INSIDE Metal Additive Manufacturing

LMD processing and testing

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SIM
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LMD Coupon printing

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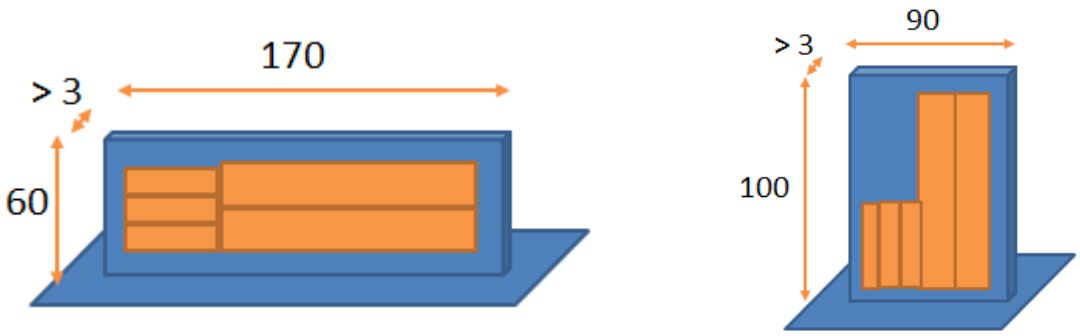
LMD Coupon printing - size

- Deposits for mechanical characterization of 17-4PH & 316L :
  - Walls built mainly in length vs height
  - Wall thickness 4,5mm using 2 adjacent passes (spot size 4.5mm)
  - Ar at 24l/min, 5min T_{ip}
  - 2500W, 1000mm/min, 30% overlap per pass
  - Walls -> hollow rectangular profiles for stable LMD deposit



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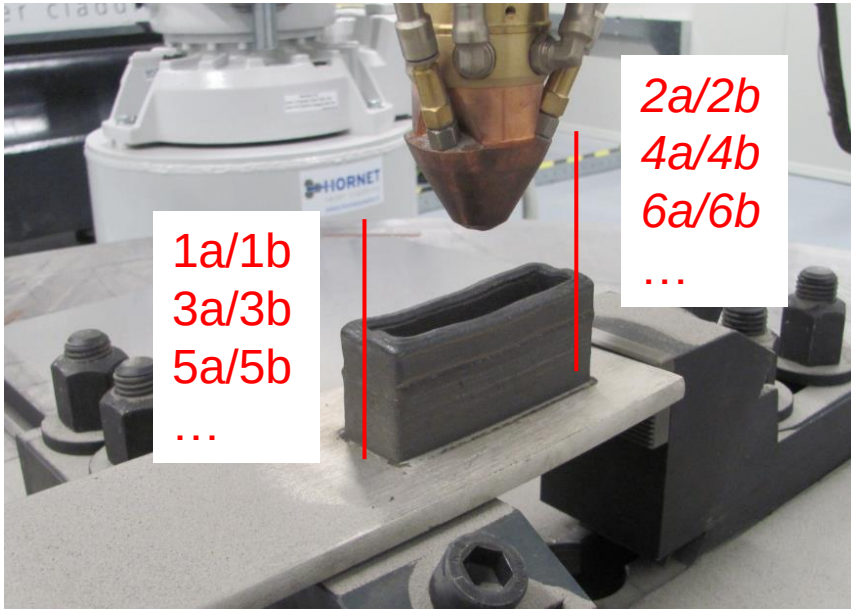
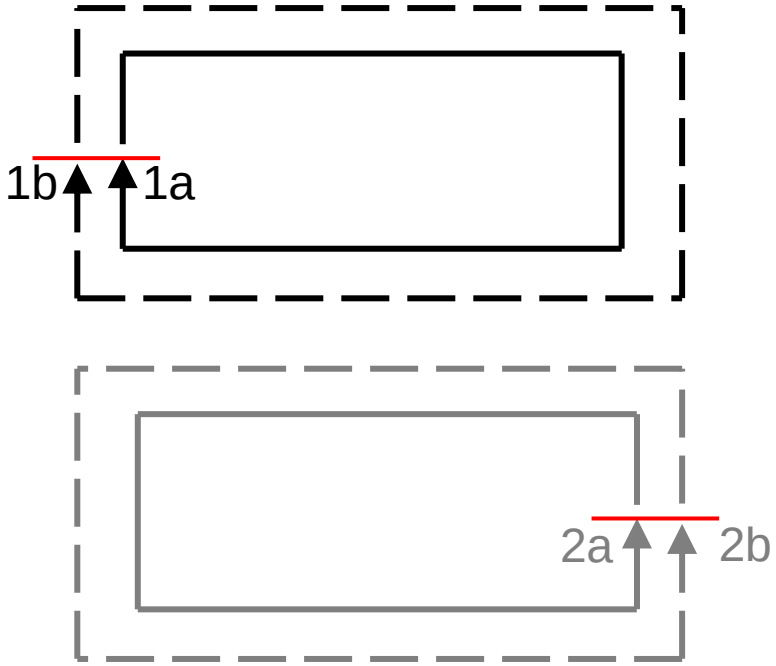
LMD Coupon printing - strategy





- ⌘ Each 2 passes (=1 layer) switching of start/end & LMD direction
- ➢ More stable build approach (stable geometry, no overheating etc.)

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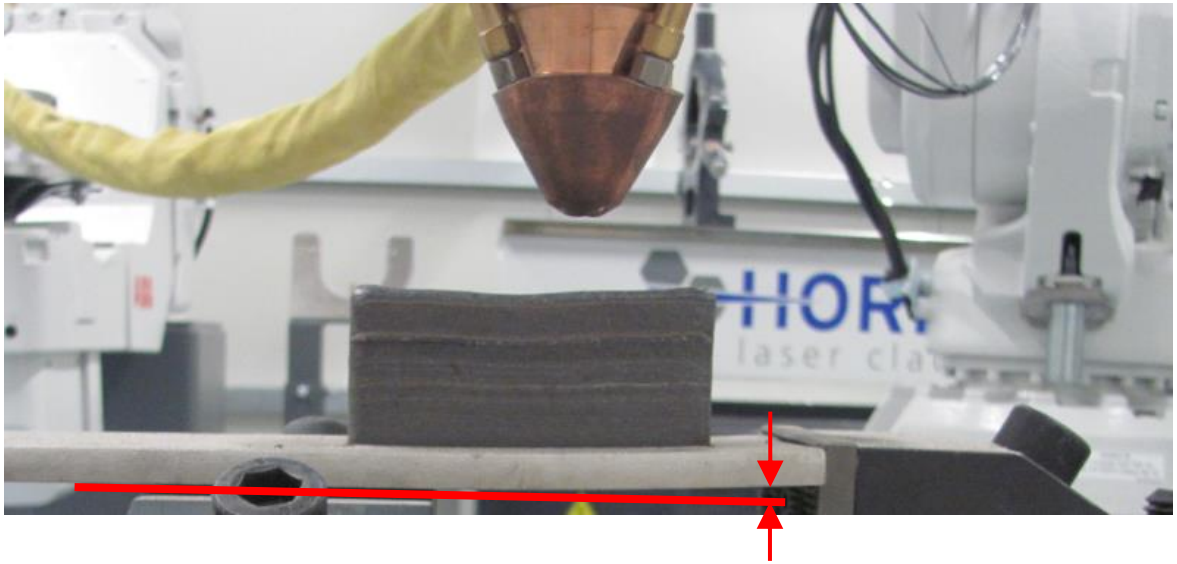
LMD Coupon printing - deformation



- Rather important deformation of substrate
  - Substrate barely clamped
  - Less than in case of WAAM

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LMD Coupon printing - Summary

- Deposits have been performed to perform the mechanical characterization
- An alternating strategy layer-by-layer with a closed rectangular shape is used to ensure printing stability
- There is a noticeable deformation of the substrate

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LMD Mechanical testing

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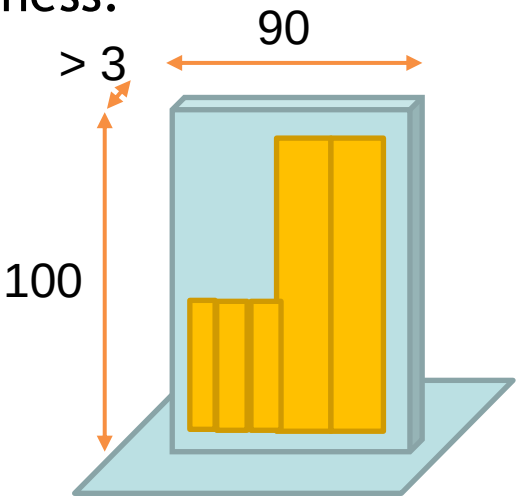
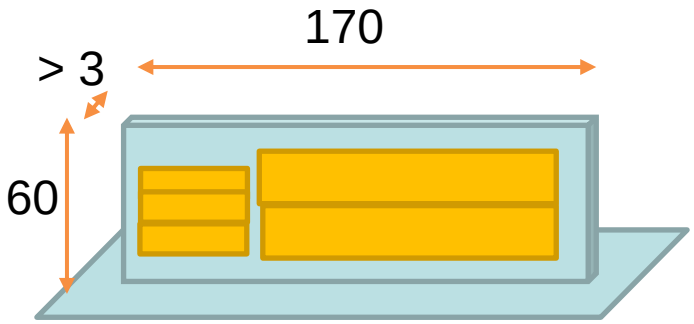
Mechanical testing – test plan

- Hardness
- To determine tensile strength and impact toughness:
- Only printing of thinner walls is possible, resulting in thinner specimens:
  - 2 flat, tensile specimen:
    - Yield strength R_{eH} / Proof strength $R_{p0,2}$
    - Tensile strength R_m
    - Elongation A
  - 3 subsize-impact specimen (2,5 mm thickness)
    - Impact toughness
- Influence of sampling direction
  - Multiple walls





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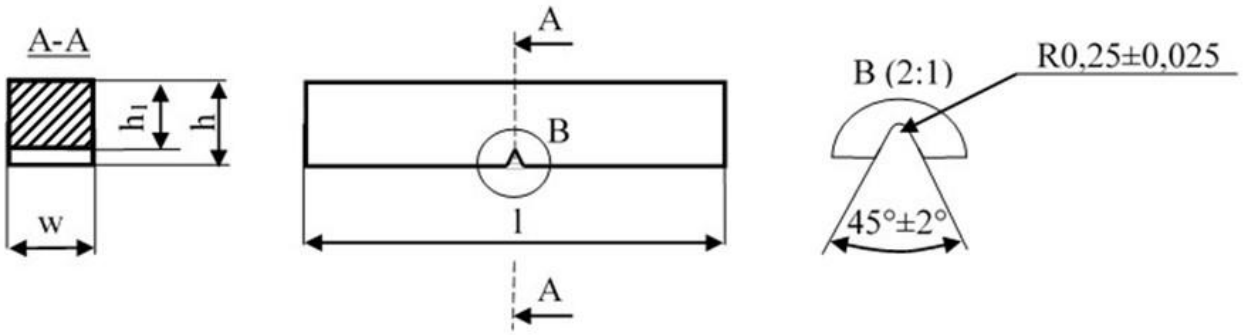
Mechanical testing – Impact test

- ISO 148-1 / ISO 9016
  - Impact toughness



	w	h	l	h_1
☐	10 ± 0,11	10 ± 0,075	55 ± 0,60	8 ± 0,075
☐	7,5 ± 0,11	10 ± 0,075	55 ± 0,60	8 ± 0,075
☐	5 ± 0,06	10 ± 0,075	55 ± 0,60	8 ± 0,075
☒	2,5 ± 0,05	10 ± 0,075	55 ± 0,60	8 ± 0,075

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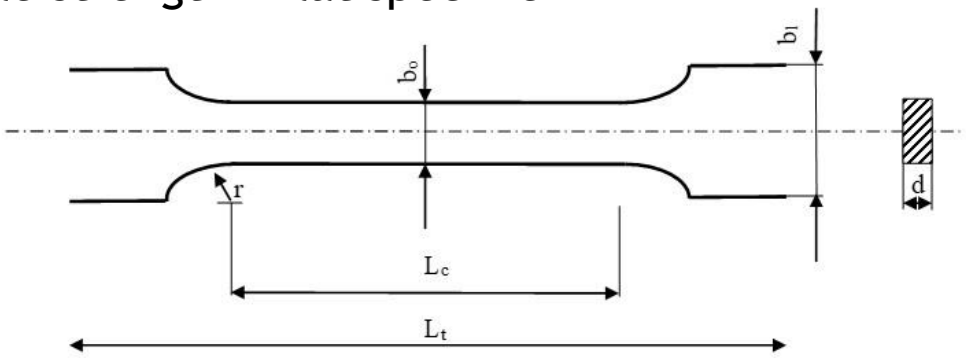
Mechanical testing – Tensile test

- ISO 6892-1
  - Tensile strength – flat specimen



	b_o	L_c	r	b_1	$L_{t,min.}$	d
	Proportionele proefstaven met $L_o = 5{,}65\sqrt{b_o \times d}$ *, afgerond naar de dichtsbijzijnde 5 mm*					
☐	20 ± 0,10		30	32		
☐	25 ± 0,10		30	37		
☐	40 ± 0,15		30	52		
☒	5 ± 0,02	26-28	12	17	90	2,5 - 3

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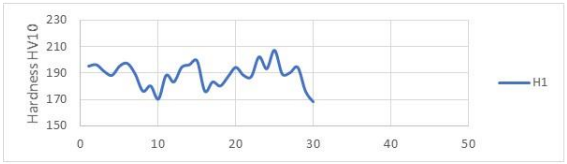
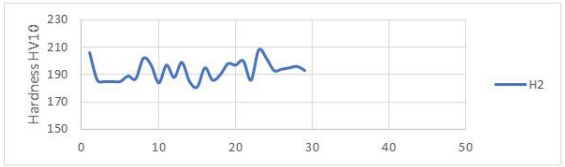
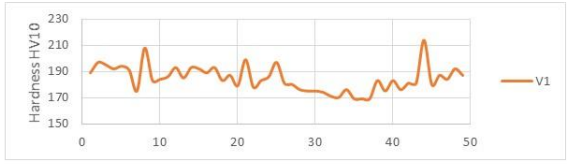
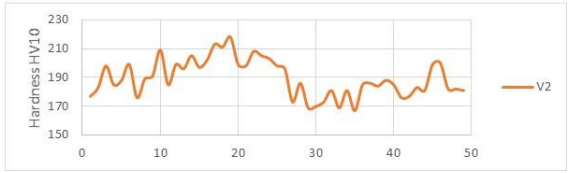
Mechanical testing – 316L
Hardness

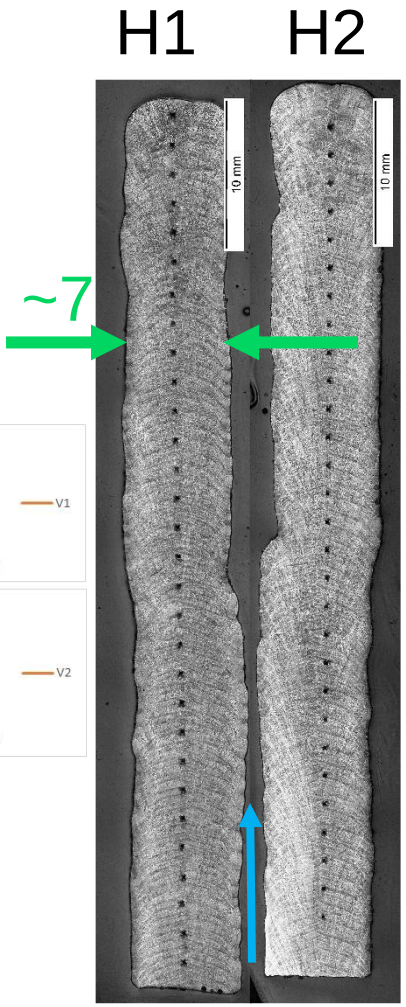
HV10	AVERAGE	MAX	MIN
H1	188	207	168
H2	193	208	181
V1	184	214	169
V2	190	218	167

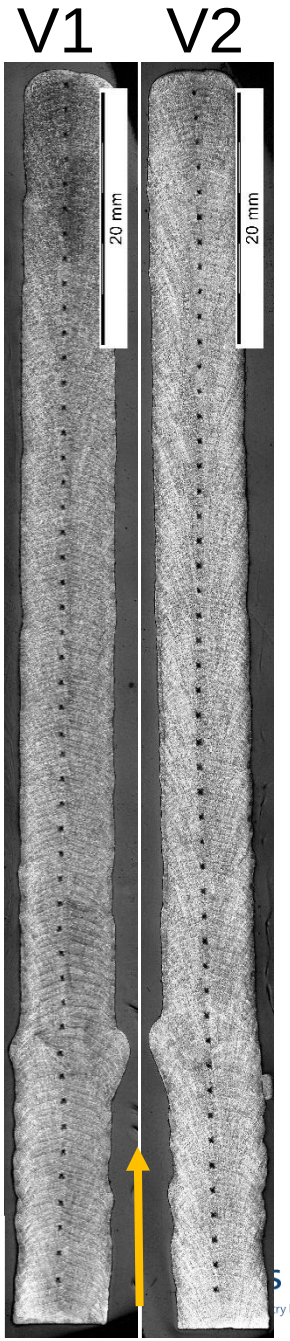












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Mechanical testing – 316L
Tensile

Longitudinal
(X-direction)

Test specimen number	Dimension diameter d_o [mm]	Test temp. T [°C]	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 [%]
ISL-HT11	4,030	23,1	366	590	20	-	38,0	58
ISL-HT12	4,012	23,1	345	583	20	-	28,0	58
ISL-HT21	4,023	23,1	342	547	20	-	34,0	67
ISL-HT22	4,017	23,1	387	601	20	-	39,5	57
ISL-HT31	4,020	23,1	374	590	20	-	31,0	44
ISL-HT32	4,023	23,1	364	582	20	-	25,5	44
ISL-HT41	4,009	23,1	361	590	20	-	28,0	38
ISL-HT42	4,026	23,1	356	584	20	-	34,5	58

Vertical
(Z-direction)

Test specimen number	Dimension diameter d_o [mm]	Test temp. T [°C]	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 [%]
ISL-VT11	4,025	23,1	322	551	20	-	37,5	67
ISL-VT12	4,027	23,1	331	552	20	-	36,5	64
ISL-VT21	4,013	23,1	343	550	20	-	35,5	58
ISL-VT22	4,018	23,1	334	563	20	-	34,0	69

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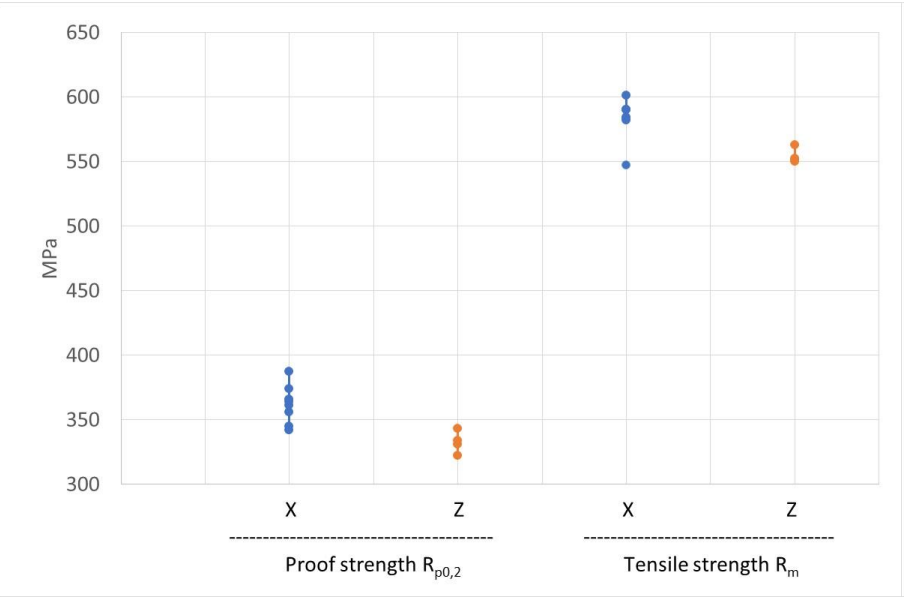
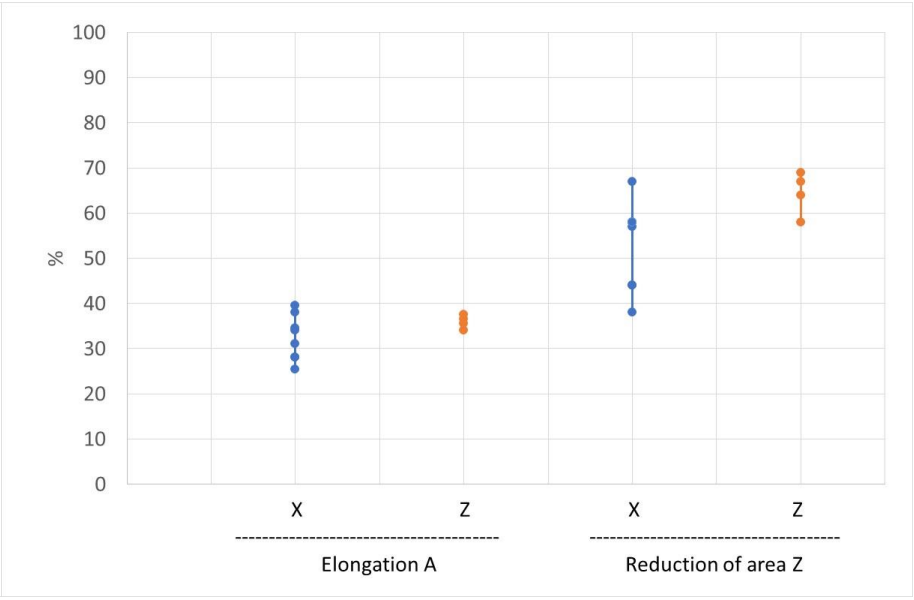
Mechanical testing – 316L Tensile

- Not substantial anisotropy between X (parallel to the base plate) & Z (perpendicular to the base plate) directions

Typical values after DED process		
316L (Höganas)	X-direction	Z-direction
Proof strength (MPa)	355	365
Tensile strength (MPa)	508	485
Elongation A (%)	20	25





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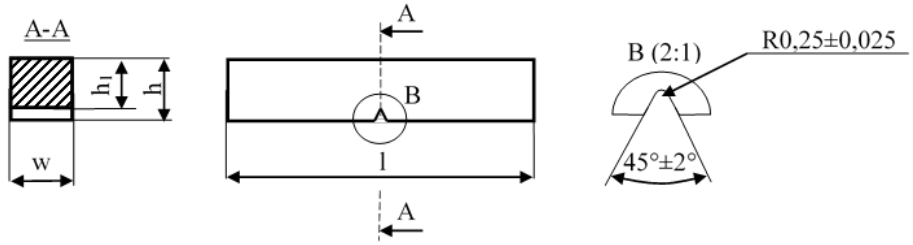
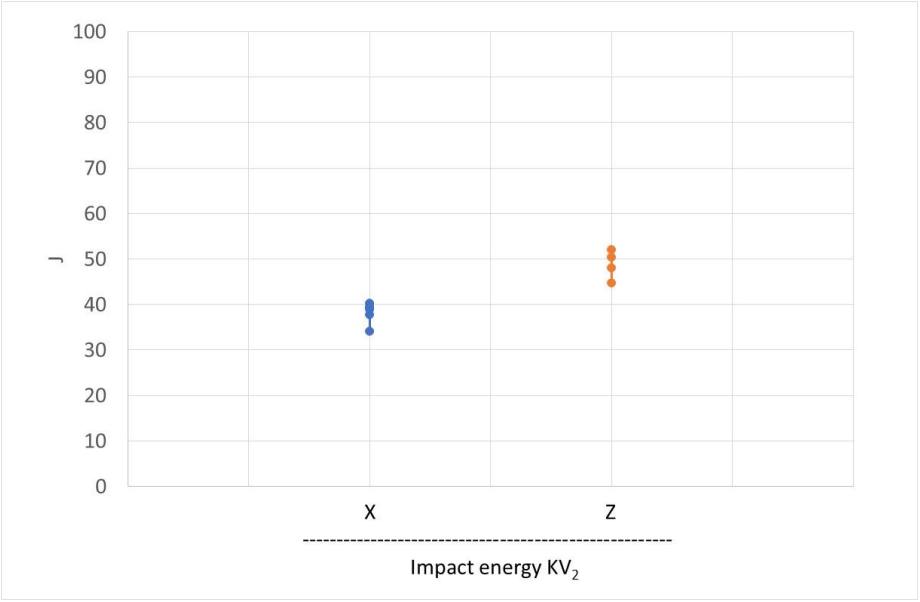
Mechanical testing – 316L
Impact V-notch

Specimen reference	Specimen orientation	Notch location	Size [mm]	Test temp. [° C]	Impact absorbed energy KV_2 [J]	Impact absorbed energy Average
ISL-HK1	longitudinal direction (X-direction)	through thickness	5 x 10	22	37,7	37,0
ISL-HK2					39,4	
ISL-HK3					34,0	
ISL-HK4	longitudinal direction (X-direction)	through thickness	5 x 10	22	39,3	39,4
ISL-HK5					38,8	
ISL-HK6					40,2	

Specimen reference	Specimen orientation	Notch location	Size [mm]	Test temp. [° C]	Impact absorbed energy KV_2 [J]	Impact absorbed energy Average
ISL-VK1	vertical direction (Z-direction)	through thickness	5 x 10	22	50,3	47,7
ISL-VK2					48,0	
ISL-VK3					44,7	
ISL-VK4	verticall direction (Z-direction)	through thickness	5 x 10	22	52,0	48,9
ISL-VK5					50,2	
ISL-VK6					44,4	





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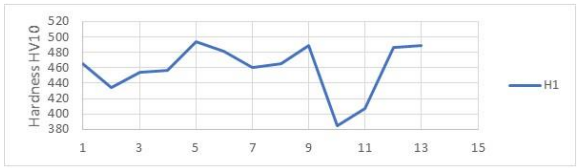
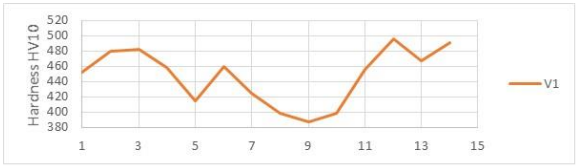
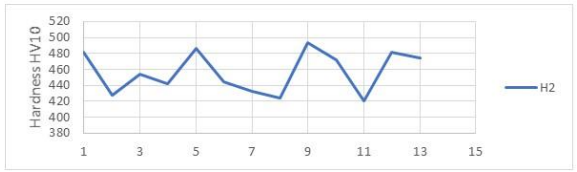
Mechanical testing – 17-4PH Hardness

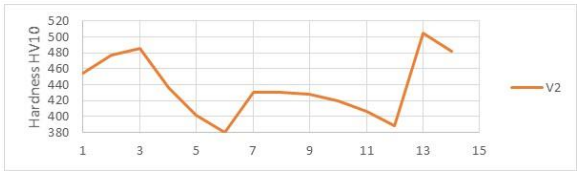
Literature	
17-4PH-H900 (480°C-1hr)	
Hardness (HV10)	375

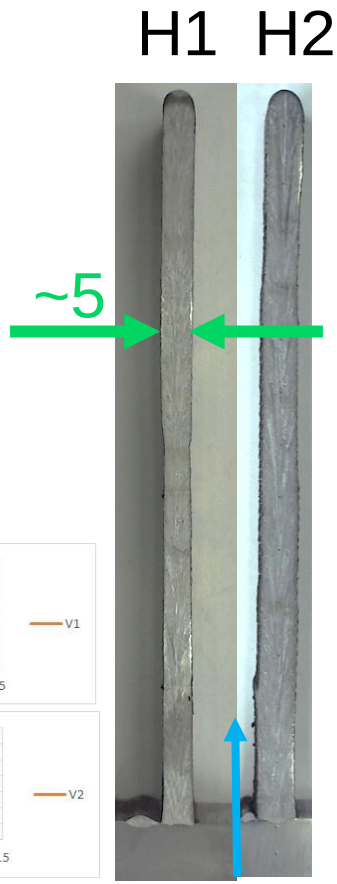
HV10	AVERAGE	MAX	MIN
H1	459	494	385
H2	457	493	421
V1	448	496	387
V2	438	505	380











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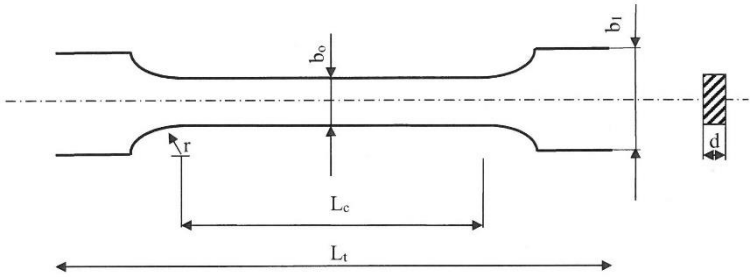
Mechanical testing – 17-4PH
Tensile



Longitudinal
(X-direction)

Vertical
(Z-direction)

Test specimen number	Dimension thick. x width a_o x b_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 [%]
ISP-HT1	2,5 x 4,99	22	-	1104	1479	20	-	16,5	-
ISP-HT2	2,49 x 4,97	22	-	1032	1476	20	-	13,1	-
ISP-HT3	2,49 x 4,92	22	-	1102	1474	20	-	12,8	-
ISP-HT4	2,51 x 4,95	22	-	1060	1469	20	-	11,4	-
ISP-VT1	2,48 x 4,89	22	-	1029	1222	20	-	9,3	-
ISP-VT2	2,48 x 4,96	22	-	977	1221	20	-	13,4	-

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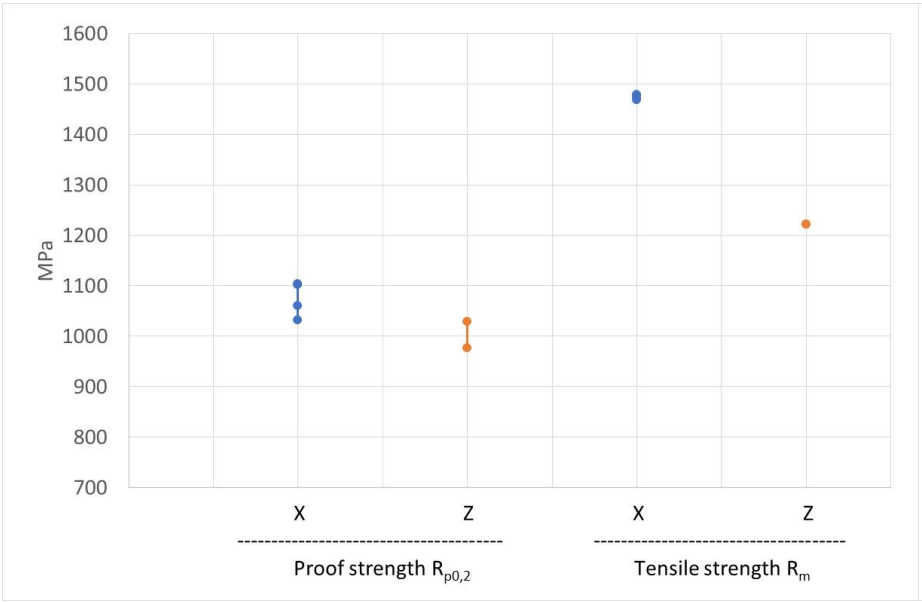
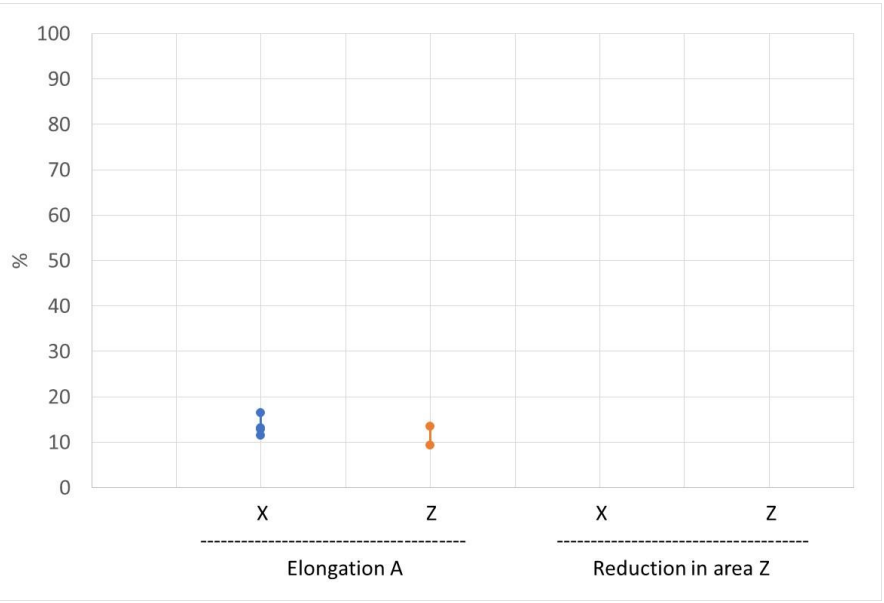
Mechanical testing – 17-4PH Tensile

- Some anisotropy between X (parallel to the base plate) & Z (perpendicular to the base plate) directions

Literature	
17-4PH-H900 (480°C-1hr)	
Proof strength (MPa)	945
Tensile strength (MPa)	1417
Elongation A (%)	15,5





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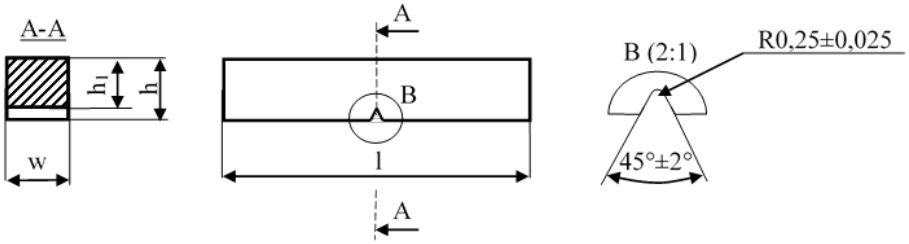
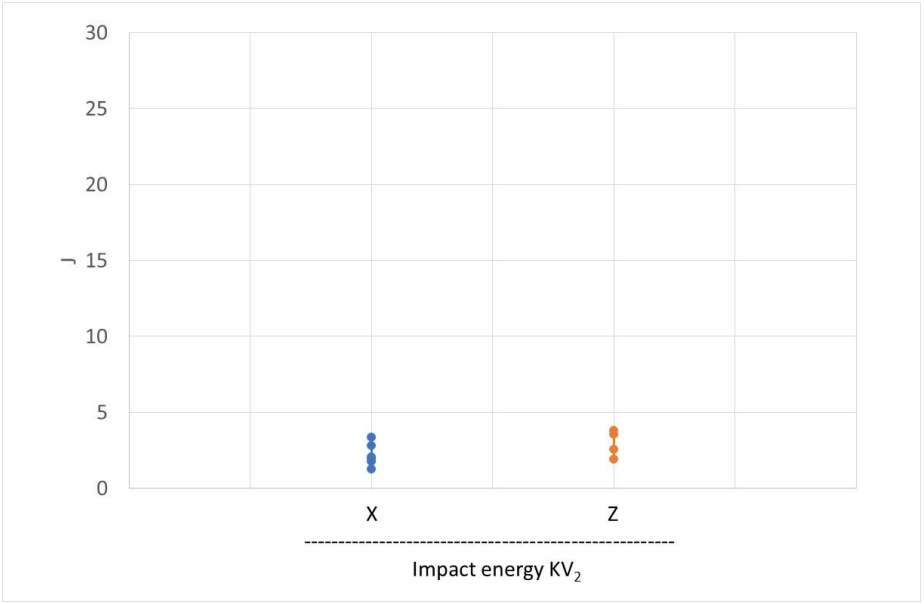
Mechanical testing – 17-4PH
Impact V-notch

Specimen reference	Specimen orientation	Notch location	Size [mm]	Test temp. [° C]	Impact absorbed energy KV_2 [J]	Impact absorbed energy Average
ISP-HK1	longitudinal direction (X-direction)	through thickness	2,5 x 10	22	1,7	2,1
ISP-HK2					1,3	
ISP-HK3					3,4	
ISP-HK4	longitudinal direction (X-direction)	through thickness	2,5 x 10	22	2,0	2,3
ISP-HK5					2,1	
ISP-HK6					2,8	

Specimen reference	Specimen orientation	Notch location	Size [mm]	Test temp. [° C]	Impact absorbed energy KV_2 [J]	Impact absorbed energy Average
ISP-VK1	vertical direction (Z-direction)	through thickness	2,5 x 10	22	3,8	2,7
ISP-VK2					2,5	
ISP-VK3					1,9	
ISP-VK4	verticall direction (Z-direction)	through thickness	2,5 x 10	22	3,5	3,2
ISP-VK5					3,3	
ISP-VK6					2,9	





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LMD Mechanical testing- Summary

- Some anisotropy is observed for 17-4PH but not for 316L
- Impact results are slightly better for 316L than for 17-4PH

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Demonstrator based on LMD

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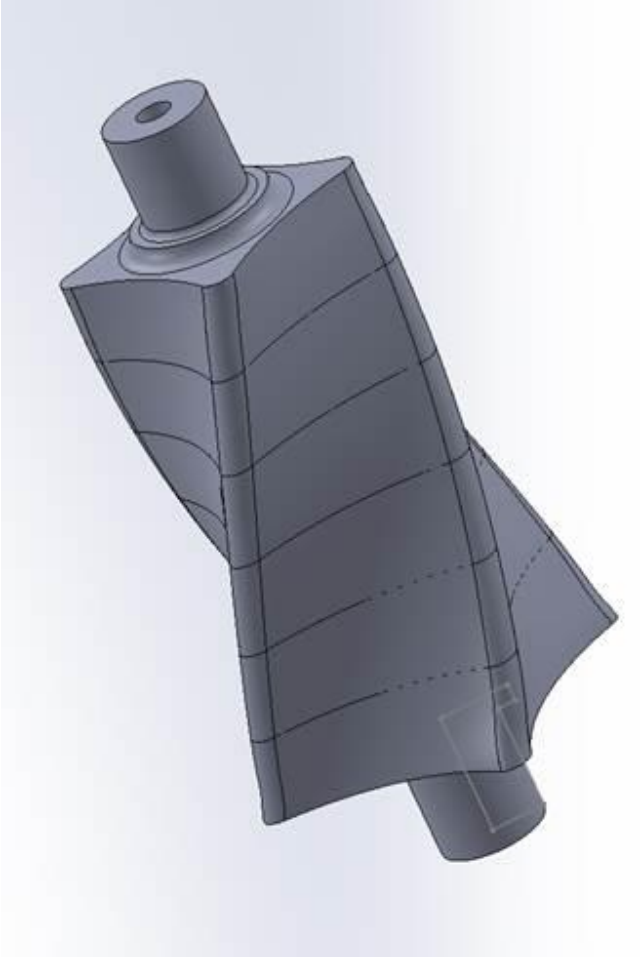
Generalized rotor



Ø Bottom: 100 mm
Height rotor: 155 mm
Total height: 225 mm

Rotation top vs. bottom: 70°
Bevel bottom to top: 2°

Wall thickness: 3 mm

(Scale 75%)

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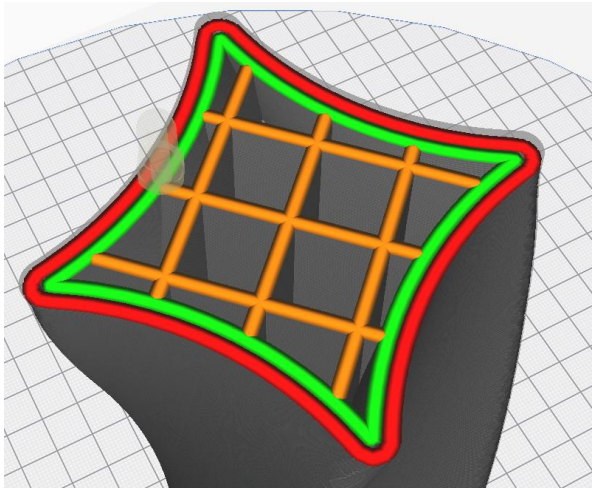
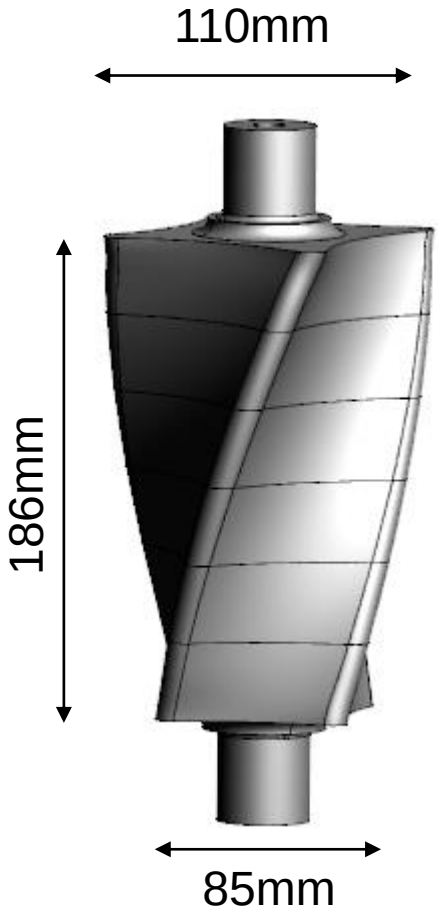
LMD demonstrator – Pump rotor

- Material : 17-4PH
- Technology : laser powder (LMD)
- Track width: 3.80 mm; Layer height: 0.47 mm
- Printing strategy (sequence) :
  - 2 contour lines; inner(green) & outer(red)
  - Infill(orange)





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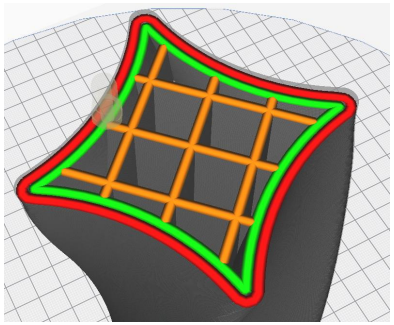
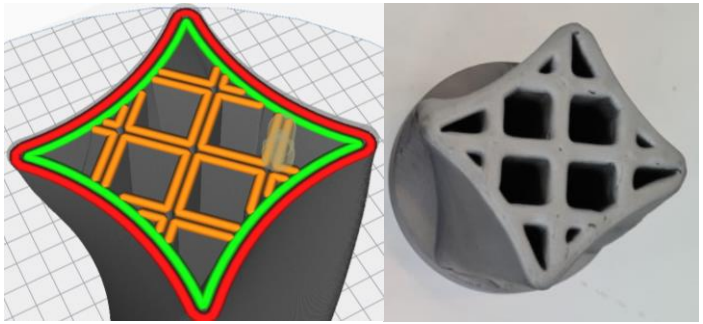
LMD demonstrator – Pump rotor

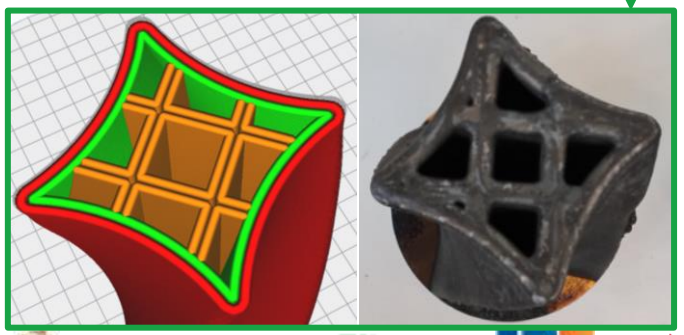
- 3 different infill patterns were tested :
  - The 1st one was problematic due to crossing tracks (crossing point → overthickness!)



  - Thus 2 other patterns of different density were tested without crossing layers



Selected filling pattern for the demonstrator



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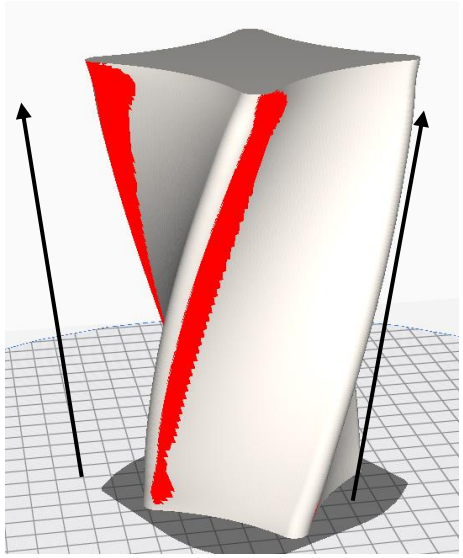
LMD demonstrator – Pump rotor

- The demonstrator was manufactured on machined 17-4PH axes
- 3 trials were performed in order to reach a good result

- 1st demonstrator failed due to the conical shape of the part → large overhanging angle (no support)

- *Previous tests on hollow dome-like structures have demonstrated potential to build overhanging LMD structures up to +/-15°*



Overhanging angle >15º in red

Demonstrator after sandblasting

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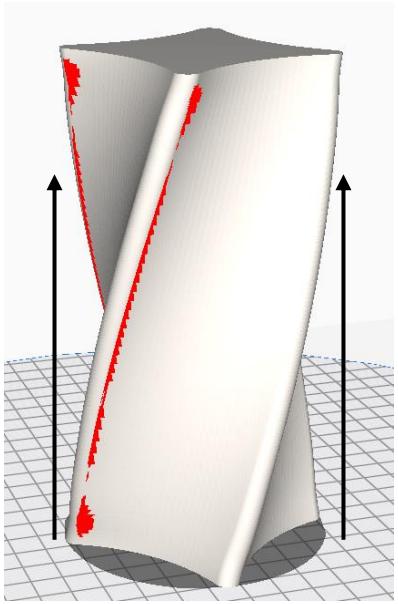
LMD demonstrator – Pump rotor

- 2nd demonstrator was not conical
- The construction was stopped before the total height was reached → the deposition of the outer contour was problematic
- -> too fast
- At mid height, process parameters were changed and the defect was partially removed
- → a 3rd demonstrator was printed with the new parameters



Overhanging angle >15º in red

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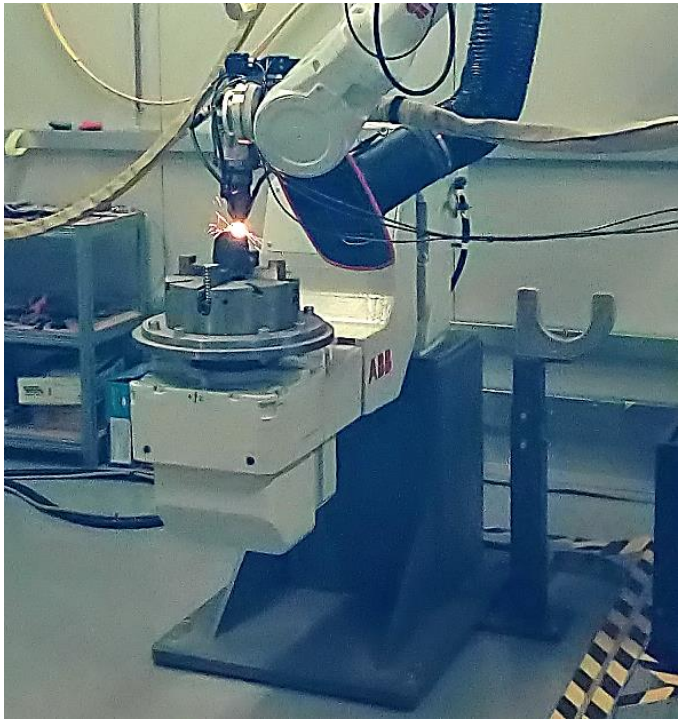
LMD demonstrator – Pump rotor

- 3rd demonstrator same as 2nd but adapted process parameters
- The printing was successful



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