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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

CU 01: DED-ARC

Session 3.1 & 3.2 – MIG/MAG DED

Prepared by: Vazquez

FOR SAM PILOT ATTENDEES AND TRAINERS ONLY

MM17,21

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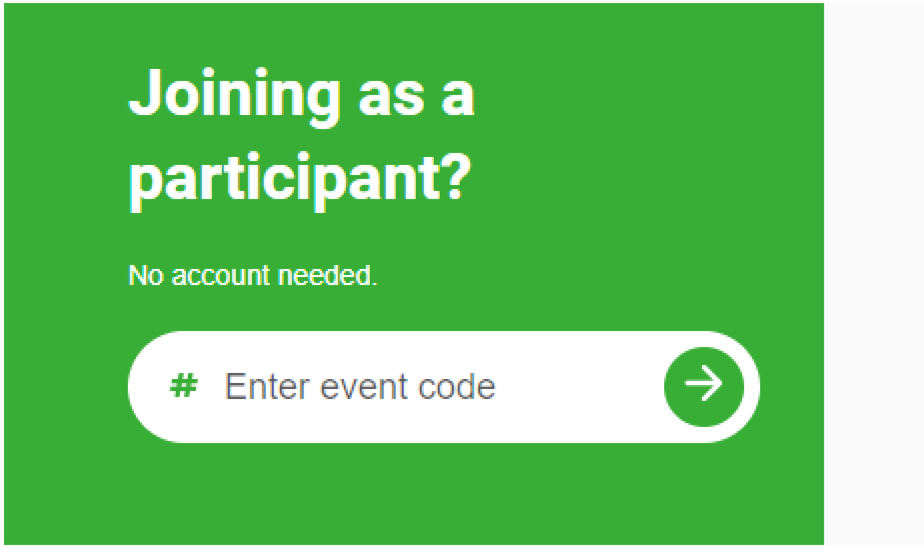

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Question. Word cloud pool

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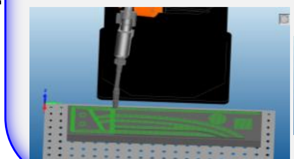
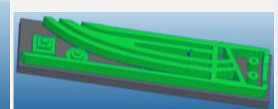
Outline

- Technologies
- Process parameters
- Alloys
- Influence of variables in the process and parts MIG/MAG
- Defects, inspection techniques and monitoring

Raw material
Wire

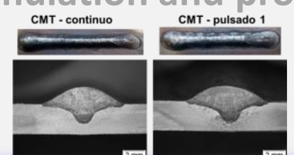
Design
CAD/CAM for AM
Adaptation design/path definiton



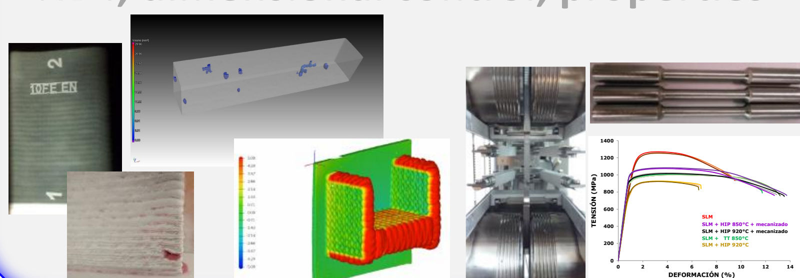


Aditive manufacturing WAAM

Process control
Selection of parameters, sensoring, simulation and processes of optimisation

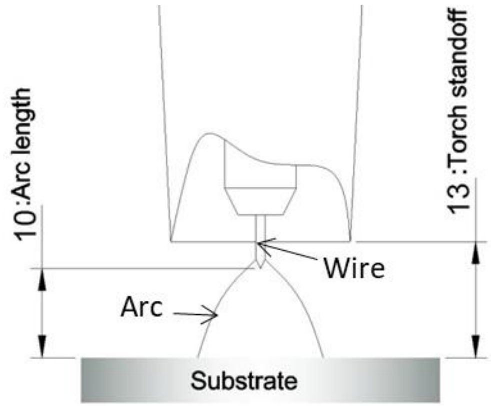


Inspection
NDT, dimensional control, properties



Post Fabrication
Thermal treatment
Machining

Technologies



Coventional processes	Characteristics	Main Limitation
GMAW **Gas Metal Arc Welding**	• Consumable wire electrode • Typical deposition rate 3-4 kg/h	• Poor arc stability, spatter
GTAW **Gas Tungsten Arc Welding**	• Non consumable electrode • Separate wire feed process • Typical deposition rate 1-2 kg/h	• Low deposition rate • Wire and torch rotation needed (non-coaxial process)
PAW **Plasma Arc Welding**	• Non consumable electrode • Separate wire feed process • Typical deposition rate 2-4 kg/h	• Wire and torch rotation needed (non-coaxial process)

Technologies

Innovative Processes	Characteristics	Advantages Compared to standard processes
CMT **Cold Metal Transfer (Fronius)**	• Improvement of standard GMAW process • Controlled short circuiting transference supported by an alternating wire movement at high frequency • Deposition rate: 2-3 kg/h	• Lower Heat Input, lower distortion • Lower spatter • Higher stability of electric arc • Improved weld quality
CMT Twin **Cold Metal Transfer (Fronius)**	• Two power sources, one welding torch, two isolated contact tips (electrodes) • Various process combinations • High deposition rate 6-8 kg/h	• Higher deposition rate • Higher welding speed • High stability of electric arc
TIG Speed **EWM**	• Improvement of standard GTAW process • Dynamic wire feed system: the continuous wire feeding is superimposed by backwards/forwards motion of the wire	• Higher stability of the process • Higher deposition rate
Top TIG **Lincoln Electric**	• New design for wire feeding incorporated in the welding torch with a specific angle	• Close to coaxiality

Technologies

In general for WAAM:

- CMT (MIG-MAG) appropriate for steels due to its high deposition rate.
- CMT PADV (MIG-MAG) appropriate for aluminium alloys due to their inclination to porosity.
- PAW and TIG appropriate for Ti-6Al-4V due to its reactivity at high temperatures with oxygen and low stability. CMT also demonstrated its viability of this alloy.

Technologies. MIG-MAG

Welding process with shield gas and consumable electrode.

- The electric arc is formed between electrode tip and manufactured part.
- Automated and continuous feed of the consumable electrode.
- Application of shield gas through a nozzle: protection against oxidation
- **Most used industrial welding process (>50%).**
- **Main advantages: Flexibility, speed (high deposition rate) and automatisation level.**

Technologies. MIG-MAG

Advantages:

- ✓ A broad number of commercial alloys can be processed
- ✓ Welding in possible in multiple positions
- ✓ No need of replacing electrode
- ✓ Highest deposition rate
- ✓ High efficiency of the electrode, up to 93-97%
- ✓ Minimum slag is created
- ✓ Easiness to adapt to robotised or automated processes

Disadvantages:

- ○ Need of protection against air currents
- ○ High level of radiation and intensity
- ○ Sensible to surface contamination that can create porosity, lack of fusion and cracks.
- ○ The equipment is more complex than TIG

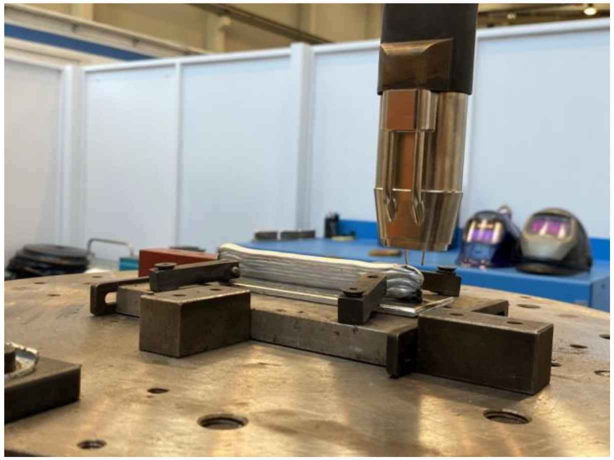
Technologies. Innovative MIG/MAG process:

- **CMT® (Cold Metal Transfer)**

- Improvement of short circuit GMAW process based on controlled dip transference.
- Characterised by alternating wire forward and retraction movement at high frequency: 70 Hz.
- Arc length is adjusted mechanically on its own.
- Advantages compared to standard processes:
  - Lower heat input, lower distortions
  - Lower spatter
  - Higher stability of electric arc
  - Improved weld quality
  - Coaxial

Technologies. Innovative MIG/MAG process:

- **Double wire and TANDEM torches:**
  - It allows the creation of in situ new chemical compositions using two wires of different chemical composition.
  - It allows the obtention of gradual composition changing the parameters during growing.
  - It allows to increase the deposition rate. WARNING: Heat accumulation need to be controlled.



- Commercial brands: CMT TWIN of Fronius, DUAL Wire 2.0 SKS welding systems, CLOOS Tandem Weld, etc.

Process parameters

- Electric parameters (welding technology)
  - Current, voltage, welding speed, wire feed speed, etc.
  - They affect to the weld bead geometry, heat input, deposition rate, etc.
- Deposition parameters (CAD-CAM)
  - Weld bead geometry
  - Overlap
  - Robot path definition, sequence of deposition
  - Interlayer dwell time
  - Wire orientation when it is not coaxial
  - Torch angle

An incorrect selection of parameters creates defects such as: pores, lack of fusion, roughness, collapse, etc.

Process parameters

Electric parameters

- Current
  - The current that flows from the electrode to the work part. It determines the heat input. Generally an increase of the current entails an increase of deposition rates, penetration and dilution.
  - **An insufficient current** difficult the arc maintenance, it produces material prominence and reduced penetration.
  - **An excessive current** provides a flat weld bead with porosity, it heats the electrode and produces sputters.

- Voltage
  - It increases with the arc length. It controls the width of the weld bead. It is directly related with he heat input.

Process parameters

Electric parameters

- Welding speed
  - The speed of the displacement of the electrode. When this speed increases, the thickness of the weld bead decreases. It affects to the heat input. When welding speed is reduced the heat input increases.
  - A very low welding speed produces overlap and can cause slag inclusions.
  - An excessive welding speed produces a thin weld bead, with fibrous aspect, low penetration, lack of fusion and high porosity.

- Wire feed speed
  - Wire speed at which it feeds the arc. It is related with the current.
  - If the wire feeds too fast, then it isn't heated enough and doesn't melt, either passing through the melt pool or "stubbing" against the substrate
  - If the wire feeds too slowly, it melts before reaching the melt pool and droplet formation occurs, forming individual drops, but no continuous track

Process parameters

Electric parameters

- Electrode diameter
  - For a bigger diameter, higher current.
- Arc length
  - Distance between the end of the electrode and the base metal.
  - A short arc length produces weld beads with sputters and inclusions, low penetration, thick and irregular. The arc is interrupted and the electrode shows high inclination to stick to the base metal.
  - A very long arc length increases the sputters, insufficient penetration and the weld beads presents excessive reinforcement and thickness. It normally has porosity.
- Contact tip welding distance
  - Distance between the contact tip and the end of the electrode.
- Polarity
  - Direction of current flux.

Process parameters

Electric parameters

- Heat input:
  - The energy supplied to the base material during welding.
  - It is very important for the impact properties due to the grain growth. An excessive heat input obtains a low impact properties.

$$Q = \frac{I \times V}{W_s} \times 60 \ (\frac{J}{cm})$$

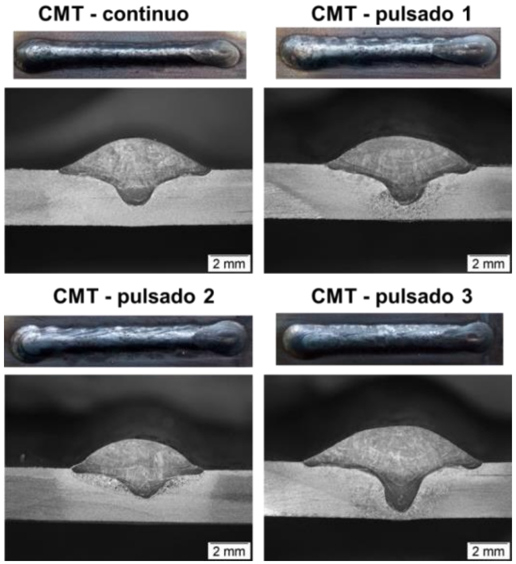
- Deposition rate:
  - Deposited material speed taking into account the wire feed speed.
  - WAAM is an AM technology characterised by a high deposition rate.

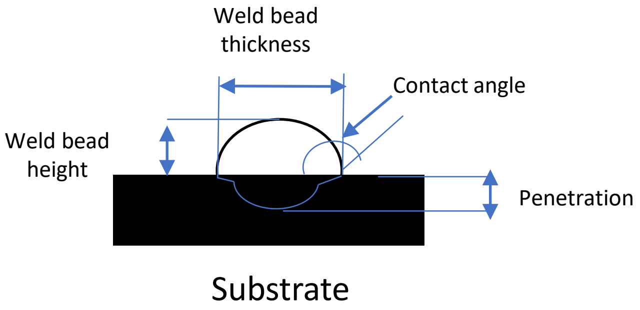
$$T = \frac{A \times WFS \times d}{1000} \ (\frac{kg}{h})$$

Process parameters

Deposition parameters

- Weld bead geometry
  - Height
  - Thickness
  - Contact angles
  - Shape
  - Penetration

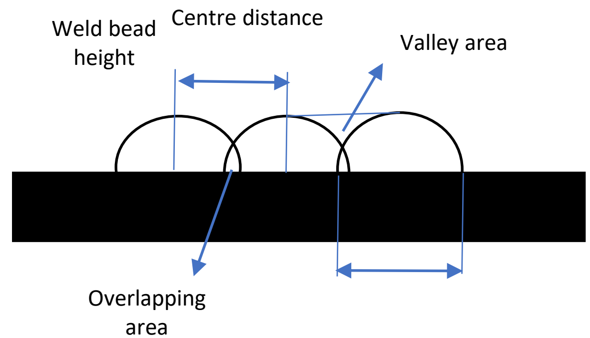


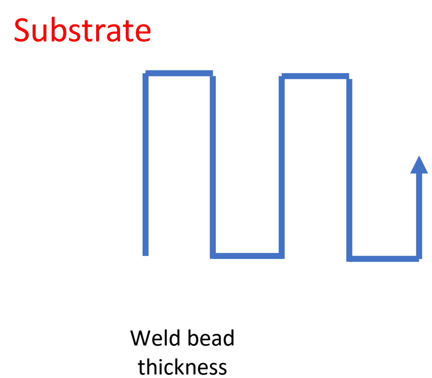


Process parameters

Deposition parameters

- Overlap of weld beads
  - Overlapping percentage between weld beads of a determined geometry obtaining a flat layer.
  - A small overlap can lead to lack of fusion.
  - An excessive overlap destabilises the homogenous growth which can entail a collapse.

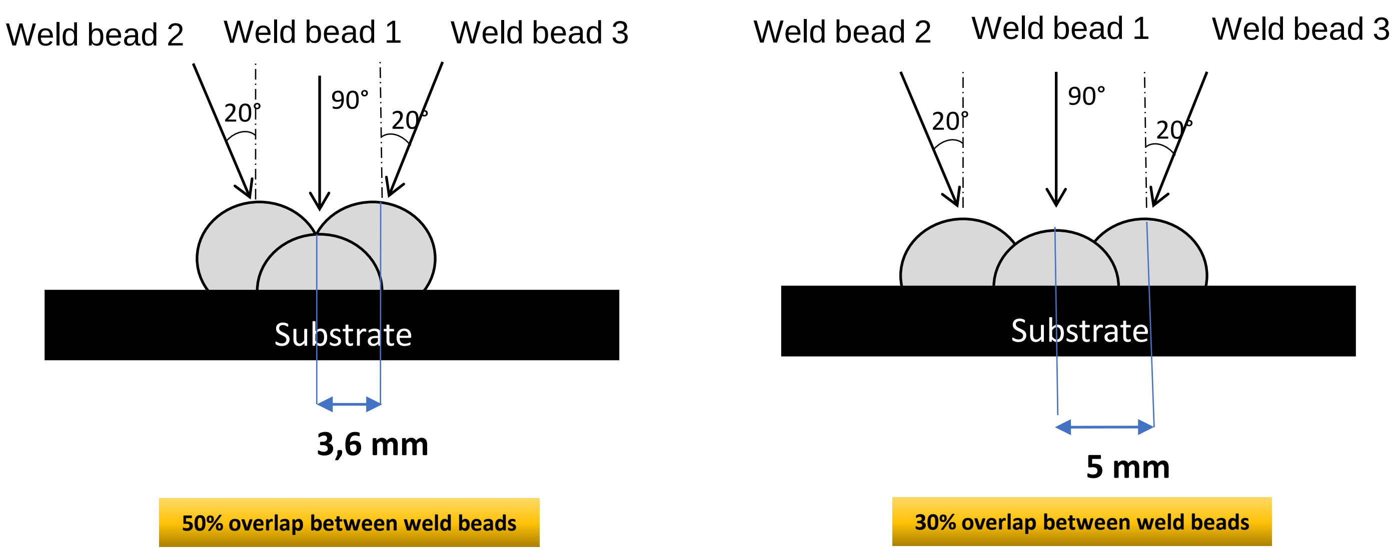




Process parameters

PULSED (PMC)	
THICKNESS (mm)	HEIGHT (mm)
7,2	2,2

Scheme of deposition strategy of triple weld bead



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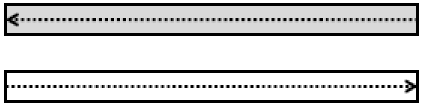
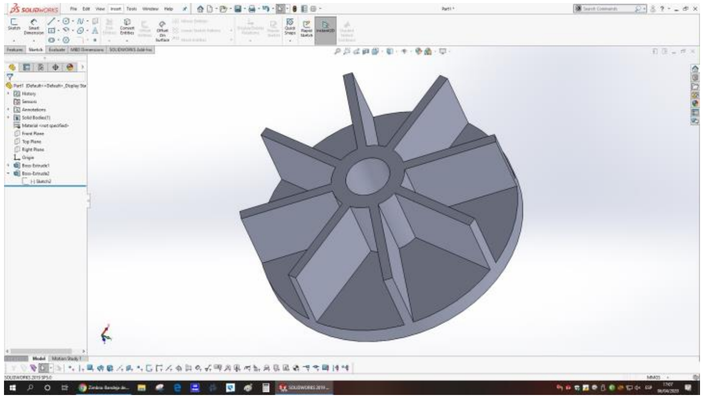
Process parameters

Deposition parameters

- Robot path definition
  - End and start zone alternation to avoid accumulation and lack of material.



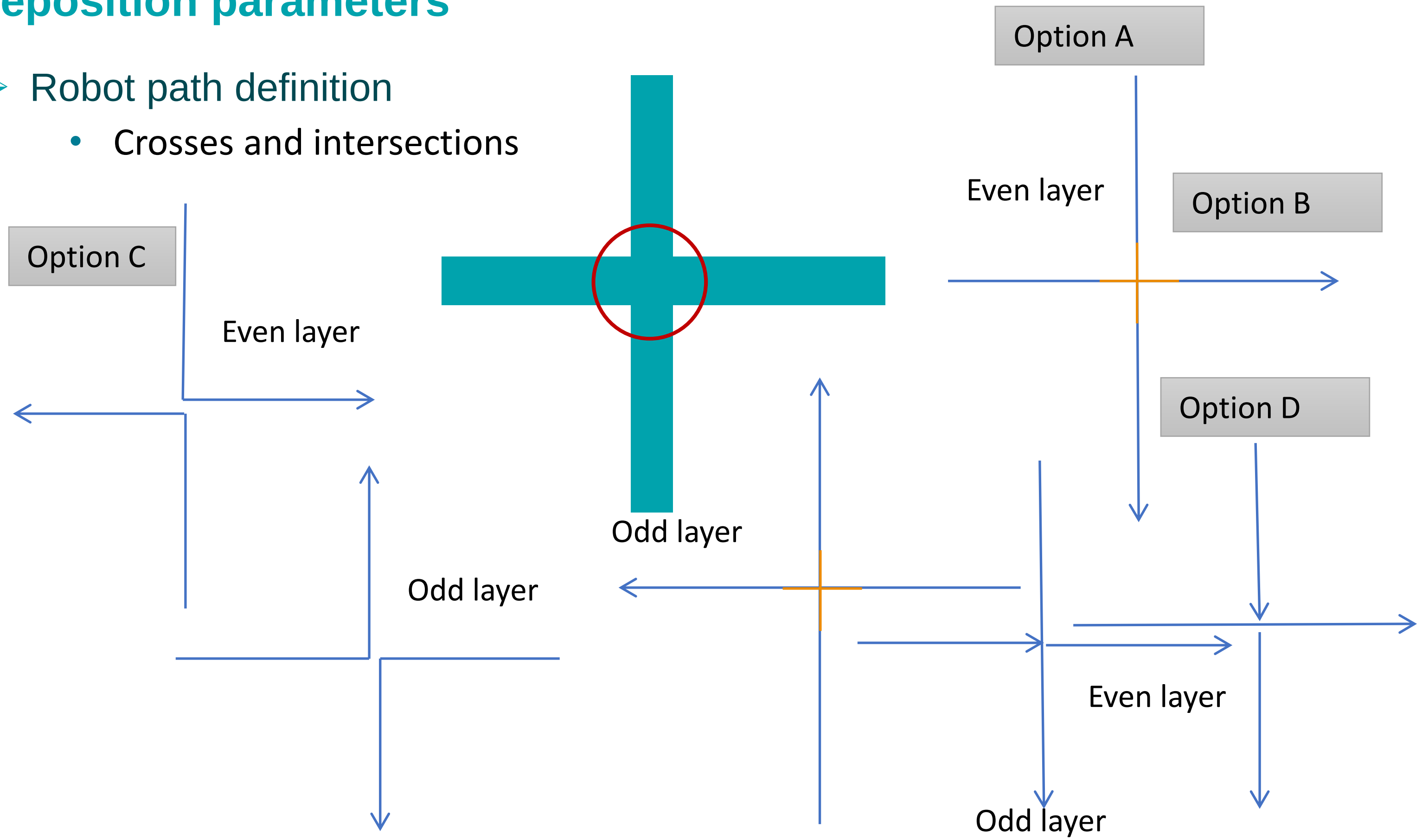
  - Crosses and intersections.



Process parameters

Deposition parameters

- Robot path definition
  - Crosses and intersections

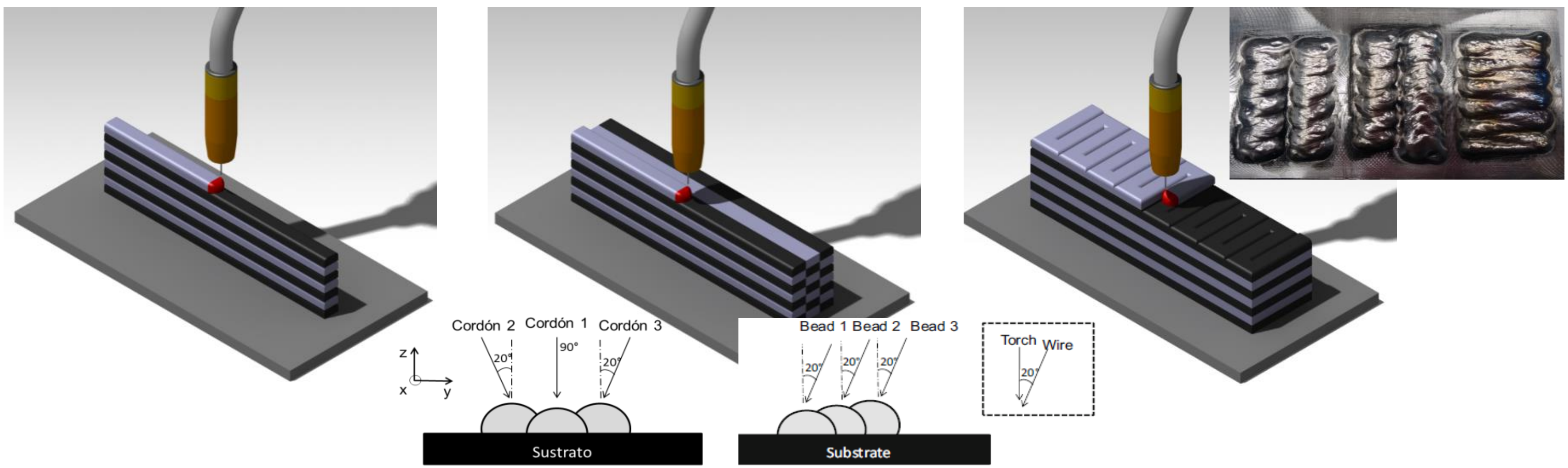


Process parameters

Deposition parameters

- Robot movement: straight, weaving, circling, etc. to obtain different thickness of parts.
- Z offset in order to grow in a controlled way.

Unitary weld bead | Triple weld bead | Weaving

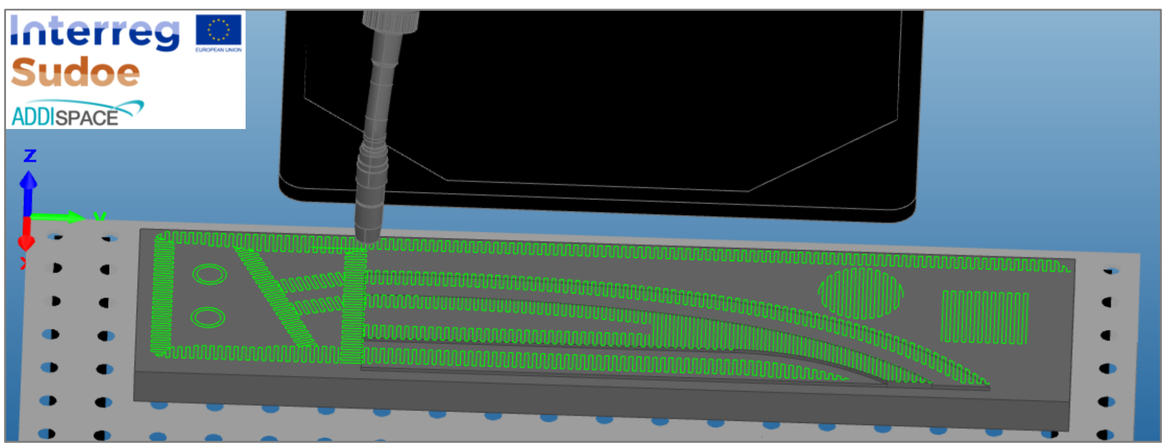


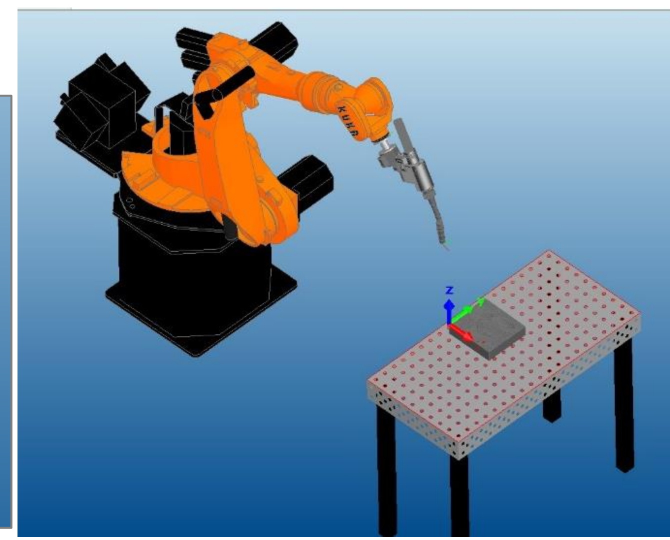
Process parameters

Deposition parameters. Robot path definition

For this, a precise knowledge of the geometry of the weld bead for each electrical parameters are needed.

In order to create the robot paths a **CAD/CAM software** is used, introducing all the mentioned parameters. This software has virtualised the robot, welding torch, table, substrate, among others, creating a virtual space which is an exact copy of the real space.

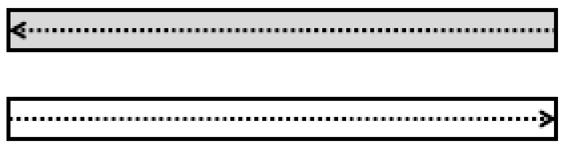




Process parameters

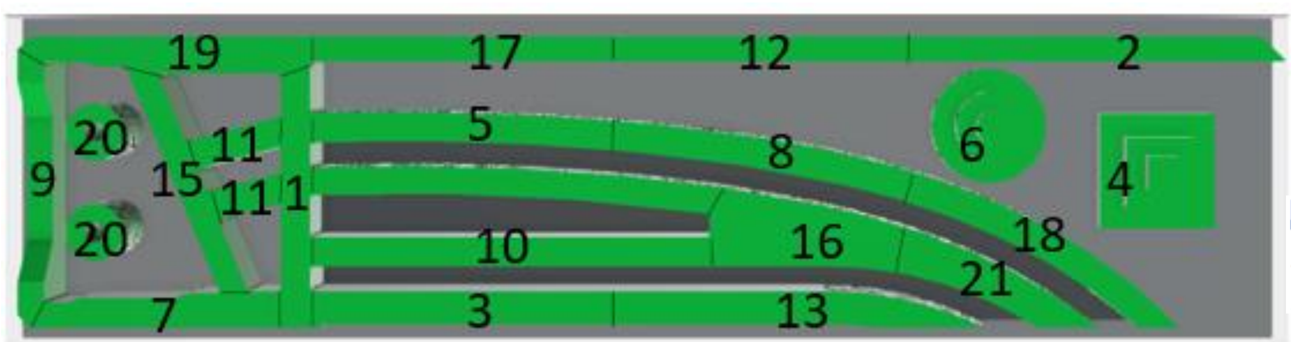
Deposition parameters. Sequence of deposition

Weld beads are alternated in order to avoid material accumulation or lack of fusion due to the arc ignition and extinction. Moreover, the order of manufacturing of the parts has to be established with the aim of avoiding high heat accumulation in the same zone of the part.



Odd layer

Even layer



Interreg Sudoe ADDISPACE

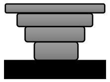
Process parameters

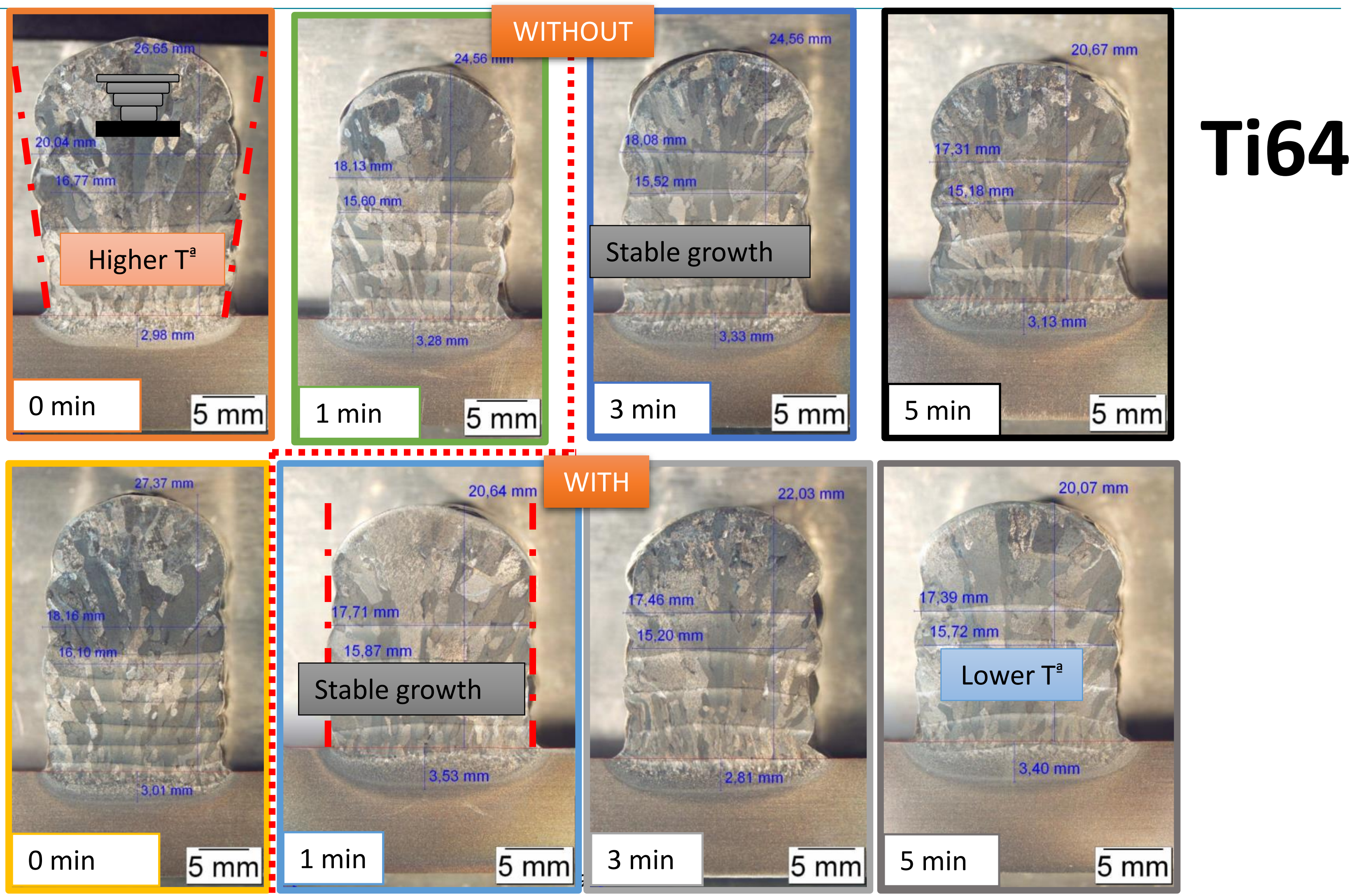
Deposition parameters

➢ Interlayer dwell time

- Time passed between successive layer deposition.
- As the part grows in height the temperature increases which affects the microstructure and finally to the mechanical properties.
- If the reached temperature is excessive → collapse.

Dwell time	
Low	**High**
Coarser α phase	
Large primary β grains	High amount of α'
Oxidation	High cooling rates
Collapse /variable wall thickness and height	Long building time (low arc ON ratio)

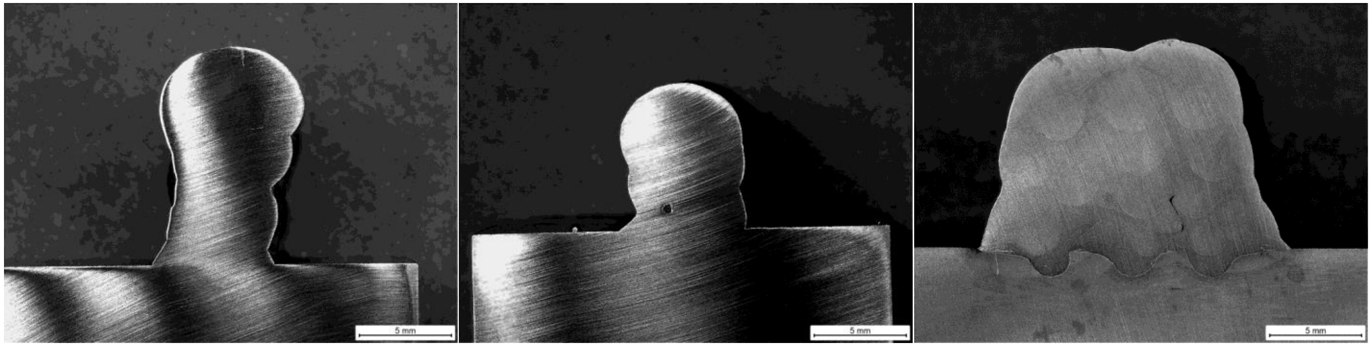



WITHOUT
WITH
Ti64
Higher Tª
Stable growth
Stable growth
Lower Tª
0 min
1 min
3 min
5 min
0 min
1 min
3 min
5 min
5 mm
26,65 mm
20,04 mm
16,77 mm
2,98 mm
24,56 mm
18,13 mm
15,60 mm
3,28 mm
24,56 mm
18,08 mm
15,52 mm
3,33 mm
20,67 mm
17,31 mm
15,18 mm
3,13 mm
27,37 mm
18,16 mm
16,10 mm
3,01 mm
20,64 mm
17,71 mm
15,87 mm
3,53 mm
22,03 mm
17,46 mm
15,20 mm
2,81 mm
20,07 mm
17,39 mm
15,72 mm
3,40 mm

Process parameters

- Defects
  - Lack of fusion
  - Pores
  - Excess of roughness
  - Shape loose (irregular, V shape, inverted V)
  - Collapse

- Parameters:
  - Dwell time (0, 90 s)
  - ΔZ (excess, exact, lack)
  - ΔX (30-50% overlap)



Process parameters

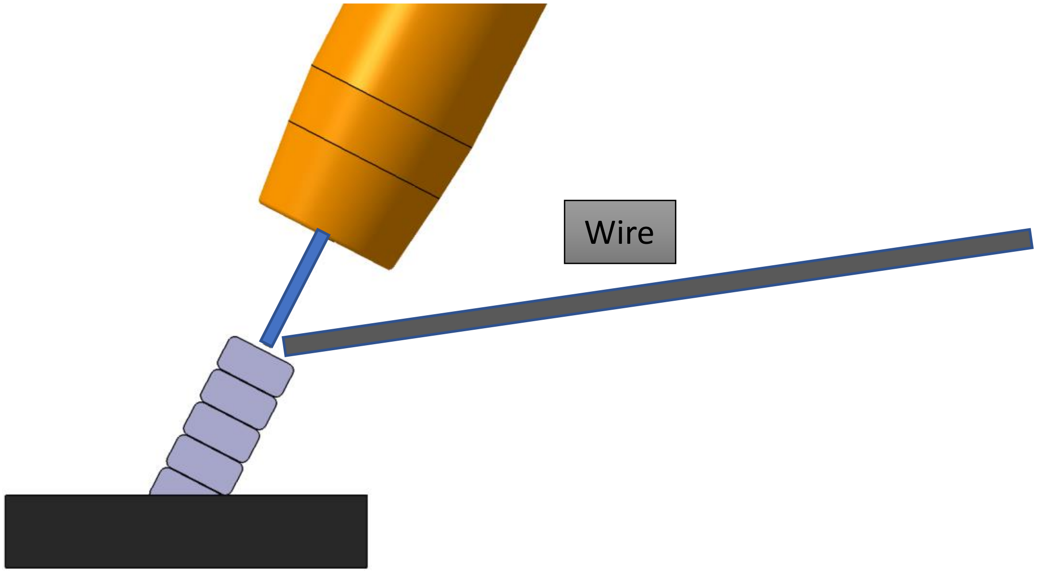
Cause	Effect
Short Z	V shape
Excess of Z	High height
	Inverted V shape
	Irregular shape
	Porosity
Excess of X (30 % overlap)	High thickness
	Porosity
	Lack of fusion
	Inverted V shape
Without dwell time	V shape

Process parameters

Deposition parameters

➢ Wire feed orientation when it is not coaxial

- TIG and PAW arc technologies need to orientate the wire feed.
- This adds bigger complexity to the programming.
- Wire feed angle



Process parameters

Deposition parameters

➢ Wire feed when it is not coaxial

- Wire can be fed into the melt pool in any direction relative to the direction of traverse of the melt pool over the substrate
- Alterations in wire fed direction have knock-on effects on clad track quality
- In rear feeding, there can be interference between the clad layer and the wire.
- Side feeding can result in melt pool asymmetry
- Front feeding is generally the most convenient one obtaining free of internal porosity and cracking parts.

Process parameters

Deposition parameters

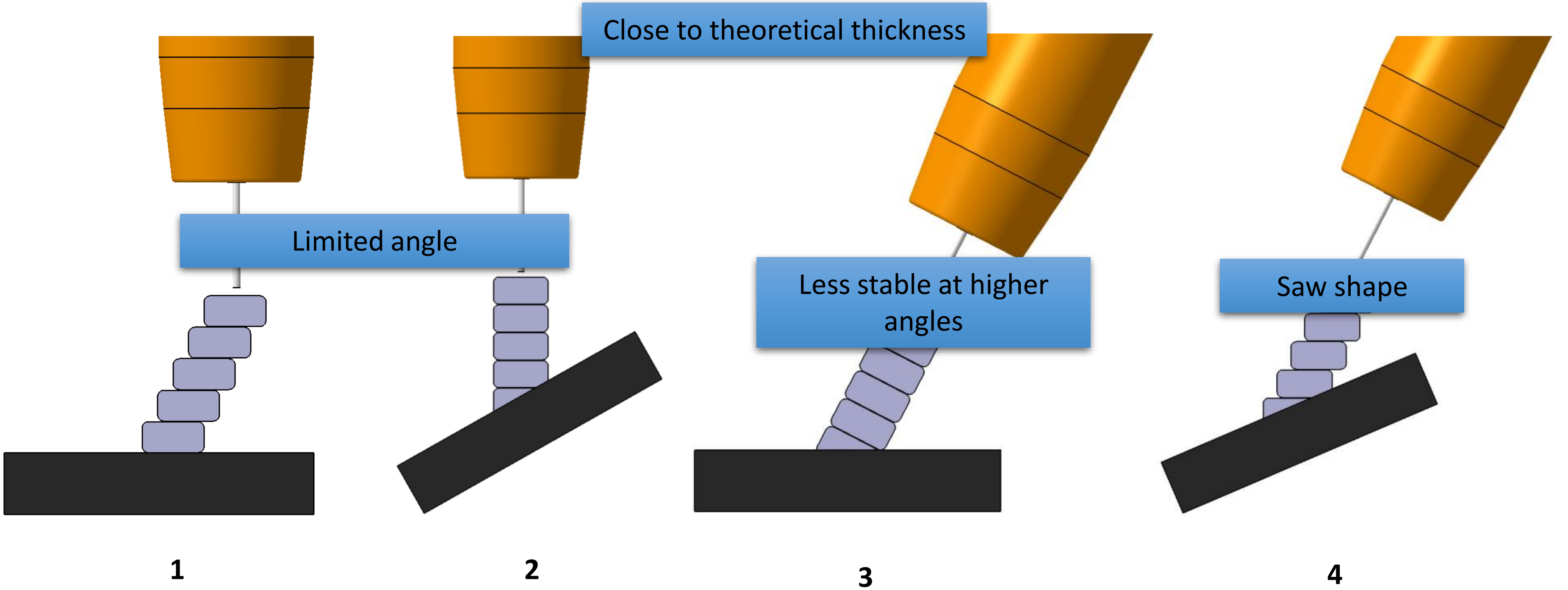
➢ Wire feed angle when it is not coaxial

- Feed angle is of critical importance in wire feeding
- Front feeding best results 20 - 60°
- Rear feeding steeper due to potential melt pool interference.
- If too shallow, insufficient melting
- If too steep, stubbing on substrate
- Has knock-on effects on wire feed rate

Process parameters

Deposition parameters

- Torch angle



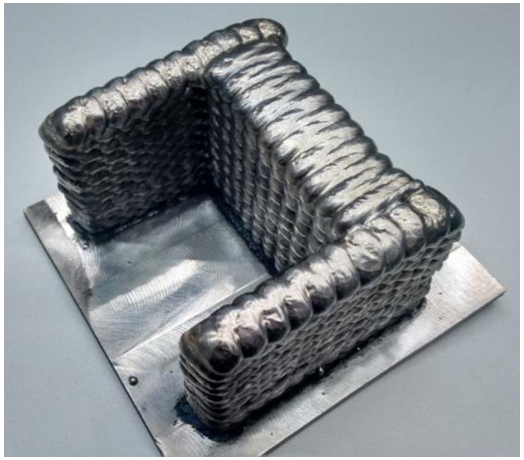
Process parameters

Deposition parameters

- Parameter adaptation to the part geometry

- Overlap: 4 mm
- Radius: 0
- Offset in Z: 4 mm
- Current: 140 A
- Wire speed: 8.5 m/min

- Thinner parts:
  - Welding speed: 70 cm/min
  - Dwell time: 3 min
  - Oscillation amplitude: 14 mm → 17 mm
- Thicker part:
  - Welding speed: 60 cm/min
  - Dwell time: 6 min
  - Oscillation amplitude: 29 mm → 33 mm

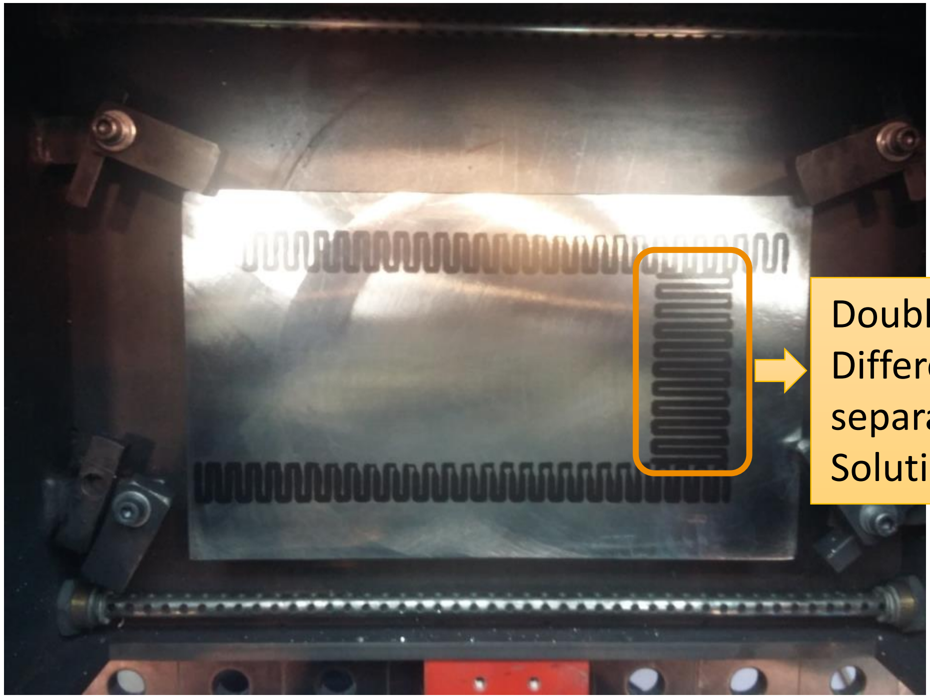


Height: 67 mm
Number of layers: 20

Process parameters

Deposition parameters

- Parameter adaptation to the part geometry



Double thickness:
Different parameters due to higher separation between intersections.
Solution: bigger overlapping.

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Question. Multiple choice

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Alloys

Materials

- Steels
  - 316L
  - 308L
  - ER60
  - ER70S-6
  - ER80S-Ni1
  - ER90-B3
  - ER120
  - Maraging 250 y 350 grades
  - …
- Aluminum alloys
  - 5356
  - 2319
  - 5183
  - 4043
  - 5087
  - …

  2024

- Others
  - Invar 36
  - IN718
  - IN625
  - Ti-6Al-4V
  - Tungsten
  - CuNi8Al6
  - Stellite 6
  - …

Alloys

- From the initial biggest interest in Ti-6Al-4V in the aeronautic sector, numerous alloys have been studied for WAAM for different applications and sectors.
- Some aluminium alloys have tendency to porosity. Al-Cu (2xxx), Al-Si (4xxx) and Al-Mg (5xxx) series can obtain good properties by WAAM, while 7xxx and 6xxx series are the most problematic ones.
- The use of WAAM for steels seeks decrease manufacturing time, weight and assembly parts.

Applications	**Typical alloy used for WAAM**				
	Steel-based	**Al-based**	**Ti-based**	**Ni-based**	**Bimetal (Fe/Al, Al/Ti)**
Aerospace		X	X	X	X
Automotive	X	X			X
Marine	X		X		
Tools and molds	X				
Corrosion resistance			X	X	X
Hight temperature			X	X	X

Influence of variables in the process and parts MIG/MAG

- The selection of parameters affects to the microstructure and mechanical properties.
- ER70S-6
- Dwell time between successive layer deposition is 60 s
- Objective: see the effect of changing **travel speed and HI**

10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Selection of optimal process parameters for wire arc additive manufacturing

Mariacira Liberini[a], Antonello Astarita[a,*], Gianni Campatelli[b], Antonio Scippa[b], Filippo Montevecchi[b], Giuseppe Venturini[b], Massimo Durante[a], Luca Boccarusso[a], Fabrizio Memola Capece Minutolo[a], A. Squillace[a]

Influence of variables in the process and parts MIG/MAG

- Parameter changes did not affect. Preeminence of the cooling curve
- Microstructural change: from pearlitic-ferritic grains until bainitic lamellae along the vertical direction
- Confirmed by microhardness along the height of the wall

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Selection of optimal process parameters for wire arc additive manufacturing

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Influence of variables in the process and parts MIG/MAG

Process Parameters	Results
Ratio between WFS/TS	•This ratio is important to control heat input
Heat input	• Increased heat input gives rise to coarse and elongated grains which result into anisotropic properties • Increased heat input will cause added material flow and collapse.
Deposition direction, nozzle tip distance, and gas pressure	• Pressure and current, nozzle tip distance has the most significant effect on tensile strength • Current has the most significant effect on hardness
Path planning trajectory	•WFS, welding current, cooling time, and interlay temperature affects dimensional accuracy and surface finish
Vibration / cold work	• Its use will decrease the average grain size as well as homogenize the grain distribution • It can reduce porosity and increase tensile strength • It can reduce or remove residual stresses and hence avoid distortion.
Forced cooling, dwell time	• They can reduce overall increase of temperature of the part • Forced cooling can help reducing the dwell time.

Influence of variables in the process and parts MIG/MAG

- Objective: study about WFS and travel speed influence
- ER70S-6
- WFS: 72, 80, 88, 120 mm/s
- TS: 2, 4, 5, 8, 10, 15 mm/s

- For a constant WFS (120 mm/s), width decreases with heat input
- For a constant TS (5 mm/s), height is higher for the highest WFS and lowest for the lowest WFS.

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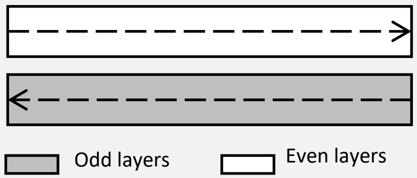
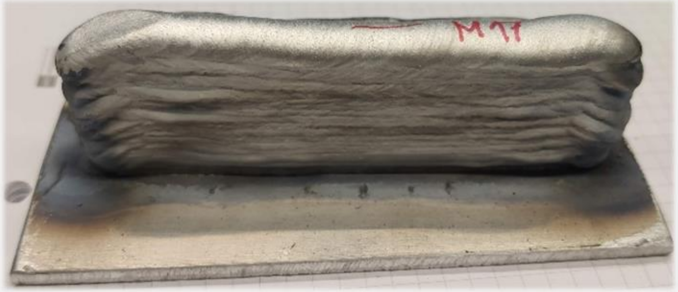
Influence of Process Parameters in Wire and Arc Additive Manufacturing (WAAM) Process

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. Different CMT modes.





Process parameters

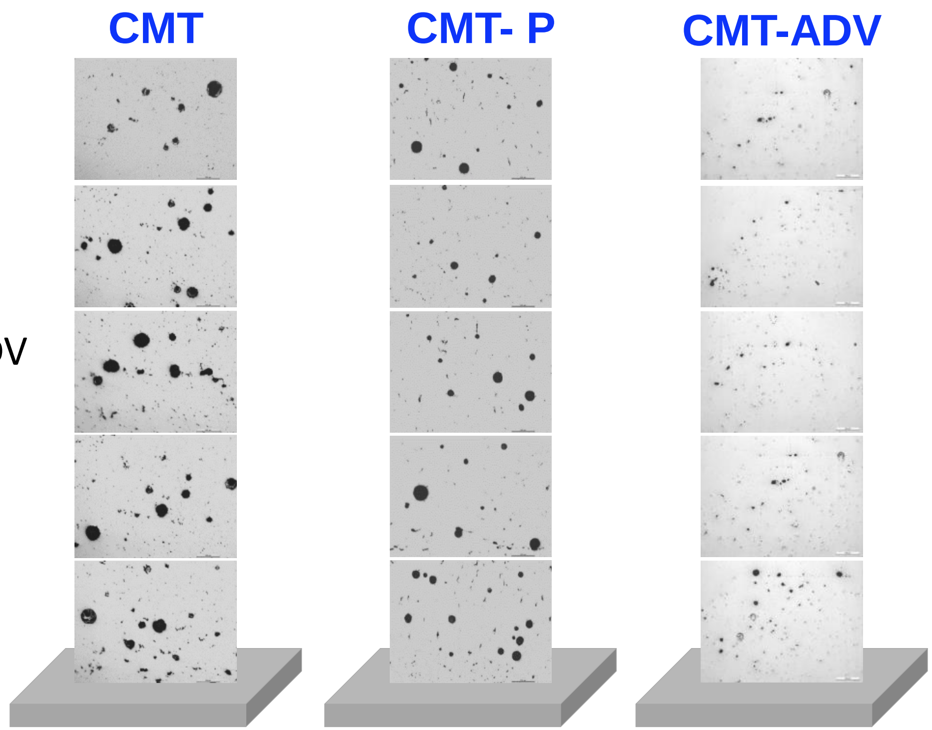
Process	I (A)	V (V)	WFS (m/min)	TS (m/min)
CMT	95	13,3	6,1	0,4
CMT-P	91	17,1	5,4	0,4
CMT-ADV	97	9,9	7,1	0,6

Ar shielding gas, 20 l/min. Z offset: 2,5 mm. Interpass time: 90 s.

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. Different CMT modes.

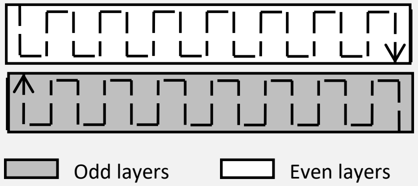
- Homogeneously distributed internal porosity
- Area fraction of porosity (%):
  CMT > CMT-P > CMT-ADV
- Significant reduction of porosity: CMT-ADV



Area fraction of porosity (%)	3 - 3,5%	2 - 2,6%	< 0,6 %

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. Different CMT modes.



Process parameters

Process	Current (A)	Voltage (V)	WFS (m/min)	TS (m/min)
CMT	81-90	12,6-13,3	5,3- 5,9	0,5-0,6
CMT-P	74-81	16,9	4,6-4,9	0,8
CMT-ADV	81-86	9,4-9,7	5,7-6,3	0,7

Ar shielding gas, 20 l/min. Z offset: 2,5 mm. Interpass time: 90 s.

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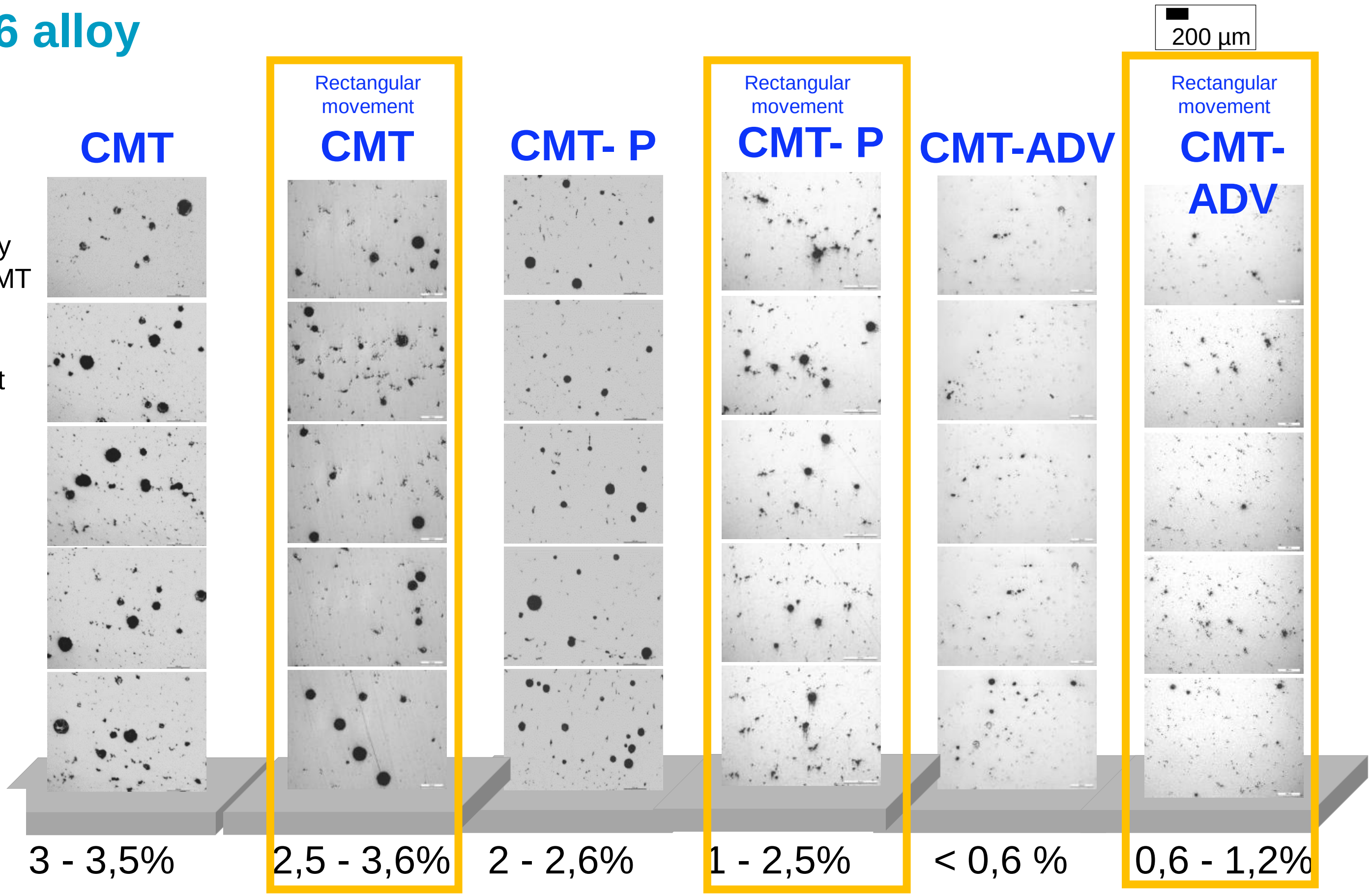
Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy

- Increased variability of the results for CMT and CMT-P
- Slight improvement



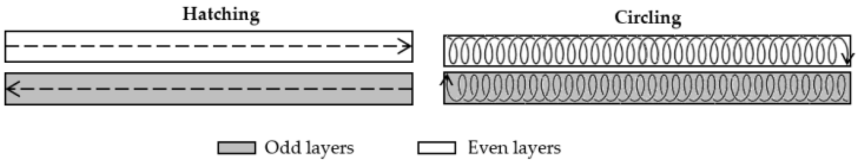
Area fraction of porosity (%)

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. CMT

Porosity reduction strategies trough:

- Adequate selection of gas protection
- Gas flux > 30 l/min
- Strategy (hatching or circling)



- The best combinations are:
  - Ar + circling
  - Stargold® + hatching
- Reduced porosity less than 0.035 %
- Reduced anisotropy

Table 3. Welding intensity for hatching and circling deposition strategies.

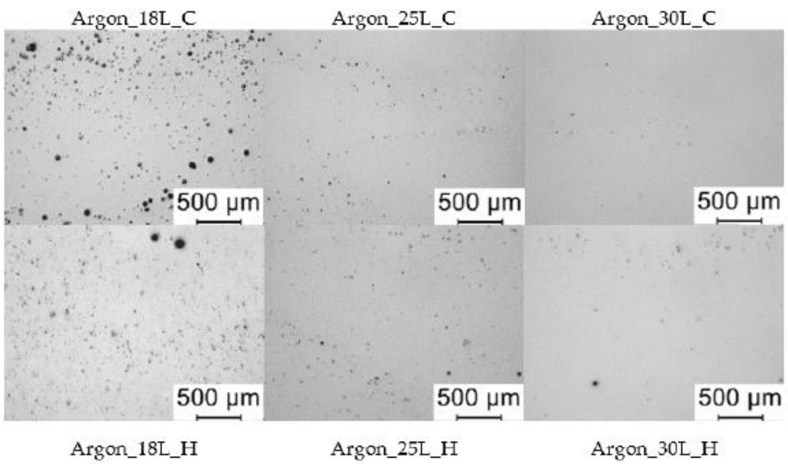
Layer	Hatching	Circling
1st layer	130 A	130 A
2nd layer	95 A	77 A
3rd layer	85 A	77 A
Rest of layers	77 A	77 A

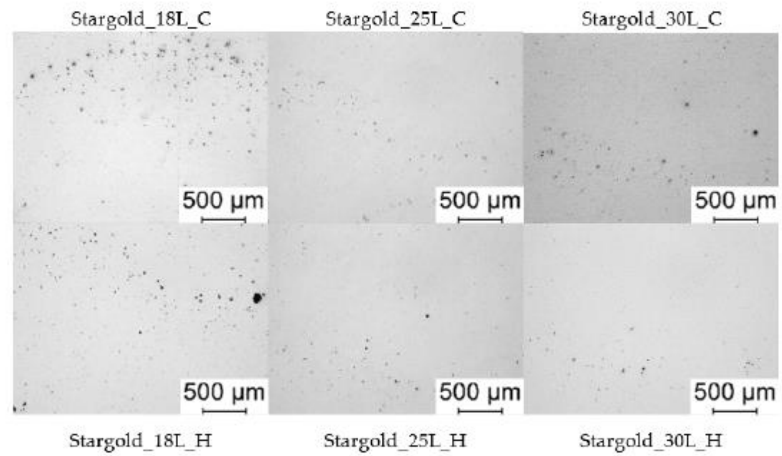
Strategies to Reduce Porosity in Al-Mg WAAM Parts and Their Impact on Mechanical Properties

by Maider Arana [1,2,*], Eneko Ukar [2], Iker Rodriguez [1], Amaia Iturrioz [1] and Pedro Alvarez [1]

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. CMT





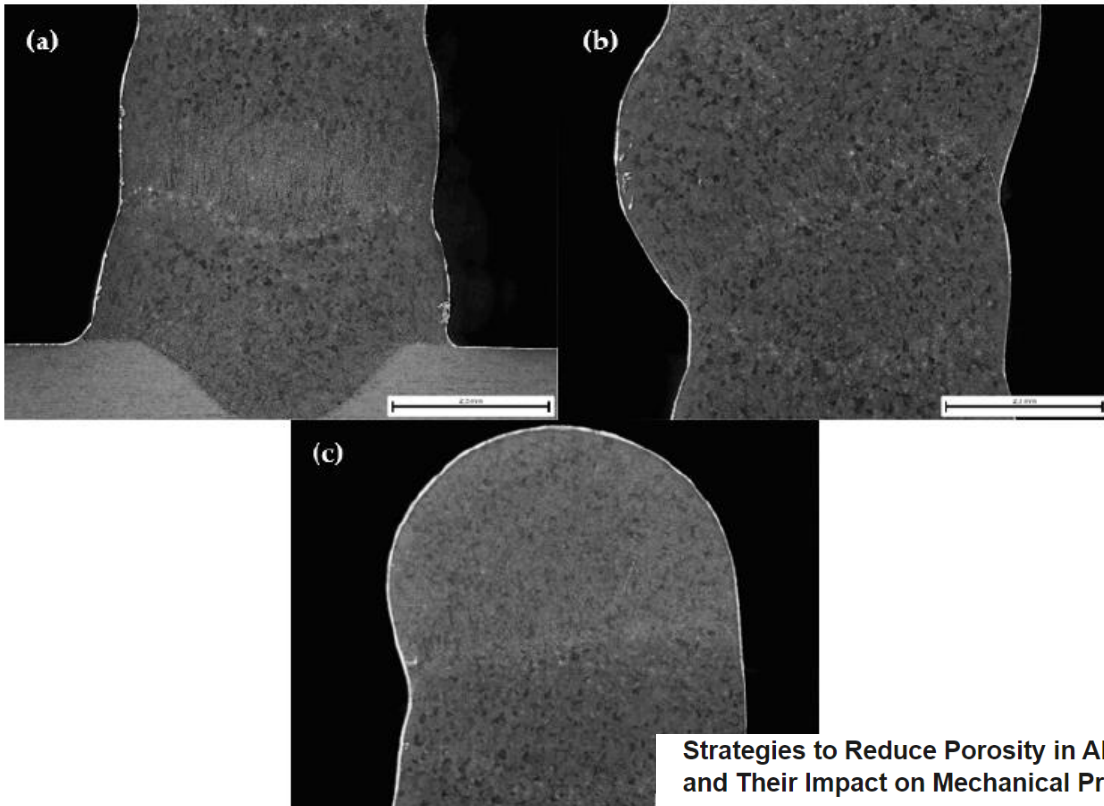
Shielding Gas	Deposition Strategy	Specimen Direction	Porosity (%)	Maximum Pore Diameter (µm)
Argon 18 L/min	Hatching	Horizontal	2.865	259
		Vertical	0.393	180
Argon 30 L/min	Hatching	Horizontal	0.480	253
		Vertical	0.241	184
	Circling	Horizontal	0.019	77
		Vertical	0.028	94
Stargold® 30 L/min	Hatching	Horizontal	0.031	90
		Vertical	0.034	165

Strategies to Reduce Porosity in Al-Mg WAAM Parts and Their Impact on Mechanical Properties

by Maider Arana [1,2,*], Eneko Ukar [2], Iker Rodriguez [1], Amaia Iturrioz [1] and Pedro Alvarez [1]

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. CMT



- Equiaxed grains in the initial layers (a)
- Dendritic structure in the last layer (c)
- In the interlayer zone uniform microstructure (b)
- The deposition of each layer remelts the previous one removing the dendritic structure

Strategies to Reduce Porosity in Al-Mg WAAM Parts and Their Impact on Mechanical Properties

by Maider Arana [1,2,*], Eneko Ukar [2], Iker Rodriguez [1], Amaia Iturrioz [1] and Pedro Alvarez [1]

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy. CMT

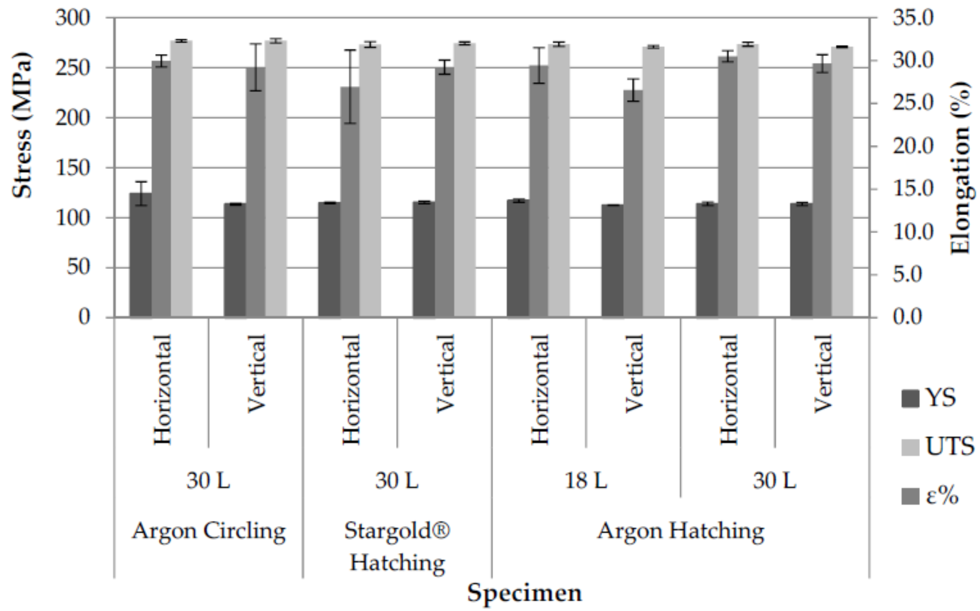


Figure 18. Mechanical properties of AA5356 with CMT.

Table 6. Anisotropy percentage (%) values from the mechanical properties.

Shielding Gas	Deposition Strategy	Anisotropy (%)		
		Yield Stress	Tensile Strength	Elongation
Argon 18 L/min	Hatching	4	1	11
Argon 30 L/min	Hatching	0	1	3
	Circling	9	0	2
Stargold® 30 L/min	Hatching	0	0	9

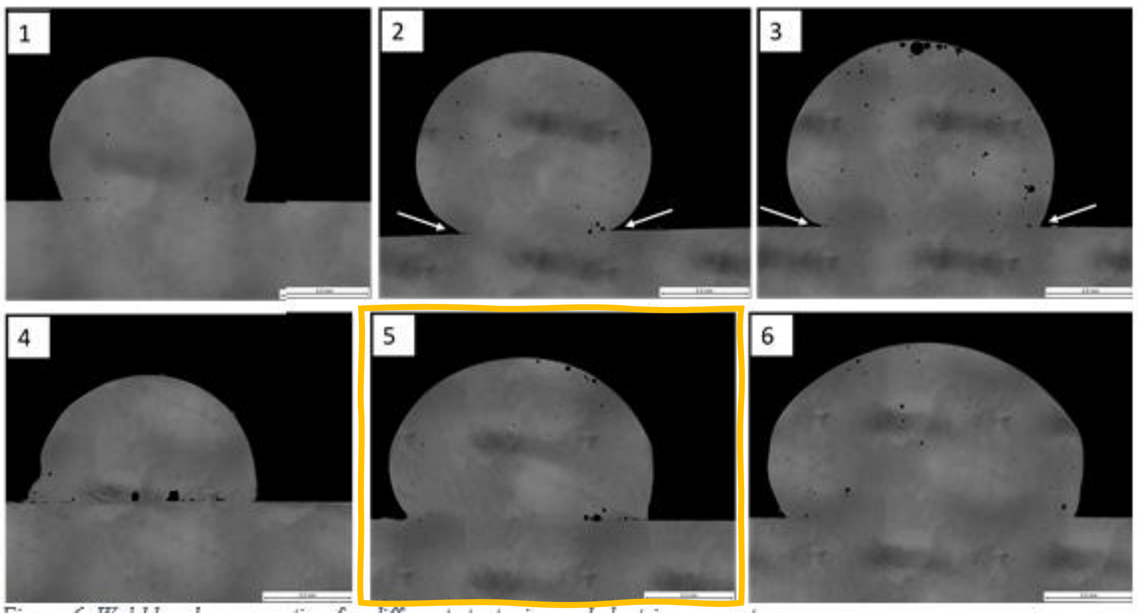
Strategies to Reduce Porosity in Al-Mg WAAM Parts and Their Impact on Mechanical Properties

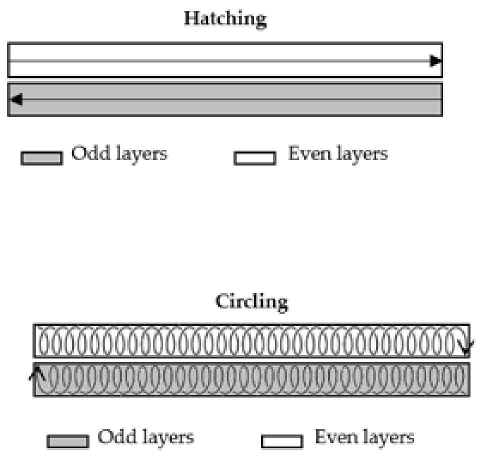
by Maider Arana [1,2,*], Eneko Ukar [2], Iker Rodriguez [1], Amaia Iturrioz [1] and Pedro Alvarez [1]

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy with TWIN

Objective: maximise the deposition rate ~ 3 kg/h





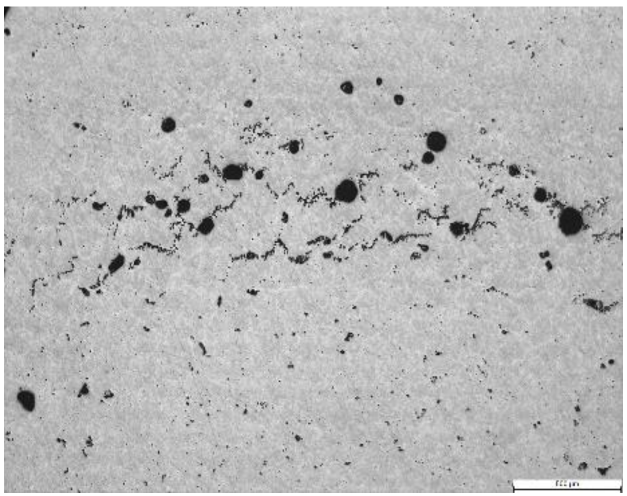
- Intermediate deposition rate was selected with circling strategy

Ensuring sound parts by maximising the deposition rate and minimising manufacturing time of 5356 aluminium alloy by WAAM using CMT-TWIN

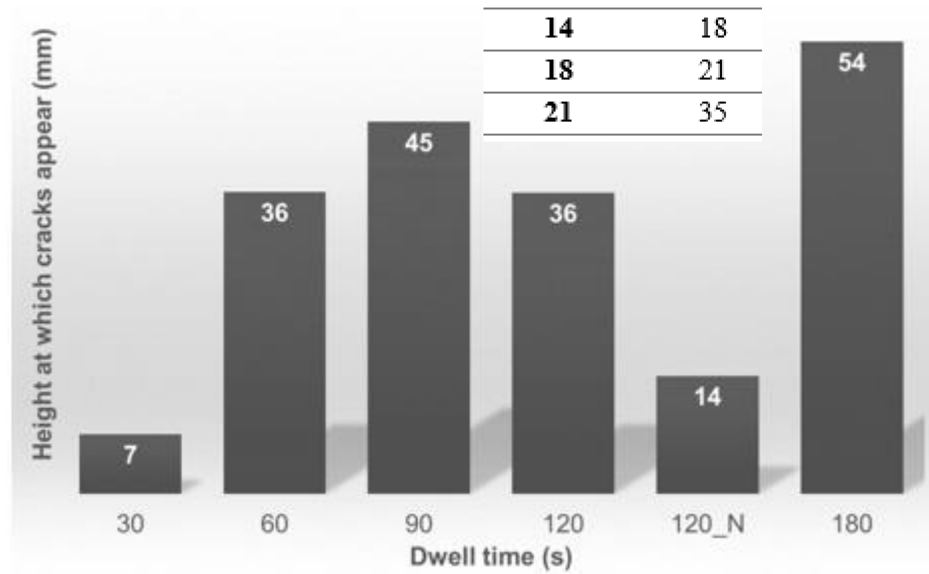
Lexuri Vázquez[1]*, Amaia Iturrioz[1], Pablo López de Uralde[1], Pedro Álvarez[1]

Influence of variables in the process and parts MIG/MAG

Al Mg 5356 alloy with TWIN



Layers	
From	To
0	1
1	9
9	14
14	18
18	21
21	35



- The high heat input of TWIN created cracks between layers.
- A proper optimisation of the dwell time need to be done to avoid cracks.

Ensuring sound parts by maximising the deposition rate and minimising manufacturing time of 5356 aluminium alloy by WAAM using CMT-TWIN

Lexuri Vázquez[1]*, Amaia Iturrioz[1], Pablo López de Uralde[1], Pedro Álvarez[1]

Influence of variables in the process and parts MIG/MAG

2024 through wire mixing with TWIN

Objective: to obtain 2024 (high strength) through the mix of wires of 2219 and 5356

- The WFS is varied to obtain the desired chemical composition

Composition	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	V	Zr	Zn	Be
2219	93,2899	0	5,9	0,15	0,01	0,29	0,12	0,09	0,04	0,1	0,01	0,0001
5356	94,06	0,125	0,01	0,4	4,9	0,125	0,25	0,13	0	0	0	0

	TW_Al_40/45	
Alloy	2219	5356
WFS (m/min)	5	3
Ø (mm)	1,2	1,2
Density (kg/dm^3)	2,84	2,64

Resultant 2024	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	V	Zr	Zn	Be	Cu/Mg ratio
wt%	93,57	0,04	3,79	0,24	1,76	0,23	0,17	0,10	0,03	0,06	0,01	0,00	2,15

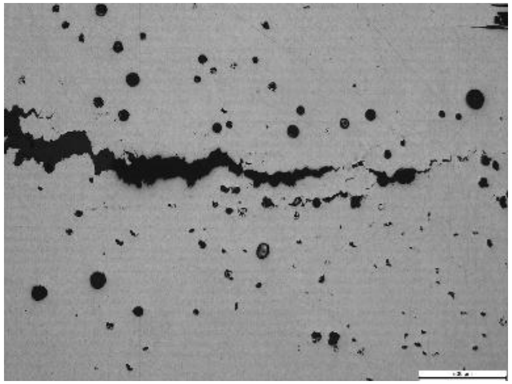
Influence of variables in the process and parts MIG/MAG

2024 through wire mixing with TWIN

Objective: to obtain 2024 (high strength) through the mix of wires of 2219 and 5356

- CMT synergic curves are varied: P+CMT CMT+CMT CMT+P/CMT+P P+P

- Porosity between 0.8 – 5.3 %
- In some cases cracking after HT



SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Influence of variables in the process and parts MIG/MAG

Al-Mg 5183

Objective: Anisotropy evaluation

- Samples are tested in three orientations (transversal, diagonal, longitudinal)
- Results are compared with laminated AA5083

- Pores and crack appearance between layers

Parameters	Values
Current (A)	30-50
Voltage (V)	14-15
WS (mm/s)	12 - 15
WFS (m/min)	2 - 3
Deposition rate (kg/h)	0.5-2
Layer height (mm)	0.5-2
Wire diameter (mm)	1.2
Shield gas	Ar 100%

AA5083 (Al–Mg) plates produced by wire-and-arc additive manufacturing: effect of specimen orientation on microstructure and tensile properties

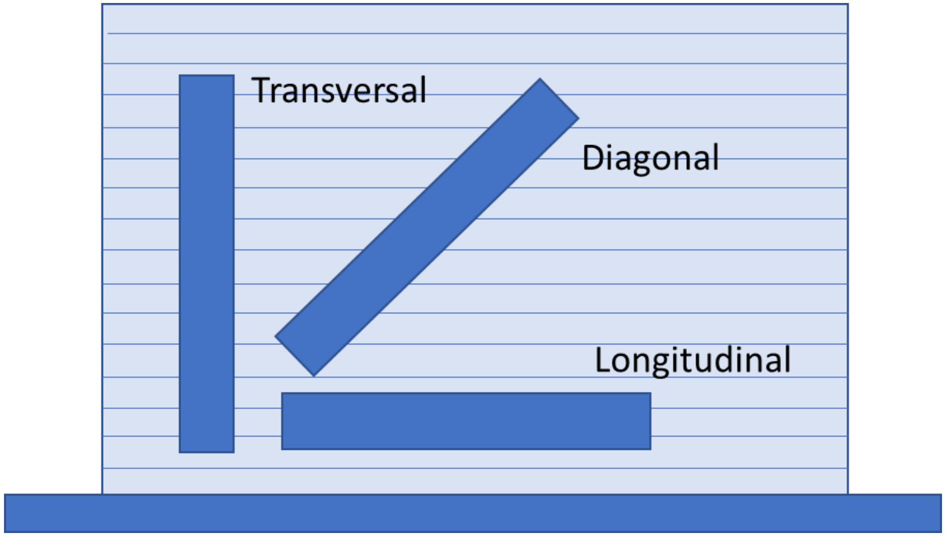
DOI: 10.1007/s40964-021-00189-z

Lavinia Tonelli[1] · Vittoria Laghi[2] · Michele Palermo[2] · Tomaso Trombetti[2] · Lorella Ceschini[1]

Influence of variables in the process and parts MIG/MAG

Al-Mg 5183

- Anisotropy
- Low values in the transversal direction (due to the pores and cracks between layers) in terms of YS, UTS, elongation and hardness
- Best properties for longitudinal orientation
- Compared to the standard, WAAM obtain better properties for longitudinal and diagonal orientations



AA5083 (Al–Mg) plates produced by wire-and-arc additive manufacturing: effect of specimen orientation on microstructure and tensile properties

DOI: 10.1007/s40964-021-00189-z

Lavinia Tonelli[1] · Vittoria Laghi[2] · Michele Palermo[2] · Tomaso Trombetti[2] · Lorella Ceschini[1]

Influence of variables in the process and parts MIG/MAG

Al-Mg 5183

- Microstructure based on: aluminum α pase and intermetallic particles of Fe and Mg distributed homogenously in the aluminum matrix.
- Gas pores and microcracks located in the interlayer.
- Relation with the lower mechanical properties in the transversal direction.

AA5083 (Al–Mg) plates produced by wire-and-arc additive manufacturing: effect of specimen orientation on microstructure and tensile properties

DOI: 10.1007/s40964-021-00189-z

Lavinia Tonelli[1] · Vittoria Laghi[2] · Michele Palermo[2] · Tomaso Trombetti[2] · Lorella Ceschini[1]

SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Co-funded by the Erasmus+ Programme of the European Union

Influence of variables in the process and parts MIG/MAG

AlSi7Mg

Objective: to obtain the same properties as with casting 356.0-T6

Welding current: 175–200 A
• Voltage: 22–28 V
• Travel speed: 330–390 mm/min
• Shielding Gas: 99.997% Ar

- Comparable properties with casting are obtained
- Benefits of WAAM are obtained (cost reduction and time shortening)

• Set A: Artificial aging heat treatment at 155 C for 2 h and 30 min
• Set B: Solution heat treatment at 540 C for 5 h followed by artificial aging at 155 C for 2 h and 30 min identical to T6 heat treatment for 356.0 casting

Development and Implementation of Wire Arc Additive Manufacturing (WAAM) Based on Pulse Spray GMAW for Aluminum Alloy (AlSi7Mg)

Mayur Patel[1] · Sanjiv Mulgaonkar[1] · Hemal Desai[1] · Tushar Borse[1]

Influence of variables in the process and parts MIG/MAG

Al-Cu 2319

- **Objective**: Compare block and thin walls

- CMT-P and CMT-ADV were compared

> - Lower hardness with lower HI in thin walls and block walls
> - Higher dispersion and heterogeneities in block walls
> - Regarding CMT modes CMT-ADV obtained very low porosity

applied sciences MDPI

Article

A Comparative Study of Additively Manufactured Thin Wall and Block Structure with Al-6.3%Cu Alloy Using Cold Metal Transfer Process

Baoqiang Cong [1,2], Zewu Qi [1,2], Bojin Qi [1,2,*], Hongye Sun [1,2], Gang Zhao [1,2] and Jialuo Ding [3]

SAM SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Influence of variables in the process and parts MIG/MAG

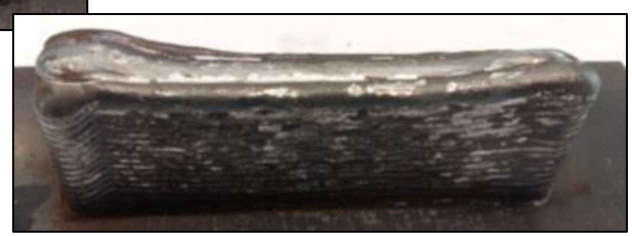
Carbon Steel with CMT

- Wire: **G3Si1, Ø:1 mm** (According to AWS:A5.18ER70S-6)
- Substrate: **Structural Steel C-Mn**
- Protective gas: **Ar-15%CO_2**

Evaluated parameters:

- Synergic curves: pure CMT, pulsed CMT
- Current (A), WFS (m/min), welding speed (cm/min)
- Electric arc stability
- Qualitative aspect of the weld bead
- Number of weld beads
- Distance between overlapped weld beads: 2-3 weld beads
- Torch orientation
- Deposition strategy
- Multilayer walls

Multilayer walls are deposited (3 overlapped weld beads, 17 layers in height) **in absence of defects**



SAM SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Co-funded by the Erasmus+ Programme of the European Union

Influence of variables in the process and parts MIG/MAG

Carbon Steel with CMT

* Interlayer dwell time: 60s each 4 weld beads.
** weld bead separation (mm)

Referencia	I (A)	V_{hilo} (m/min)	V (V)	V_{soldeo} (cm/min)	Tasa deposición (Kg/h)	Nº cordones	Geometría	
							H (mm)	W (mm)
C1184+P - 1.1	100	5,5	21	40	2,0	1	1,9	6,9
C1184+P - 1.2	100	5,5	21	60	2,0	1	1,7	5,6
C1184+P - 2.1	150	8,5	22,8	60	3,1	1	1,9	7,1
C1184+P - 2.2	150	8,5	22,8	90	3,1	1	1,9	6,7
C1184+P - 3.1	200	12	25,5	80	4,4	1	1,8	7,4
C1184+P - 3.2	200	12	25,5	120	4,4	1	1,9	6,5
C1053 - 1	204	9,4	16,4	80	3,5	1	2,4	4,7
C1053 - 2	204	9,4	16,4	80	3,5	4		5
C1185+P - 3	270	16,6	29,7	140	6,1	1	1,9	5,3
C1185+P - 4	270	16,6	29,7	140	6,1	4		6
C1184+P - 5	237	15	27,5	80	5,5	1	3,3	6,7
C1184+P - 6	237	15	27,5	80	5,5	4		7
C1184+P – 7	150	8,5	22,8	80	3,1	23*	20	<9
C1184+P – 8	150	8,5	22,8	80	3,1	23	<24	<7
C1184+P – 9	100	4,8	21	60	1,8	1		
C1184+P – 10	100	4,8	21	60	1,8	23	25	<5
C1184+P – 11	100	5,5	21	60	2,0	2x1 (2)**		7,2
C1184+P – 12	100	5,5	21	60	2,0	2x1 (3)		8,5
C1184+P – 13	100	5,5	21	60	2,0	2x23 (3)		
C1184+P – 14	100	5,5	21	60	2,0	2x3 (6)		
C1184+P – 15	100	5,5	21	60	2,0	2x3 (3)	-	10
C1053 – 16	200	9,4	19,3	80	3,5	2x3 (3)	-	10
C1184+P – 17	150	8,5	22,8	80	3,1	2x3 (3)	-	8
C1185+P – 18	200	12	25,5	100	4,4	2x3 (3)	-	10
C1053 – 19	200	9,1	19,3	80	3,4	3x7 (3-3)	12	15
C1053 – 20	200	9,1	19,3	80	3,4	3x17 (3,5-3,5)	28	15,5

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Influence of variables in the process and parts MIG/MAG

Carbon Steel with CMT

Reference	I (A)	WFS (m/min)	V (V)	Welding speed (cm/min)	Deposition rate (Kg/h)	Nº weld beads	Geometry	
							H (mm)	W (mm)
C1184+P – 7	150	8,5	22,8	80	3,1	23*	20	9
C1184+P – 8	150	8,5	22,8	80	3,1	23	24	7
C1184+P – 9	100	4,8	21	60	1,8	1	-	-
C1184+P – 10	100	4,8	21	60	1,8	23	25	5

* Interlayer dwell time: 60s each 4 weld beads. Modification for the next ones: 60 seconds per weld bead.

8

7

10

- High melting of the feeding material and high amount of sputters are observed.
- A dwell time is introduced. Sputters are slightly reduced. Slightly taller and thinner weld beads are obtained.
- Current, welding speed and WFS are reduced. A thinner, slithly taller and more homogenous in thickness wall is obtained.

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Influence of variables in the process and parts MIG/MAG

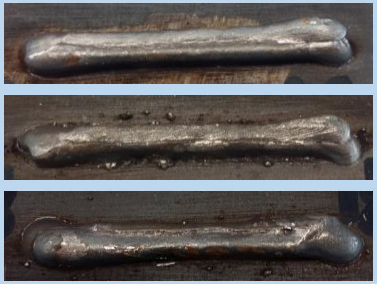
Carbon Steel with CMT

Referencia	I (A)	V_{hilo} (m/min)	V (V)	V_{soldeo} (cm/min)	Tasa deposición (Kg/h)	Nº cordones	Geometría H (mm)	Geometría W (mm)
C1184+P – 11	100	5,5	21	60	2,0	2x1 (2)*	-	7,2
C1184+P – 12	100	5,5	21	60	2,0	2x1 (3)	-	8,5
C1184+P – 13	100	5,5	21	60	2,0	2x23 (3)	-	-
C1184+P – 14	100	5,5	21	60	2,0	2x3 (6)**		
C1184+P – 15	100	5,5	21	60	2,0	2x3 (3)	-	10
C1184+P – 17	150	8,5	22,8	80	3,1	2x3 (3)	-	8
C1053 – 16	200	9,4	19,3	80	3,5	2x3 (3)	-	10
C1185+P – 18	200	12	25,5	100	4,4	2x3 (3)	-	10
C1053 – 19	200	9,1	19,3	80	3,4	3x7 (3-3)	12	15
C1053 – 20	200	9,1	19,3	80	3,4	3x17 (3,5-3,5)	28	15,5

* 2x1(2): 2 cordones depositados, 1 capa en altura, (2) separación en mm entre los cordones depositados

** Orientación de la antorcha: 20º desde la vertical

13



16

17

18

- The torch orientation is modified
- Electric parameters are modified and different sinergic curves are checked.

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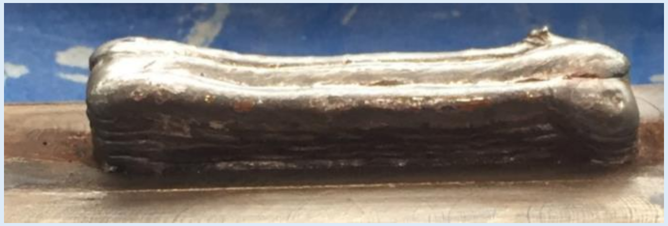
Influence of variables in the process and parts MIG/MAG

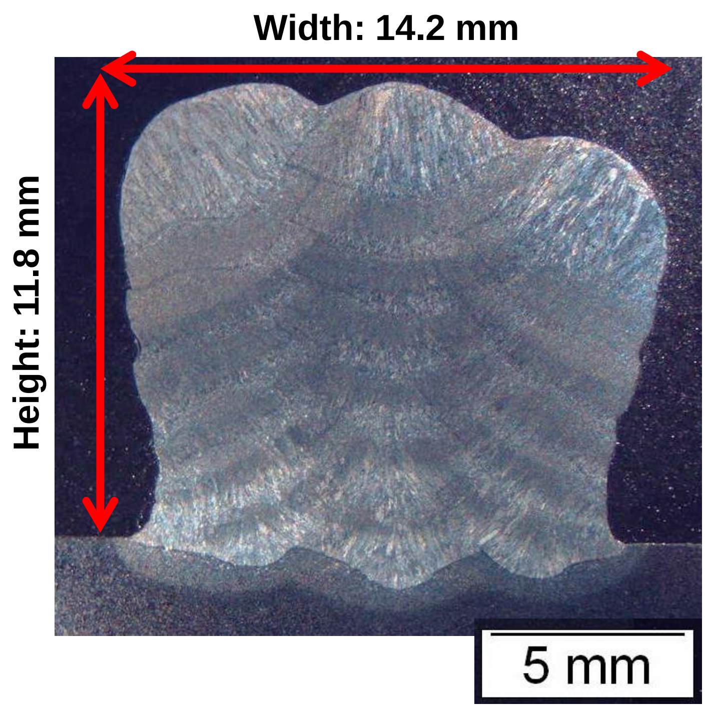
Carbon Steel with CMT

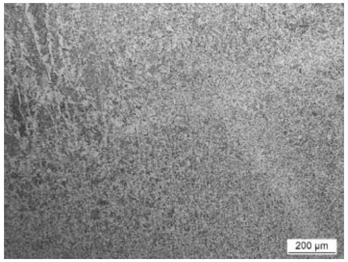
Referencia	I (A)	V_{hilo} (m/min)	V (V)	V_{soldeo} (cm/min)	Tasa deposición (Kg/h)	Nº cordones	Geometría H (mm)	Geometría W (mm)
C1053 – 19	200	9,1	19,3	80	3,4	3x7 (3-3)	12	15
C1053 – 20	200	9,1	19,3	80	3,4	3x17 (3,5-3,5)	28	15,5

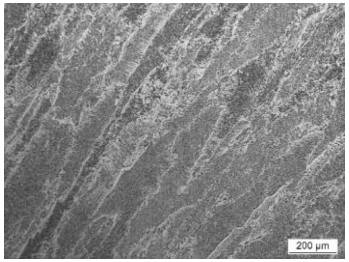


Influence of variables in the process and parts MIG/MAG

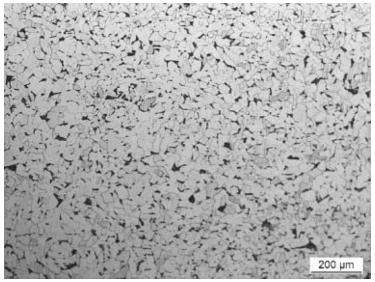
Carbon Steel with CMT







WAAM material



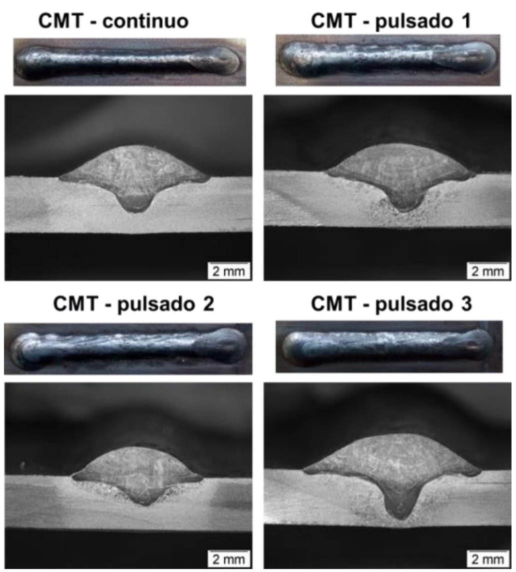
Substrate

Lenght (mm)	Height	Width	Dilution	HAZ
Sample end 1	13.9	16.9	1.0	0.9
Centre	11.9	14.2	1.3	0.6
Sample end 2	14.7	17.2	1.3	0.6

Influence of variables in the process and parts MIG/MAG

Stainless Steel with CMT

- Wire: 316L, Ø: 1mm
- Substrate: Stainless Steel 316L
- Protective gas: Ar-2.5%CO_2



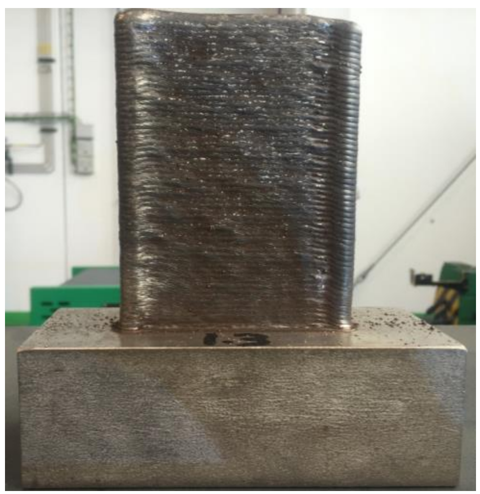
Reference	Current (A)	WFS (m/min)	Voltage (V)	Welding speed (m/min)	Deposition rate (Kg/h)	Weld bead geometry	
						Height (mm)	Width (mm)
CMT-continuo	150	8	14,2	0,6	3	1,4	6,5
CMT-pulsado 1	200	9,4	23,3	0,6	3,4	1,5	7
CMT-pulsado 2	220	10	26,8	1,0	3,7	1,4	6,5
CMT-pulsado 3	220	10	26,2	0,8	3,7	1,7	9

- In some cases the use of different parameters are recommended when the thickness of the wall is changed, for the first and last deposited weld beads.

Influence of variables in the process and parts MIG/MAG

Stainless Steel with CMT

Referencia	I (A)	V_{hilo} (m/min)	V (V)	V_{soldeo} (cm/min)	Tasa deposición (Kg/h)	Nº cordones	Geometría Cordón	
							H (mm)	W (mm)
C0877	150	8	14,2	60	3,0	1	1,4	6,5
C0882+P	200	9,4	23,3	60	3,4	1	1,5	7
C0882+P	220	10	26,8	100	3,7	1	1,4	6,5
C0882+P	220	10	26,2	80	3,7	1	1,7	9
C0882+P– 1.1	200	9,4	23,3	80	3,4	3X5	<13	<14
C0882+P – 1.2	200	9,4	23,3	80	3,4	3X28	56	<14
C0882+P – 1.3	200	9,4	23,3	80	3,4	3X57	114	<14
C0882+P – 1.4	200	9,4	23,3	80	3,4	3X35	70	<14



57 layers

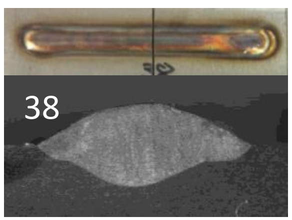
Influence of variables in the process and parts MIG/MAG

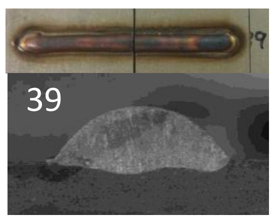
Stainless Steel with TopTIG

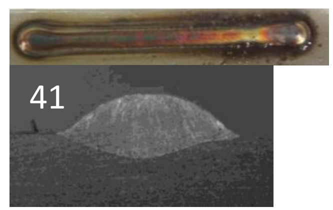
Unitary weld beads:

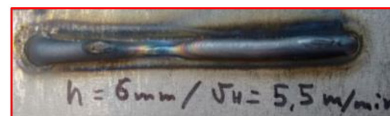
								GEOMETRÍA		
PROGRAMA	**ID**	**Nº CORDONES**	**I (A)**	**V_A (m/min)**	**V_H (m/min)**	**h_{arco} (mm)**	**tipo / caudal gas (l/min)**	**h (mm)**	**e (mm)**	**Tasa deposición (kg/h)**
continuo	38	1	220	0,7	2,9	3	Ar puro / 16	1,1	4,9	1,1
continuo	39	1	220	0,7	5	5	Ar puro / 16	1,6	5,1	1,9
pulsado	41	1	350/187	0,8	5,5/2,9	5	Ar puro / 16	1,1	4,4	1,6
continuo	69	1	220	0,7	4	5	Ar puro / 16	1,3	5,0	1,5

Optimised parameters



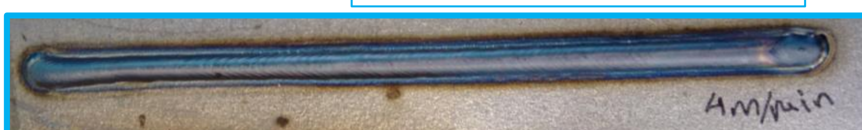


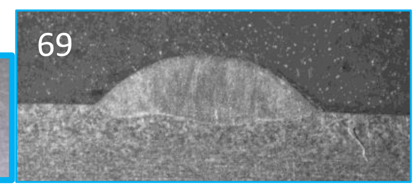




The WFS is very high and the wire hits the substrate.

Deposition rate: 1.5 kg/h





Influence of variables in the process and parts MIG/MAG

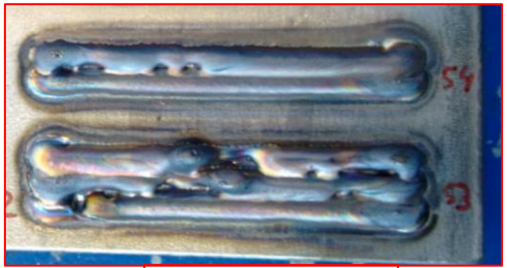
Stainless Steel with TopTIG

Horizontally overlapped weld beads:

PROGRAMA	ID	Nº CORDONES	I (A)	V_A (m/min)	V_H (m/min)	h_{arco} (mm)	tipo / caudal gas (l/min)	t entre pasadas (s)	solape horizontal (mm)
continuo	52	1x3	220	0,7	5	5	Ar puro / 16	90	3
continuo	53	1x3	220	0,7	5	5	Ar puro / 16	90	3,5
continuo	54	1x2	220	0,7	5	5	Ar puro / 16	90	3,2

Different overlaps have been tested taking into account the thickness of the unitary weld bead ~ 5 mm

Horizontal overlap: 3 mm



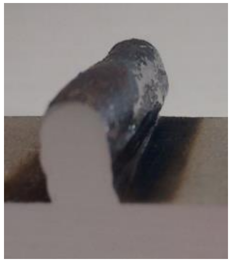
They separate

Influence of variables in the process and parts MIG/MAG

Stainless Steel with TopTIG

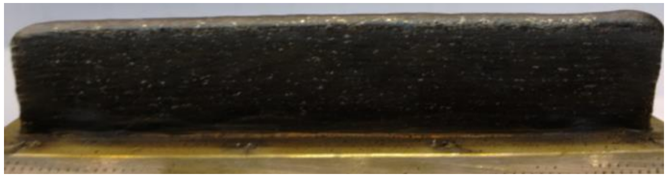
Vertical overlapped weld beads:

PROGRAMA	ID	Nº CORDONES	I (A)	V_A (m/min)	V_H (m/min)	h_{arco} (mm)	tipo / caudal gas (l/min)	t entre pasadas (s)	GEOMETRÍA h (mm)	GEOMETRÍA e (mm)	offset en Z (mm)
continuo	59	1x6	22	0,7	5	5	Ar puro / 16	90	6,3	5,3	1,6



Offset in Z taking into account the height of unitary weld bead ~ 1,6 mm

PROGRAMA	ID	Nº CORDONES	I (A)	V_A (m/min)	V_H (m/min)	h_{arco} (mm)	tipo / caudal gas (l/min)	t entre pasadas (s)	offset en Z (mm)
continuo	67	1x31	220	0,7	4	5	Ar puro / 16	60	1,7



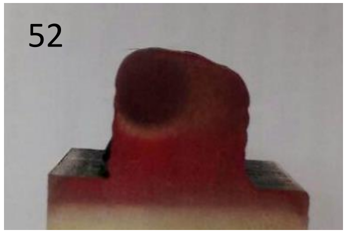
Interlayer dwell time: **60 segundos**

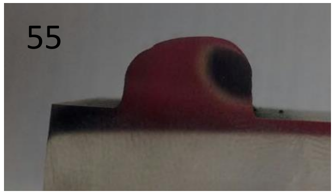
Influence of variables in the process and parts MIG/MAG

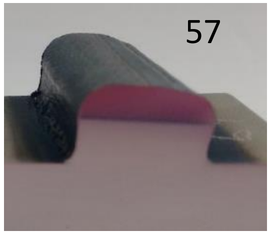
Stainless Steel with TopTIG

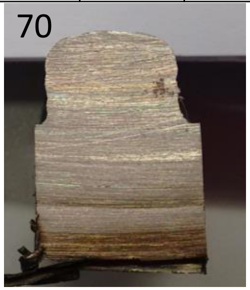
Small walls of 6 weld beads in height and 3 in horizontal:

									GEOMETRÍA				
PROGRAMA	ID	Nº CORDONES	I (A)	V_A (m/min)	V_H (m/min)	h_{arco} (mm)	tipo / caudal gas (l/min)	t entre pasadas (s)	h (mm)	e (mm)	solape horizontal (mm)	offset en Z (mm)	Tasa deposición (kg/h)
continuo	52	3x6	220	0,7	5	5	Ar puro / 16	90	9,0	10,1	3	1,6	1,9
continuo	55	3x6	220	0,7	2,9	3	Ar puro / 16	90	5,9	10,3	3	1,6	1,1
pulsado	57	3x6	350-187	0,8	5,5-2,9	5	Ar puro / 16	90	5,9	10,0	3	1,2	1,6
continuo	70	3x6	220	0,7	4	5	Ar puro / 16	60	7,5	10,9	3	1,7	1,5

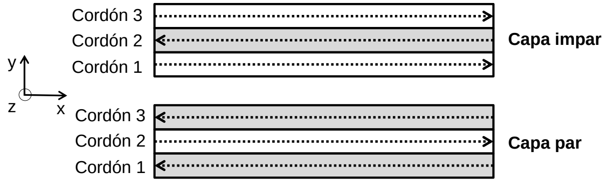


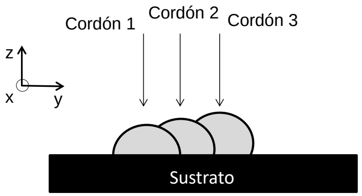






Deposition strategy alternating arc start and stop.





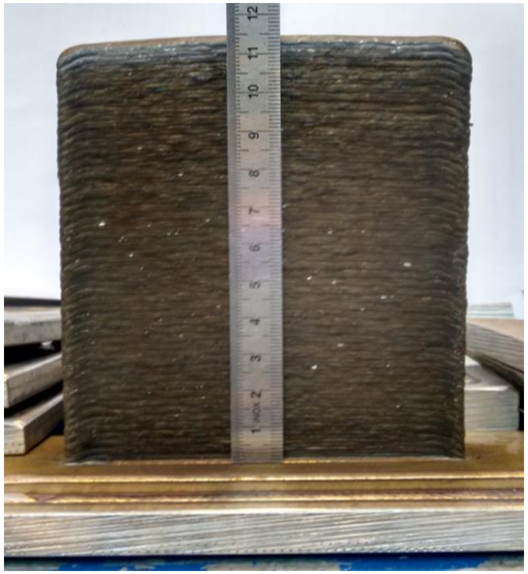
No defects are found

Influence of variables in the process and parts MIG/MAG

Stainless Steel with TopTIG

Walls:

PROGRAMA	ID	Nº CORDONES	I (A)	V_A (m/min)	V_H (m/min)	h_{arco} (mm)	tipo / caudal gas (l/min)	t entre pasadas (s)	solape horizontal (mm)	offset en Z (mm)	Tasa deposición (kg/h)
continuo	68	3x50	220	0,7	4	5	Ar puro / 16	60	3	2,3	1,5
continuo	72	3x103	220	0,7	4	5	Ar puro / 16	60	3	2,3	1,5



Walls. Z is constantly adjusted to maintain an arc height of 5 mm. Final estimated offset in Z is 2.25 mm.

Properties

Stainless Steel: TopTIG vs. CMT

Deposition rate:

Tecnology	Material	Deposition rate (kg/h)
CMT	Stainless Steel 316L	3.4
TopTIG	Stainless Steel 316L	1.5

Mechanical properties: **Stainless Steel 316L** in as built

Reference	Orientation	E(GPa)	$Rp_{0.2}$ (MPa)	R_m (MPa)	e (%)
Top-TIG continuous	Vertical	91,2 ± 9,5	322,2 ± 2,7	539,9 ± 14,7	43,1 ± 6,9
	Horizontal	91,3 ± 10,1	365,5 ± 8,7	590,3 ± 3,6	42,3 ± 2,7
CMT continuous	Vertical	96,8 ± 2,1	336,9 ± 1,7	574,1 ± 7,9	42,0 ± 3,7
	Horizontal	102,8 ± 5,7	364,3 ± 13,9	577,3 ± 4,0	43,4 ± 4,7
REFERENCE 316L		-	346	651	47

Lower strength in the vertical orientation in both technologies. The **elongation is very similar** between both technologies and orientations.

Influence of variables in the process and parts MIG/MAG

Steel ER70S-6

Objective: to find the best strategy for this alloy

- Overlap and weaving strategies

- Better results with weaving
- Both strategies obtain similar values to the alloy nominal's ones

Analysis of the Wall Geometry with Different Strategies for High Deposition Wire Arc Additive Manufacturing of Mild Steel

Eider Aldalur [1], Fernando Veiga [1,*], Alfredo Suárez [1], Jon Bilbao [2] and Aitzol Lamikiz [3]

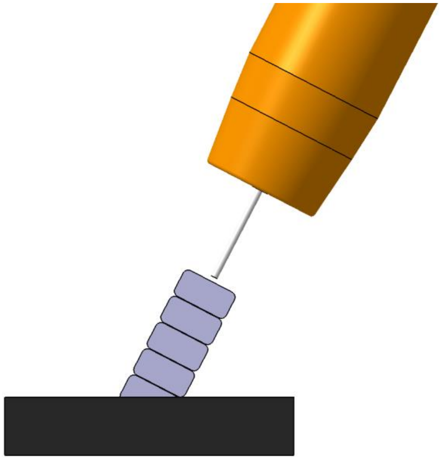
Influence of variables in the process and parts MIG/MAG

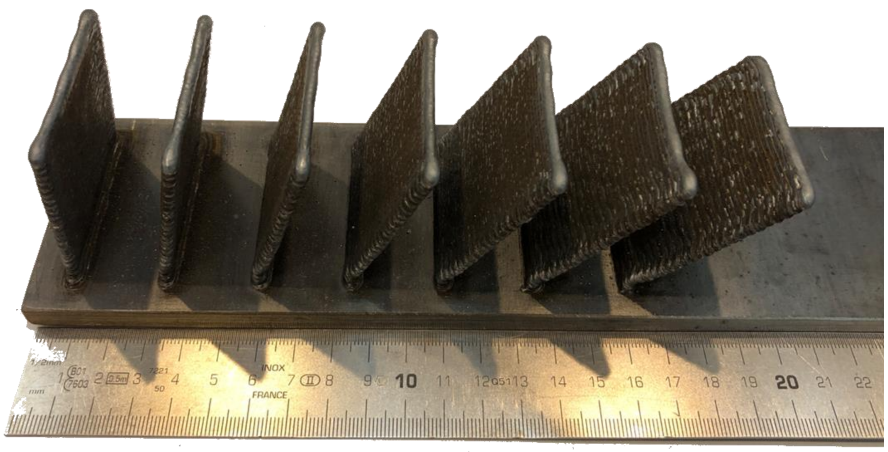
Steel ER70S-6

Objective: inclined walls and cross section part fabrication

- CMT
- Without tilting the substrate

- Limitations were found regarding the maximum angle without tilting the substrate





Up to 30 ° OK

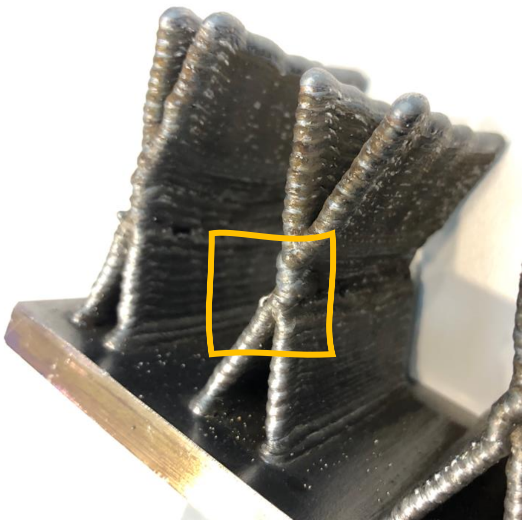
Influence of variables in the process and parts MIG/MAG

Steel ER70S-6

Objective: inclined walls cross section part fabrication

- CMT
- Without tilting the substrate

- Material accumulation when growing from one weld bead



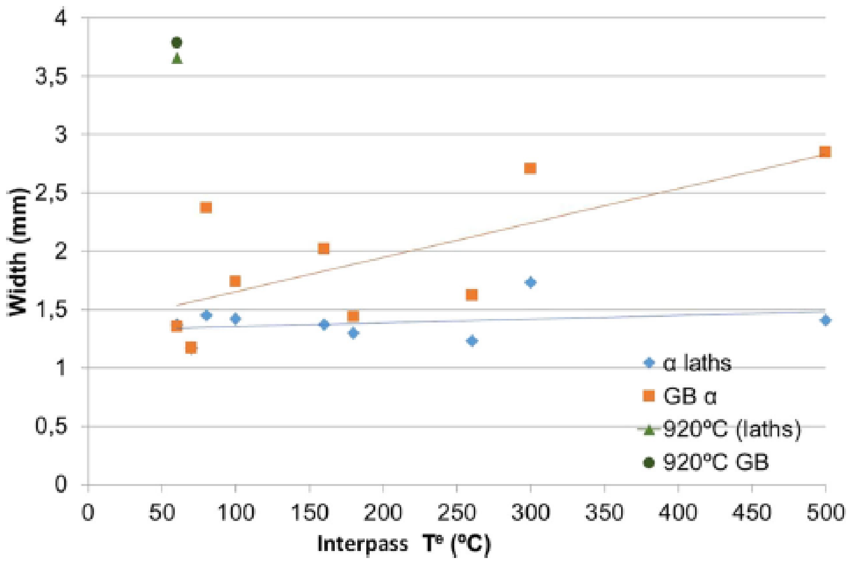
Influence of variables in the process and parts MIG/MAG

Ti-6Al-4V

Objective: to find the best cooling conditions

➢ Use of different dwell times and cooling plate

Interpass Tª (°C)	Dwell t (min)	Cooling plate
500	0	Without
300	0	With
160	1	With
80	5	Without
60	9	Without



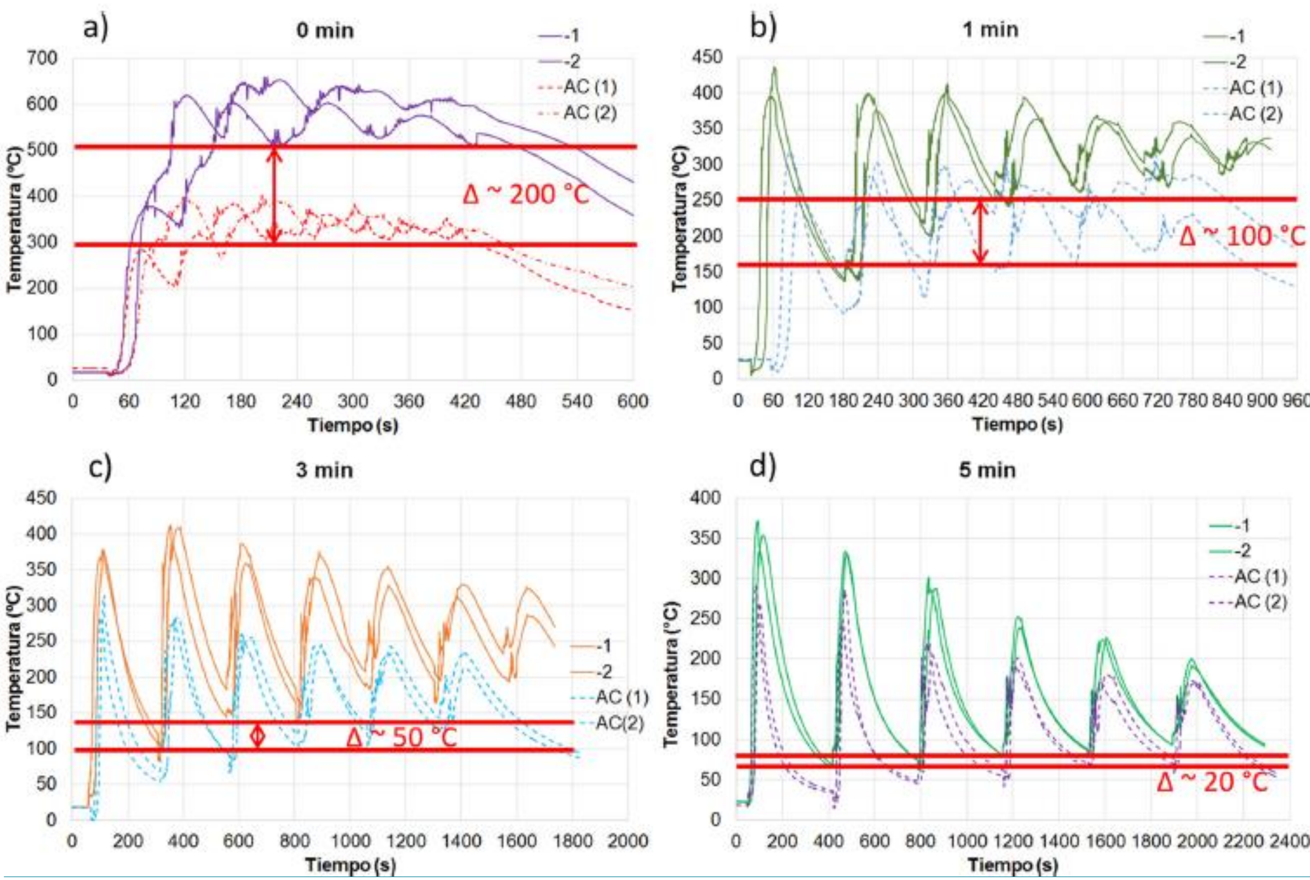
- Direct effect was found between the thickness of α phase in the grain boundary and the interpass temperature

Influence of interpass cooling conditions on microstructure and tensile properties of Ti-6Al-4V parts manufactured by WAAM

L. Vázquez[1] · N. Rodríguez[1] · I. Rodríguez[1] · E. Alberdi[1] · P. Álvarez[1]

Influence of variables in the process and parts MIG/MAG

Ti-6Al-4V



- Highest difference in interpass temperature is evidenced with the use of cooling plate when no dwell time is used.

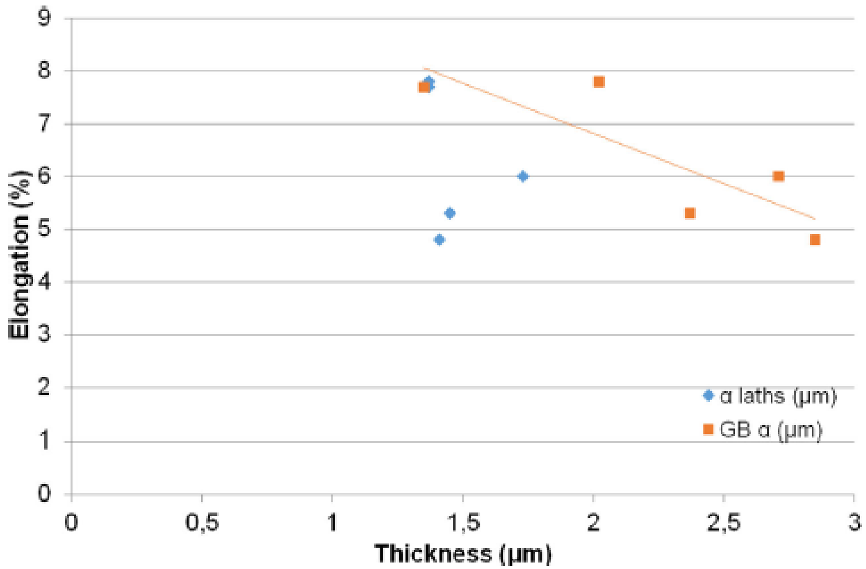
Influence of interpass cooling conditions on microstructure and tensile properties of Ti-6Al-4V parts manufactured by WAAM

L. Vázquez[1] · N. Rodríguez[1] · I. Rodríguez[1] · E. Alberdi[1] · P. Álvarez[1]

Influence of variables in the process and parts MIG/MAG

Ti-6Al-4V

Dwell t (min)	Cooling plate	YS (MPa)	UTS (MPa)	e (%)	GB α (μm)
0	Without	794.3 ± 4.2	900.3 ± 16.4	4.8 ± 0.4	2.85
0	With	794.8 ± 18.0	895.4 ± 10.0	6 ± 0.7	2.71
1	With	843.0 ± 22.5	944.5 ± 14.7	7.8 ± 1.4	2.02
5	Without	848.1 ± 14.3	943.5 ± 12.3	5.3 ± 1	2.37
9	Without	872.1 ± 8.1	995.0 ± 2.3	7.7 ± 1.2	1.35
9 + 920 °C	Without	829.6 ± 6.9	942.3 ± 11.4	11.3 ± 1.[illegible]	3.79
Standard AMS 4985C-2003		827	896	6	



- Forced cooling helps on reducing dwell time from 9 to 1 min.
- Direct effect was found between the thickness of α phase in the grain boundary and β grain shape and mechanical properties.

Influence of interpass cooling conditions on microstructure and tensile properties of Ti-6Al-4V parts manufactured by WAAM

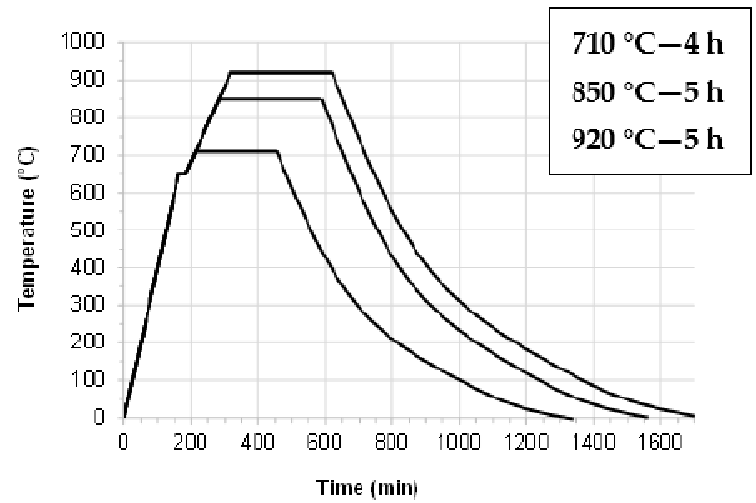
L. Vázquez[1] · N. Rodríguez[1] · I. Rodríguez[1] · E. Alberdi[1] · P. Álvarez[1]

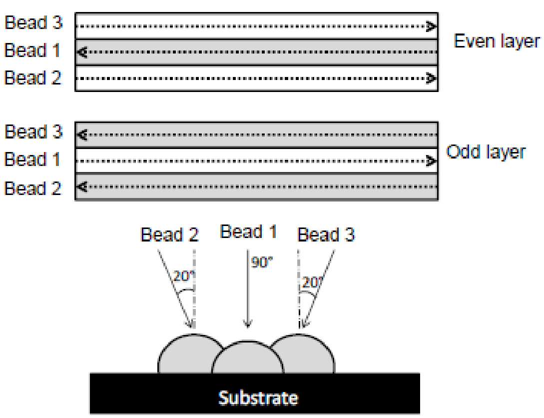
Influence of variables in the process and parts MIG/MAG

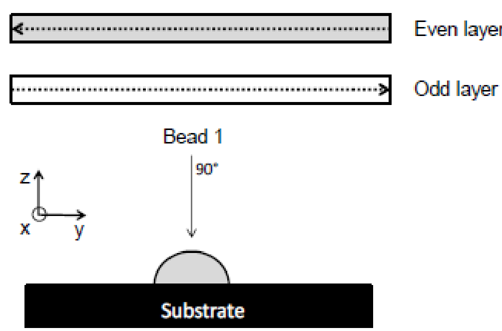
Ti-6Al-4V

Objective: to find the best HT for different build strateg

- ➢ Two different strategies
- ➢ Different HT temperatures







Article

Influence of Post-Deposition Heat Treatments on the Microstructure and Tensile Properties of Ti-6Al-4V Parts Manufactured by CMT-WAAM

Lexuri Vazquez *, Maria Nieves Rodriguez, Iker Rodriguez and Pedro Alvarez

Influence of variables in the process and parts MIG/MAG

Ti-6Al-4V

Three overlapped weld bead

Temperature of Thermal Treatment	Orientation	Rp0.2 (MPa)	Rm (MPa)	e (%)
As built	Z	946.9 ± 8.1	1038.5 ± 8.3	8.2 ± 1.4
	X	958.8 ± 3.4	1046.1 ± 3.2	6.1 ± 0.7
710 °C	Z	970.5 ± 4.2	1027.3 ± 5.1	5.5 ± 0.9
	X	967.2 ± 7.6	1030.2 ± 9.2	5.8 ± 0.6
850 °C	Z	902.9 ± 5.0	989.1 ± 4.4	11.2 ± 0.9
	X	922.5 ± 1.0	1005.0 ± 2.2	6.1 ± 0.3
920 °C	Z	859.7 ± 2.6	973.1 ± 2.7	15.8 ± 1.3
	X	880.5 ± 3.9	981.0 ± 6.5	10.6 ± 1.8

Single weld bead

Temperature of Thermal Treatment	Orientation	Rp0.2 (MPa)	Rm (MPa)	e (%)
As-built	Z	917.5 ± 8.1	1007.0 ± 4.7	9.4 ± 5.6
	X	884.9 ± 10.3	986.0 ± 13.2	8.2 ± 2.0
850 °C	Z	911.6 ± 11.1	994.5 ± 13.9	14.3 ± 1.6
	X	866.9 ± 4.8	948.8 ± 3.5	11.1 ± 0.8
920 °C	Z	855.2 ± 9.5	968.7 ± 10.6	17.5 ± 1.1
	X	809.8 ± 12.2	919.4 ± 5.0	15.2 ± 1.5

- Anisotropy is found for both strategies.
- In general the strategy based on single weld beads obtains better results.

Article

Influence of Post-Deposition Heat Treatments on the Microstructure and Tensile Properties of Ti-6Al-4V Parts Manufactured by CMT-WAAM

Lexuri Vazquez *, Maria Nieves Rodriguez, Iker Rodriguez and Pedro Alvarez

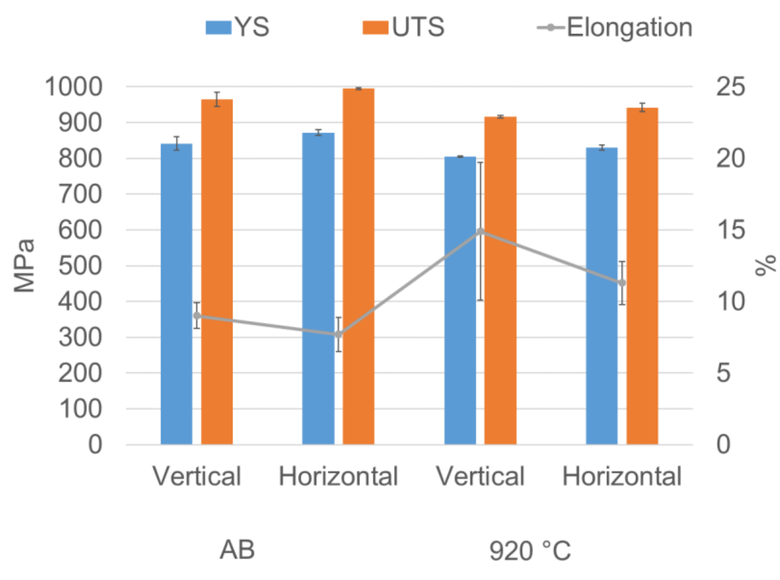
Influence of variables in the process and parts MIG/MAG

Ti-6Al-4V

Mechanical properties are directly linked with obtained microstructure and the presence of defects. Ti6Al4V deposited by WAAM demonstrated that the tensile properties are comparable with the ones required for cast and forged parts of Ti6Al4V according to the standards:

Reference	$Rp_{0,2}$ (MPa)	R_m (MPa)	e (%)
AMS 4985C-2003 (investment casting)	>827	>896	>6
ISO 5832-3 (wrought)	>780	>860	>10

Mechanical properties of standards for wrought and cast of Ti6Al4V.



Anisotropy		AB	920 °C
	YS	2%	2%
	UTS	2%	1%
	Elongation	8%	14%

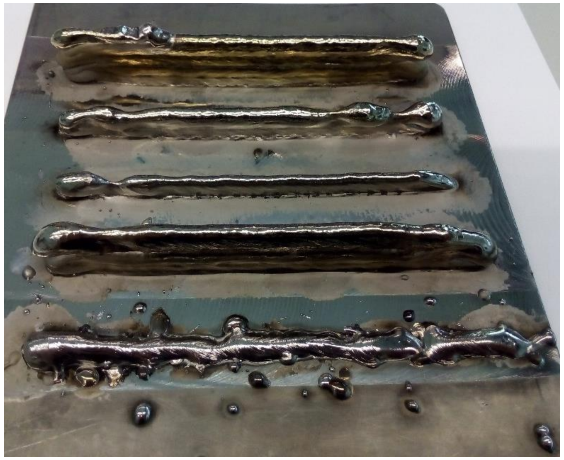
Influence of interpass cooling conditions on microstructure and tensile properties of Ti-6Al-4V parts manufactured by WAAM
L. Vázquez, N. Rodríguez, I. Rodríguez, E. Alberdi, P. Álvarez
Welding in the World, 2019

Defects, inspection techniques and monitoring

- In WAAM process, based on the application of multiple layers, layer defects can influence the quality of the previous or next layer, even the quality of the whole part.
- Defects are produced by an inadequate selection and control of manufacturing parameters.
- Therefore, the application of different non-destructive techniques and monitoring actions will help reducing the apparition of defects and improve, as a consequence, the quality of manufactured parts.

Defects, inspection techniques and monitoring

Defects in WAAM can be easily associated to the ones encountered in welding and joining processes. These are some of the typical defects:



- **Porosity:** caused by trapped gas or lacks of fusion among layers. Gas porosity arises due to an excessive deposition rate, giving as a result that the protective gas is trapped within the melted pool.
- **Cracks:** typically related to hot cracking susceptibility.
- **Lack of Fusion:** associated to low energy density in the melt pool or feeding wire quality or movement. Related as well to the arc working distance (too short).
- **Humping:** non-uniform material deposition transformed in an excess or lack of material. It is connected to a discoordination among wire-speed and advancing-speed.

Defects, inspection techniques and monitoring

- The following table, resumes major AM defect classes and subclasses:

Defect Class	Defect Subclass
Surface	roughness, underfill, powder shorting, overfill, crater, stair stepping, meets surface spec
Porosity	spherical gas porosity, microporosity, void, surface breaking
Cracking	hot cracking, cold cracking, crater, cracking, HAZ as in DED to substrate, tearing
Lack of Fusion	cold lap, trapped powder, oxide lap, linear, planar, post HIP
Part Dimensions	external, internal, lattice, custom
Density	density, weight, volume, meets partial density spec
Inclusions	inclusions, segregation, banding, planar
Discoloration	oxidation, other
Residual Stress	…

Co-funded by the Erasmus+ Programme of the European Union

Defects, inspection techniques and monitoring

Aluminum alloys

- Problems in WAAM processed aluminium
- Defects:
  - Porosity
  - Cracking

➢ The majority of pores are non diluted hydrogen due to the high difference of solubility in liquid and solid state.

➢ Others due to cavities formed during the solidification.

➢ The constant heat input during the layer deposition acts as a low temperature HT favouring the pore growth.

➢ The alloys with higher number of eutectic phases as 2219 tend to form dendrites with a big interdrendritic space being these zones preferent for pore nucleation.

➢ In 5087 pores tend to be small, which are thought to be formed due to volatilization of Mg. These pore grow after the HT.

Defects, inspection techniques and monitoring

Aluminium alloys

Recommendations to remove porosity:

- Use of gas of the best quality, non organic tubes, short tubes, hermetic seal
- Use of MIG process with AC
- Temperature profile control to obtain a fine grain and equiaxial microstructure
- Optimisation of the weld bead geometry
- Cleanness of the wire and the substrate
- Control of the quality of the wire
- Cold work in the deposited material

Defects, inspection techniques and monitoring

- Non-Destructive Techniques (NDT) are referred as the techniques employed to inspect and monitor parts seeking for discontinuities and, as a result, evaluate their defects.

- With these methods, it is possible to retrieve information related to the physical properties and imperfections of the part, allowing quality or production process evaluation.

Defects, inspection techniques and monitoring

- Nowadays, there are no standards or QA methods for WAAM.
- Every technique has an application field, with a series of advantages and disadvantages
- In this way, it is possible to relate the type of measuring technique with the phenomenon capable of detecting:

thermal

- thermography
- laser thermography
- induction thermography

optical

- visual
- dye penetrants
- photodiodes
- spectrometry
- machine vision
- laser profilometry

acoustic

- ultrasounds
- phased arrays
- electromagnetic ultrasounds
- electromagnetic laser ultrasounds

electromagnetic

- magnetic particles
- eddy current

radiographic

- X-ray
- XBT
- XCT

Defects, inspection techniques and monitoring

- Nowadays, there are no standards or QA methods for WAAM.
- Every technique has an application field, with a series of advantages and disadvantages
- In this way, it is possible to relate the type of measuring technique with the phenomenon capable of detecting:

thermal

- emissivity
- thickness
- thermal contours
- porosity
- cracks
- delamination
- deformation

optical

- dimensions
- deformation
- reflectivity
- cracks
- superficial defects

acoustic

- cracks
- holes
- delamination
- density
- dimensions
- inclusions

electromagnetic

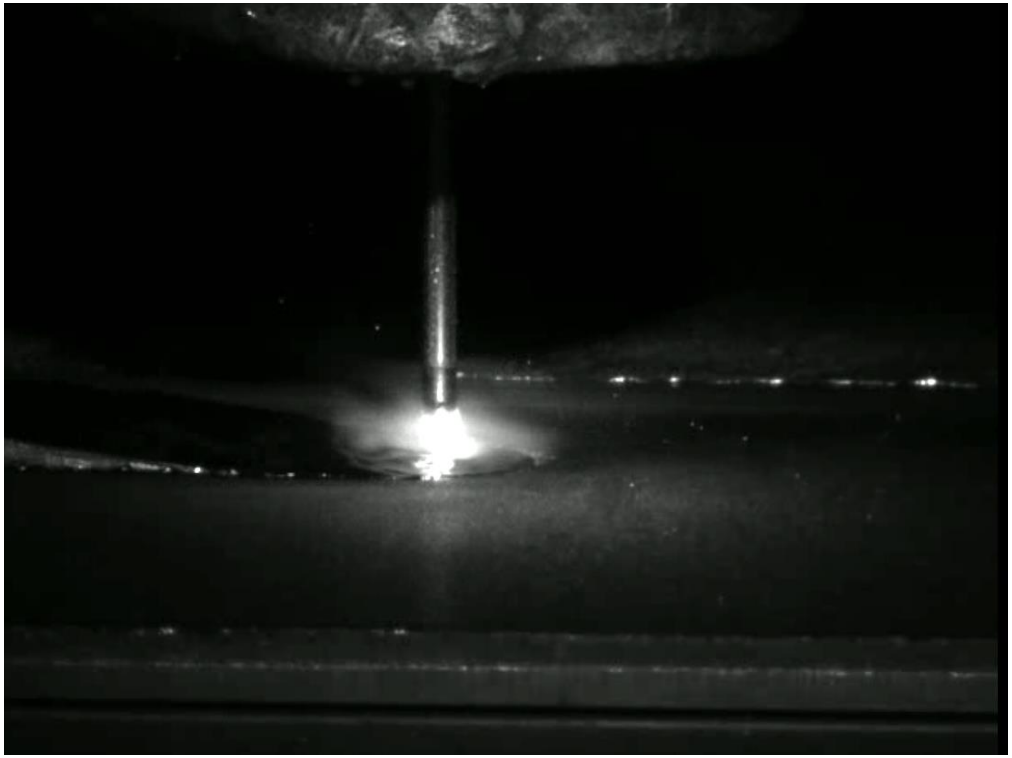
- alloy
- anisotropy
- deformation
- hardness
- cracks
- inclusions
- thickness

radiographic

- cracks
- density
- inclusions
- micro-porosity
- shrinking
- thickness
- holes

Defects, inspection techniques and monitoring

Watch the monitoring video



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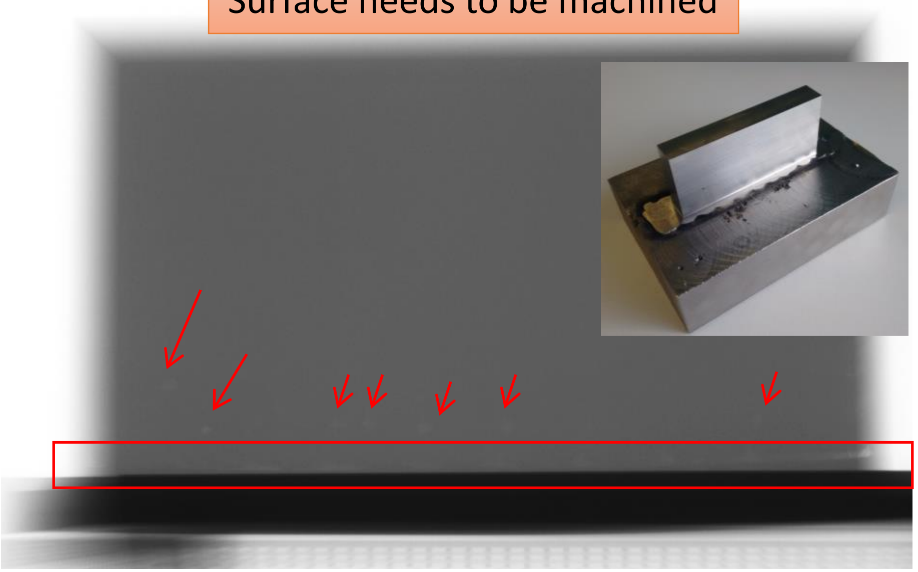
Defects, inspection techniques and monitoring

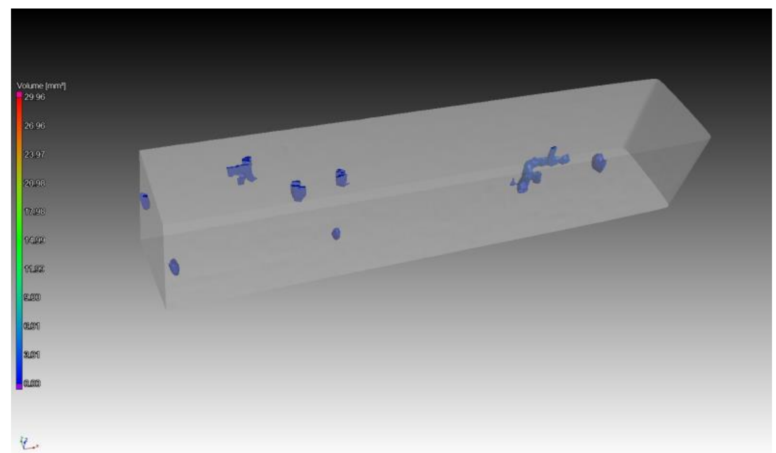
XDR or XCT tests (machining of the surface is recommended) for the detection of:

- Pores
- Lack of fusion
- Cracks

Surface needs to be machined



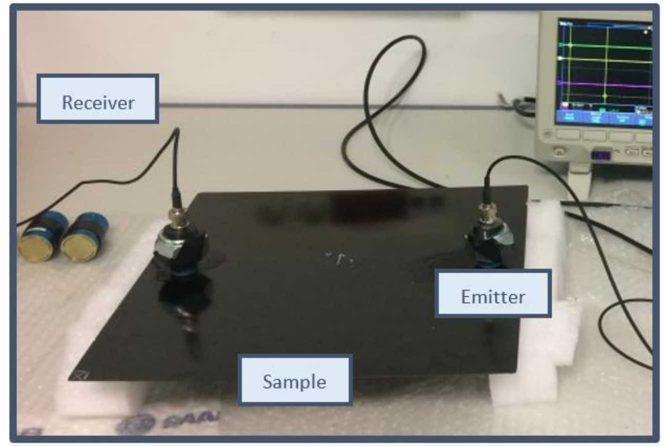
XCT for small zones.
No need of surface machining



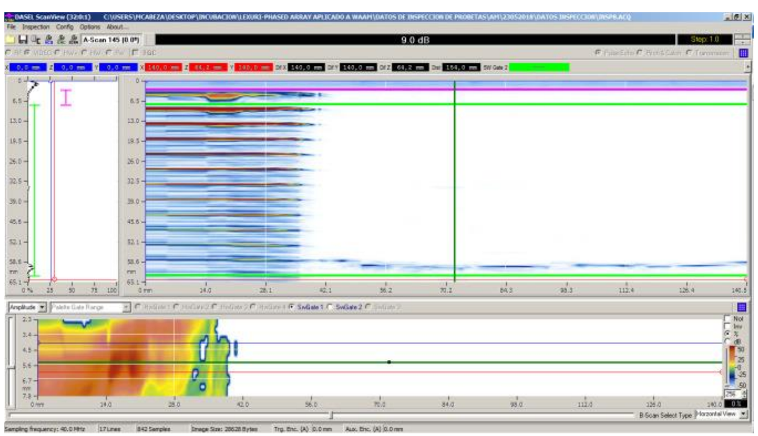
Defects, inspection techniques and monitoring

UT (machining of the surface is recommended) for the detection of :

- Pores
- Lack of fusion
- Cracks



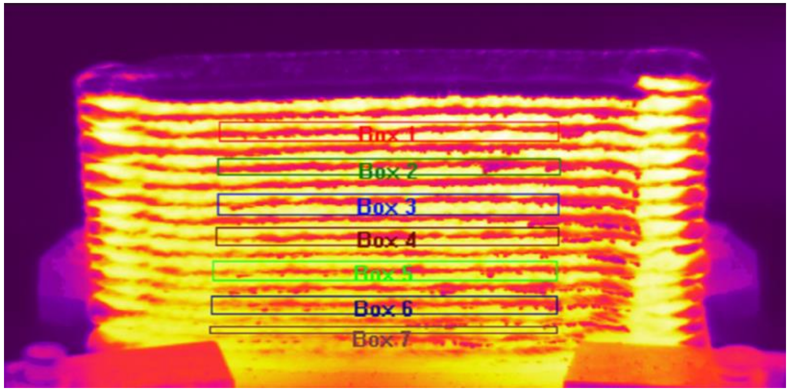
The ultrasonic waves enter in the material and detect internal defects. While these waves go across the material they loose energy (atenuation). Received waves are reflected and show discontinuities with their size and location.

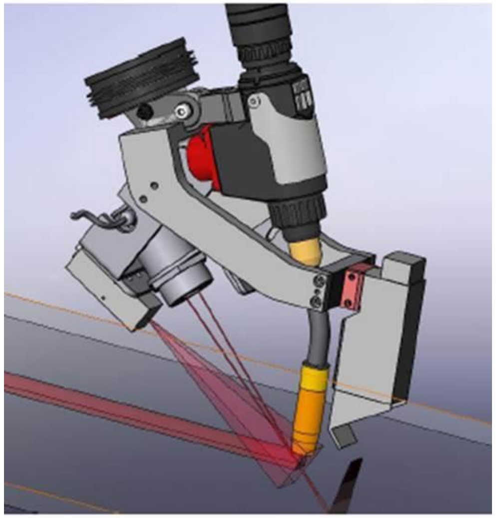


Defects, inspection techniques and monitoring

Whenever possible, the most interesting approach is process monitoring (on-line) in order to detect insitu anomalies in the signals associated with defects:

- Thermography to monitor the temperature
- Multisensor system to detect anomalies: melt pool temperature, deposited weld bead geometric characteristics, electric parameters, WFS, protective gas control and displacement data.





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Question. Quizz

Key ideas

- A good selection of parameters is necessary to assure the quality of the manufactured part.
- Apart from assuring the lack of defects, a proper selection of parameters could optimise the mechanical properties.
- A good balance between the deposition rate and quality need to be done.
- Each part or zone of a part would require adapted parameters to its specific geometry.
- In general the aluminium alloys give rise to porosity and cracking problems → follow recommendations and validate with NDT or monitoring
- The anisotropy is difficult to remove but it can be reduced to very low values

Questions from the audience

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Thank you

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