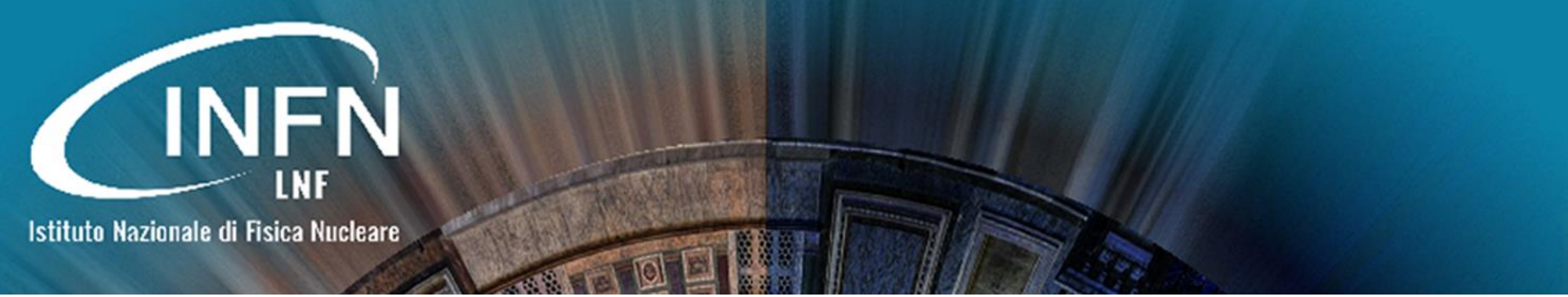

Titanium orbital welding: 3D printed parts to bulk

Cecilia Rossi*[1], Mickael Denis Crouvizier[2], Julien Debeux[2], Gilles Favre[2], Romain Gerard[2], Jerome Hebert[3]

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Titanium welding test

Abstract

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Additive Manufacturing (AM) is an incredibly interesting solution for high energy physics due to its design flexibility and to its light weighting opportunities. As this technology is spreading in physics experiments, several new issues have to be solved. The integration of parts produced by AM is one of the open questions. This study described the tests done on orbital welding of Ti6Al4V Grade 5 pipes produced with AM and standard bulk Ti6Al4V Grade 2 (pure Titanium) pipes. Welding procedure was optimized, and the finished parts were then verified following most of the procedures described in ISO 15614-5 regulation. Computed micro-tomography (CT), leak test, pressure test up to MDP (Maximum Design Pressure), leak test after pressurization and destructive tests such as metallographic examination and tensile transverse test are presented in this work.

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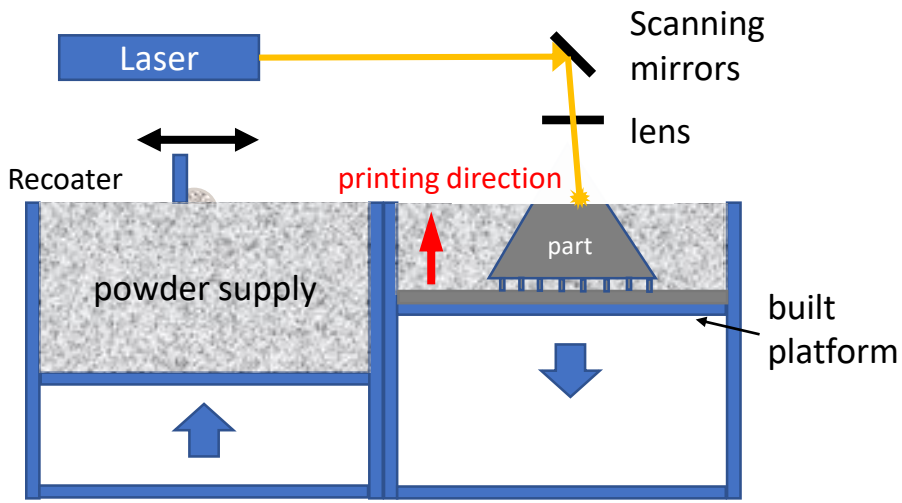
Titanium welding test

AIM:

Investigate feasibility of weldings between 3D printed and standard Titanium.

Selective Laser Melting (SLM) technology



Working principle: the recoater spreads a metallic powder bed on the built platform, the laser selectively melts the powder and part is build layer by layer from bottom to top.

Why are we interested in performing these tests?

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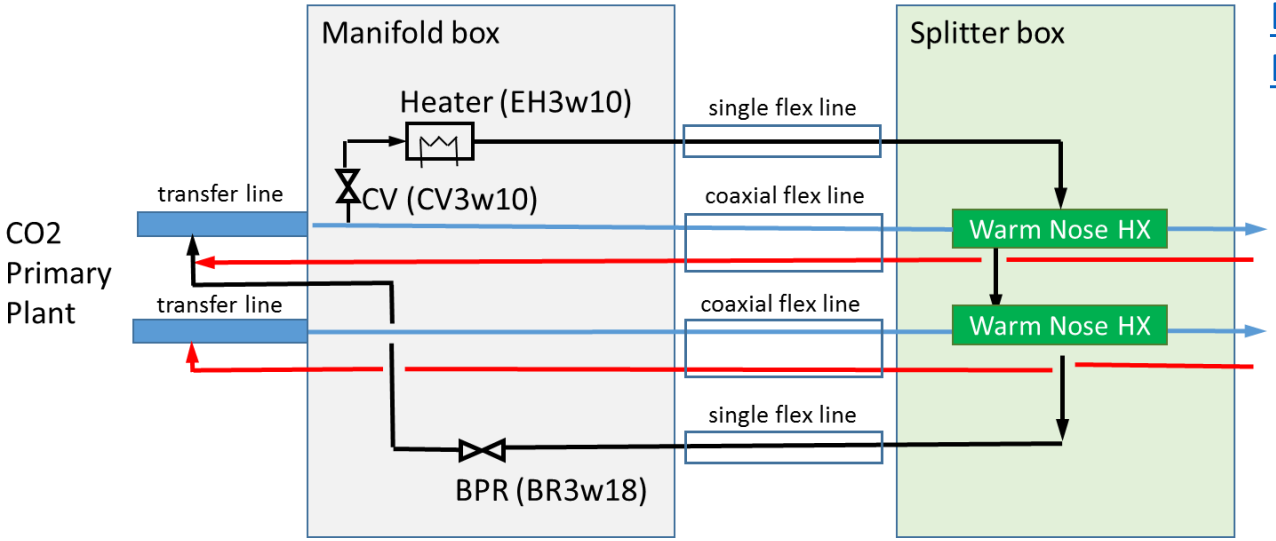
Titanium welding test

Warm Nose heat exchanger (WN HX) are foreseen in ATLAS ITk upgrade for Strips and Pixel systems.

Warm nose working principle:

- avoid that instability, related to the Liquid Super Heating, occurs at the detector
- regulate detector temperature without technical intervention in its unreachable areas during runs.



EDMS 2307865
EDMS 2307866

- Part of liquid CO_2 is drawn from the main stream and processed to reach the 2-phase status, i.e. WN loop
- Temperature in WN loop is controlled by a Back-Pressure Regulator (BR3w18).
- WN HX→ heat exchange between WN loop and subcooled liquid directed to the detector.
- Heater (EH3w10) to get WN loop in 2-phase and control the vapour quality of the loop
- Mass flow in the circuit is controlled by a carrel valve (CV3w10)

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Titanium welding test

Warm Nose Materials:

All the material used must be radiation hard, 316L is therefore a good material.

However, in the PP1 area the weight must be minimized in order for better tracking, timing performance and fluence in downstream detectors and avoid activation → Titanium must be used to reduce weight (4.5 g/cm^3 vs. 8 g/cm^3)

EDMS 2307865
EDMS 2307866

Geometrical limits:

IDEP area → all services must stay in a maximum height of 95 mm (*EDMS 1905419 v.1.9 / AT2-IC-EP-0001 v.1.9)*

PP1 area → 3 HXs must stay in max vol of approx. (h=214 mm, l=264 mm, w=39-179mm)

Due to the power required and limited space
→ **metal additive manufacturing.**

These heat exchanger will have to be welded to the plant (i.e. bulk material)
→ issues?

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Titanium welding test

Ti6Al4V Samples characteristics and tests done

	AM part		Bulk (cold drawn pipe)		Tests done
	Grade	Dimension	Grade	Dimension	
Test 1	Grade 5	original: OD9.52 x 1.0 mm remachined* to: OD9.46 x 0.86 mm	Grade 2 (pure Titanium)	original: OD10 x 1.0 mm remachined**: OD9.63 x 1.06 mm	<u>PART 1: Welds AM/bulk</u> Visual inspection Leak test to 10^{-9} mbar l/s Pressure test at 162 bar Leak test to 10^{-9} mbar l/s after P Micro Tomography <u>PART 2: Full material welds</u> Micro Tomography
	Grade 23	original: OD9.52 x 1.0 mm Remachined* to: 0D9.49 x 0.97 mm	Grade 2 (pure Titanium)	original: OD10 x 1.0 mm remachined**: OD9.63 x 1.06 mm	
Test 2	Grade 5	OD9.97 x 1.05 mm no remachining	Grade 2 (pure Titanium)	OD10 x 1.0 mm	<u>Welds AM/bulk</u> Micro Tomography Leak test to 10^{-9} mbar l/s Pressure test at 162 bar Leak test to 10^{-9} mbar l/s after P Metallographic destructive tests

* Impossible to find 3/8" pipes even in UK. → AM Ti pipe re-machined to 3/8" OD.

** cold drawn pipe was also remachined: The diameter has been reduced to fit with the other tubes, therefore the thickness increases

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Titanium welding test

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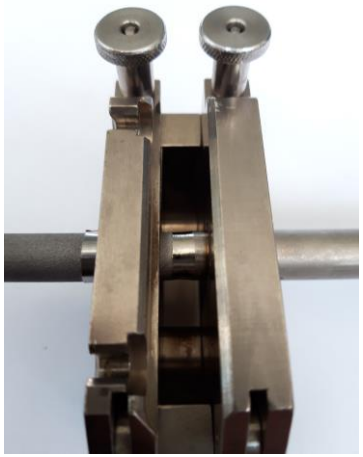
Titanium welding test

TESTS 1 – PART 1:

Test Plan

- Development of orbital TIG welding parameters
- Orbital welding of 4 samples:
  - n. 2) bulk Gr. 2 (pure Titanium) to Gr. 5 additive manufacturing
  - n. 2) bulk Gr. 2 (pure Titanium) to Gr. 23 additive manufacturing
  - AM samples produced by two different companies
- Visual inspection
- Leak test
- Pressure test @162 bar
- Leak test
- Micro tomography



EDMS 2595639

Thanks to D. Lombard, B. Bulat

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Titanium welding test

Samples:

Titanium alloy	Elaboration	Specified dimension	Final dimension
Grade 2	Drawn without welds	OD10 x 1.0 mm	OD9.63 x 1.06 mm
Grade 5	Additive Manufacturing	OD9.52 x 1.0 mm	OD9.46 x 0.86 mm
Grade 23	Additive Manufacturing	OD9.52 x 1.0 mm	OD9.49 x 0.97 mm

Orbital welding procedure:

Automatic orbital TIG welding, done with an AMI equipment. The welding head model is AMI 9-500, and the power source is an AMI 207A. 4 l/min Ar purging gas. Alcohol degreasing before welding. No machining of the surface.

Weldings:

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Titanium welding test

TEST 1 – PART 1

Weld Reference	Type of test/ examination	Acceptance criteria	Report	Result / Comment
W1 – W2 W3 – W4	Visual examination	ISO 5817 Level B	No report	Compliant
W1 – W2 W3 – W4	Leak test before pressure test	$\leq 10^{-9}$ mbar l/s	No report (see Annex 1 EDMS 2595639)	2.0×10^{-9} mbar l/s The result is not precise, due to a malfunction of the leak detector
W1 – W2 W3 – W4	Hydraulic pressure test	162 bar	EDMS 2595100	Compliant
W1 – W2 W3 – W4	Leak test after pressure test	$\leq 10^{-9}$ mbar l/s	No report (see Annex 1 EDMS 2595639)	1.6×10^{-10} mbar l/s compliant

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Titanium welding test

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W1 – W2 W3 – W4	Micro-Tomography	ISO 5817 Level B	EDMS 2597930	The analysis shows out of tolerance gas pores

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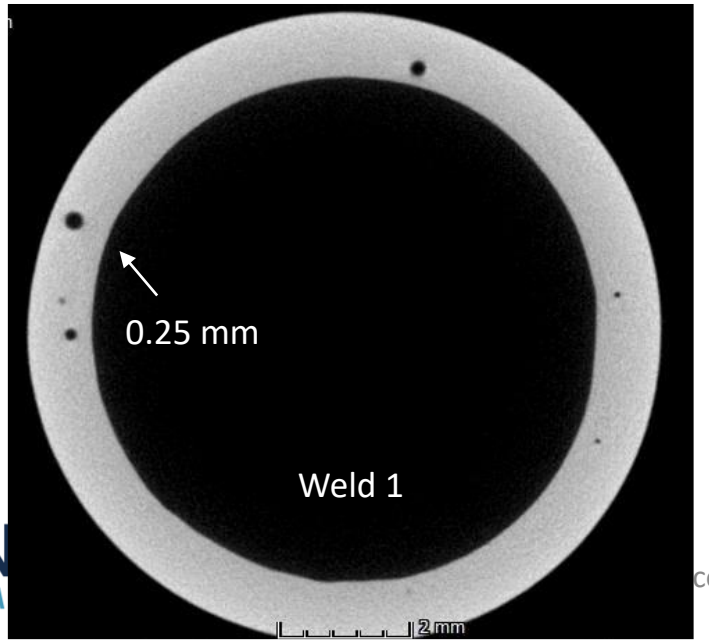
Titanium welding test

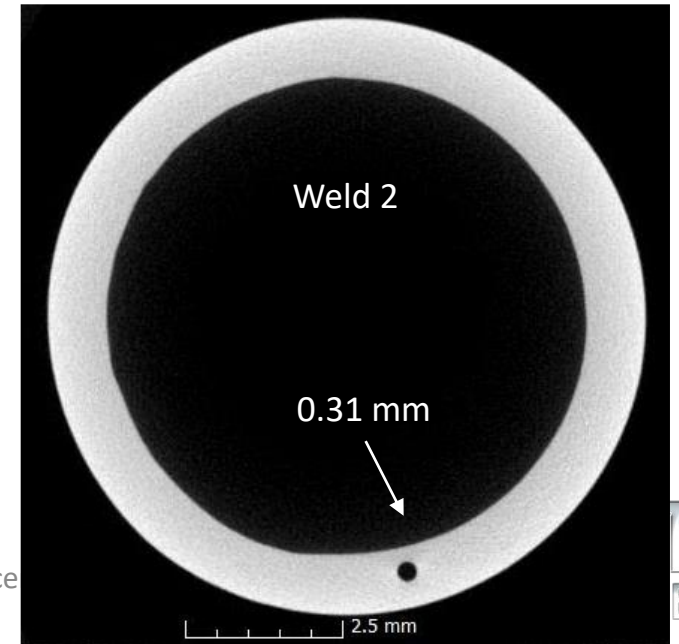
Micro-tomography:

Four scans with high resolution (16.15 µm) were performed. In 3 out of 4 welds samples presence of the voids was confirmed.

According to the EN ISO 5817 quality level B for the material thickness of 1.00 mm there should be no presence of voids bigger than 0.20 mm.

In weld samples number 1,2,4 –at least one void of the size greater than 0.20 mm was found. In sample number 3 no significant events were spotted.





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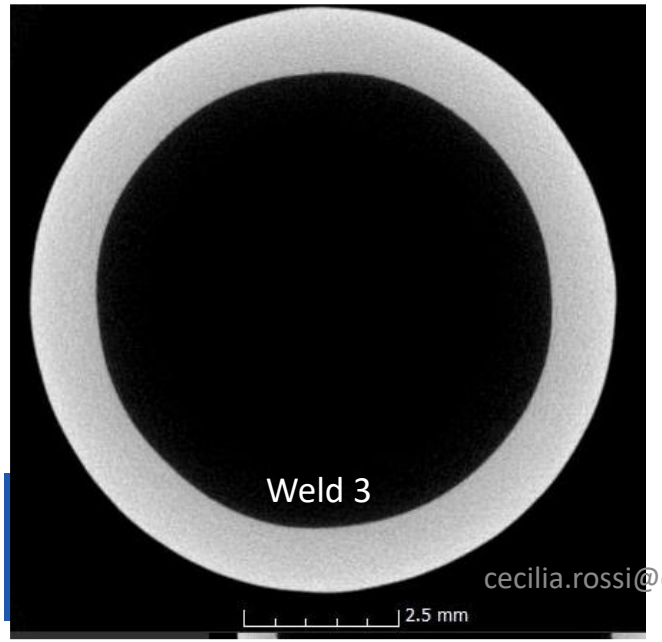

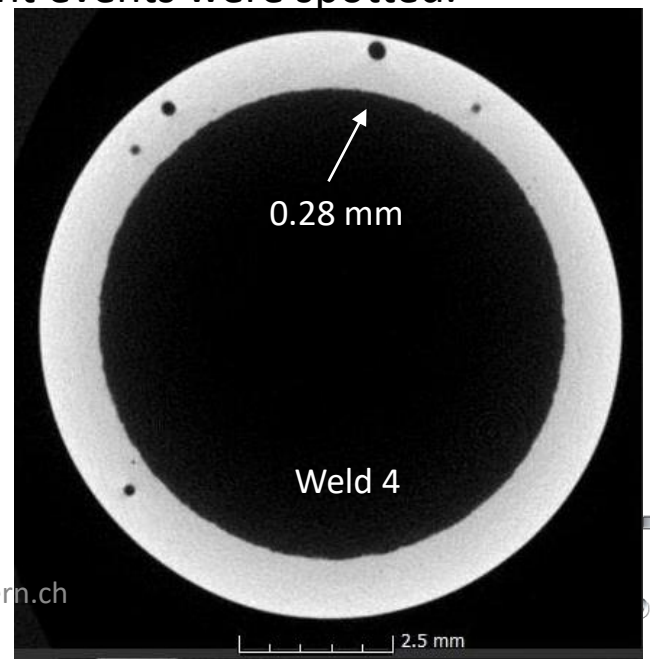

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Titanium welding test

Conclusions of the 1° tests (Part 1)

Out of tolerances pores have been observed by micro-tomography in many welds (1, 2, 4)
(i.e. on both AM samples produced by different companies)

Further tests shall be carried out to identify the reason of these imperfections:

- *Material?*

→ Full material welding in Gr.2 (standard), Gr. 5 (3D), Gr. 23 (3D)

- *Adjustment?*

→ Welding parts with good adjustment

- *Piece preparation?*

→ Work on the additive manufactured part before welding (machining, cleaning, etching, …).

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Titanium welding test

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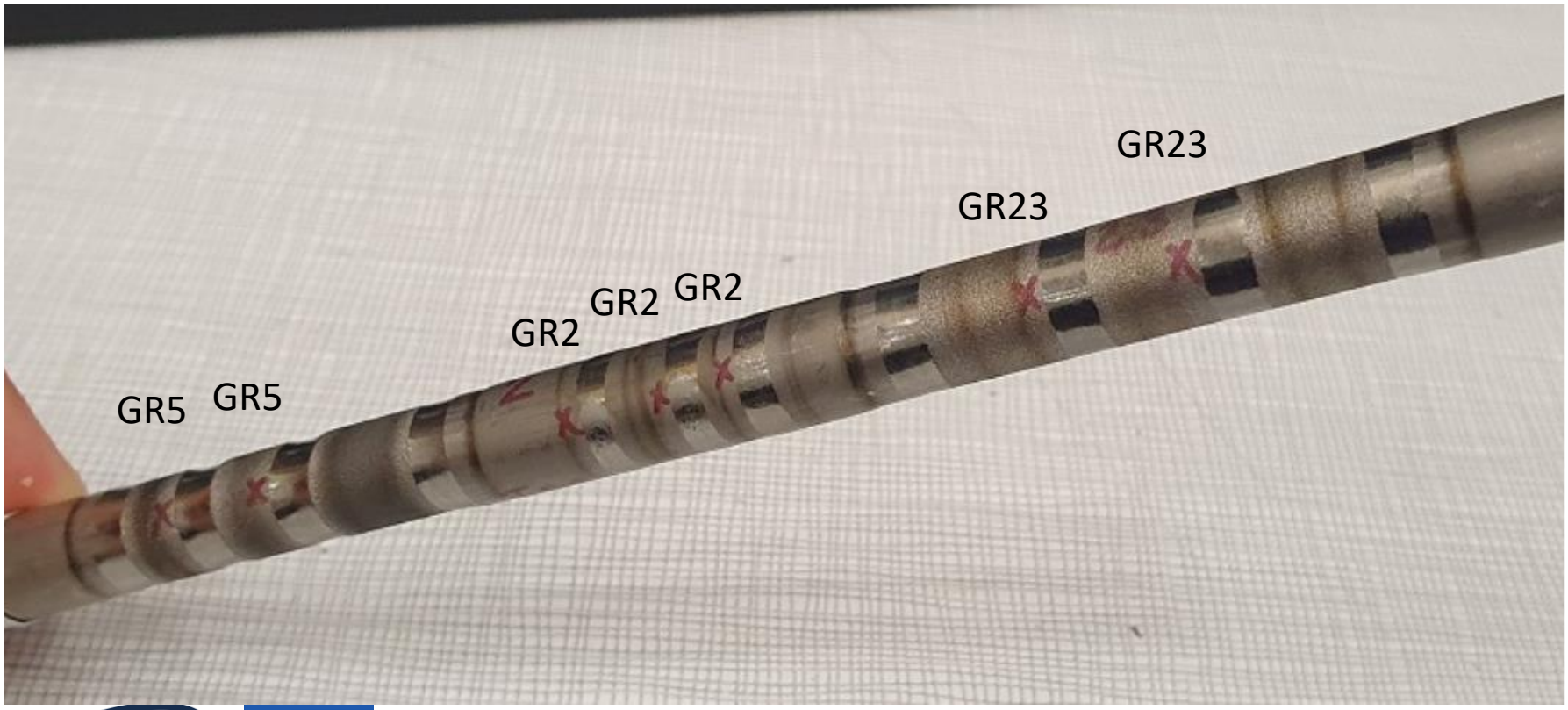
Titanium welding test

Full material weldings:

The same sample of the previous test was used.
TIG weldings were added both in bulk and AM material



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Titanium welding test

Full material weldings:

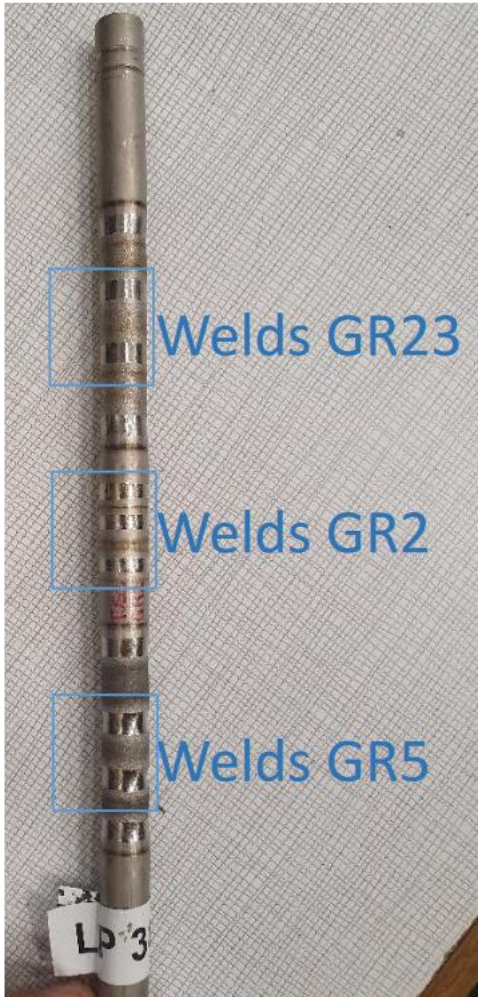
Scans with high resolution (24.85 µm) were performed.

→ No porosities were seen in specified welds.
(only small porosities visible in 3D printed material, compliant with ISO 5817 Level B).

EDMS 2597930

The results are very good and encouraging.

Probably the problem in related to the difference in geometry (i.e. the bad adjustment)



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  → Welding parts with good adjustment

- *Piece preparation?*

  → Work on the additive manufactured part before welding (machining, cleaning, etching, …).

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Titanium welding test

Conclusions of the 1° tests (Part 2)

The adjustment is identified as the most reasonable issue

Production of new AM part with same dimension of bulk pipe

2° tests

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Titanium welding test

TEST 2

Tests done following most of the tests proposed by regulation NF EN ISO 15614-5

Test plan:

1. Produce new Ti 3D printed samples in Ti6Al4V Gr. 5.
2. Metrology measurements @INFN Genova
3. Welding test @CERN
4. Tomography
5. Leak test to 10^{-9} mbar l/s
6. Pressure test at 162 bar
7. Leak test to 10^{-9} mbar l/s after pressurization
8. Metallographic destructive tests :
   - Transverse tensile test
   - test pliage
   - macro/micro

   To be decided which of them to perform on our welds

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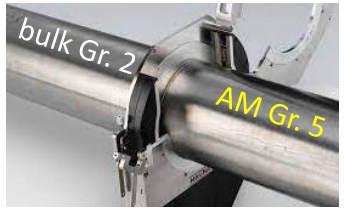
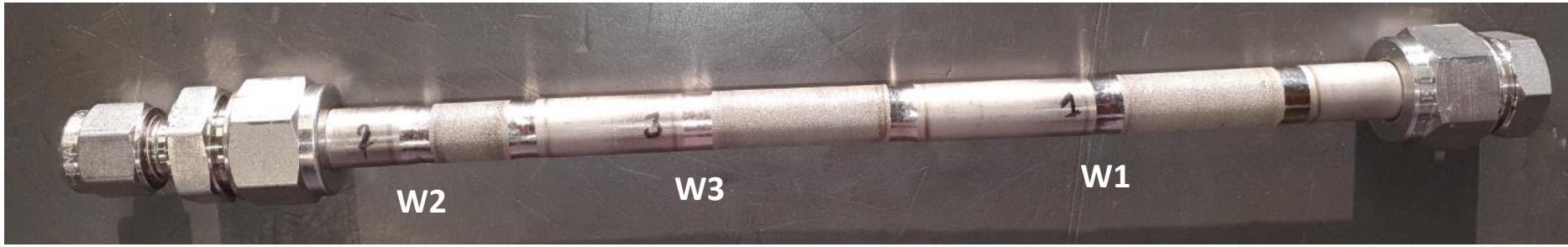
Titanium welding test



1. Metrology measurements @INFN Genova → Passed
   CMM Dea Mistral 070705 (Precision ±(4.50 + 5.00 * L/1000, L in mm)
2. Tomography: EDMS 2671618
3. Leak test: job #11-S04 → Passed
4. Pressure test (to easy the test the 3 samples were welded: EDMS 2713038
5. Leak test after pressure test: job #191 → Passed
6. Metallographic destructive tests EDMS 2722680:
   - Metallographic inspection (weld 2)
   - Transverse tensile test (welds 1 and 3)



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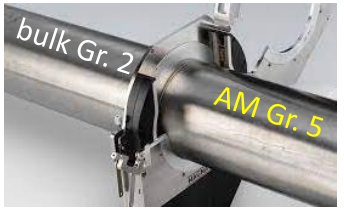
Titanium welding test



1. Tomography: EDMS 2671618

Samples were scanned with high resolution of 7.45 µm

Aim:

- Analyze the presence of porosity on 3 samples.
- Evaluation according to ISO 5817 – level B.

Results:

Weld No.	Pore size [mm]	Weld wall thickness [mm]	Porosity Path Length Ratio [%]
1	0.116	0.962	12.1
2	0.222	0.979	22.7
3	0.130	1.035	12.6

Welds 1 and 3 comply with level B welding qualification, weld 2 doesn't
(Porosity Path Length Ratio > 20% (for 2 pores))
The good point is that porosities found in the AM are not merging into the welds

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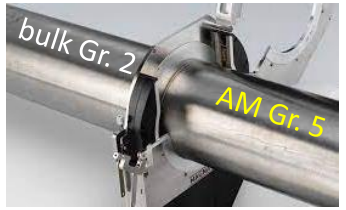
Titanium welding test



Metallographic destructive tests EDMS 2722680:

- Metallographic inspection (weld 2)
- Transverse tensile test (welds 1 and 3)

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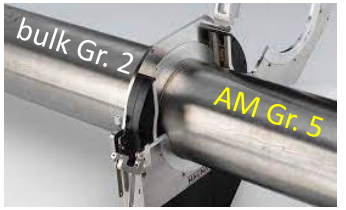
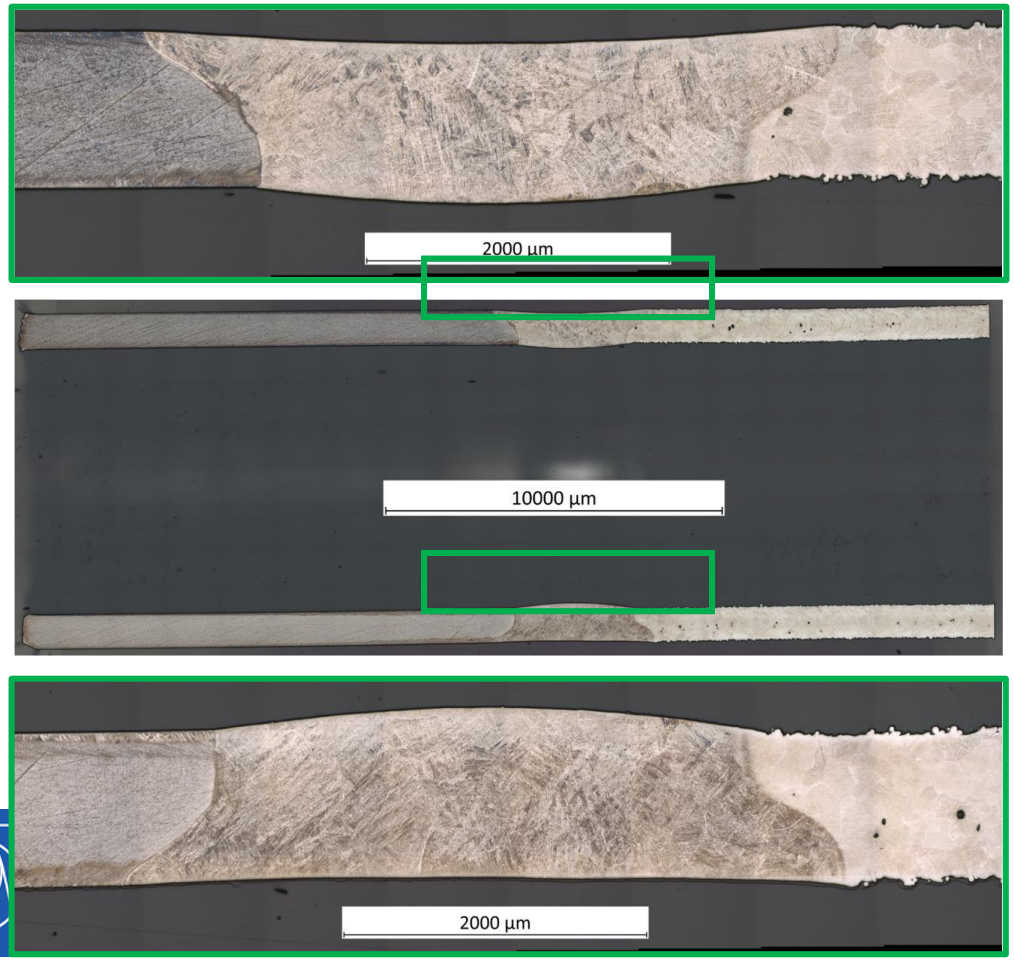
Titanium welding test

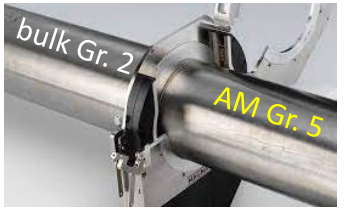


Metallographic destructive tests EDMS 2722680:

- Metallographic inspection (weld 2) according to ISO 5817 Level B:
  - Good quality butt weld joints
  - Joint free from imperfections

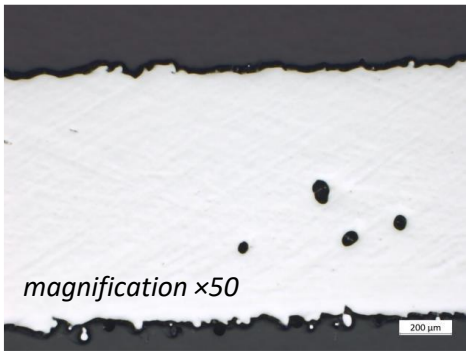


Titanium welding test

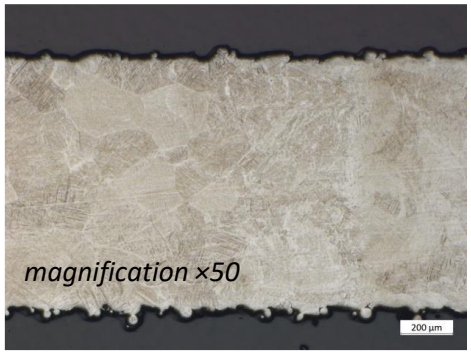


Metallographic destructive tests EDMS 2722680:

- Metallographic inspection (weld 2):
  - 0.35% porosities on Ti Gr. 5 surface of produced by AM (max individual D=100 um)

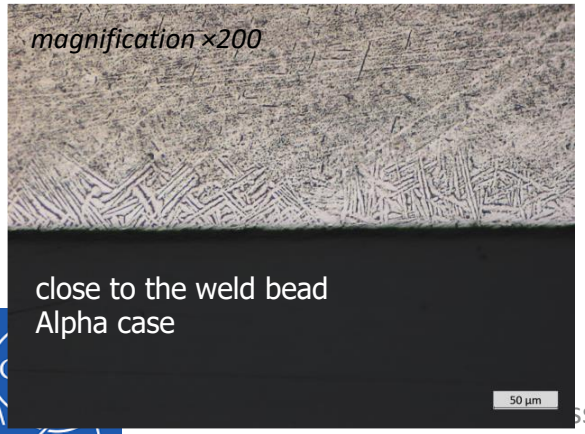


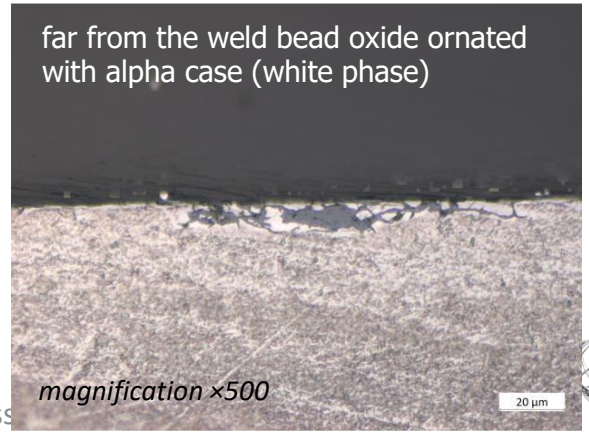
as-polished, pores are clearly visible



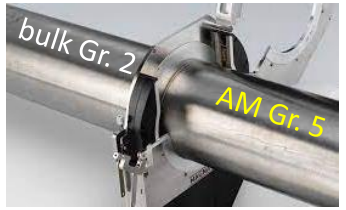
after etching – grain size can be appreciated

  - Some alpha case and oxides observed at inner wall of the titanium Gr. 2 tube at HAZ





Titanium welding test



Metallographic destructive tests EDMS 2722680:

- Transverse tensile test (welds 1 and 3) according to ISO 6892-1 Method A2

Weld	Rp0.2 (MPa)	**Rm (MPa)**	A15mm (%)
n. 1	423.4	**515.0**	13.2
n. 3	435.8	**542.7**	9.2
Mean ± std dev	429.6 ± 6.2	**528.9 ± 19.6**	11.2 ± 2.0

min required strength = min strength of Ti Gr. 2 (345 MPa) → ok

Breakdown occurred always at HAZ of titanium grade 2

Fractographic examination:

- Keyence VHX-6000 → confirm the ductile breakdown
- SEM Carl Zeiss Sigma with EDS detector → identification of weld regions and analysis of fractured surface - smooth transition between the weld seam and both parent materials. Confirmation of oxides in Ti Gr. 2 “standard” pipe

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Titanium welding test

TEST 2

Weld Reference	Type of test/ examination	Acceptance criteria	Report	Result / Comment
W1 – W2 W3	Visual examination	ISO 5817 Level B	No report	Compliant
W1 – W2 W3	Leak test before pressure test	≤ 10^{-9} mbar l/s	job #11-S04	2.8 x 10^{-10} mbar l/s Compliant
W1 – W2 W3	Hydraulic pressure test	162 bar	EDMS 2713038	Compliant
W1 – W2 W3	Leak test after pressure test	≤ 10^{-9} mbar l/s	job #191	2.6 x 10^{-10} mbar l/s Compliant
W1 – W2 W3	Micro-Tomography	ISO 5817 Level B	EDMS 2671618	W1 – W3 complaint W2 better result but not complaint
W2	Metallographic inspection	ISO 5817-1	EDMS 2722680	Compliant
W1 – W3	Tensile transverse test	ISO 6892-1 Method A2	EDMS 2722680	Compliant

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CONCLUSIONS

- AM represents often the only technology solutions for some results
  - We cannot avoid considering this technology for our applications
- No problem in both test for pressure and leak tests
  - Good result for very demanding specs (162 bar and ≤ 10^{-9} mbar l/s)
- Transverse tensile tests exhibit tensile strength far above the min required
  - Rm = 529 MPa *vs.* min Rm 345 MPa
  - Very good mechanical behaviour of welds
- Metallography highlighted potential initiation sites for crack on the AM Titanium grade 5 surface.
  - Further investigation are needed
  - Optimization of surface roughness could to be envisaged if fatigue is a concern

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CONCLUSIONS

- Micro-tomography results on full material welds – fully complaint with ISO 5817 Level B
  - It is possible to obtain very goods welds on additive manufactured titanium

- Micro-tomography results on 2nd test
  - Much better than 1st tests
    - Adjustment is extremely important
      - Stock on AM part are remachining is recommended
  - Only one of the sample exhibit some porosities
    - More statistics are needed
    - Further test with different heat treatments on AM parts?
    - Do we need to cope with Level B of ISO 5817, considering the other results ?

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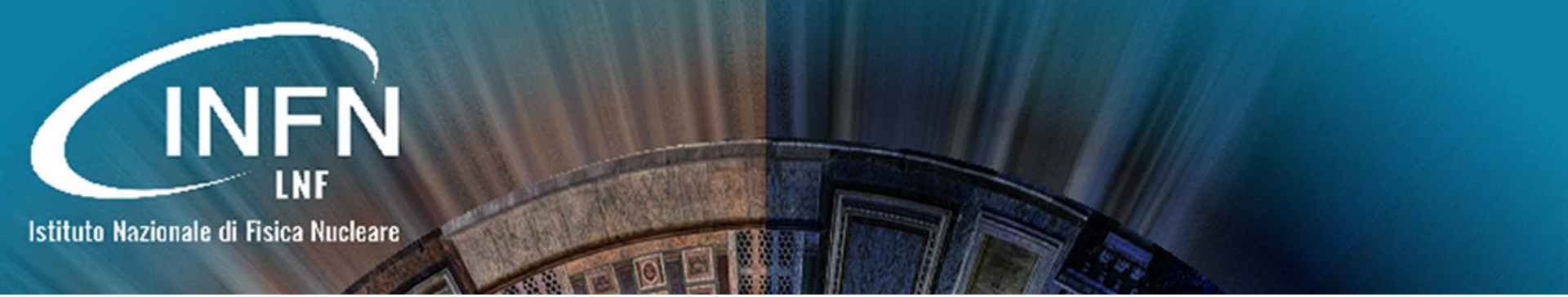

Questions?

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Back up slides

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Titanium welding test

EDMS References

Warm Nose Splitter Boxes	EDMS 2307865 EDMS 2307866
Welding process and pWPS Welding test on bulk material	EDMS 2595639
Pressure test (1° batch)	EDMS 2595100
X-ray Computed Tomography (1° batch)	EDMS 2597930
Pressure test (2° batch)	EDMS 2713038
X-ray Computed Tomography (2° batch)	EDMS 2671618
Metallographic destructive tests	EDMS 2722680

Leak test: job #11-S04
Leak test after pressure test: job #191

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