INSIDE Metal Additive Manufacturing

WAAM processing and testing

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WAAM Coupon printing – Overview

LMD Coupon printing - Materials

S355 :

Typical Chemical Composition of Wire (%)

C	Si	Mn	P	S
0.07	0.83	1.48	0.017	0.020

Typical Mechanical Properties of All-Weld Metal

YS MPa(lbs/in²)	TS MPa(lbs/in²)	EL (%)	Temp. ℃ (℉)	CVN-Impact Value J (ft · lbs)
430 (62,400)	540 (78,400)	28	-29 (-20)	70 (52)

316LSi :

C	Mn	Si	P	S	Cr	Ni	Mo
0.020	1.4	0.85	≤ 0.025	≤ 0.020	19	12.5	2.6

Re-Lim Elast (MPa)	Rm_Resist meca (MPa)	Allongement A5 (%)	Résilience ISO - V (J)	
			+20 °C	-120 °C
≥350	≥510	≥30	≥80	>32

Gaz test : M13

Duplex 2209 :

C	Mn	Si	P	S	Cr	Ni	Mo	Nb	Cu	N	Ferrite
0.02	1.70	0.50	≤ 0.030	≤ 0.020	23	9	3	-	-	0.15	30-65

Heat Treatment	Yield Strength N/mm^2	Tensile Strength N/mm^2	Elongation A5 (%)	Impact Energy ISO - V (J) 20°C	Hardness
As Welded	≥ 450	≥ 600	≥ 26	≥ 80 J	-

M13(Cargal1)

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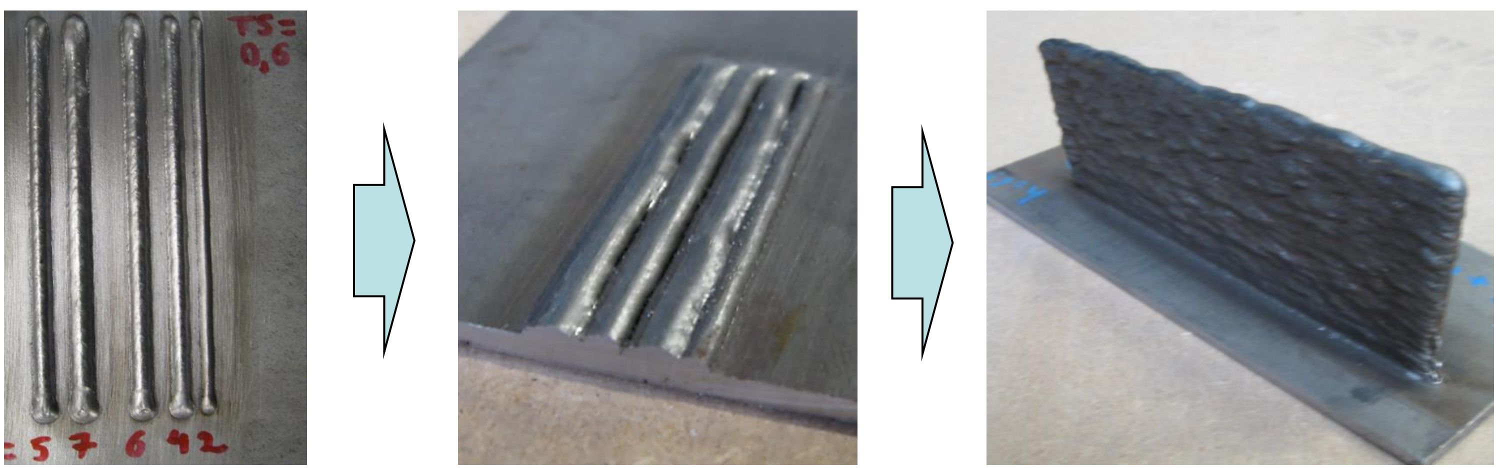
LMD Coupon printing

- Approach for the different subsequent WAAM tests :
  - Bead on plate (initial acceptable proces param. WFS, TS ...)
  - WAAM of different passes/layers (effect of overlap, strategy etc. on porosity, layer adhesion ...)
  - WAAM walls (for characterization based on ≠ param. e.g HI ...)



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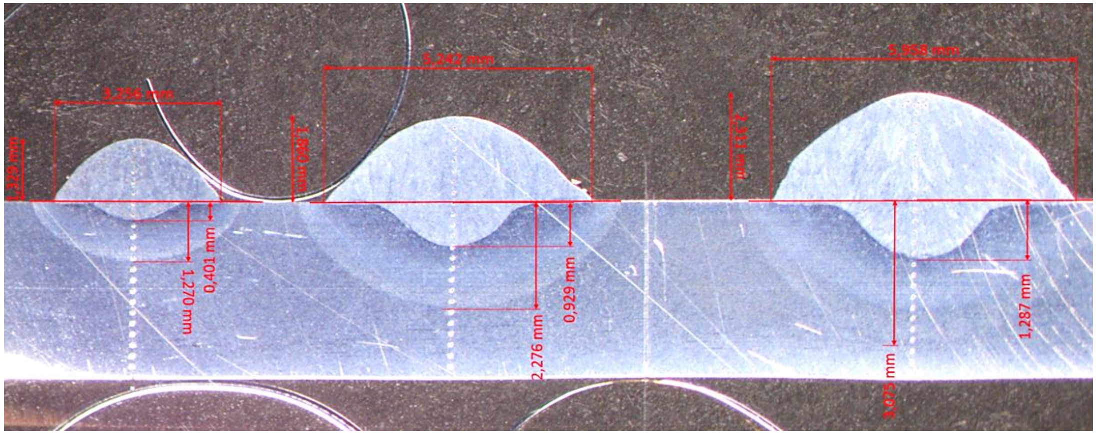
LMD Coupon printing - Beads

- Bead on plate tests for param. screening (S355, 316L, 2209) :
  - ≠ synergic curves for standard, CMT and CMT-P (Fronius)
  - Deposition speed TS up to 0,6m/min (if > ten humping effect)
  - Wirediam. 1.2mm, wire speeds WFS up to 8m/min (200A/20V)
  - Ar + 18%CO_2 (S355), Ar & Ar + 2%CO_2 (316L and duplex 2209)
  - Deposit widht +/- 2,5 to 7mm and height +/- 1,5 à 3mm



S355, CMT, TS0.5m/min, WFS 2 & 4 & 6m/min

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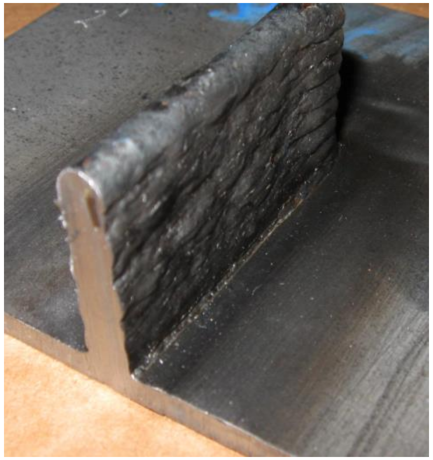
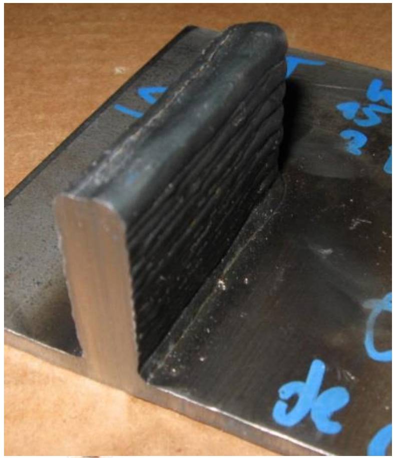
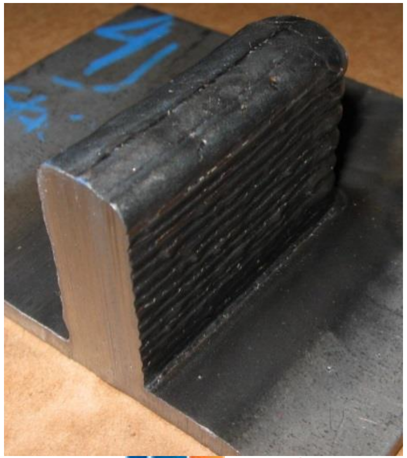
LMD Coupon printing - Coupons

- Multiples passes/layers (for S355, 316L, 2209) based on :
  - ≠ synergic CMT curves for S355 vs. 316L & 2209
  - Deposit speed 0.5m/min, 2 ≠ wire speeds for ≠ heat input
  - 1, 2 and 3 passes in 15 layers (each layer change o/t WAAM direction)
  - Overlap 65% to 75% (arc stability vs. waviness) for multi-pass
  - Interpass <u>temperature</u> (T_{ip}) 100° C and 200° C vs. Interpass <u>time</u> 30sec







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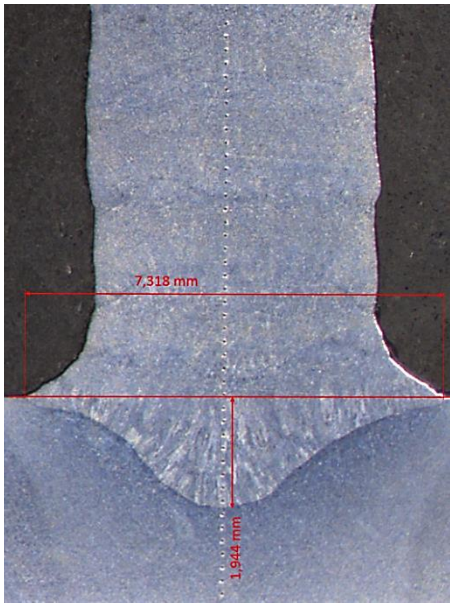
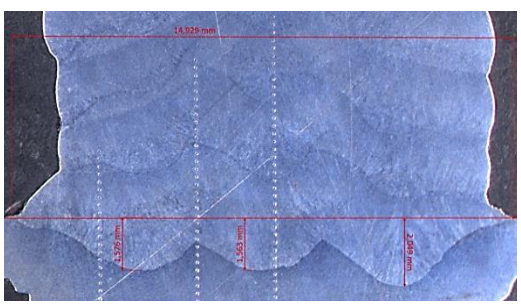
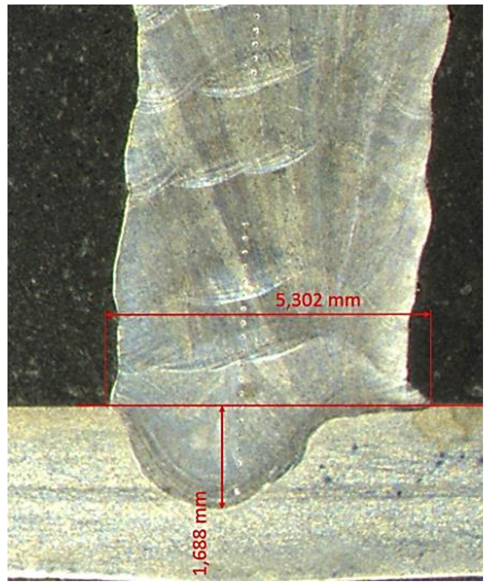
LMD Coupon printing - Microstructures

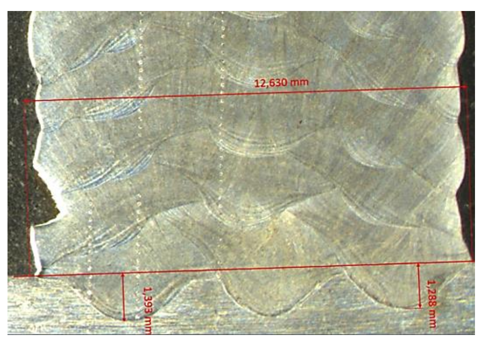
S355



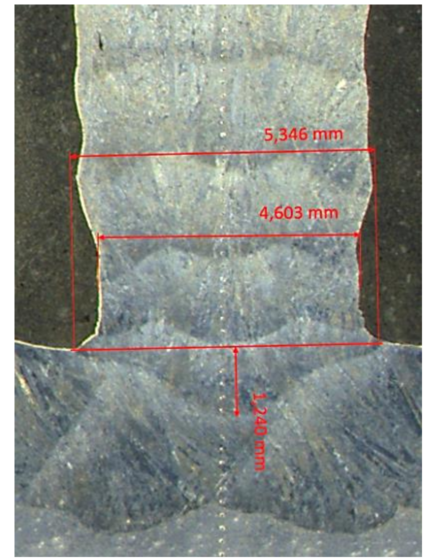


316L





2209



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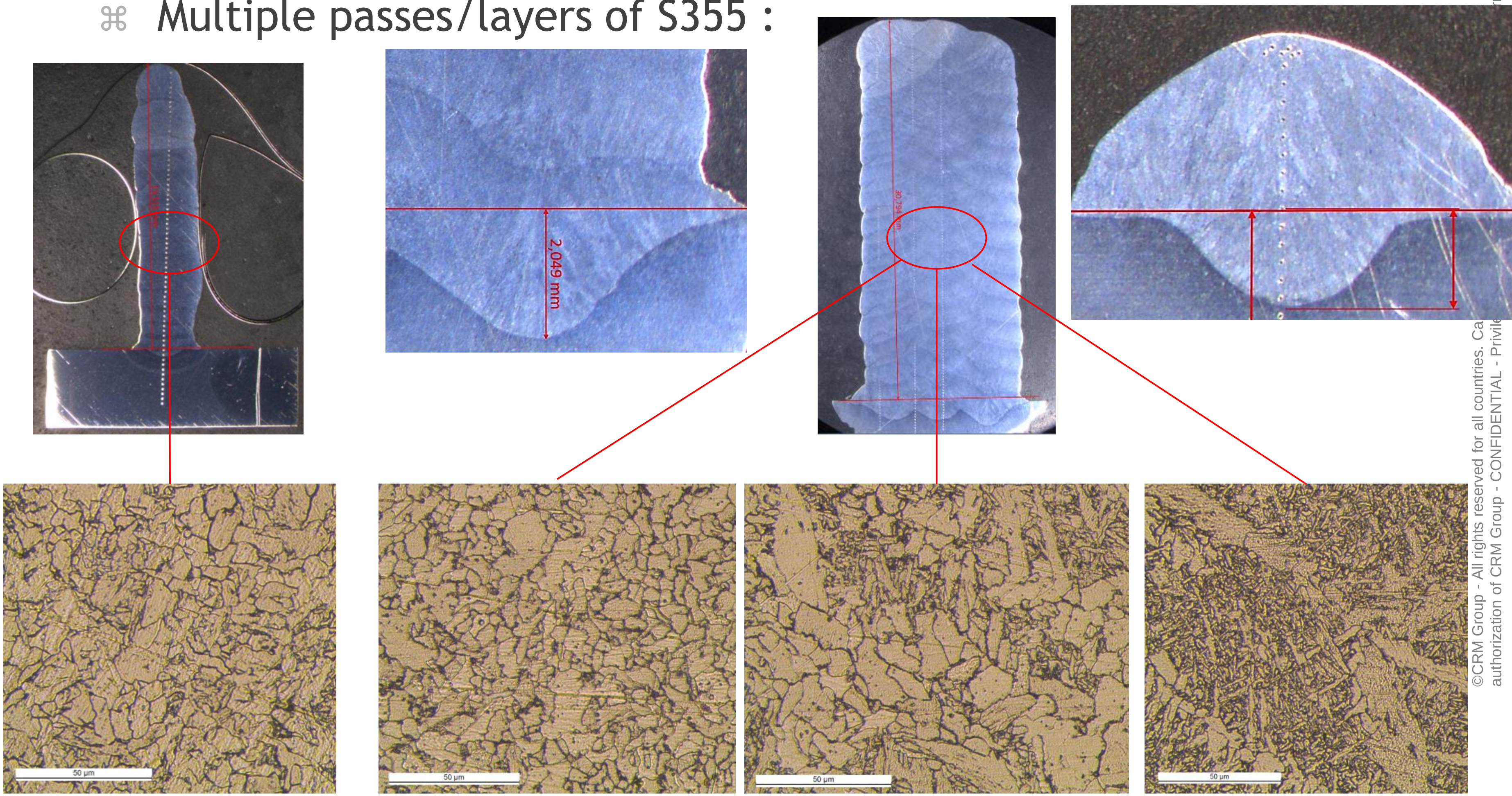
LMD Coupon printing - Microstructures

- Multiple passes/layers of S355 :



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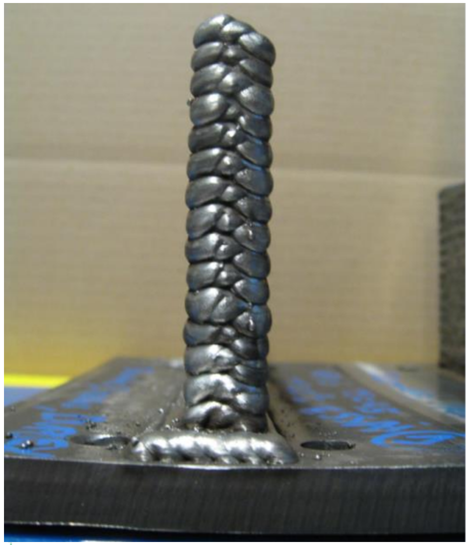
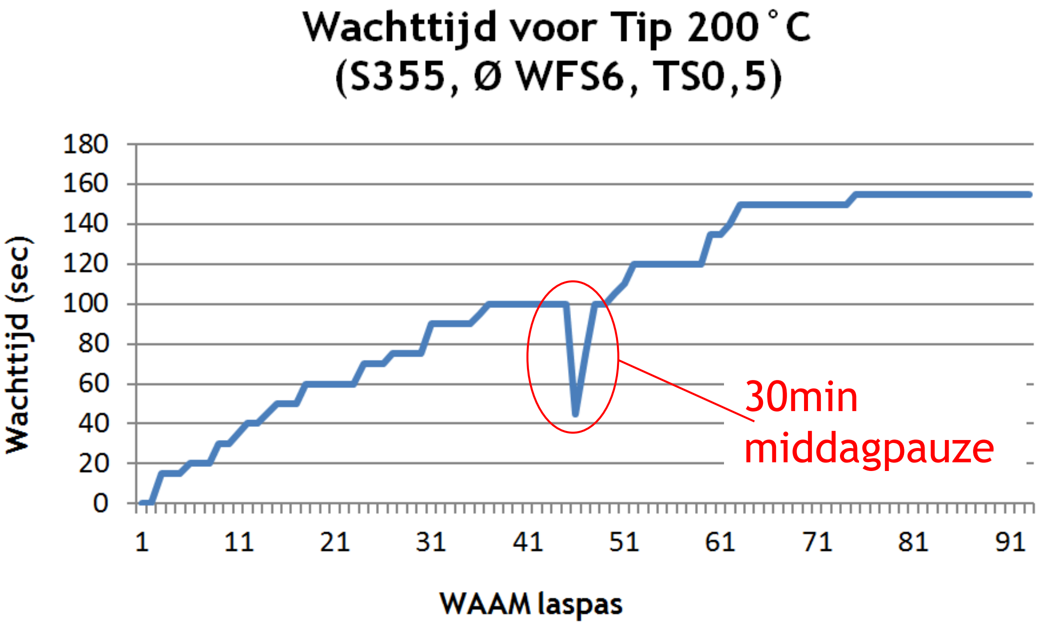
WAAM Coupon printing and characterization – S355

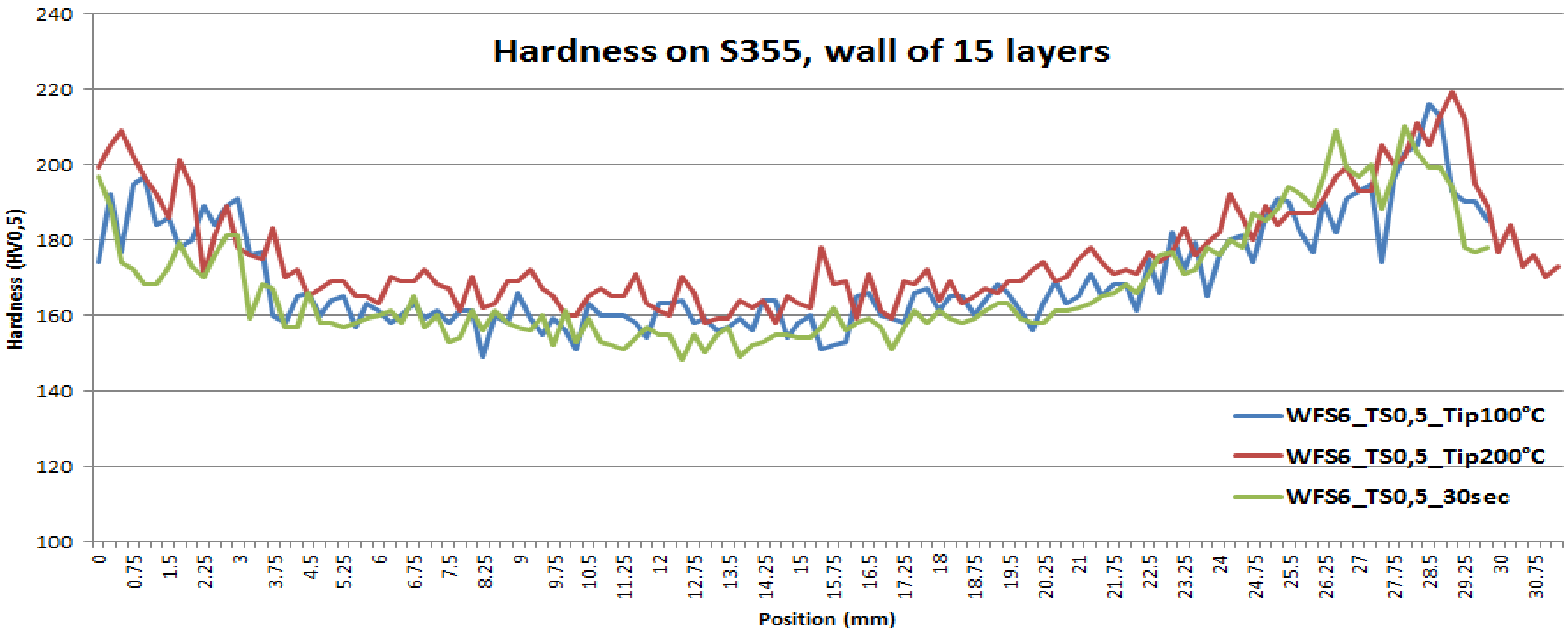
S355 printing – Interpass temperature

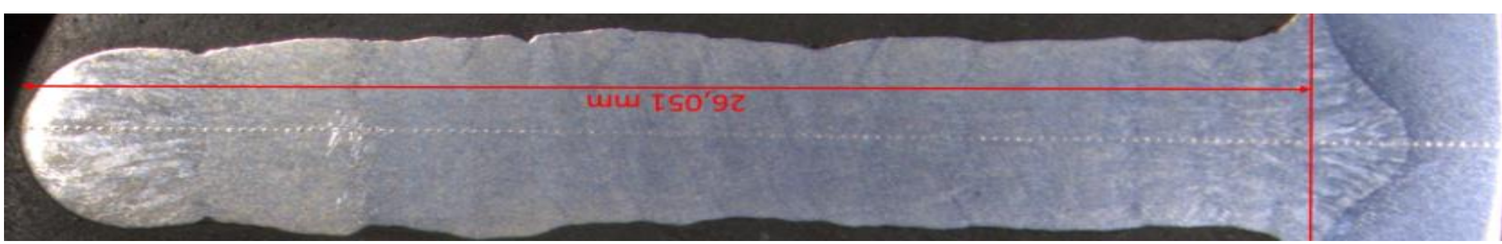


- Interpass temperature set to 200 °C
- Waiting time increases with the coupon height

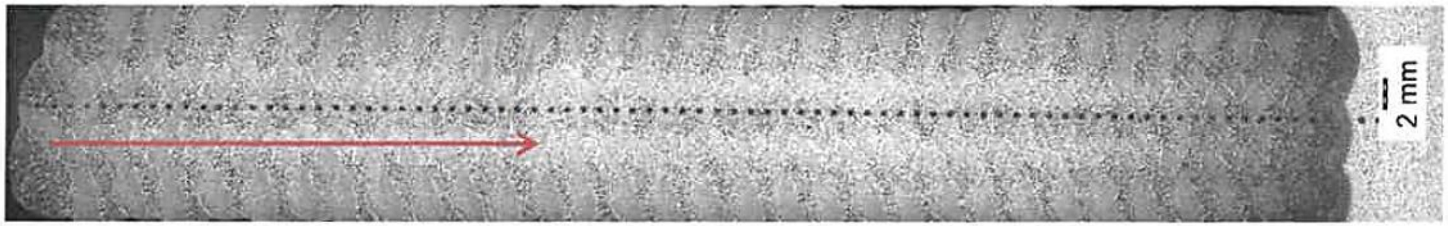


S355 printing – Hardness thin wall





S355 printing – Hardness thick wall



	Row of indentation: R1						**Vickers:** HV 10						**Requirement:** n.a.				
n°	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
	193	211	213	200	195	205	185	201	197	188	199	196	190	203	185	197	189
n°	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	
	191	202	184	199	182	193	191	191	201	185	194	188	193	199	187	198	
	Row of indentation: R2						**Vickers:** HV 10						**Requirement:** n.a.				
n°	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**
	189	193	206	191	206	195	197	205	194	209	186	205	200	192	204	193	208
n°	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	
	197	198	204	197	208	186	205	196	198	202	191	205	195	200	211	198	
	Row of indentation: R3						**Vickers:** HV 10						**Requirement:** n.a.				
n°	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**	**76**	**77**	**78**	**79**	**80**	**81**	**82**	
	219	189	208	202	213	229	200	225	211	217	238	211	245	282	193	189	

- Values typically 180HV$_{10}$ - 220HV$_{10}$ *(1st pass zone up to 282HV$_{10}$)*

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S355 printing – Tensile testing

Hyundai SM-70 ECO, 18%CO_2

Typical Chemical Composition of Wire (%)

C	Si	Mn	P	S
0.07	0.83	1.48	0.017	0.020

Typical Mechanical Properties of All-Weld Metal

YS MPa(lbs/in²)	TS MPa(lbs/in²)	EL (%)	Temp. ℃ (℉)	CVN-Impact Value J (ft · lbs)
430 (62,400)	540 (78,400)	28	-29 (-20)	70 (52)

Test specimen number	Dimensions diameter d_0 [mm]	Test temp. T [°C]	Yield strength R_{eH} [MPa]	Proof strength $R_{p0,2}$ [MPa]	Tensile strength R_m [MPa]	Original gauge length L_0 [mm]	Elongation at R_m A_g [%]	Elongation after fracture A [%]	Reduction of area Z [%]
ISS-HT1	Ø 5,013	21	-	486	595	25,40	-	32,8	78
ISS-HT2	Ø 5,007	21	-	485	603	25,56	-	30,2	78
ISS-VT1	Ø 5,005	21	-	-	593	25,63	-	-	79
ISS-VT2	Ø 5,004	21	-	476	595	25,43	-	31,7	79

- Tensile test results better than typical values (even elongation!)
- HT & VT direction nearly identical results

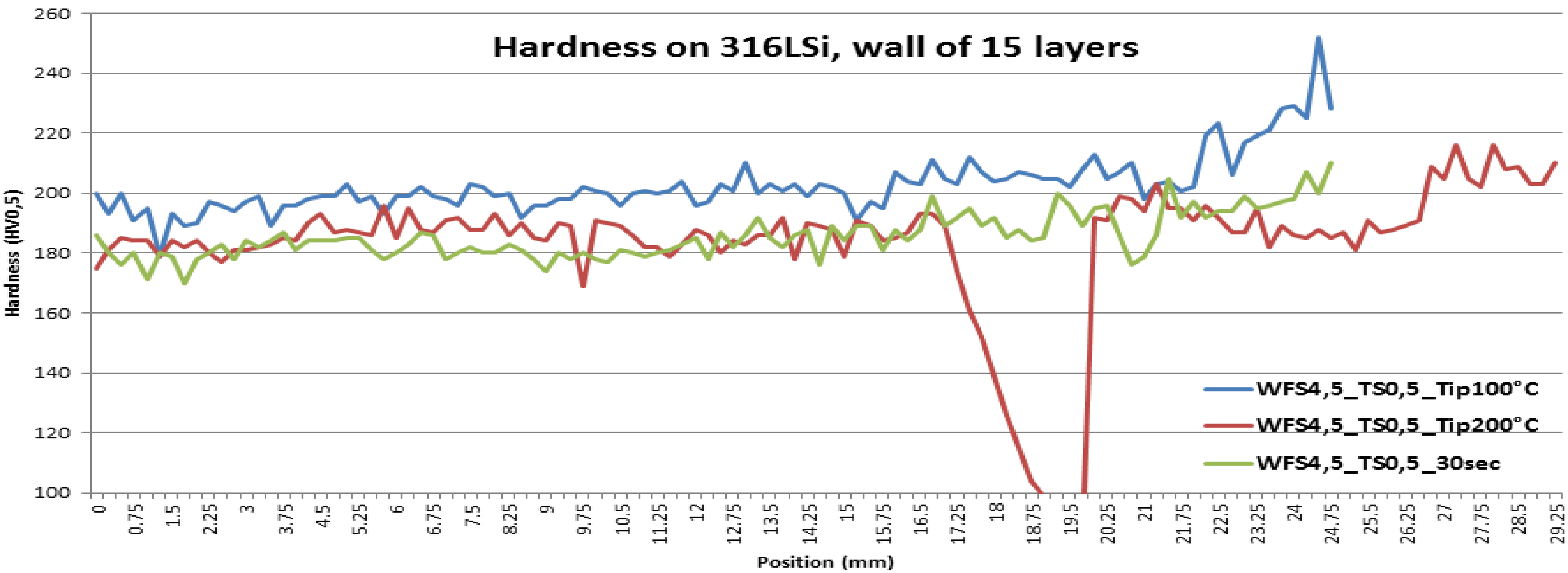
S355 printing – Impact testing

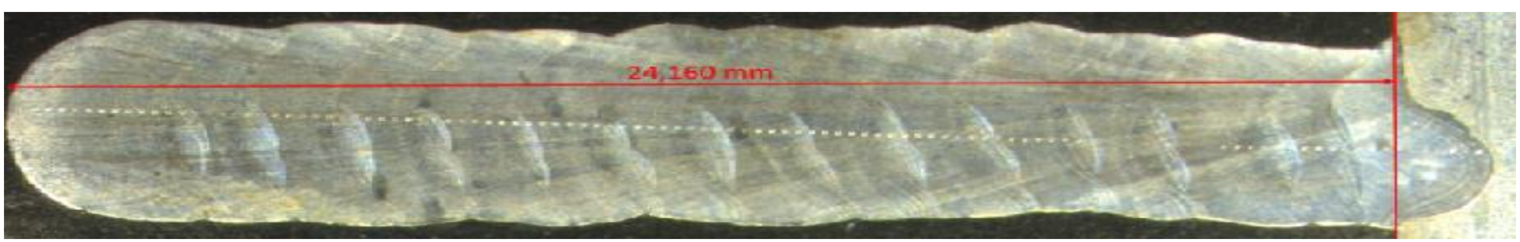
Specimen reference	Specimen orientation	Notch location	Size	Test temp.	Impact absorbed energy		Remarks
			[mm]	[°C]	KV_2 [J]	Average	
ISS-HK1	longitudinal direction	surface	10 x 10	-29	145,7	146,8	
ISS-HK2					151,3		
ISS-HK3					143,2		
ISS-VK1	vertical direction	surface	10 x 10	-29	169,4	165,9	
ISS-VK2					157,1		
ISS-VK3					171,3		

- Impact test results a lot better than typical values (70J @ -29° C)
- Samples in VT direction somewhat more ductile

WAAM Coupon printing and characterization – SS 316L

316L printing – Influence of interpass temperature on hardness – thin wall





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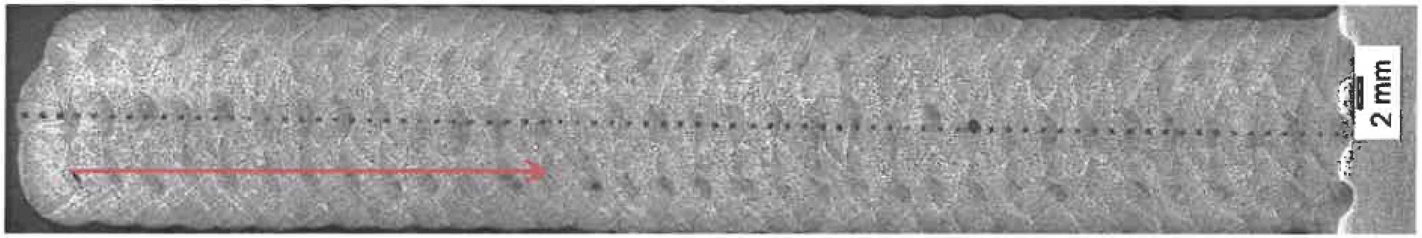
316L printing – Hardness thick wall



Row of indentation: R1						Vickers: HV 10							Requirement: n.a.				
n°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	191	199	184	183	193	194	207	206	204	218	212	221	196	207	203	212	207
n°	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	
	205	208	199	209	194	207	201	210	194	202	211	206	197	209	203	202	

Row of indentation: R2							Vickers: HV 10							Requirement: n.a.			
n°	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
	209	204	200	199	198	195	195	204	203	202	194	202	202	200	206	203	204
n°	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	
	208	197	202	195	204	-	190	193	203	205	198	199	198	203	206	196	

Row of indentation: R3							Vickers: HV 10						Requirement: n.a.
n°	67	68	69	70	71	72	73	74	75	76	77	78	79
	207	208	214	200	205	201	194	208	207	201	220	207	248

- Values typically $180HV_{10}$ - $220HV_{10}$ *(1st pass zone up to $248HV_{10}$)*

316L printing – Tensile Testing

SAF Filinox 316LSi, 2%CO_2

C	Mn	Si	P	S	Cr	Ni	Mo
0.020	1.4	0.85	≤ 0.025	≤ 0.020	19	12.5	2.6

Re-Lim Elast (MPa)	Rm_Resist meca (MPa)	Allongement A5 (%)	Résilience ISO - V (J)	
			+20 °C	-120 °C
≥350	≥510	≥30	≥80	>32

Gaz test : M13

Test specimen number	Dimensions diameter d_o [mm]	Test temp. T [°C]	Yield strength R_{eH} [MPa]	Proof strength $R_{p0,2}$ [MPa]	Tensile strength R_m [MPa]	Original gauge length L_0 [mm]	Elongation at R_m A_g [%]	Elongation after fracture A [%]	Reduction of area Z [%]
ISA-HT1	Ø 5,012	21,0	-	378	584	25	-	40,5	62
ISA-HT2	Ø 5,013	21,1	-	375	583	25	-	32,0	57
ISA-VT1	Ø 5,011	21,1	-	372	628	25	-	36,0	75
ISA-VT2	Ø 5,011	21,1	-	364	616	25	-	37,5	67

- Tensile test results better than typical values (even elongation!)
- HT & VT direction seem not so different

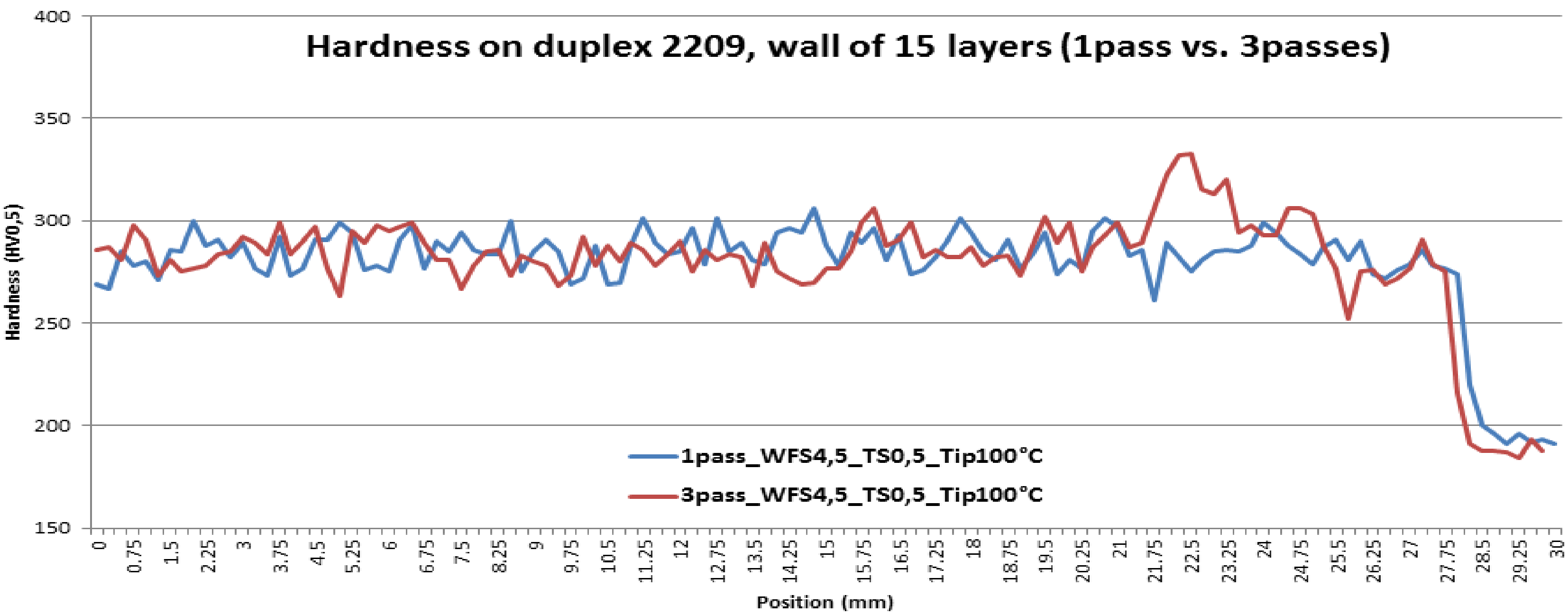
326L printing – Impact Testing

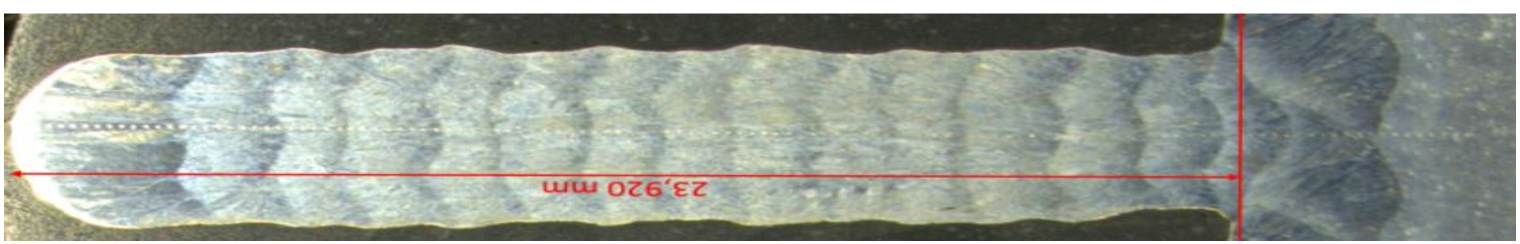
Specimen reference	Specimen orientation	Notch location	Size [mm]	Test temp. [°C]	Impact absorbed energy KV_2 [J]	Average	Remarks
ISA-HK1	longitudinal direction	surface	10 x 10	20	104,1	108,6	
ISA-HK2					114,0		
ISA-HK3					107,6		
ISA-VK1	vertical direction	surface	10 x 10	20	141,0	130,5	
ISA-VK2					127,3		
ISA-VK3					123,3		

- Impact test results a lot better than typical values (80J @ 20° C)
- Samples in VT direction clearly more ductile
- *More in-depth metallography to be performed*

WAAM Coupon printing and characterization – 22 9 3 welding wire for duples stainless steels

22 9 3 printing – Hardness thin wall





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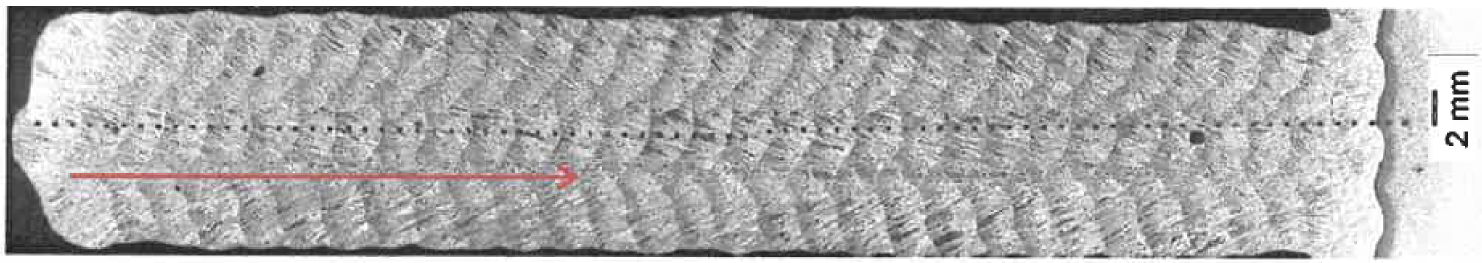
22 9 3 printing – Hardness thick wall



Row of indentation: R1							Vickers: HV 10						Requirement: n.a.				
n°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	267	267	276	278	279	275	282	292	285	283	284	288	277	290	295	281	278
n°	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	
	286	296	282	268	293	299	281	276	281	292	275	282	291	285	285	287	
Row of indentation: R2							Vickers: HV 10						Requirement: n.a.				
n°	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
	269	281	276	297	285	267	290	279	285	270	280	281	278	267	275	280	279
n°	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	
	275	275	278	275	287	270	285	200	281	270	277	283	294	290	280	278	
Row of indentation: R3							Vickers: HV 10						Requirement: n.a.				
n°	67	68	69	70	71	72	73	74	75	76	77	78	79	80			
	275	292	282	293	272	283	249	285	289	278	260	274	219	194			

- Values typically 260HV_{10} - 300HV_{10}

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22 9 printing – Tensile testing

Oerlikon Inertfil 22 9 3, 2%CO_2

C	Mn	Si	P	S	Cr	Ni	Mo	Nb	Cu	N	Ferrite
0.02	1.70	0.50	≤ 0.030	≤ 0.020	23	9	3	-	-	0.15	30-65

Heat Treatment	Yield Strength N/mm²	Tensile Strength N/mm²	Elongation A5 (%)	Impact Energy ISO - V (J) 20°C	Hardness
As Welded	≥ 450	≥ 600	≥ 26	≥ 80 J	-

M13(Cargal1)

Test specimen number	Dimensions diameter d_0 [mm]	Test temp. T [°C]	Yield strength R_{eH} [MPa]	Proof strength $R_{p0,2}$ [MPa]	Tensile strength R_m [MPa]	Original gauge length L_0 [mm]	Elongation at R_m A_g [%]	Elongation after fracture A [%]	Reduction of area Z [%]
ISD-HT1	Ø 5,015	21,9	-	604	810	25	-	27,0	59
ISD-HT2	Ø 5,007	21,9	-	619	804	25	-	27,0	62
ISD-VT1	Ø 5,011	22,0	-	564	761	25	-	25,5	51
ISD-VT2	Ø 5,016	22,1	-	579	772	25	-	31,5	65

- Tensile test results better than typical values (elongation only +/-)
- HT & VT direction seem not so different

22 9 3 printing – Impact testing

Specimen reference	Specimen orientation	Notch location	Size [mm]	Test temp. [°C]	Impact absorbed energy KV_2 [J]	Average	Remarks
ISD-HK1					87,1		
ISD-HK2	longitudinal direction	surface	10 x 10	20	86,9	86,2	
ISD-HK3					84,6		
ISD-VK1					100,9		
ISD-VK2	vertical direction	surface	10 x 10	20	96,6	98,1	
ISD-VK3					96,9		

- Impact test results better than typical values (80J @ 20° C)
- Samples in VT direction somewhat more ductile (as with 316L)
- *More in-depth metallography etc. to be performed (ferrite % and N%)*

WAAM study on the printing of Duplex stainless steel 2209

WAAM of duplex steel 2209

- Use of CEWELD 2209 (welding wire) :
  - Most WAAM with Ar-2.5%CO_2 and 2 different wire feed speeds (WFS)
  - Robustness WAAM processing → deposition, defects … & NDT (PT, RT)
  - Material/Structure/Process → Metallography
  - Mechanical characterization
    - Hardness measurements
    - Tensile testing

ANALYSE CHIMIQUE DU MÉTAL DÉPOSÉ

C	Mn	Si	Cr	Ni	Mo	N
0,025	1,60	0,5	23,0	9,0	3,0	0,14

PROPRIÉTÉS MÉCANIQUES TYPE DU METAL DÉPOSÉ HORS DILUTION

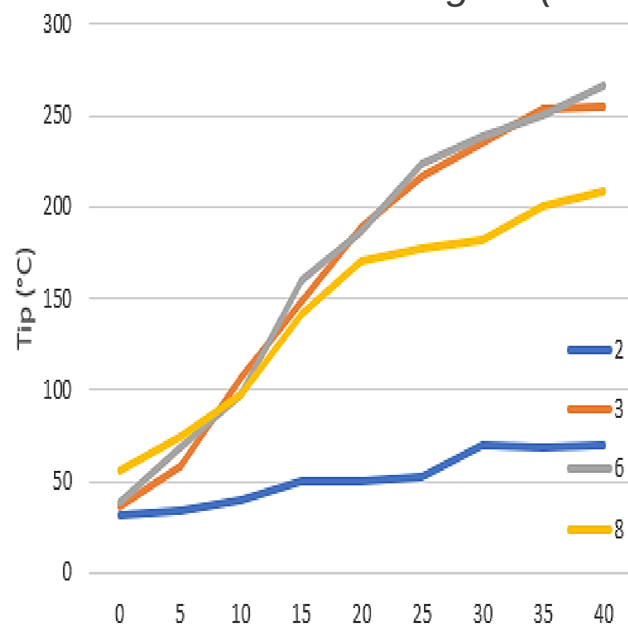
TTH	$Rp_{0,2}$ (N/mm^2)	Rm (N/mm^2)	A5 (%)	Résilience (J) ISO-V			Dureté HRc / HV
				20°C	-40°C	-60°C	
Brut	> 560	> 730	26	>80		>37	

WAAM of duplex steel 2209 – Control of interpass temperature and Heat input

- Wall height & width variation f(parameters, Tip, WFS)
- Thermal balance i.e finding equilib. between heating up (HI …) and cooling down (Tip or tip, heat sink, …)

Sample N°	Wire (brand)	WFS (m/min)	Interpass (sec)	Cleaned (y/n)	Width (mm)	Height (mm)
2	CE	2.5	120	y	3.65	61.6-62.5
3	CE	2.5	60	n	3.7	60.3-61.5

Interpass temperature measured at different wall heights (WFS2.5)

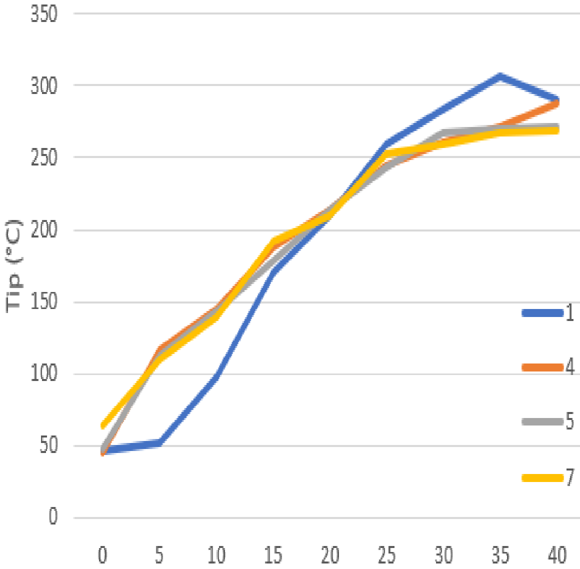


WAAM of duplex steel 2209 – Control of interpass temperature and Heat input

- No arc start problems
- Thermal balance → microstructural & mech. characteristics ?

Sample N°	Wire	WFS	Interpass (sec)	Cleaned (y/n)	Width (mm)	Height (mm)
1	CE	6.5	120	y	8.8	64.6-66.2
4	CE	6.5	120	n	7.1	67-70.3

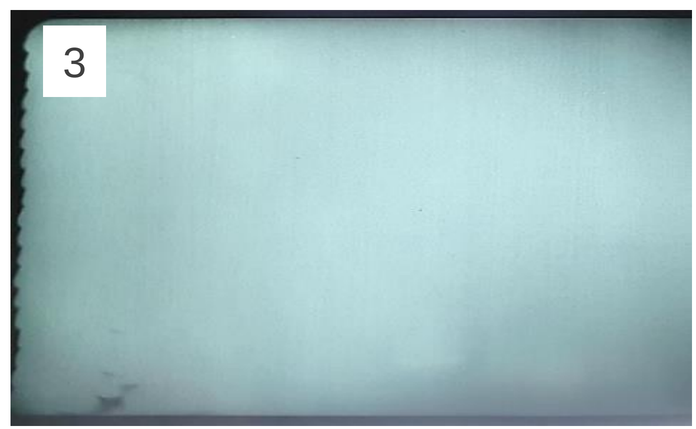
Interpass temperature measured at different wall heights (WFS6.5)



WAAM of duplex steel 2209 – Porosity at low heat input

- WAAM processing at WFS2.5 followed by Radiographic Testing
  - Limited porosity
  - Hardly any difference without/with interpass cleaning (brushing with compressed air rotating tool)

Sample N°	Wire (brand)	WFS (m/min)	Interpass (sec)	Cleaned (y/n)	Width (mm)	Height (mm)
2	CE	2.5	120	y	3.65	61.6-62.5
3	CE	2.5	60	n	3.7	60.3-61.5



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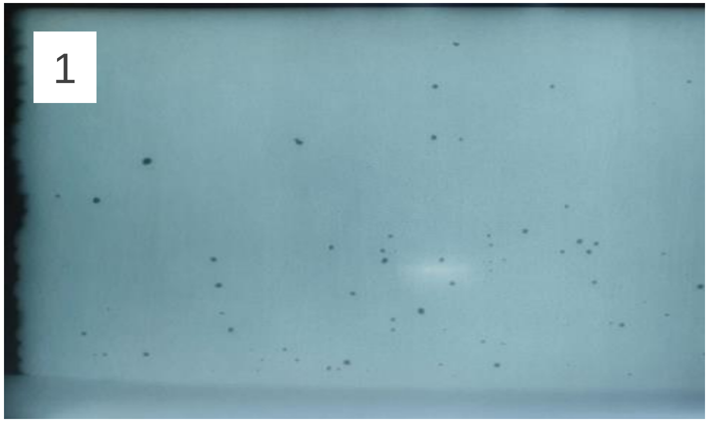
WAAM of duplex steel 2209 – Porosity at high heat input

- WAAM processing at WFS6.5
  - Rather important distributed “mm” size porosity
  - Arc length is known to be important for limiting porosity so probably to be optimized

Sample N°	Wire	WFS	Interpass (sec)	Cleaned (y/n)	Width (mm)	Height (mm)
1	CE	6.5	120	y	8.8	64.6-66.2
4	CE	6.5	120	n	7.1	67-70.3



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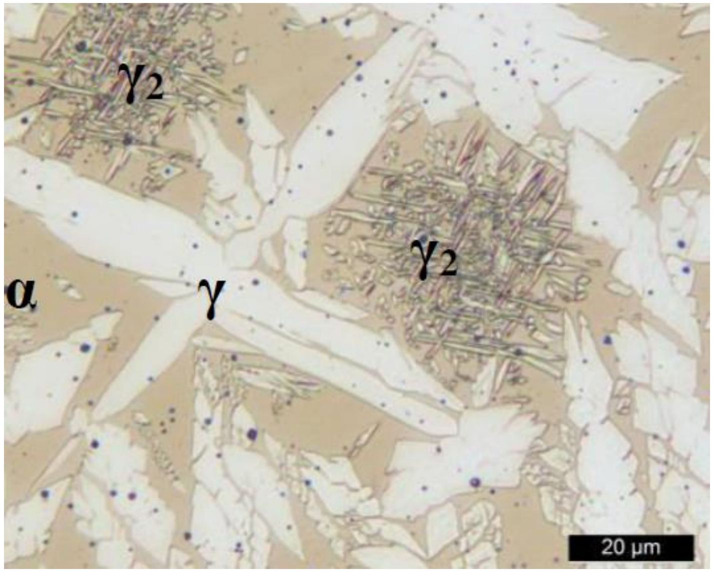
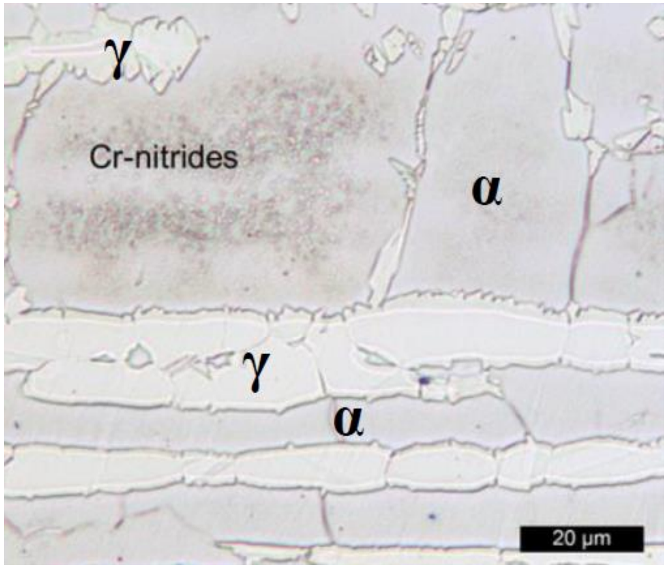
WAAM of duplex steel 2209 – Microstructure

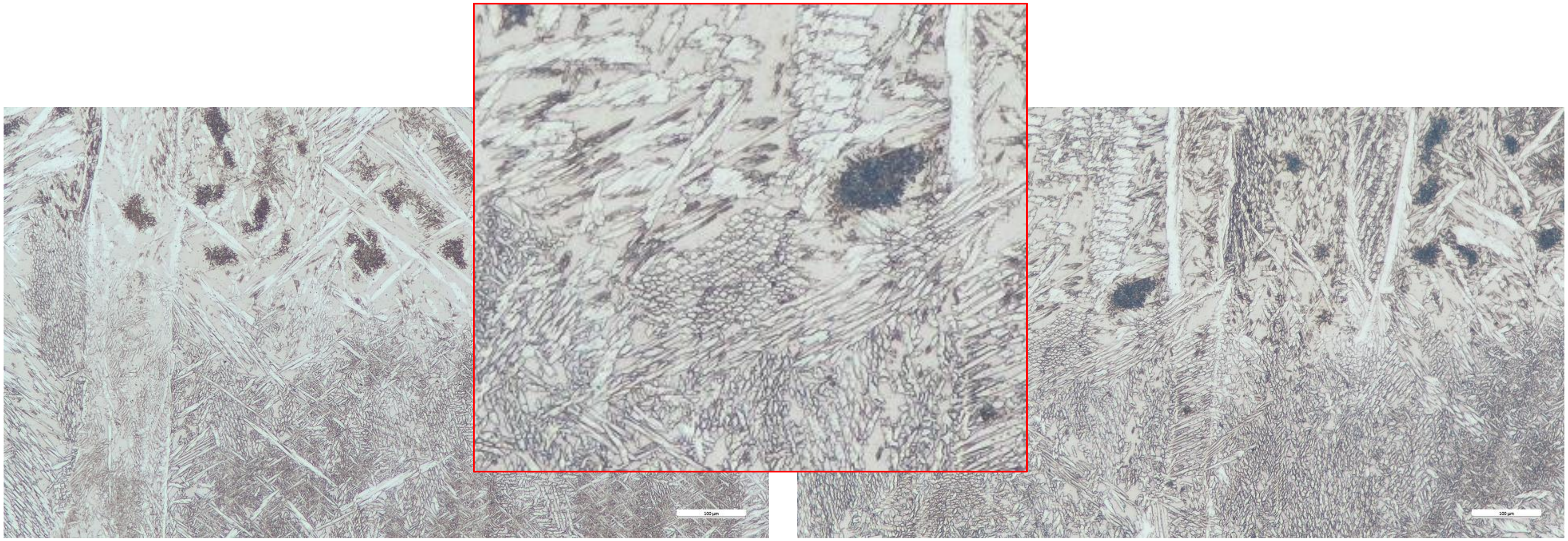
- Metallography of duplex steel welds (typically presence of):
  - Primairy ferrite en austenite (balanced)
  - Secundary austenite
  - CrN (detrimental)





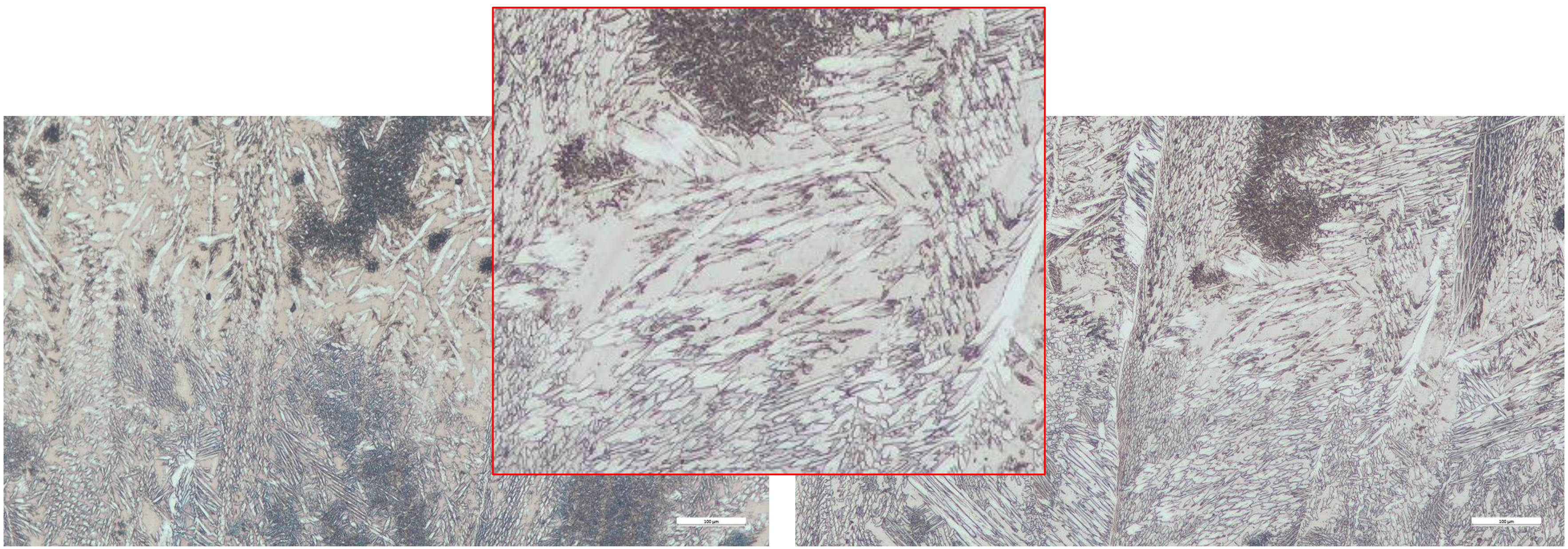
WAAM of duplex steel 2209 – Microstructure

- ⌘ Microstructure at the top o/t wall with WFS2.5m/min
  - Clear difference between heat affected zone (finer structure) and the new deposit



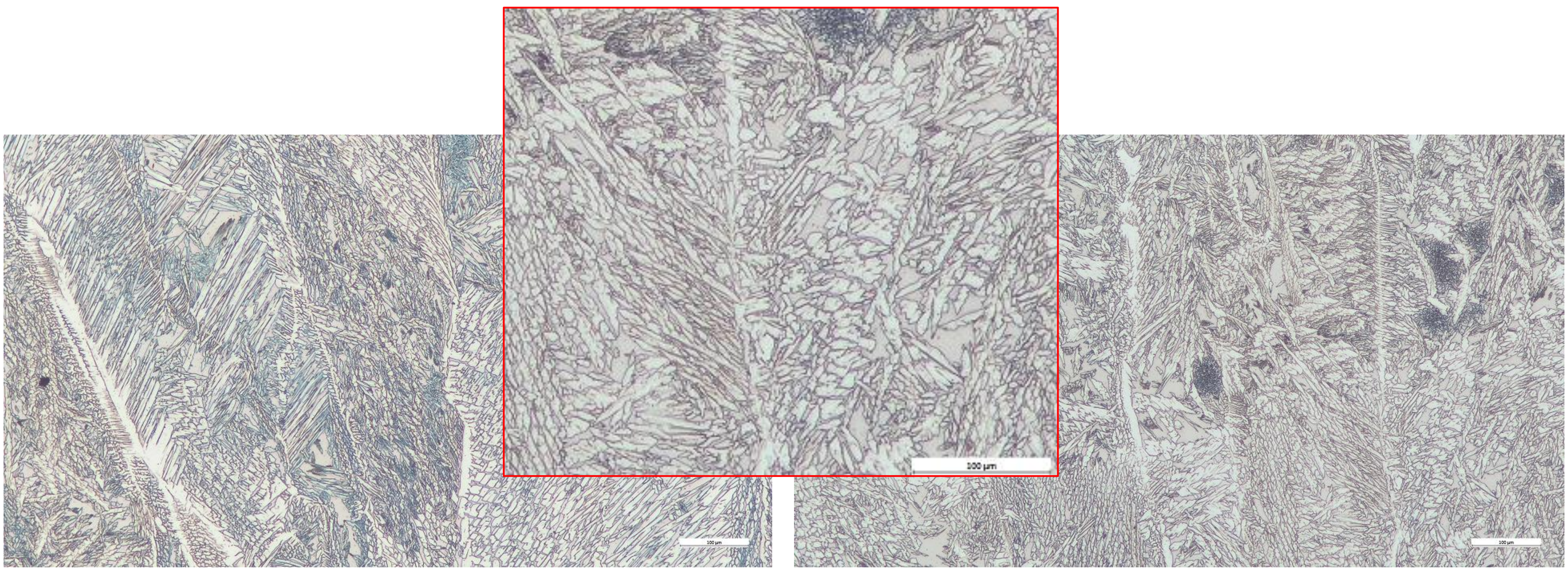
WAAM of duplex steel 2209 – Microstructure

- Microstructure at the bottom o/t wall with WFS2.5m/min
- Microstructure seems to be somewhat coarses compared to top o/t wall



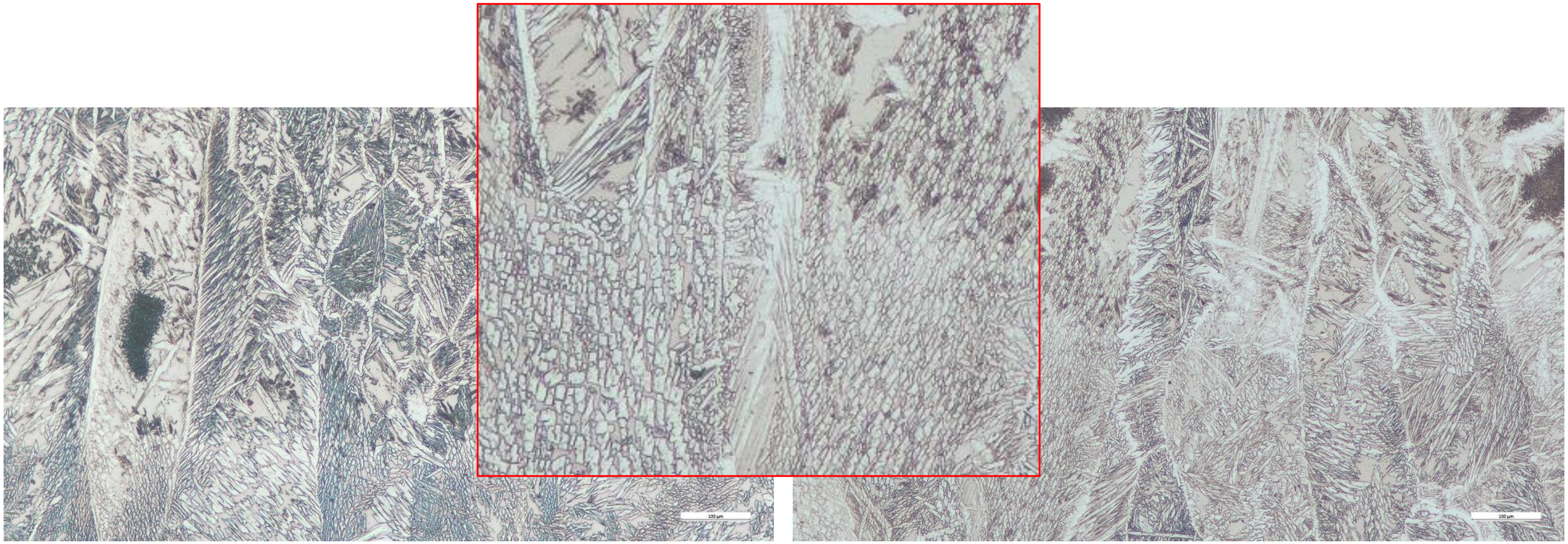
WAAM of duplex steel 2209 – Microstructure

- Microstructure at the top o/t wall with WFS6.5m/min
  - Microstructure seems to contain less ferrite compared to WFS2.5



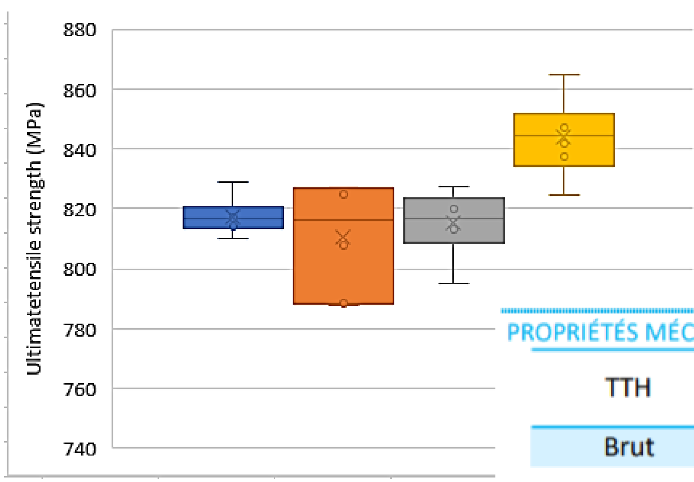
WAAM of duplex steel 2209 – Microstructure

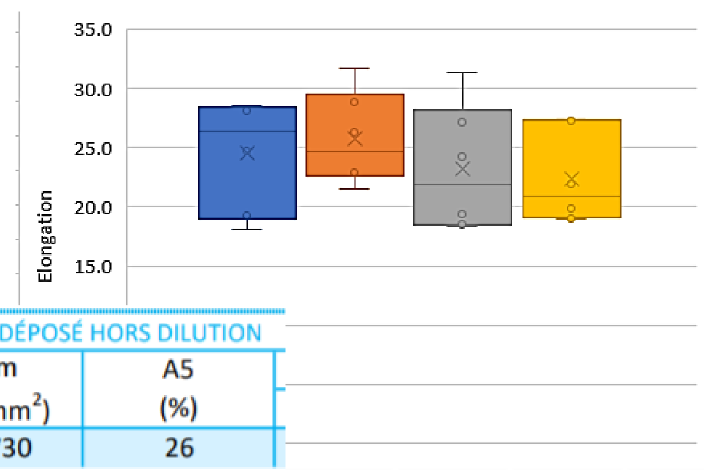
- Microstructure at the bottom o/t wall with WFS6.5m/min
  - Microstructure seems to contain less ferrite compared to WFS2.5



WAAM of duplex steel 2209 – Tensile testing

- Tensile tests (TR) :
  - Only WFS2.5m/min, longitudinal samples (along wall length), As Built
  - 3pcs of size "8x2mm" over wall height (top/middle/bottom)
  - "stronger" than reference value but elongation is mostly lower (multiple heating cycles during WAAM)





PROPRIÉTÉS MÉCANIQUES TYPE DU METAL DÉPOSÉ HORS DILUTION

TTH	$Rp_{0,2}$ (N/mm^2)	Rm (N/mm^2)	A5 (%)
Brut	> 560	> 730	26

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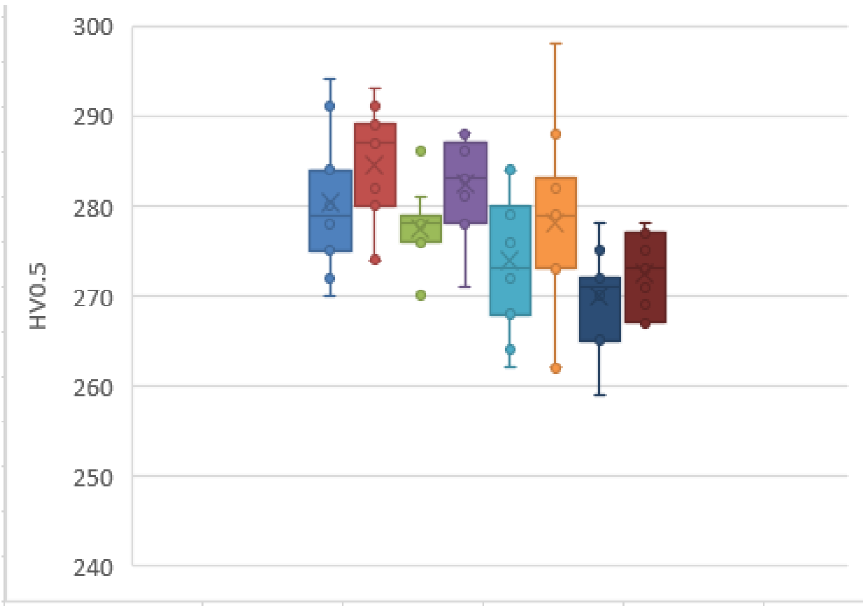
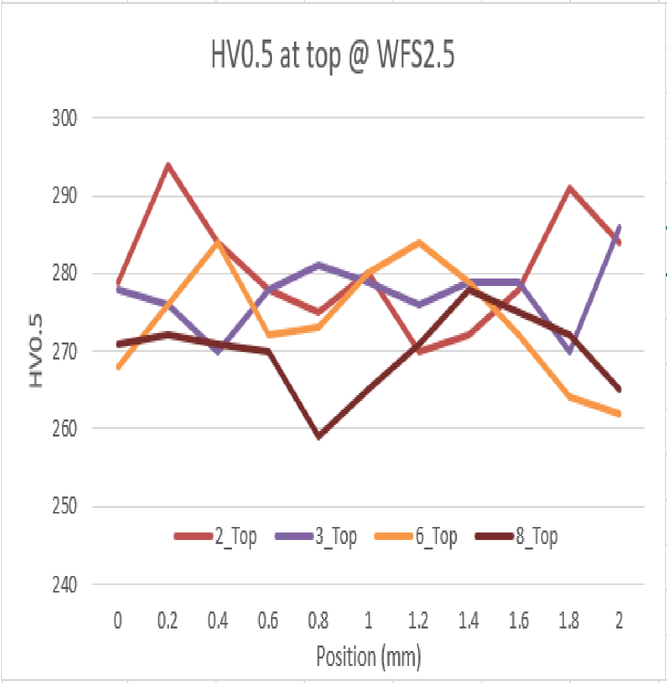
WAAM of duplex steel 2209 – Hardness measurements low heat input

- Hardness measurements (HV):

Sample N°	Wire (brand)	WFS (m/min)	Interpass (sec)	Cleaned (y/n)
2	CE	2.5	120	y
3	CE	2.5	60	n

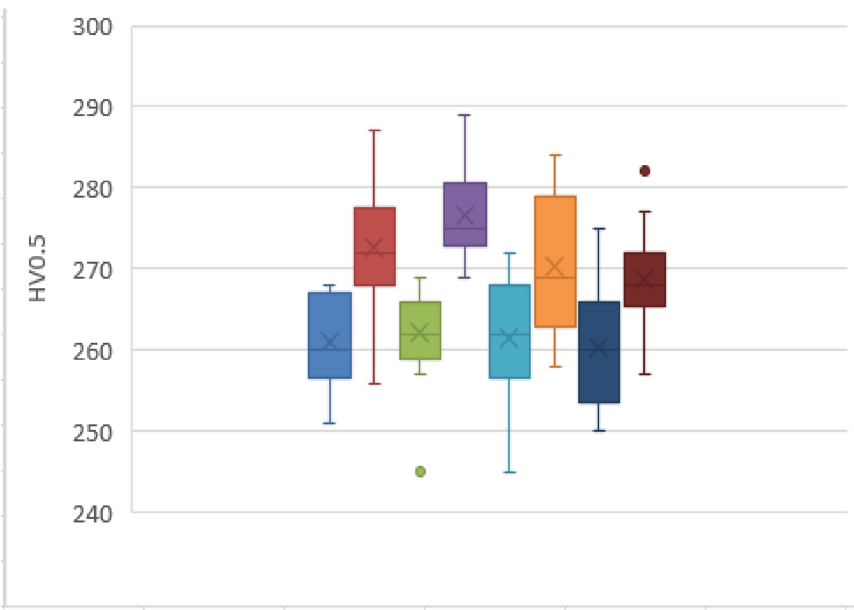


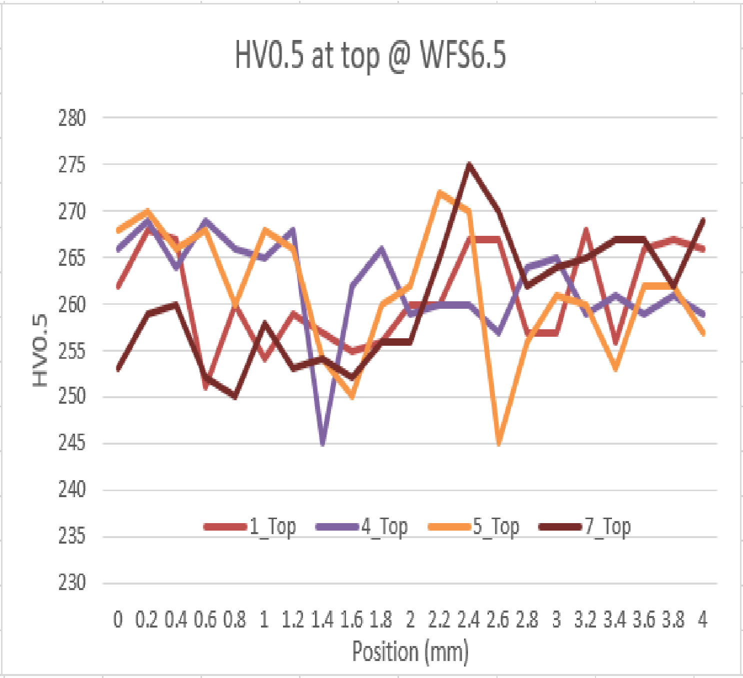


WAAM of duplex steel 2209 – Hardness measurements high heat input

- Hardness measurements (HV):

Sample N°	Wire	WFS	Interpass (sec)	Cleaned (y/n)
1	CE	6.5	120	y
4	CE	6.5	120	n





WAAM of duplex steel 2209

- Hardness measurements :
  - The bottom area is typically somewhat harder than the top and difference increases with HI (1.5% at WFS 2.5 vs 4% at WFS 6.5)
  - Differences in HV0.5 between sample deposits seem to be limited (hardly more than difference between top and bottom of wall)

WAAM of duplex steel 2209 – Impact testing

- Trends :
  - At WFS2.5 (low heat input) the impact resistance is a bit better (≈ 20%)
  - Calculation of conversion factor for 10x10mm samples (i.e. x4) only acceptable after validation
  - *The values are in the As Built condition*

→ what about after heat treatment?

→ 2209 is not suitable for HT (too rapid cooling required)

→ 2205 duplex to be used if combined with HT

Sample	Kc (Joule)
1A-1	5.9
1A-2	5.9
1A-3	5.9
	5.9
1B-1	3.9
1B-2	7.8
1B-3	3.9
	5.2
1C-1	5.9
1C-2	3.9
1C-3	3.9
	4.6
1D-1	5.9
1D-2	3.9
1D-3	3.9
	4.6

WAAM of duplex steel 2209 – Chemical composition

- Chemical composition (COMP) :
  - Analysis by ICP & OES
    - Samples extracted at middle height & length of WAAM walls
    - comparaison Ar-2.5%CO_2 vs “quad mix” shielding gas (Arcal129)
    - With Arcal129 the waviness o/t wall is a lot more regular (smoother surface), this probably due to He content

Arcal 129 composition

Components (% Vol. abs)		
N_2	1,7 %	±0,2 %
CO_2	1,8 %	±0,2 %
He	5 %	±0,5 %
Ar	Balance	

Wall surface with 2.5%CO_2

Wall surface with ternary gas

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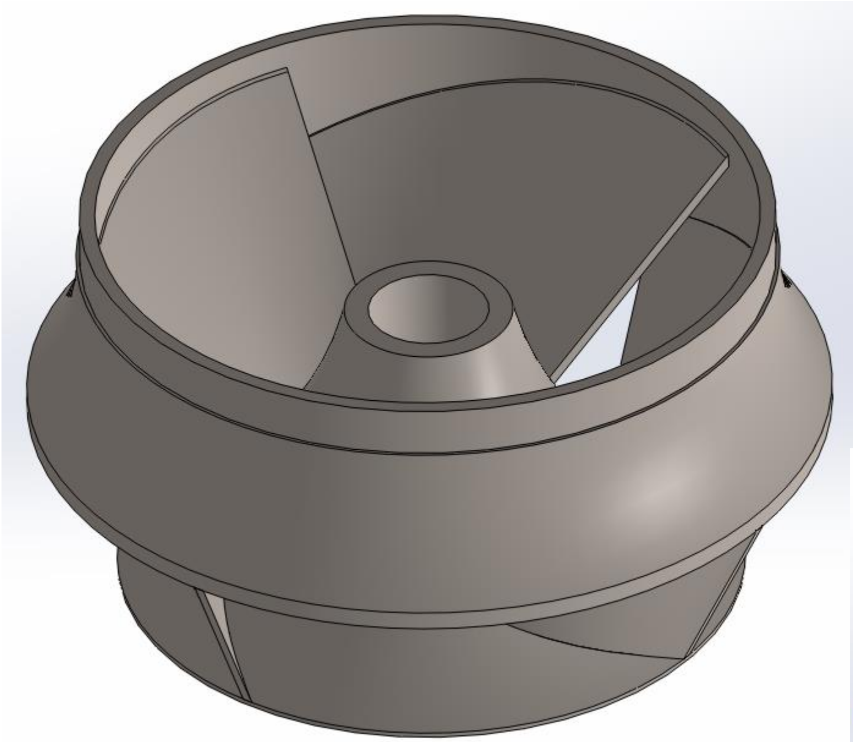
WAAM of duplex steel 2209 – Chemical composition

- Chemical composition %C, %S, %N (weight %) :
  - Certain high quality wires are known to contain less S
  - C pick-up due to deposit (x2) with 2.5% CO_2 gas

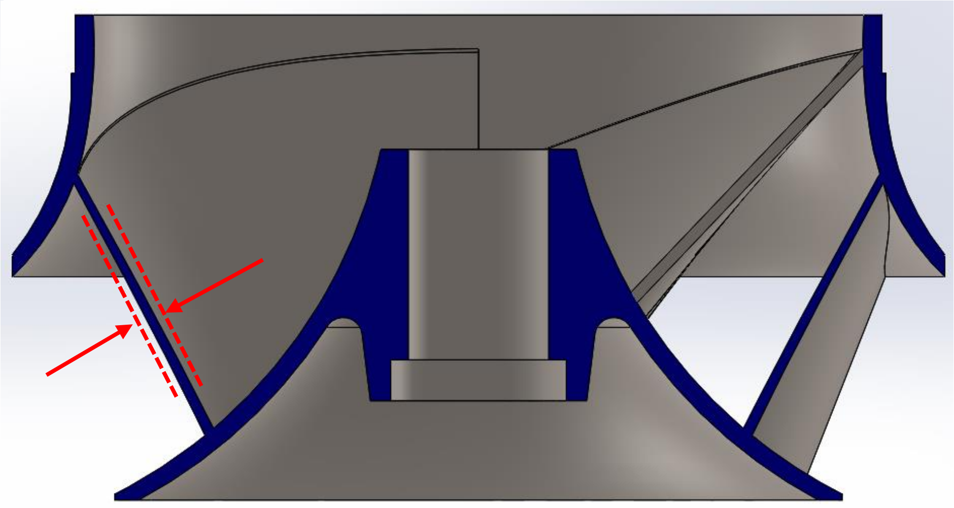
	Wire samples *CEWELD*	WFS 6.5m/min *CEWELD*
	CE	10/1
C (%)	0.014	0.025
S (%)	0.0022	0.0021
N (%)	0.16	0.17

WAAM print of a demonstrator – Duplex 2209

WAAM demonstrator – Pump body

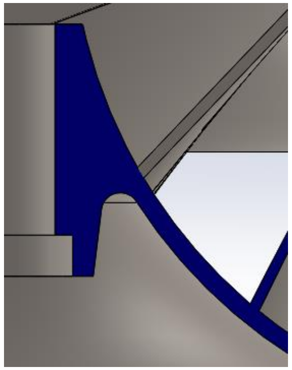


ENGIE
Laborelec

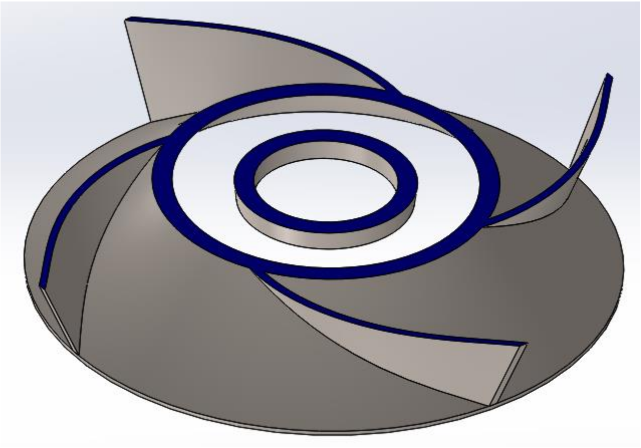


WAAM demonstrator – Pump body

- Remarks & risk assessment :
  - Overhanging surfaces (deposition position)
  - Local thickness variation (blade to central tube)
  - Central tube support
  - Deformation during deposition

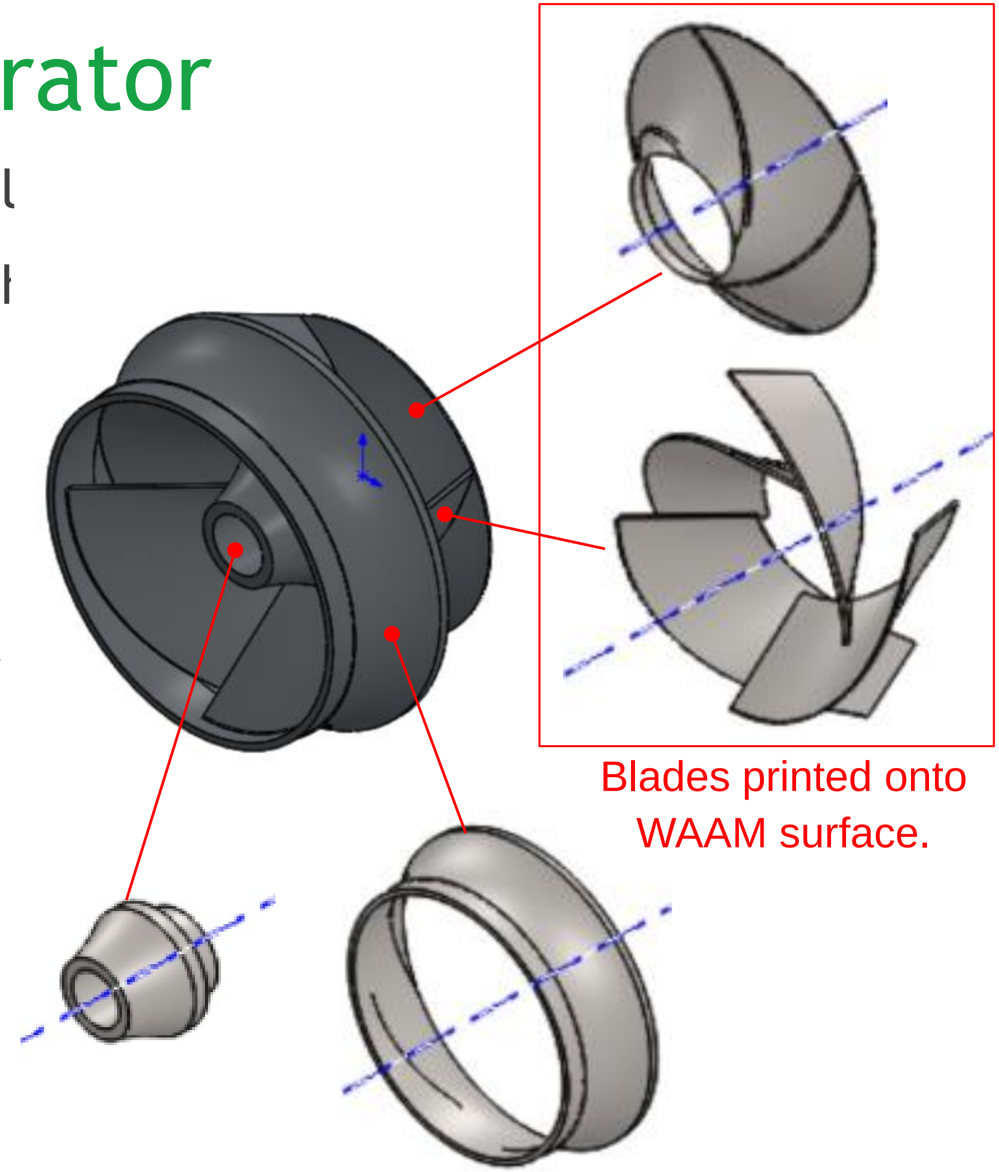


- Mitigation & simplification :
  - Mock-up print of challenges
  - Central tube as separate “weld in”
  - …
  - To be discussed



WAAM demonstrator

- Duplex steel pump body model at reduced scale (1/3) but with increased impeller blade thickness
- Deposit 65kg, ø530x280mm
- Impeller split in 4 features for easier WAAM trajectories
  - insufficient torch access …
- Afterwards all parts are welded together (GMAW)
- Incl. 2mm machining surplus



WAAM demonstrator

- Fabrication on 6 axis ABB robot with rotation table
  - No dedicated WAAM trajectory/optimization software
- Features with higher risk are first manufactured separately (not to full height)
  - Curved impeller blade on inclined surface
  - Thick-walled central part
  - Curved impeller walls
- Voestalpine 3Dprint 2205 wire ø 1.2mm
  - All previous tests with 2209 welding wire, no processing ≠ experienced

Product Name	C	Si	Mn	Cr	Mo	Ni	N	
3Dprint AM 2209	0.025	0.5	1.6	23	3	9	0.14	Duplex steel (no heat treatment)
3Dprint AM 2205	0.025	0.5	1.5	22	3	5	0.15	Duplex steel (with solution annealing heat treatment)

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WAAM demonstrator

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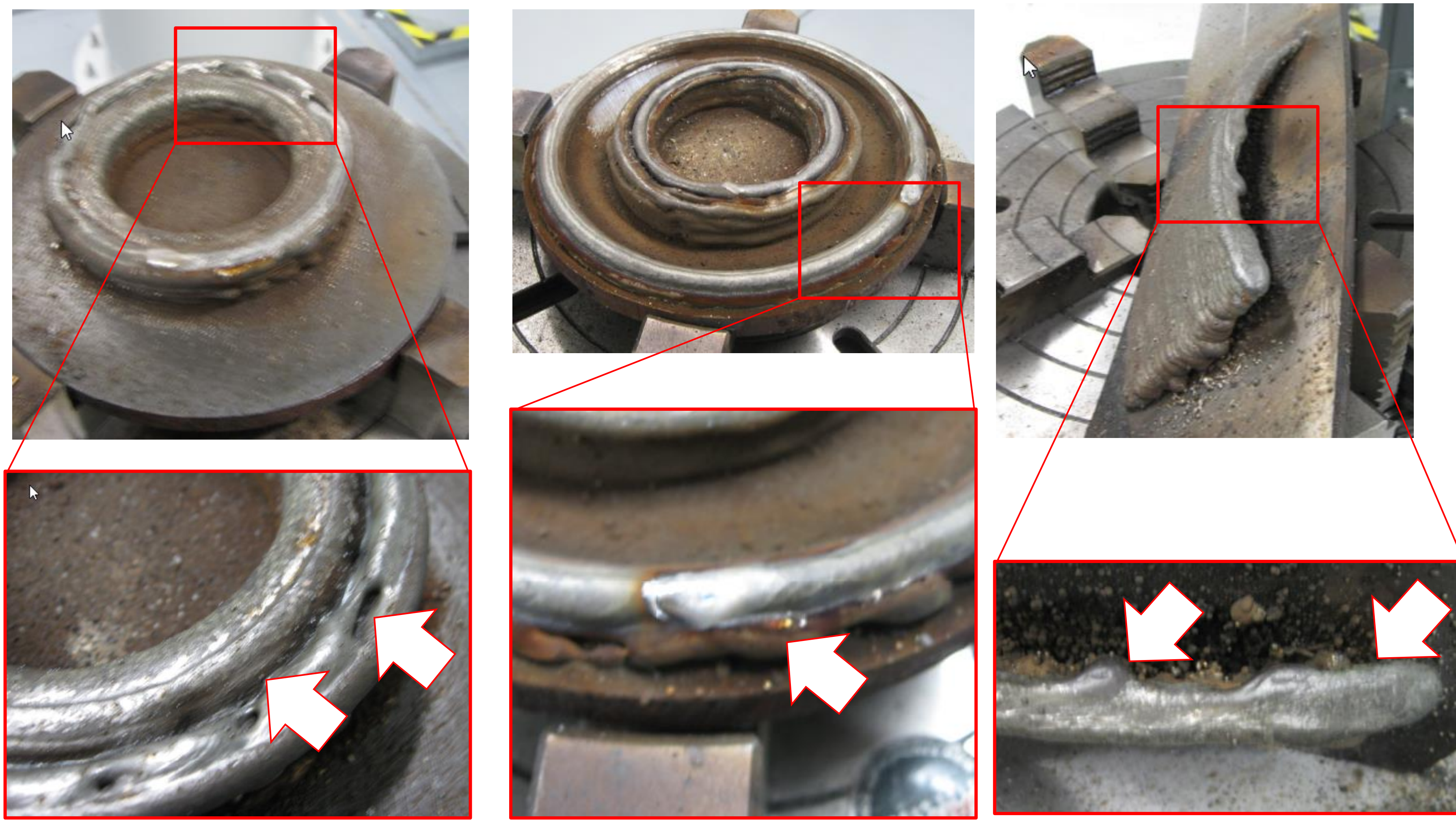
WAAM demonstrator



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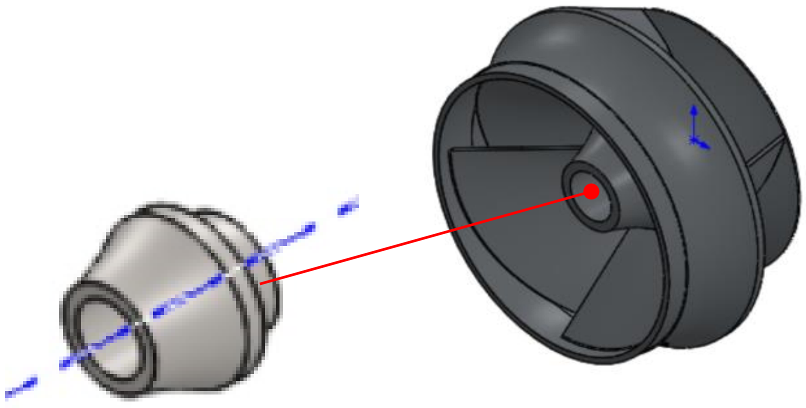
WAAM demonstrator

- Central cylindrical part
- Weighs 15kg (1 GMAW spool)
- WAAM time approx. 11h
- 1.75 – 2.25 kg/h
- Shielding gas Ar + 2% CO_2
- Typical welding speeds 0.45m/min +/- 15% (hot vs cold deposits)
- Typical Heat Input approx. 0.3-0.45kJ/mm (< 200A)
- On thick-walled central part
  - # passes per layer deposited (4 to 17) followed by 3 - 10min cooldown
  - max. cont. interpass temperature of +/- 300° C (only in thickest area)



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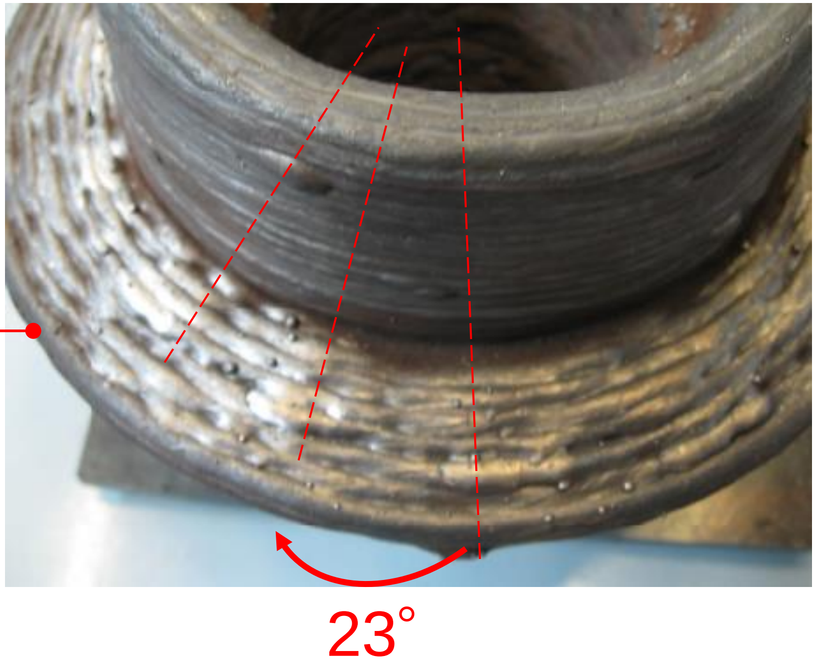
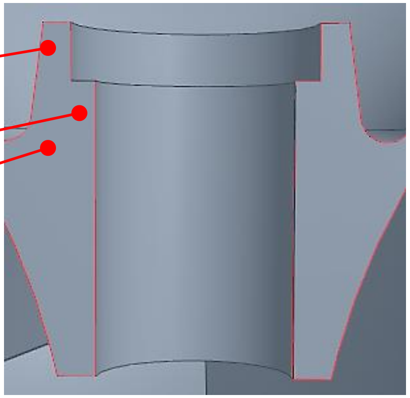
WAAM demonstrator

WAAM demonstrator

- Up to 17 passes next to another at highest wall thickness (62mm)
  - Cold deposit at the outer edge (for meltpool support)
  - Hotter deposits in the intermediate area, +/- 4.5mm bead width (filling)
  - Each filling pass start shifts 23°
- Thickness variation
  - 16mm
  - 30mm
  - 62mm





WAAM demonstrator

- Insufficient melt pool support at path/arc start (worse when wall more inclined)
- Deposit passes typically 55-65% overlap (depending on required wall thickness)
- When welding with longer **arc less** projections (but arc easily deviated!) vs short arc is stable (but more spatter!)

WAAM demonstrator

- Current software for programming WAAM trajectories and processing uses the following info:
  - (1) WAAM parameters (speed, welding job …)
  - (2) Pass overlap schedule
  - (3) In/out trajectory sequence
- On real parts (1) is not an issue but (2) and (3) are rarely optimized or even suitable
  - Finally a lot of manual programming was required for stable deposit conditions

WAAM demonstrator – lessons learnt

- Apropriate software (optimized trajectories, parameter variation…)
- Optimized temperature control (cooling plate …)
- Process control (ideal would be measure ? & modify parameters)
- Arc start/stop optimization (ramp up/down, peak current …)
- Contact tube wear/tear (each 1-2h changed)
- First passes on substrate hotter
- On each circular deposit 4° overlap (5-10mm)
- *Arc length / wire length to be constant*
- *Control of melt pool size*
- *Geometrical control (theoretical vs real pass height, CAD vs deposit)*