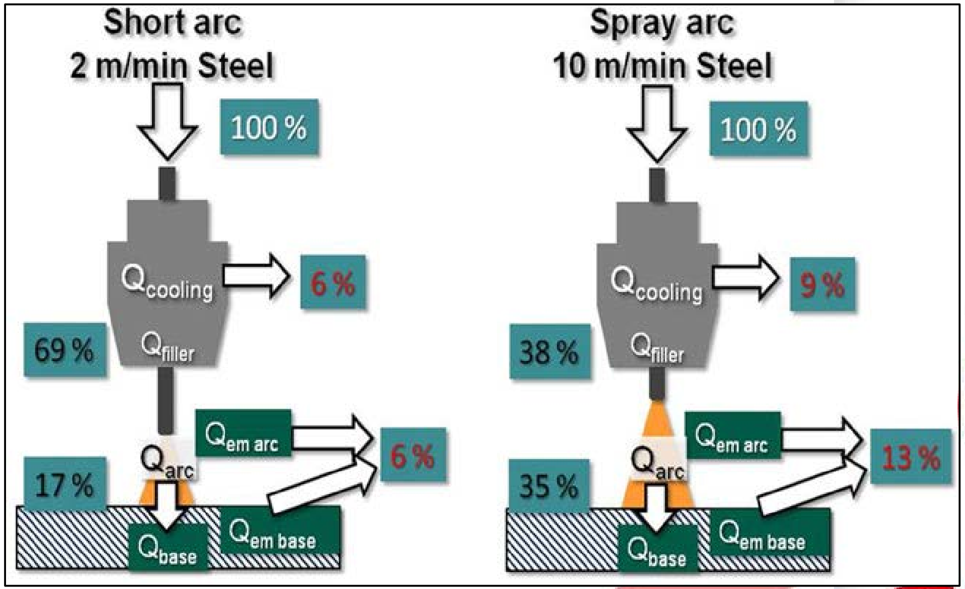
Energy distribution of a typical laser cladding process [Leyens et al].

Arc welding process (MIG/MAG) – energy efficiency

- Electrical efficiency of electric power source (welding machine) is >90%.
- Process efficiency is depending on process parameters (mode, travel speed etc.), but efficiency on MIG/MAG welding is anyway 70 - 80%.

Electrons are cheaper than photons?"

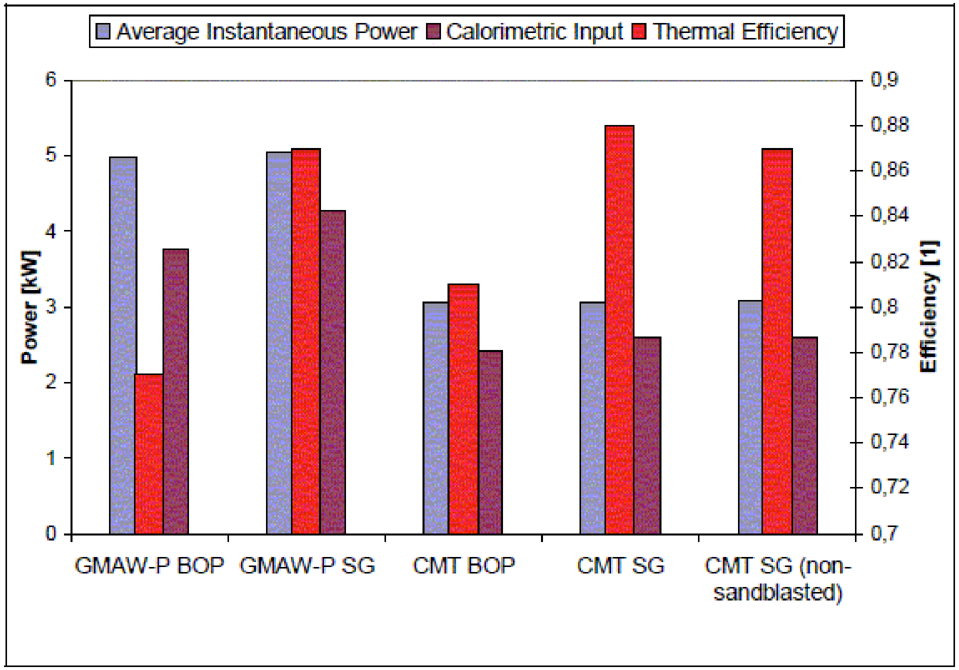
Process	Short arc	Spray arc
Feedstock material	69%	38%
Base material	17%	35%
Torch cooling	6%	9%
Radiation	6%	13%
Process efficiency	86%	73%
Wall plug efficiency	77%	66%



Process efficiency on MIG/MAG welding with short arc and spray arc process modes [Hälsig, Mayr]

Arc Welding process – energy efficiency

- CMT process has been shown to have slightly higher efficiency (80-88%) compared to pulsed MIG/MAG welding (77-87%)

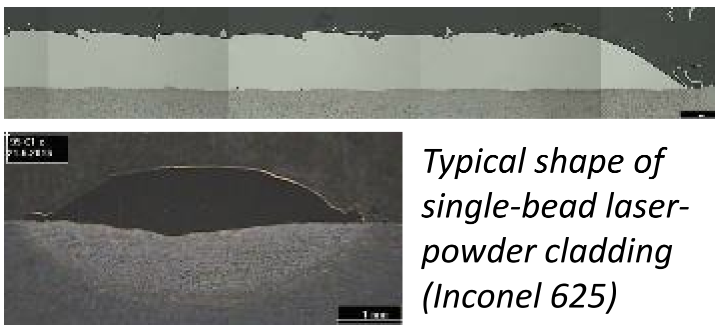


GMAW-P: Pulsed Gas Metal Arc Welding (MIG/MAG)
BOP: Bead On Plate
SG: Square Groove
[Egerland, Colegrove]

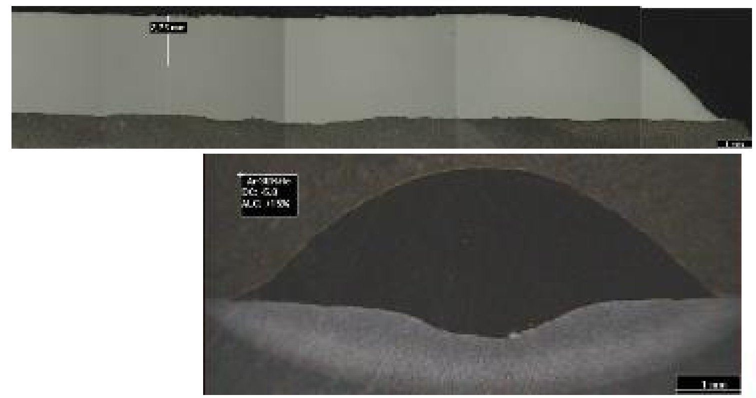
Laser vs. CMT on cladding

Single stringer bead with Inconel 625:

- Laser and powder
- CMT and ∅1,2 mm wire



Typical shape of single-bead laser-powder cladding (Inconel 625)



Typical shape of single-bead CMT (wire) cladding. (Inconel 625)

Measured results from cross section

	Power kW	Bead height mm	Bead width mm	Bead area mm^2	Yield kg/h	Dilution %	Base material			Hardness HV_5
							Penet-ration mm	Melted area mm^2	HAZ area mm^2	
Laser	3,5 (laser)	0,86	4,7	3,0	1,5	12	0,23	0,4	4,3	227
CMT	3,5 (I x U)	2,0	7,2	9,7	4,9	13	0,61	1,51	9,8	229

CMT Cold Metal Transfer – benefits of both laser and electric arc

Laser:

+ Best focusability
  → large energy density
  → cutting and deep penetration welding
+ Low dilution and heat input on base material on cladding
- Expensive device
- Poor energy efficiency
- Need of precise positioning
- Feedstock material on powder form
  → more expensive
  → utilisation rate ~70% - some powder is wasted

Electric arc:

+ Cheap device
+ Good energy efficiency
+ No need of precise positioning
+ Wire utilisation rate ~100%
- Poor focusability
  → low penetration
  → no cutting, low penetration on fusion welding

Benefits of laser and electric arc are combined on overlay welding with CMT:
+ Cheap
+ Good energy efficiency
+ Low penetration and dilution
+ Good utilisation of feedstock material

MAG vs. CMT – High speed camera video

- MAG short arc process: continuous wire movement, spatter
- CMT process: wire is retracted, no spatter

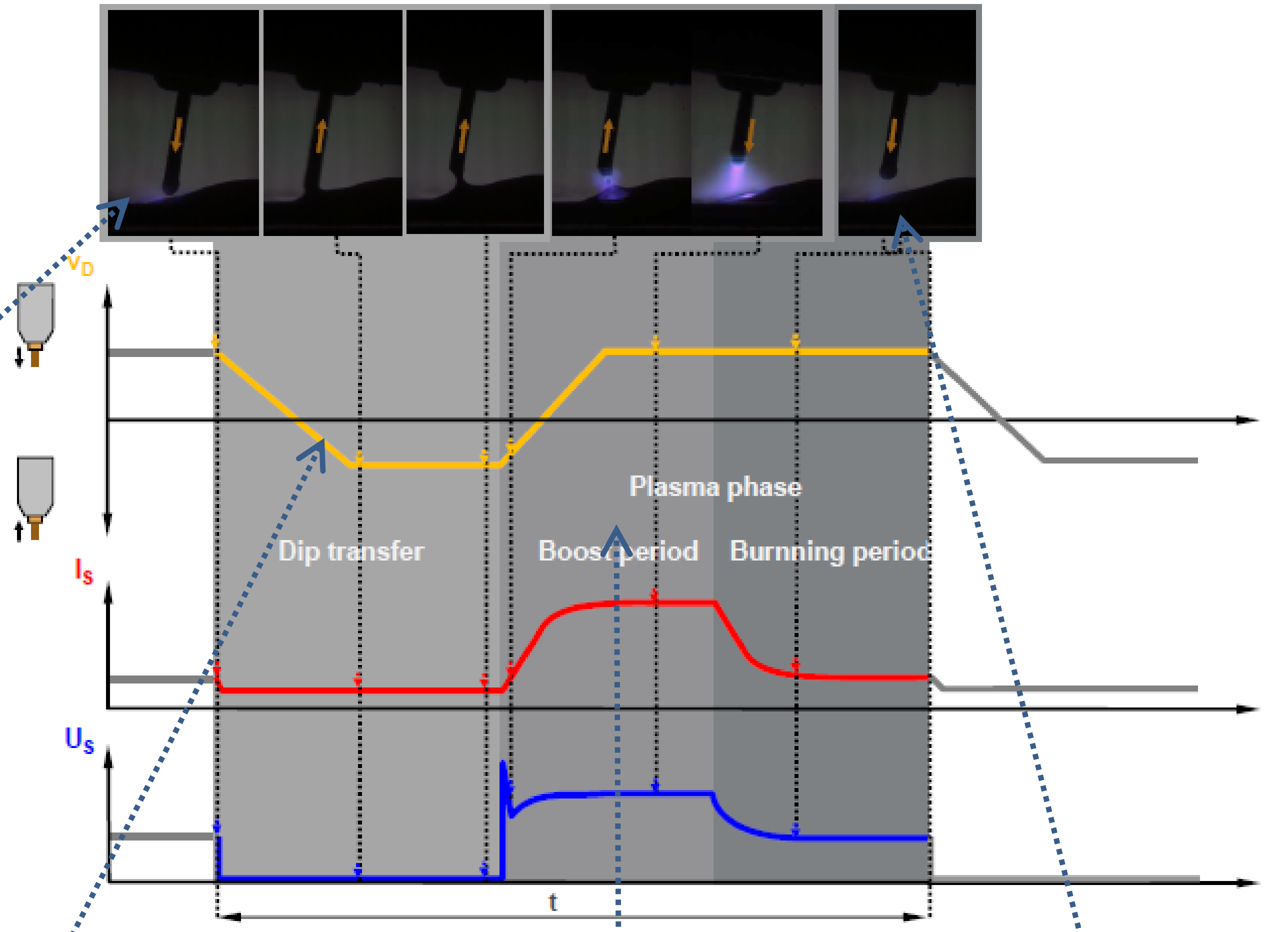
MAG short arc process - high speed camera video.

CMT process - high speed camera video.

CMT process

Three main variables on CMT process:

1. Wire movement direction
2. Current
3. Voltage



When wire hits the melt pool (short circuit), arc diminishes, and welding current level lowered

Wire retraction starts that helps to loose melt drop from the tip of the wire

During the arc phase, wire is moved towards melt pool.

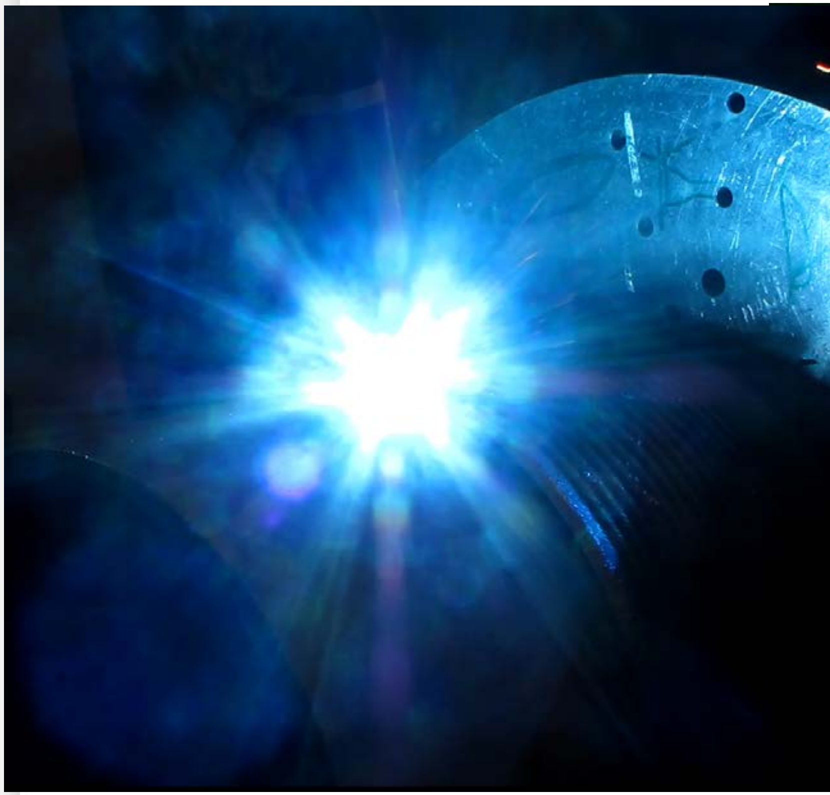
Current and voltage values are lowered and wire starts to reach the melt pool

MAG vs. CMT

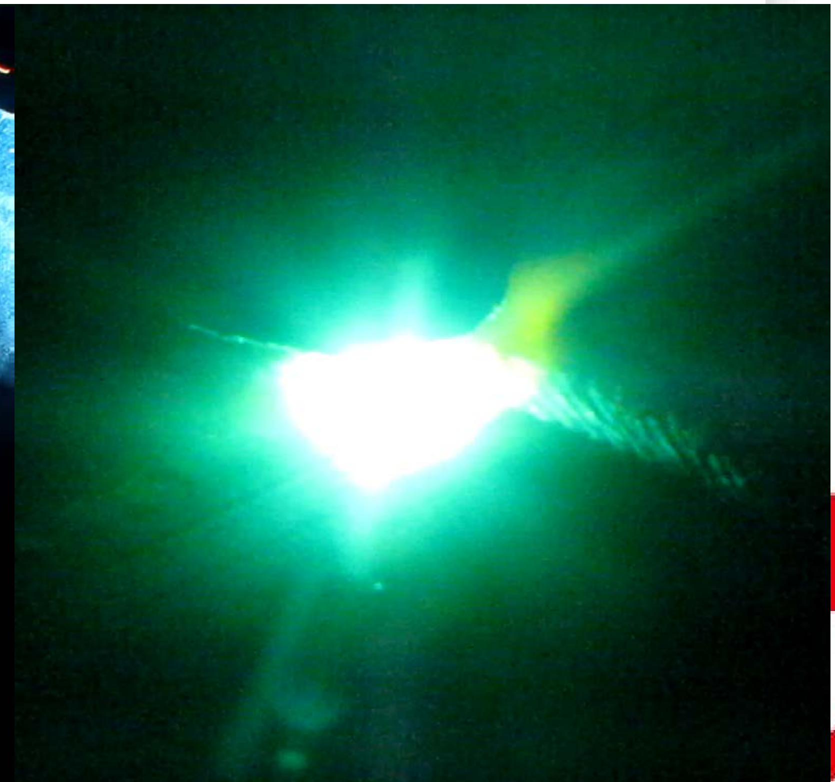

Shortarc
Mild Steel 1,2mm
wfs=6m/min
82Arg/18Co2
© by Fronius 2005


CMT
Mild Steel 1,2mm
wfs=7m/min
82Arg/18Co2
© by Fronius 2005

Cladding of large diameter tube



Cladding of large diameter, thin walled tube. video

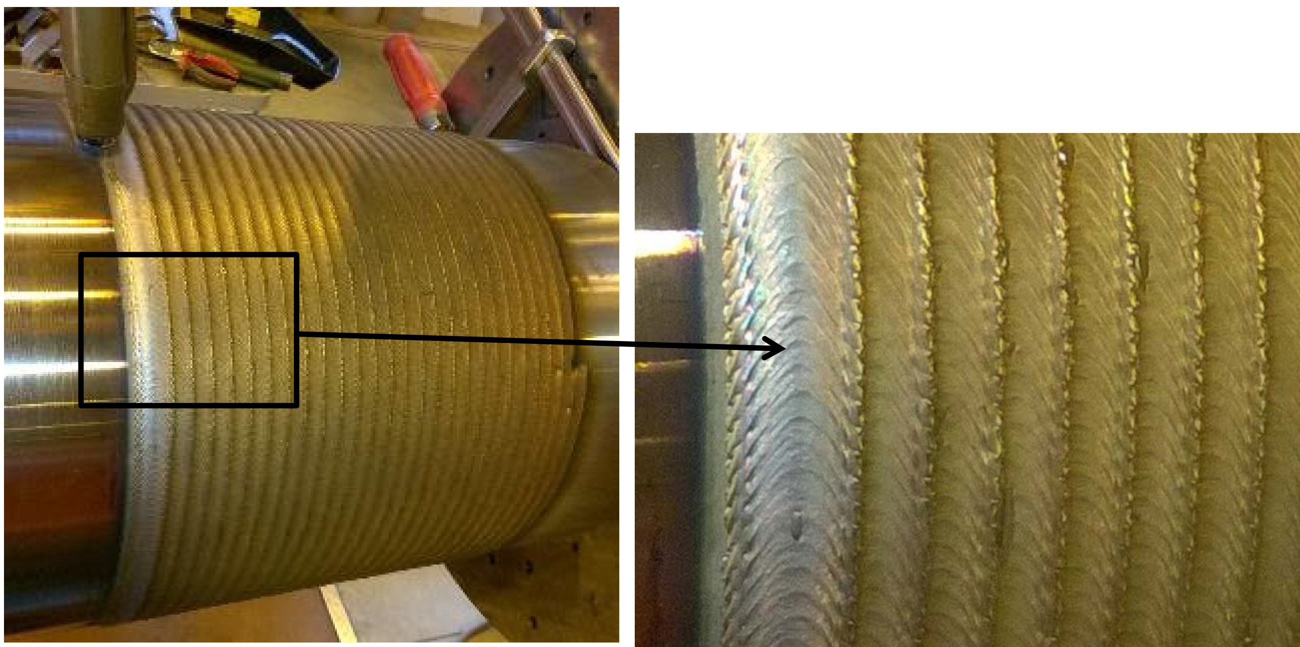


Video through the welding shield glass.

CMT cladding of large diameter tube

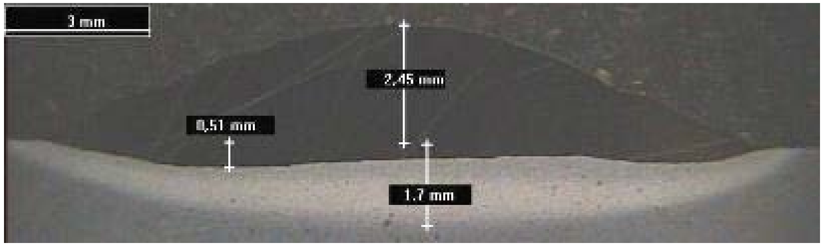
- Shaft diameter: Ø320 mm
- Wall thickness: 20 mm
- 316LSi wire, Ø1,2 mm
- Weaving movement.
- Coating thickness: ~2,5 mm

- Wire feed speed setting: 8,5 m/min
- Deposition rate: 4,5 - 5 kg/h
- Covering rate: 0,29 m^2/h
- Arc power: 2700 W (I x U)
- Tube surface temperature: max 250°C.

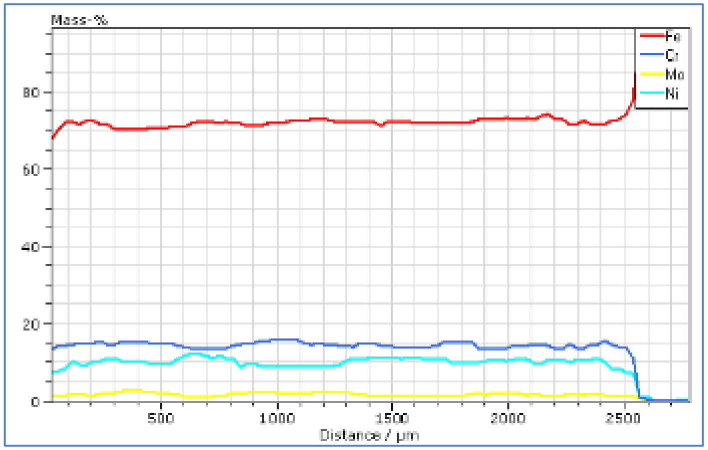


CMT cladding of large diameter tube

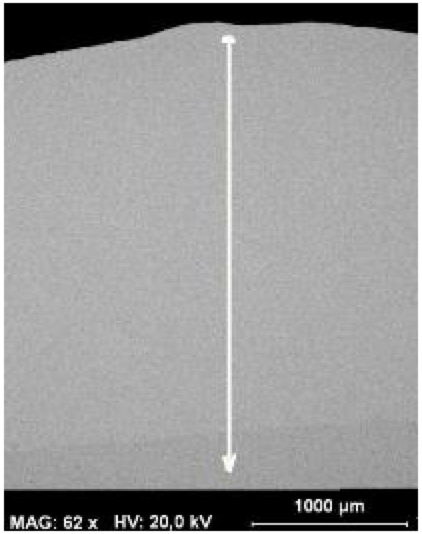
Measurements made on process parameter test sample



316LSi stainless steel. Single bead (weaving) test sample cross section, graphical dilution 17% .



EDS line scan across the cladding

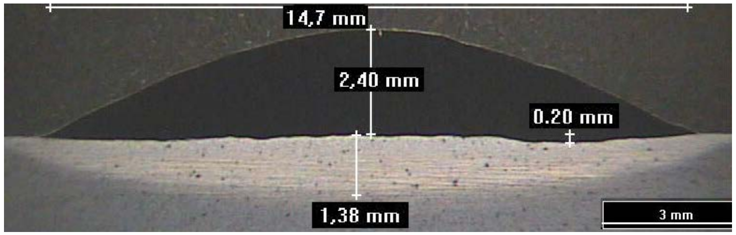


EDS line scan across the cladding

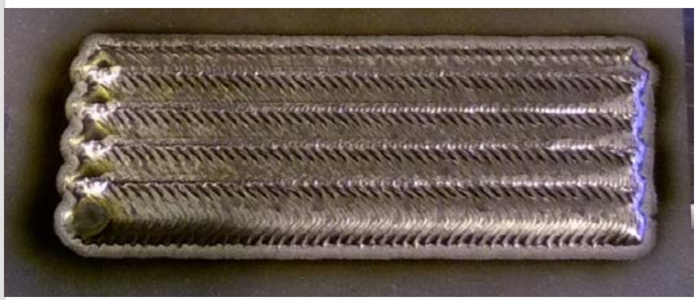
Wire nominal composition and EDS line scan results (to the 1 mm depth)

	Fe	Cr	Ni	Mo	Si
Wire	bal	18,4	12,2	2,6	0,9
Cladding	71,4	14,9	10,3	2,2	0,9

CMT cladding - nickel based Inconel 625

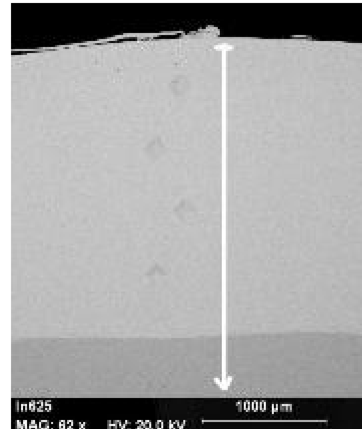


Inconel 625 single bead test (weaving) cladding. Cross section

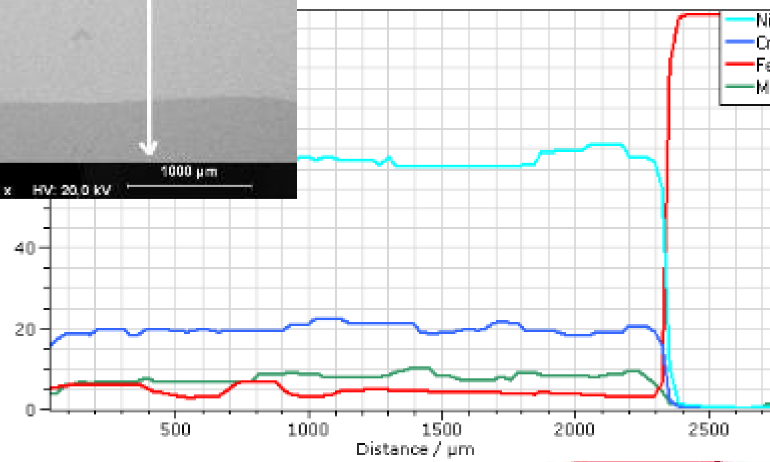


Inconel 625 test cladding with adjacent beads.

Last bead. Cross section. Low penetration and dilution Hardness 224 HV_5.



EDS line scan across the cladding



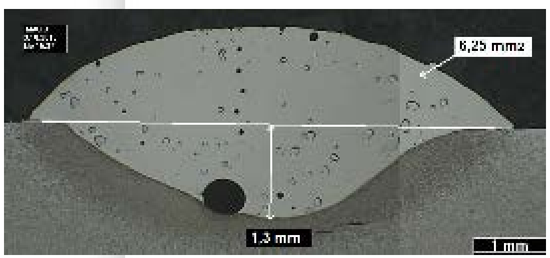
Wire nominal composition and EDS line scan results (to the depth of 1 mm)

	Ni	Cr	Mo	Fe	Nb
Wire	bal	22,1	9,1	0,3	3,5
Cladding	64,1	19,6	7,3	**5,2**	2,7

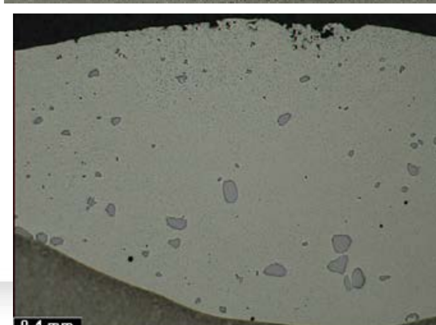
MAG vs. CMT – Ni-WC cored wire hardfacing

- Nickel based tungsten carbide (Ni-WC) hardfacing wire – single stringer beads
- Carbides should stay undissolved during the process
- Normal MAG welding mode is not stable until the higher voltage and arc power values.
- Pulsed MAG welding mode is cooler that normal MAG, but hotter than CMT.

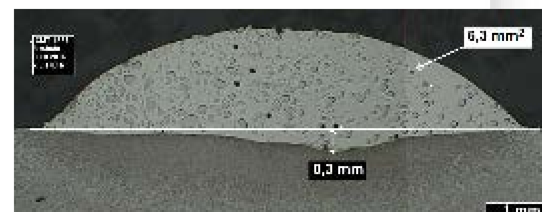
MAG mode
Arc voltage: 23,5 V
Arc power: 4500 W
Reinforcement area: 6,25 mm^2
Dilution: 39%
Matrix hardness: 424 HV_1
Carbide hardness: 2050 $HV_{0,5}$
Most of carbides dissolved

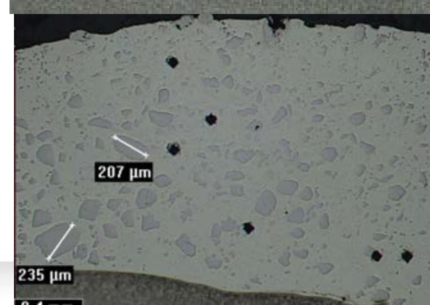


Pulsed MAG mode
Arc voltage: 18,3 V
Arc power: 2600 W
Reinforcement area: 4,2 mm^2
Dilution: 33%
Most of carbides dissolved



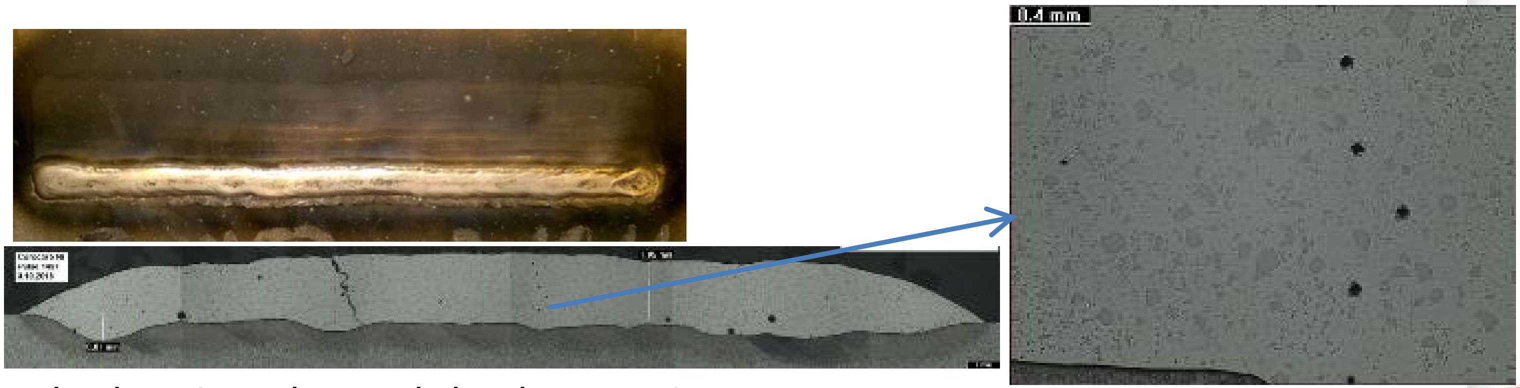
CMT mode
Arc voltage: 14,5 V
Arc power: 2500 W
Reinforcement area: 6,30 mm^2
Dilution: 10,5%
Matrix hardness: 421 HV_1
Carbide Hardness: 2150 $HV_{0,5}$
More carbides left undissolved



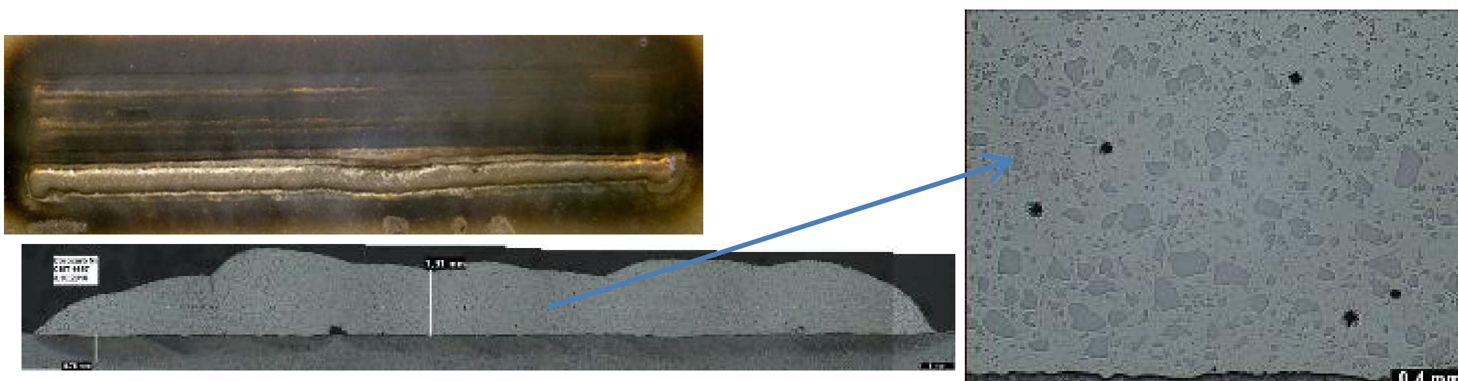


MAG vs. CMT – Ni-WC cored wire hardfacing

- Test claddings made with Pulsed MAG (cool) mode and CMT
- Actual rating need to be tested with abrasion tests.



Pulsed MAG mode. Matrix hardness: 442 HV1.



CMT mode. Matrix hardness: 422 HV1.

Overlay welding with CMT - summary

Benefits:

- Good energy efficiency
- Cold process – tungsten carbides remain undissolved
- Small dilution values - as low as 5% Fe is possible with Ni based alloys.
- Large deposition rate:
    - Single wire: 5 kg/h, max covering rate: ~0,3 m^2/h
    - TWIN wire: ~10 kg/h, max covering rate: ?
- Flexible process
- Wide variety of available feedstock materials – all solid and cored wires, Ø1,2 mm and below (Ø1,6 mm ?)

Limitations:

- Minimum cladding thickness: ~2 mm.

Tested feedstock materials:

- Stainless steels: austenitic 316L and 307, Duplex 22-5-3
- Stellite 21 cored wire
- Inconel 625
- Cored wire harfacings: Ni-WC, Fe-mixed carbide
- Aluminium bronze
- Martensitic steel

Metal Additive Manufacturing (AM)

Some History of Additive Manufacturing

- 1926 Baker – patented "The use of an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers
- 1988 First commercial machine (plastic) by 3D systems, stereolithography, SLA
- 1990's – Rapid Prototyping.
- 2000 → Additive manufacturing

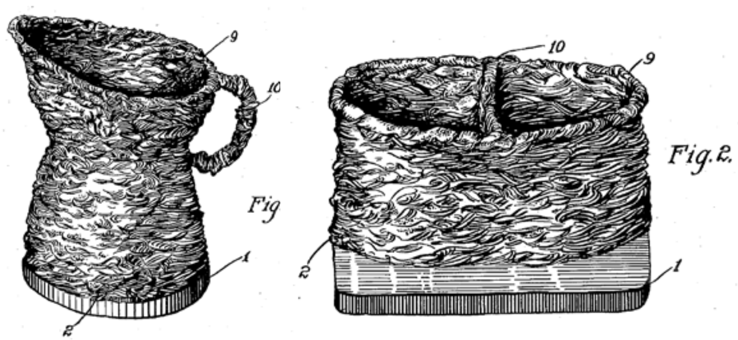


Image on the patent on 1926

Vase produced in metal using robotic MAG welding process based on the CAD model in 1994 [Ribeiro et al, Cranfield]

Metal Additive Manufacturing (AM) methods

- Wide variety of processes
- Most processes or available machines rely on laser-powder-bed processes (DMLS, SLS, SLM).
- Some processes (LENS, LC) are basically the same as laser cladding.
- Also some electron beam processes.
- **WAAM** = **W**ire and **A**rc **A**dditive **M**anufacturing

Classification of metal AM processes [Ding et al]

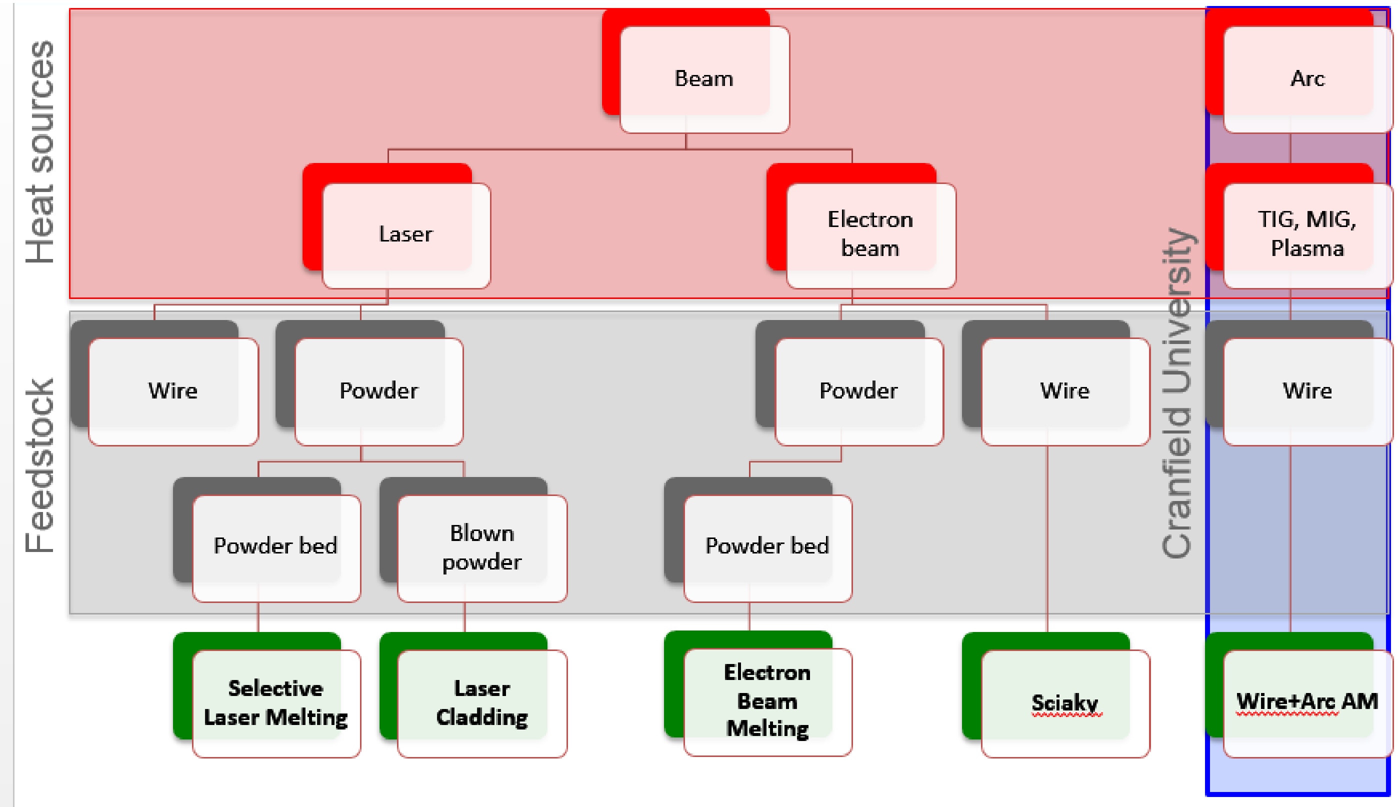
Classification	Terminologies	Ref.	Material
Powder bed fusion	Direct metal laser sintering (DMLS)	[9]	Metal powder
	Electron beam melting (EBM)	[10]	
	Selective laser sintering (SLS)	[11]	
	Selective laser melting (SLM)	[12]	
Directed energy deposition	Electron beam freeform fabrication (EBF^3)	[13]	Metal powder, metal wire
	Laser engineered net shaping (LENS)	[14]	
	Laser consolidation (LC)	[15]	
	Directed light fabrication (DLF)	[16]	
	Wire and arc additive manufacturing (WAAM)	[17]	
Binder jetting	Powder bed and inkjet 3D printing (3DP)	[18]	Metal powder
Sheet lamination	Laminated object manufacturing (LOM)	[19]	Metal laminate, metal foil
	Ultrasonic consolidation (UC)	[20]	

Comparison of some metal AM processes [Ding et al]

Additive materials	Process	Layer thickness (μm)	Deposition rate (g/min)	Dimensional accuracy (mm)	Surface roughness (μm)
Powder	LC	N/A	1–30	±0.025–±0.069	1–2
	SLM	20–100	N/A	±0.04	9–10
	SLS	75	~0.1	±0.05	14–16
	DLF	200	10	±0.13	~20
Wire	WAAM	~1500	12 (0,7 kg/h)	±0.2	200
	EBF^3	N/A	Up to 330	Low	High

Metal Additive Manufacturing methods

WAAM = **W**ire and **A**rc **A**dditive **M**anufacturing

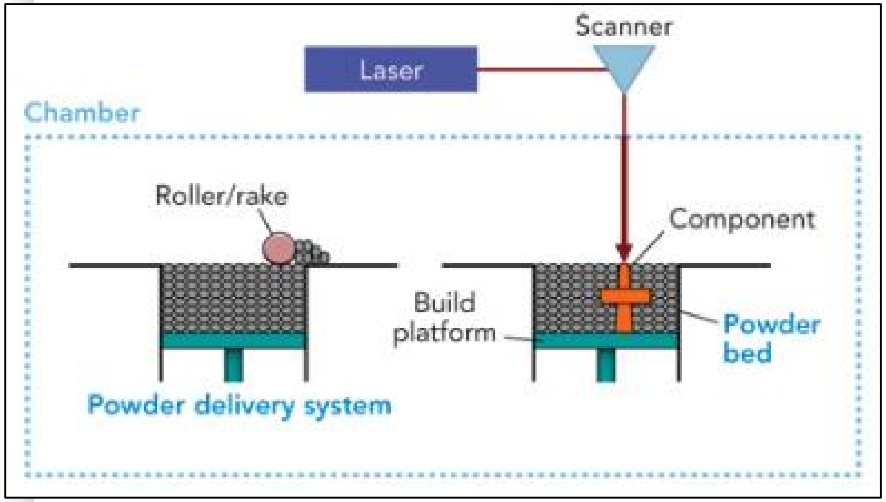


Classification of Metal AM method [Williams]

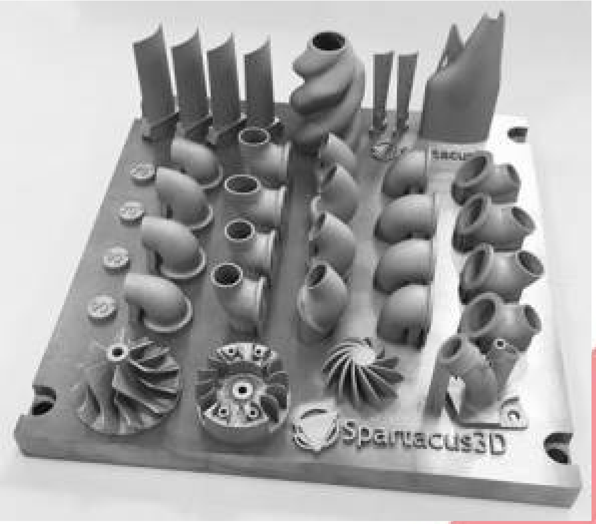
Metal AM state of the art – laser powder bed

Powder-bed AM methods:

- Components to be made are limited both by the chamber size and poor deposition rate.



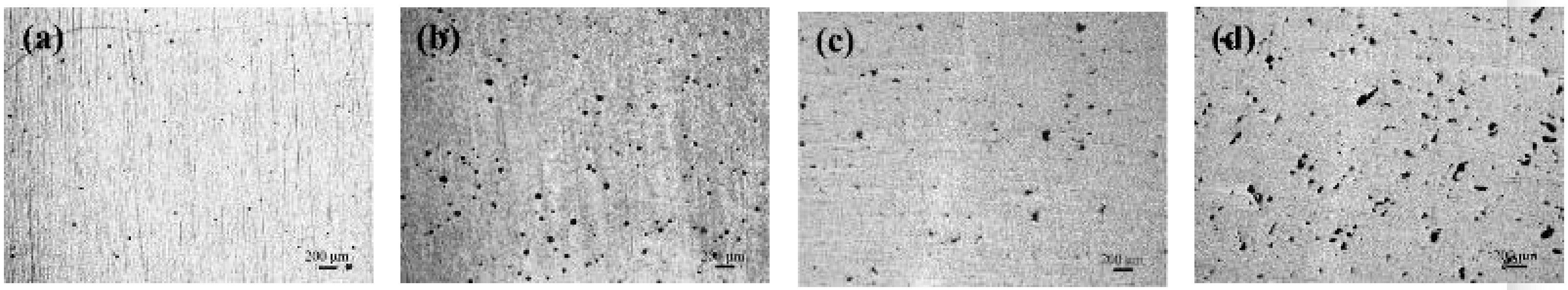
Powder bed AM process, schematic [Industrial lasers]



Typical powder bed AM products [Farinia]

Metal AM – porosity on laser powder bed material

- Laser powder-bed layered material contain some porosity.
- Porosity has small effect on (static) mechanical properties, but the effect on fatigue properties can be large.

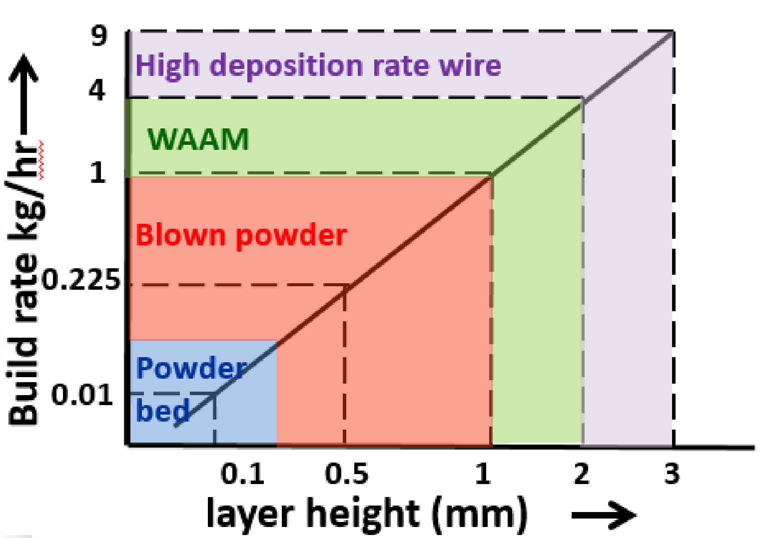


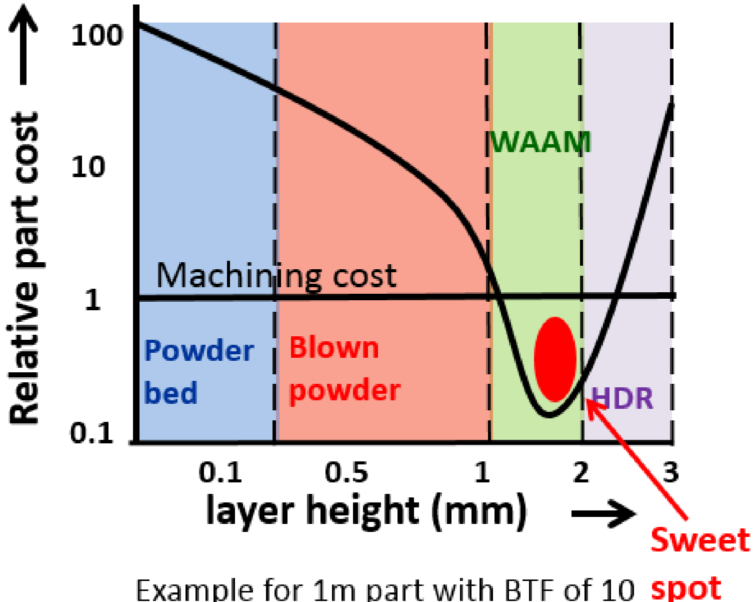
Varying porosity rate on SLM (Selective Laser Melted) Ti-Al6-4V materiali

	Rockwell Hardness Rc	Tensile Strength (MPa)	Yiled Strength (MPa)	Elongation %
Density 1	36 ± 2.5	1257 ± 74	1150 ± 91	8 ± 2
Density 2	34 ± 4	1148 ± 80	1066 ± 91	5.4 ± 3.8
Density 3	33 ± 2.5	1112 ± 13	932 ± 16	6.6 ± 1.4
Density 4	27 ± 2.5	978 ± 78	813 ± 23	3.7 ± 0.6

WAAM vs other AM methods

Wire and Arc AM methods are competitive over laser powder-bed methods on a certain area.

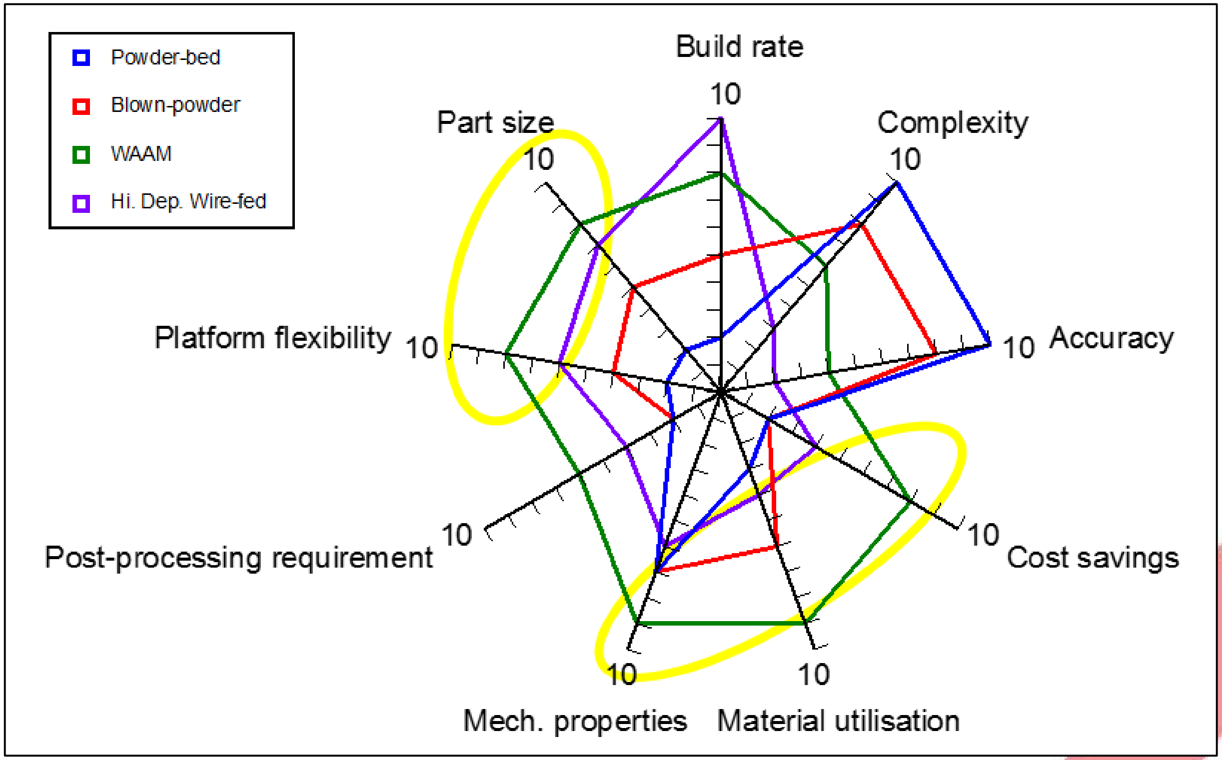




Example for 1m part with BTF of 10

Basics of metal AM systems – What process or hardware should you use [Williams]

WAAM vs other AM methods



Assessment of metal AM methods by Cranfield university [Williams]

WAAM vs laser powder-bed

Laser or arc? [Williams]

		Laser	Arc
Cost	Capital	Very High (£200k - 4 kW)	Low (£25k – 4 kW plasma or CMT)
	Running	Medium	Low
Efficiency	Power source	25%	90%
	Coupling	40%	85%
	Total	10%	80%
Safety issues		Very high	medium
Build rate		Medium -high	High – very high
Feature size		0.2 mm upwards	1 mm upwards

Metal Additive Manufacturing methods

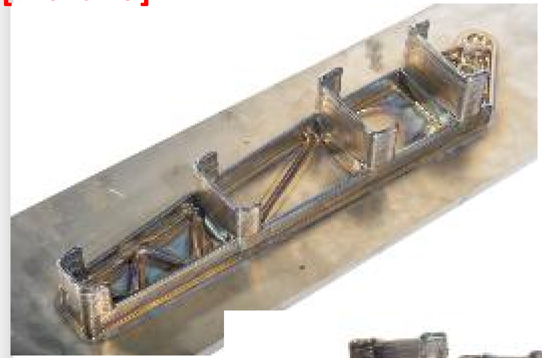
Laser powder-bed vs CMT

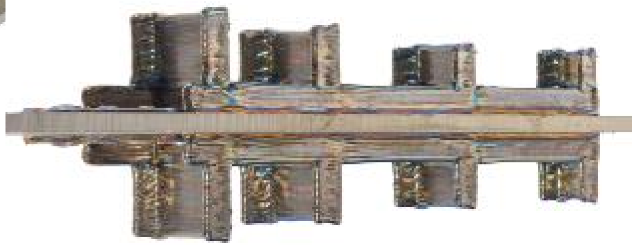
Laser – powder-bed:
EOSINT M270:
~400 000 €

Robot:	*20 000 - 50 000 €*
CMT (1 pcs):	*20 000 - 30 000 €*
Total:	*40 000 – 80 000 €*

WAAM Case studies

Fokker titanium wing frame (0.5 m) [Martina]





Design option	BTF	Cost (£k)	Cost red.
Machined from solid	69	4.9	-
WAAM option 1 (thin substrate)	4	2.6	67%
WAAM option 2 (thick substrate)	4	2.4	69%

Bombardier rib [Williams]

BTF = **B**uy **T**o **F**ly ratio

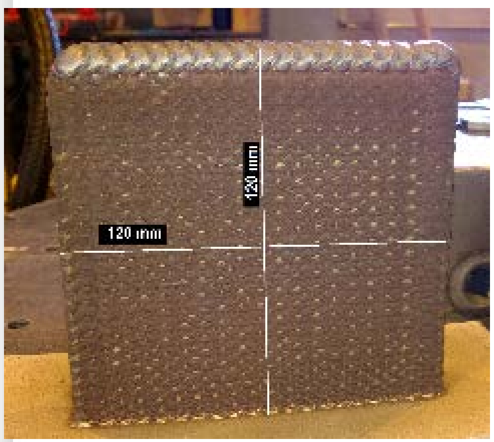
Design option	Mass (kg)	BTF	Cost (k£)	Cost red.
Original, machined	36	12	1,6	-
WAAM + machining	36	2,3	0,7	55%

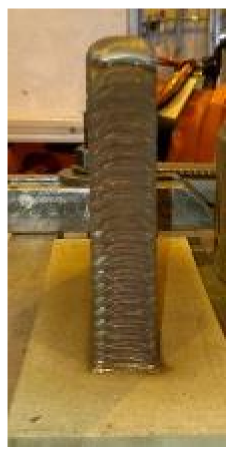
AM with CMT and duplex Stainless Steel

- Avesta 2205 wire, Ø1,2 mm
- Large AM with ZigZag movement
  - Length: 120 mm
  - Width: 20 mm
  - Height: 120 mm
- Arc-on time: ~1 h
- Total time: ~2 h
- Productivity: **1,3 kg/h** (cooling time included)
- **Good mechanical properties**

Duplex wire composition

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	N
0,01	0,5	1,5	0,015	0,001	22,9	3,1	8,6	<0,1	0,16





Layered sample

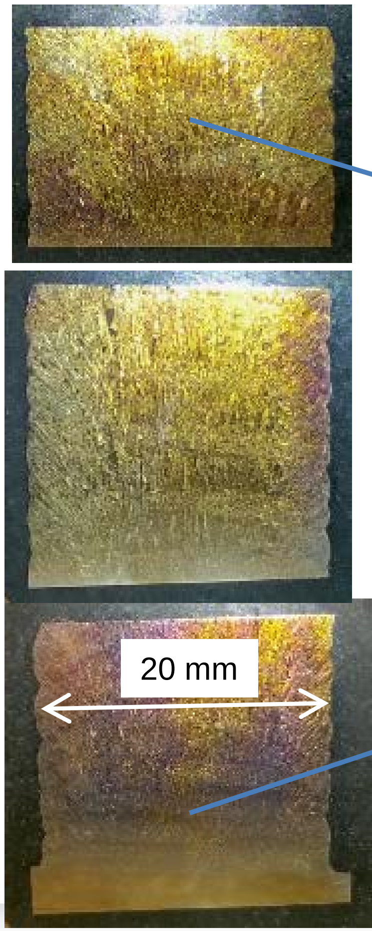
Tensile test samples

Tensile test results

	Tensile strength MPA	Elongation
AM sample results	756	**39%**
All weld metal	≥ 700	> 25%
Typical for all weld metal	830	28%
Wrought material	640 - 840	>25%

AM with CMT and duplex SS - Microstucture

- Defect-free structure
- Slightly higher austenite content compared to cast material.
- Hardness on the same level as on wrought material

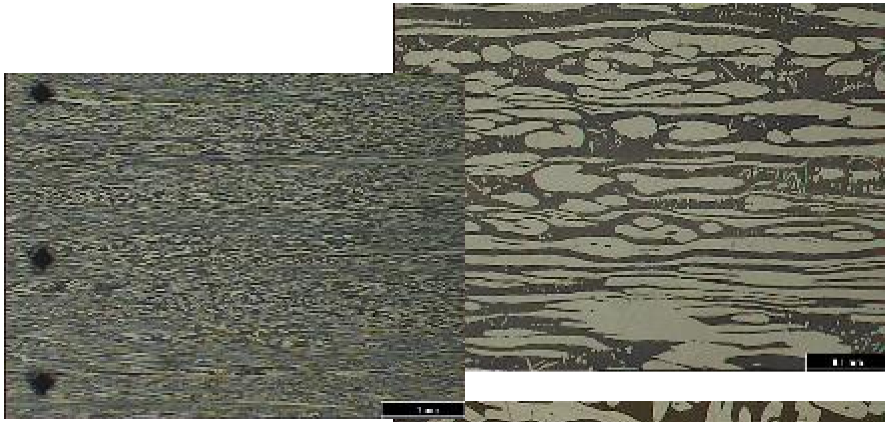


Upper part. Hardness: 240 HV_{10}, austenite content: 58%

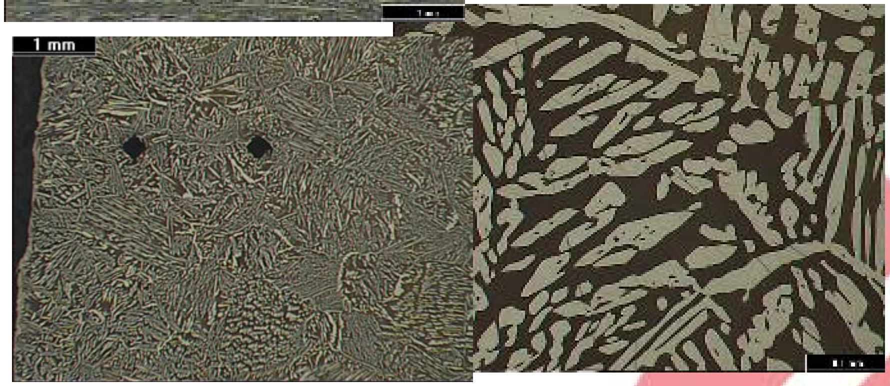
Lower part. Hardness: 248 HV_{10}, austenite content: 55%

Duplex SS – Microstructure of cast and wrought material

- Tensile tests are about to be made.



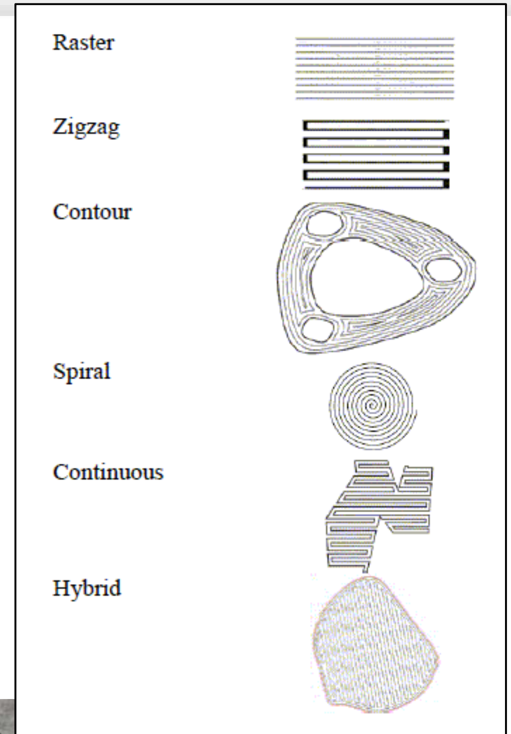
Wrought material.
Hardness: 246 HV_{10}
Austenite content: 54% (±3%)



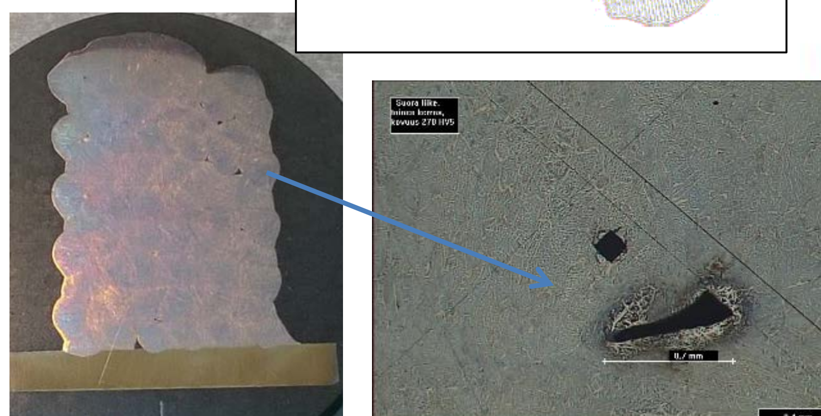
Cast material.
Hardness: 221 HV_{10}
Austenite content: 46% (±2%)

Challenges on metal AM with wire

- Avoiding defects, especially lack of fusion defects
- Achieving and maintaining the specified layer height
- Residual stresses
- From CAD model to component: build path strategy



Distortion due to residual stresses



Lack of fusion defects

Wire and Arc AM methods are coming strongly

Norsk to open 70,000 sq. ft. titanium additive manufacturing facility in New York

September 27, 2016

Source: ASM International

Norsk Titanium U.S. Inc., Plattsburgh, N.Y., a subsidiary of Norsk Titanium AS, Norway, announces that in Q4 2016 it will open a nearly 70,000-sq.-ft. additive manufacturing production and training facility that will complement its new headquarters and manufacturing plant, which is currently in the design and planning phase with a targeted completion date in 2017.

The new plant features Norsk Titanium's 'ultra lean cell' (ULC), which demonstrates a production line that turns CAD files into finished aerospace parts in a space of approximately 120 feet. The ULC showcases the 3D printing, heat treatment, nondestructive testing, and final machining of aerospace-grade titanium parts in a process time of less than 40 hours.

The facility has space for up to ten Merke IV rapid plasma deposition machines, the first of which has arrived from Norway and is in the process of being installed. Each Merke IV production machine weighs 11 metric tons, and requires several weeks to assemble. Each machine can produce approximately 20 metric tons of aerospace-grade structural titanium components per year by the rapid plasma deposition of titanium wire. The first titanium aerospace components to be produced by Norsk in Plattsburgh are planned for November 2016.

According to Norsk Titanium President & Chief Executive Officer Warren M. Boley Jr., "As the industrial scale RPD factory next door comes online during the next year or so, we will move the bulk of production there, while retaining this PDQC building as a qualification and training center as well as a showcase for our latest innovations and technology."

www.norsktitanium.com

http://www.asminternational.org/web/tss/news/-/journal_content/56/10180/26840363/NEWS

Additive manufacturing with CMT - Summary

- Wire and arc AM methods will enter the market.
- Wire and arc AM methods are competitive on large components with less need on accuracy, but with a need of large deposition rate.
- CMT will be one Wire and Arc AM method

Commercial WAAM machine:
Muhan Value Arc MA5000-S1

Bowl, deposition rate: 0,4 kg/h

References

- A. Parab. Introduction to welding processes http://www.slideshare.net/parab-ajinkya0070?utm_campaign=profiletracking&utm_medium=sssite&utm_source=ssslideview
- D. Johns. Laser Beam Machining. http://slideplayer.com/slide/4158476/
- J. Paul. Casting, Forming & Welding ME31007. http://www.slideshare.net/surajaggarwal094/welding-lectures-4-6
- D. Ding, Z. Pan, D. Cuiuri and H. Li. Wire-feed additive manufacturing of metal components: technologies, developments and future interests. International Journal of Advanced Manufacturing Technologies. October 2015.
- C. Leyens, F. Brückner, S. Nowotny. Latest Development Work on Induction Assisted Laser Cladding Processes. LAM - Laser Additive Manufacturing Conference Houston 2012.
- S. Williams + WAAMMat team. Wire + Arc Additive Manufacture – Current and Future Developments. 2016. http://waammat.com/documents
- S. Williams + WAAMMat team. Large Scale Metal Wire + Arc Additive Manufacturing of Structural Engineering Parts. 2016. http://waammat.com/documents
- F. Martina. Recent developments in large-scale Wire+Arc Additive Manufacturing. 2016. http://waammat.com/documents
- WAAM Technology October 2015
- S. Egerland and P. Colegrove. Using Solid State Calorimetry for Measuring Gas Metal Arc Welding Efficiency.
- GSI SLV, International Welding Engineer, course material HG2 and HG3.
- http://www.farinia.com/additive-manufacturing/3d-technique/metal-additive-manufacturing-production-systems
- http://www.industrial-lasers.com/articles/print/volume-29/issue-5/features/process-monitoring-in-laser-additive-manufacturing.html
- http://www.insidemetaladditivemanufacturing.com/blog/how-do-slm-process-defects-impact-ti64-mechanical-properties
- Ribeiro, F., Norrish, J., McMaster, R.S. Practical case of rapid prototyping using metal arc welding
- Ch. Louppe. The art of Weld Overlay