

T5.5 Case study Problem-Based Learning (PBL)

Title of Case Study / Problem-based learning case:

Importance of aluminium filler metal quality in DED-ARC/WAAM to reduce porosities and improve mechanical properties for Aerospace and Defence Applications

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Background

- Process: DED-Arc
- Aluminium:
 - ER5183: see datasheet



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Welding consumables for aluminum and aluminum alloys



Union AlMg 4,5 Mn

Solid Wire, aluminium

Classifications

EN ISO 18273
 S Al 5183 (AlMg 4,5Mn0,7(A))

AWS A5.10 / SFA-5.10
 ER5183

Characteristics and typical fields of application

Solid wire for GMAW and GTAW of AlMg alloys. The weld metal is resistant against sea water.

Base material should be cleaned near the seam. Pre-heating 150°C for plates > 15 mm

Base materials

EN AW-5083 AlMg4,5Mn 3.3547

EN AW-5086 AlMg4Mn 3.3545

EN AW-5019 AlMg5 3.3555

EN AW-6060 AlMgSi0,5 3.3206

EN AW-6005A AlMgSi0,7 3.3210

EN AW-6082 AlMgSi1 3.2315

EN AW-6061 AlMg1SiCu 3.3211

EN AW-7020 AlZn4,5Mg 3.4335

EN AC-51300 G-AlMg5 3.3561

EN AC-51400 G-AlMg5Si 3.3261

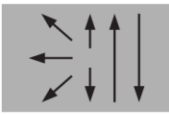
Typical analysis of the solid wire

wt.-%	Mn	Cr	Ti	Al	Mg
	0.5 – 1.0	0.05 – 0.25	< 0.15	bal.	4.3 – 5.2

Mechanical properties of all-weld metal - typical values (min. values)

Condition	Yield strength R _{p0.2}	Tensile strength R _m	Elongation A (L ₀ =5d ₀)
	MPa	MPa	%
u	125	275	17

Operating data



Dimension mm
 0.8
 1.0
 1.2
 1.6

Approvals

TÜV (02195), DB (61.132.03), ABS, BV, DNV GL, LR, CE

GMAW

- 7075T6 (no datasheets available)

Filler metal / Manufactured wall	Contents in %wt.								
	Al	Cr	Cu	Zn	Mg	Si	Ti	Fe	C
EN 573-3			1.20						
EN AW 7075	Rem.	0.18 –	–	5.10 –	2.10 –	max	max	max	–
(base metal)		0.28	2.00	6.10	2.90	0.40	0.20	0.50	

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ER7075-FM-1	90.2	0.19	1.3	5.37	2.31	0.05	0.02	0.19	0.09
ER7075-wall 1	90.9	0.19	1.27	4.65	2.24	0.04	0.02	0.18	0.05
ER7075-FM-2	89.7	0.2	1.44	5.6	2.75	0.02	0.02	0.04	0.07
ER7075-wall 2	90.1	0.21	1.58	5.02	2.38	0.03	0.01	0.06	0.05

Table 1: chemical composition of 7075 base metal, Filler Metal (FM) and printed walls

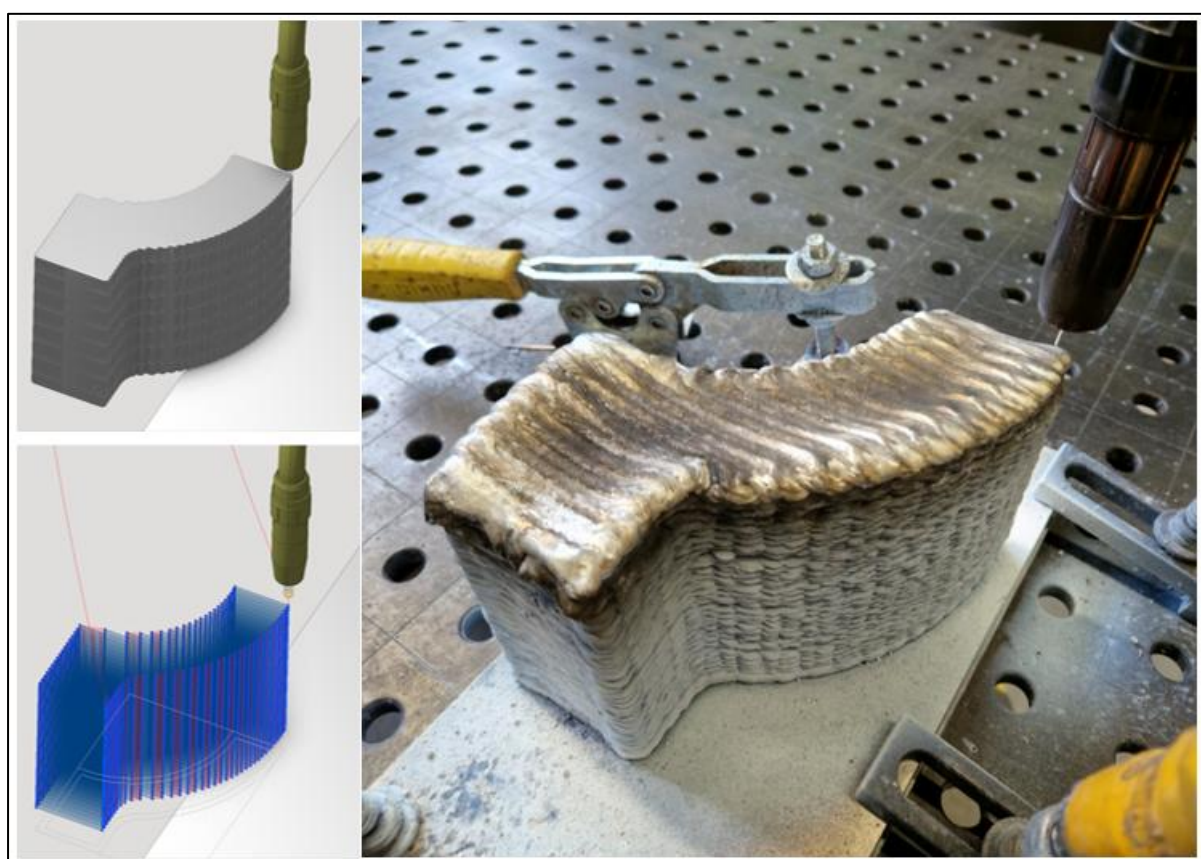


Figure 1: example of print path/strategy (left) and the printed part

Technical challenge

- Which aluminium (AWS 5.10 ER5183, EN AW-7075-T6) is more critical for porosities/other defects/weldability? And why?
- Explain how and why porosities percentage/size in DED-Arc could be reduced or increased?
- How do you verify and control the aluminium wire quality during production?



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- NDT
 - Which NDT technology (surface and internal/volumetric) could be used to detect porosities?
 - Any preparation to perform this tests

Illustration of the case study

Which aluminium (AWS 5.10: ER5183 or EN AW-7075-T6) is more critical for porosities/other defects/weldability? And why?

Feature / Criteria	ER5183 (Al-Mg4,5Mn0,7)	EN AW 7075-T6 (Al-Zn-Mg-Cu)
Primary Alloy Element	Magnesium (~5%)	Zinc (~5.6%), Mg, Cu
Strength	Standard Filler Wire	High-Strength
Weldability Rating	Excellent	Poor / "Unweldable" (Via conventional fusion)
Porosity Risk & Mechanism	Low: allows hydrogen gas to escape easily before freezing. => See Figure 3	Higher ¹ : depending on welding parameters and path strategy => See Figure 5
Hot Cracking Risk	Very Low: Chemistry is optimized to stay safely out of the hot-cracking zone.	Extreme: Low-melting-point eutectics remain liquid at grain boundaries, causing severe tearing as it cools.
Cleanliness & Handling Demands	Standard industrial clean storage and standard shielding gas.	N/A (Rarely fusion welded; typically joined via Friction Stir Welding to avoid defects).

Explain how and why porosities percentage/size in DED-Arc could be reduced or increased in wire?

¹ Pore suppression and performance improvement mechanisms in wire-arc directed energy deposition of 7075 alloy (VIRTUAL AND PHYSICAL PROTOTYPING2025, VOL. 20, NO. 1, e2464953 (24 pages), <https://doi.org/10.1080/17452759.2025.2464953>)



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Two main causes for porosities:

- 1) Hydrogen
- 2) Zinc (or other elements): only for EN AW-7075-T6

Porosity can often be a problem when welding aluminium. It is caused by hydrogen gas becoming entrapped within the solidifying aluminium weld pool, resulting in voids in the completed weld. Hydrogen is highly soluble in molten aluminium, and for this reason, the potential for excessive amounts of porosity during arc welding of aluminium is considerably high. Hydrogen is sometimes introduced unintentionally during the welding operation through contaminants within the welding area. It is important to thoroughly understand the many sources of these contaminants in order to detect the cause and take the necessary action to resolve porosity problems. Hydrogen originates from a contaminant, either a hydrocarbon (e.g. grease, skin and oils) or moisture, both of which can break down in the arc plasma to produce atomic hydrogen.

In the EN AW-7075-T6 wire there is also around 5% Zn: Gas bubbles (zinc but also hydrogen) do not simply rise straight up to the surface. They follow the currents (convection) in the molten bath. Zinc bubbles are heavier and find it harder to escape from the molten bath than hydrogen bubbles, which explains why zinc evaporation is so detrimental to quality. ²

Both the Zn-bubble and H-bubble do not directly flow upward, but flow with the molten pool convection. The higher density of Zn-bubble makes it more difficult to escape from molten pool, and therefore a high percentage of Zn-pore is formed. ³

A low WFR in EN AW-7075-T6 wire decreases the sources of Zn vapour and hydrogen rather than promotes the bubble escape, thus decreasing the porosity.

The table below outlines various hydrogen sources that can cause porosity. Footnotes provide details on their specific impacts and mitigation strategies.

	Hydrogen sources
Production of wire	Hydrocarbons Surface quality Surface roughness Different chemical composition of wire (Zn, Cu,)

² Pore suppression and performance improvement mechanisms in wire-arc directed energy deposition of 7075 alloy. <https://doi.org/10.1080/17452759.2025.2464953>

³ Pore suppression and performance improvement mechanisms in wire-arc directed energy deposition of 7075 alloy. <https://doi.org/10.1080/17452759.2025.2464953>



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Storage and Use of Aluminium Filler Metal	Vacuum packed Overnight storage Heated wire feed cabinet Lube-Matic Wire Kleener Pad ⁽¹⁰⁾
Shielding gas	Dew point measurement at torch ⁽⁴⁾ Use of gas with H ₂ O (5 bar) ≤ 5 Spatter buildup inside the gas nozzle ⁽²⁾ Gas turbulence (eg. Possible due to weaving) Piping lines with low permeation ⁽⁸⁾ Mechanical joints for connections ⁽⁹⁾ Add helium (5-30%) to the Argon
During printing	Removal hydrated aluminium oxide ⁽¹⁾ Atmospheric humidity measurement Pre-flow before printing Overnight flow ⁽³⁾
Welding Conditions	Arc length control ⁽⁵⁾ High current – Heat input/balance ⁽⁶⁾ Polarity ⁽⁷⁾

(1) The oxide layer was not removed between runs. It is unlikely that hydrated aluminium oxide is a source of moisture because the part remains hot during printing. Test with laser cleaning were performed to remove robotically oxide layer. Risk during overnight stop can be reduced due to pre-heating

(2) automatic intermediate cleaning?

(3) In a cold environment, when shielding gas is not flowing (perhaps overnight), condensation can create a build-up of moisture within the gas lines.

(4) preferably below -50°C

(5) a long arc length can give molten metal droplets more time to pick up environmental moisture and introduce it into the weld pool

(6) higher welding current can increase the temperature of the weld pool, increasing the hydrogen solubility and allowing it to absorb more hydrogen which can be ejected on solidification. However, an increase in welding current, as well as a reduction in travel speed, can also potentially reduce porosity by giving hydrogen more time to "bubble out" of the weld pool, if the rate of gas evolution is higher than the rate of gas absorption. This can also be aided by preheat, heating the backing bar (if one is used), or by using an Ar-He shielding gas, rather than pure argon. Note that a higher weld current implies also a higher wire feed speed for MAG processes: Higher welding current / heat input and greater wire surface area per unit time => increased zinc vaporisation and hydrogen introduction, which intensifies turbulent gas generation within the molten pool.

(7) the electrode is always positive and so cleans by default: When the electrode is positive, the workpiece surface has electrons stripped from it and it is bombarded with ions, which break-up and disperse the oxide film

(8) Gas should be delivered to the torch and shielding areas through flexible polyethylene hoses; rubber hoses are not recommended for gas delivery because of the high permeability



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of rubber and the potential for contamination of the shielding gas. Stainless steel being the most expensive but most effective for dealing with long distances the distance the gas has to travel from source to the torch should be minimised

(9) Mechanical joints are generally considered more prone to leaks than brazed or welded joints

(10) <https://www.crcindustries.com/lube-matic/>

Table 2 : sources of hydrogen that could lead to porosities [AWS A5.32M_A5.32 Welding Consumables Gases and Gas Mixtures for Fusion Welding and Allied Processes] [TWI - <https://www.twi-global.com/technical-knowledge/job-knowledge/Avoiding-Porosity-When-Welding-Aluminium>] [AWS Welding Handbook, VOL-5 - 9th Ed (2011) - Materials and Applications, Part 2 (page 33-36)].

How do you verify and control the aluminium wire quality during production?

hydrocarbon contamination:

- 1) White cloth test: wipe wire with acetone to look for black residues
- 2) Hydro carbon test: see Figure 13

Surface quality:

- 1) Feeding Resistance test : see Figure 13
- 2) Visual inspection
- 3) Microscope
- 4) SEM: see Figure 2



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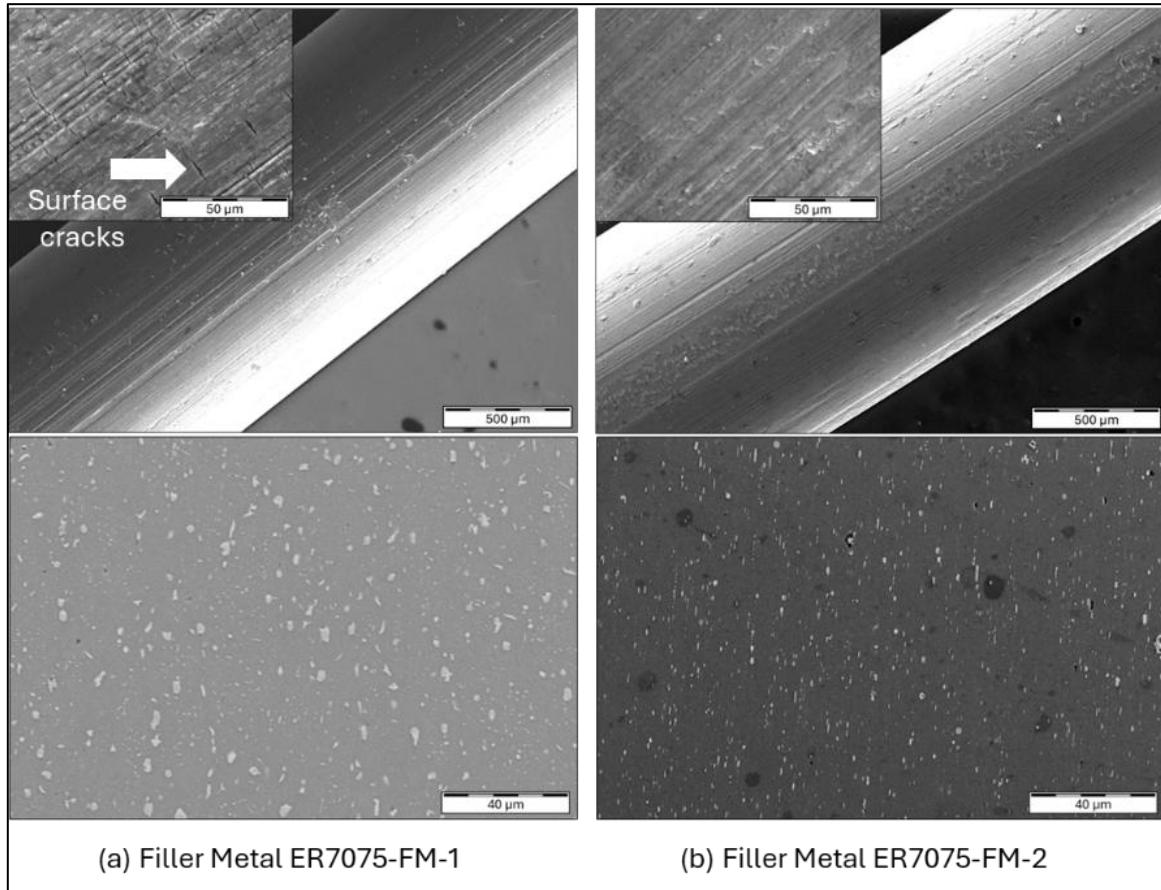


Figure 2 – SEM analysis of filler metals (a) ER7075-FM-1, (b) ER7075-FM-2 highlighting their surface cracks..

Chemical analysis:

- 1) Wet analysis (accurate)
- 2) SEM (indicative)

Other:

- 1) Cast and Helix: Figure 14
- 2) Bead on plate to make a microsection

Which NDT technology (surface and internal/volumetric) could be used to detect porosities?

- For both, surface and internal defects, the surface of DED-Arc must be grinded flat or machined



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- Surface porosities

Method	Usefulness for surface porosity	Notes
Visual Testing (VT)	(very) good	Use good lighting + magnification.
Penetrant Testing (PT)	very good	Best for open-to-surface porosity. Dye enters pores, developer draws it out as small dots/rounded indications.
Magnetic Particle Testing (MT)	limited	Only for ferromagnetic materials. Better for cracks; porosity may appear as weak/round indications if open or near-surface.
Eddy Current Testing (ET)	possible	Can detect small surface-breaking defects, but interpretation of porosity can be harder. Useful on conductive materials.

- Internal volumetric porosities
 - In **ultrasonic testing (UT)**, different defect types interact with sound waves differently (see also Figure 9):
 - **Attenuation UT for porosity:** Porosity consists of many small gas pores dispersed in the material. These pores scatter and absorb the ultrasonic energy, causing a reduction (attenuation) in the signal amplitude as the wave travels through the material. Rather than producing a strong, distinct echo, porosity often appears as a loss of backwall signal or a region of increased signal attenuation.
 - **Reflection UT for cracks:** Cracks are planar discontinuities that act as strong reflectors. When the ultrasonic beam strikes a crack at a suitable angle, a significant portion of the sound energy is reflected back to the probe, producing a distinct echo. The position and amplitude of this reflected signal can be used to locate and size the crack.
 - In short:
 - Porosity → detected mainly by signal attenuation/scattering (loss of transmitted energy).
 - Cracks → detected mainly by signal reflection (strong discrete echoes).
 - In (digital) radiography: see Figure 10, Figure 11
 - larger porosities can be observed but small ones not.
 - for small porosities a macro sectioning is necessary
 - In CT (computed tomography): small porosities can be easily observed: Figure 3



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Additional pictures/information

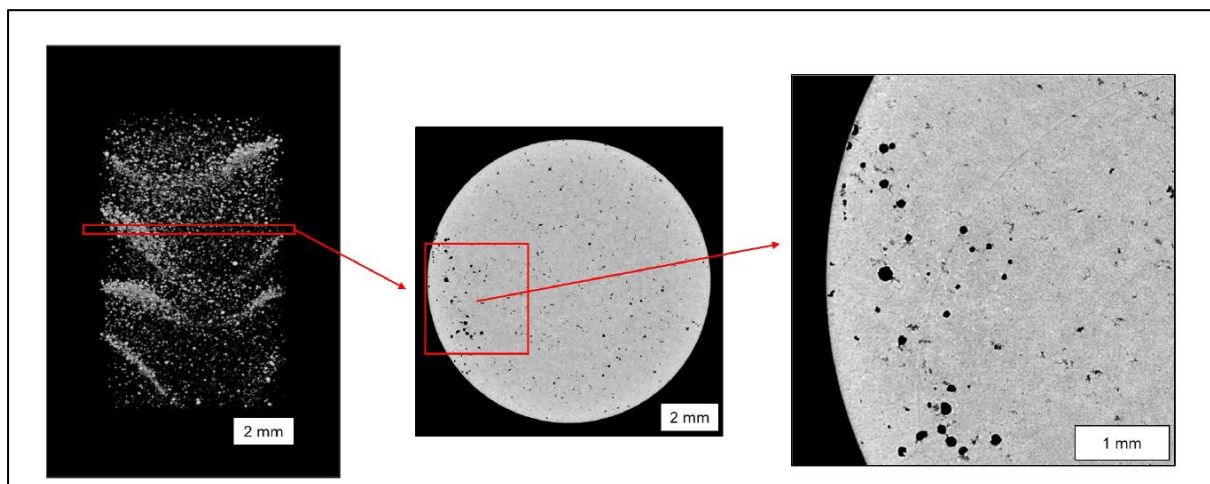


Figure 3: 5183 DED-Arc printed part: left CT scan with porosity distribution & middle/right macro section



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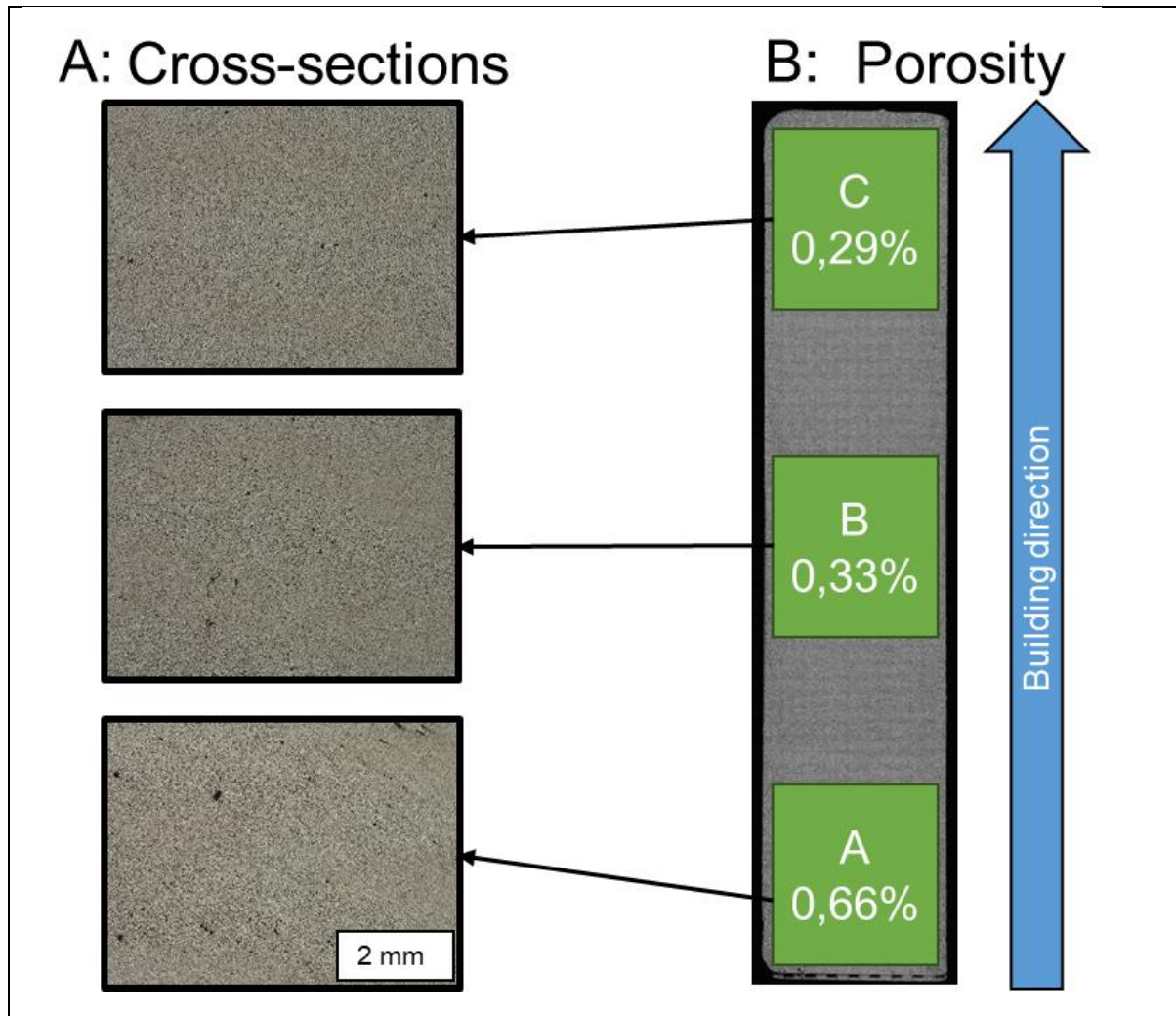
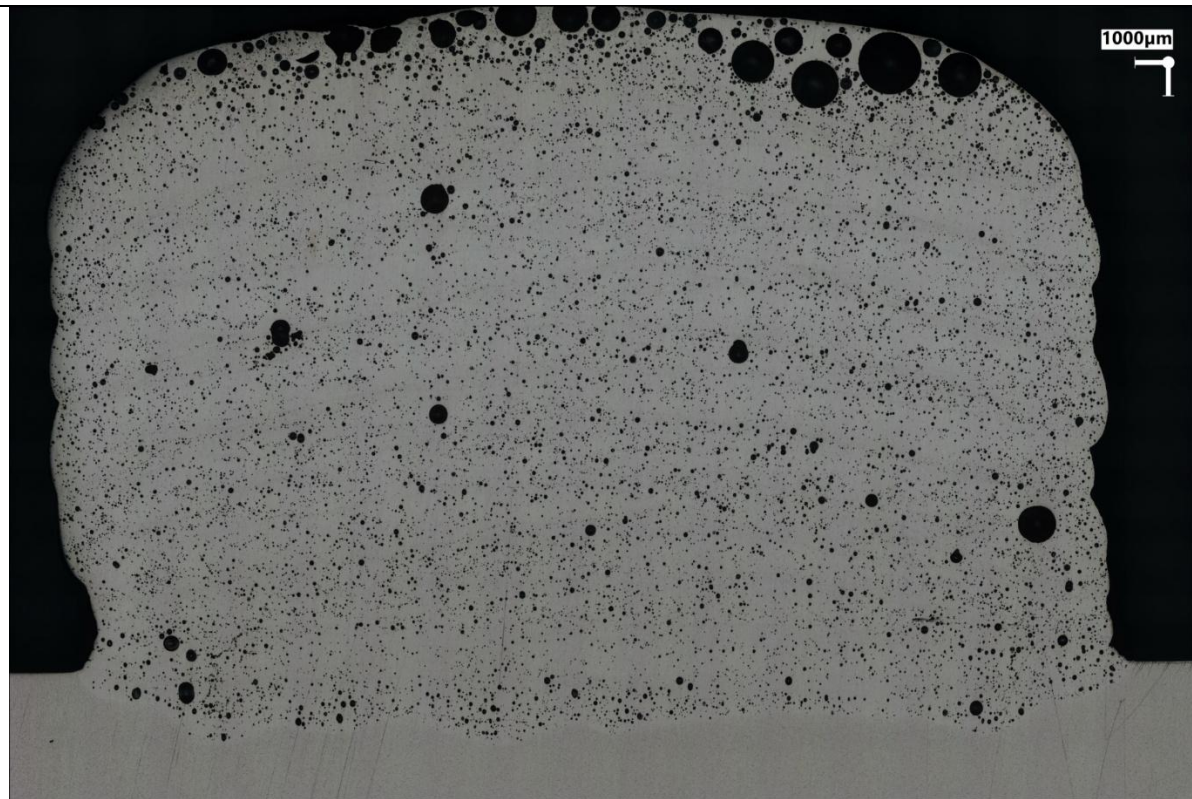


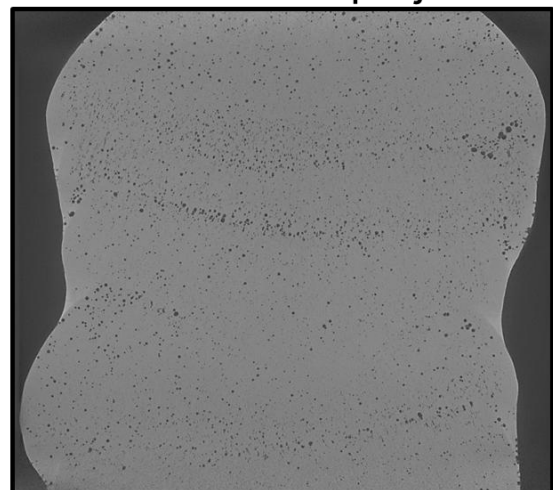
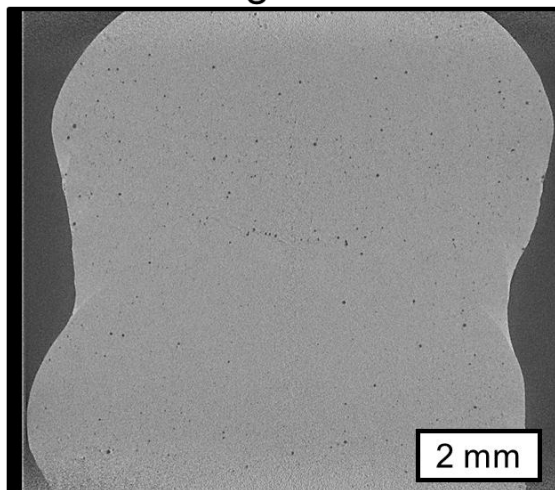
Figure 4: Typical porosities values for 5183 - weaving strategy



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≈ 9% porosities, also larger pores



≈ 1% porosities

Figure 5: porosities on macro section 7075 with weaving strategy (top) - straight deposition/strings & optimized parameters with a small process window (bottom)



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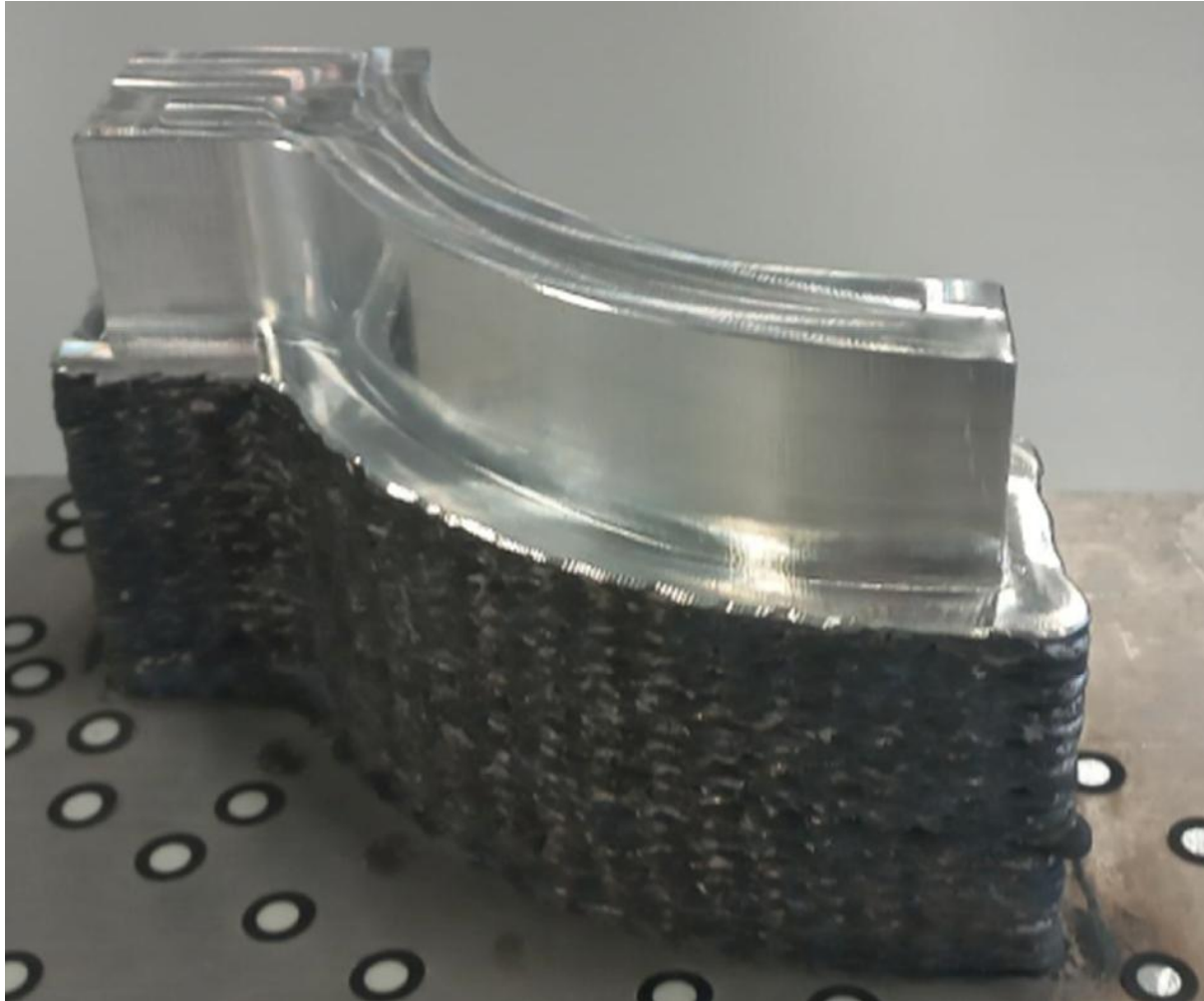


Figure 6: Image of a DED-arc printed part which has been partly machined on the top, bottom part is as printed (material 5083)



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Figure 7: image of penetrant testing with round and more linear indications on a machined surface



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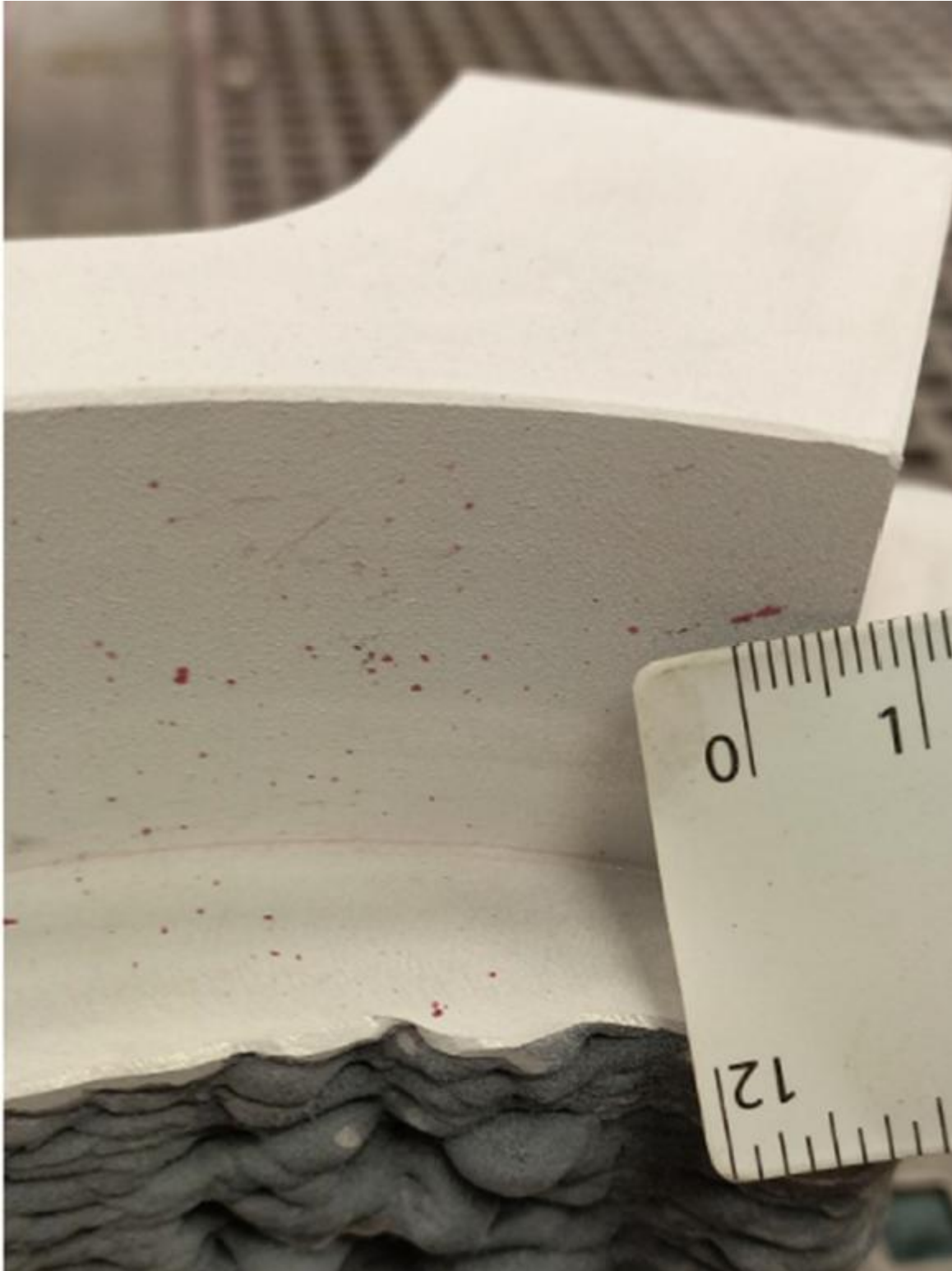


Figure 8: detailed image of penetrant testing with round and more linear indications on a machined surface



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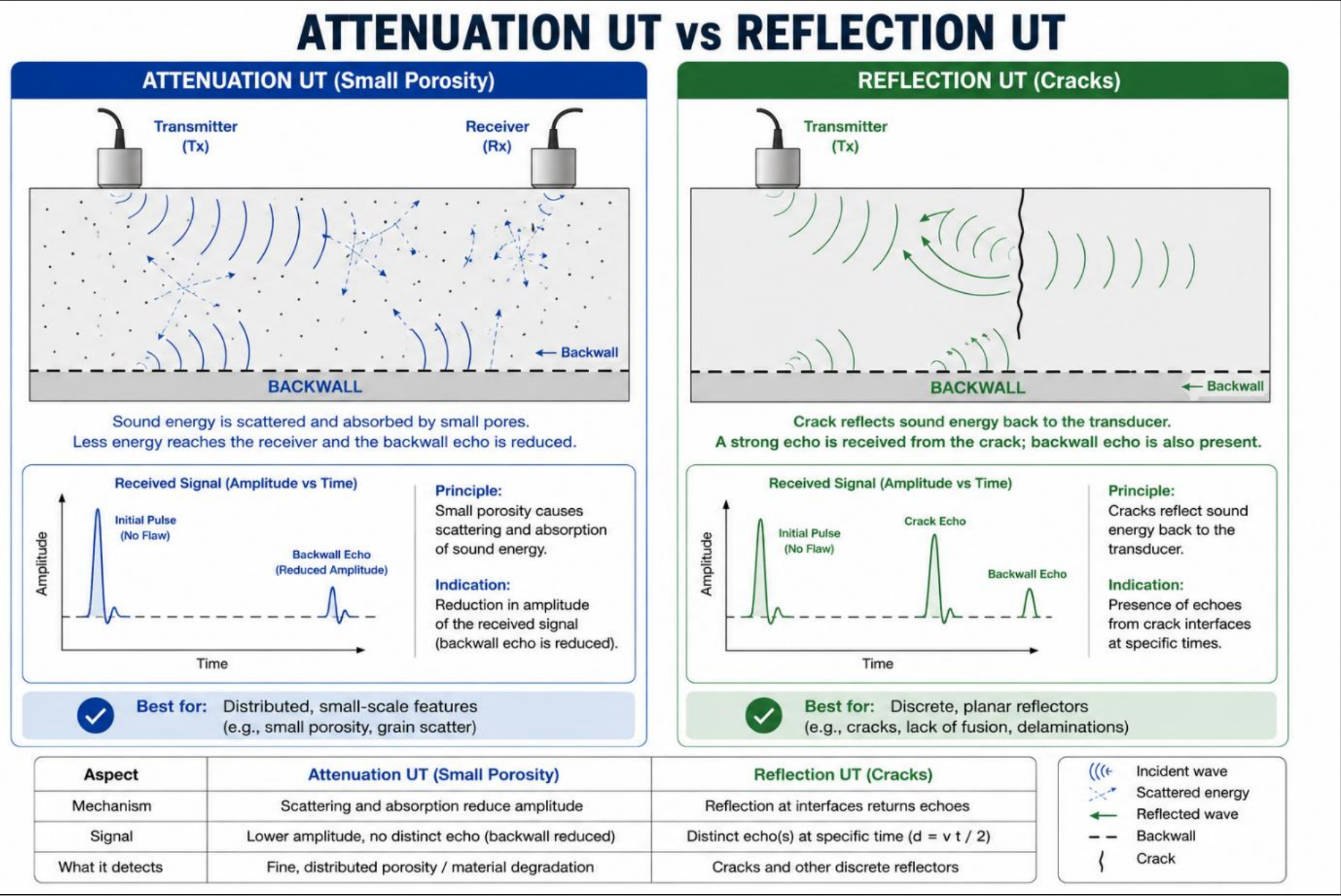


Figure 9: Schematic representation of attenuation UT vs reflection UT

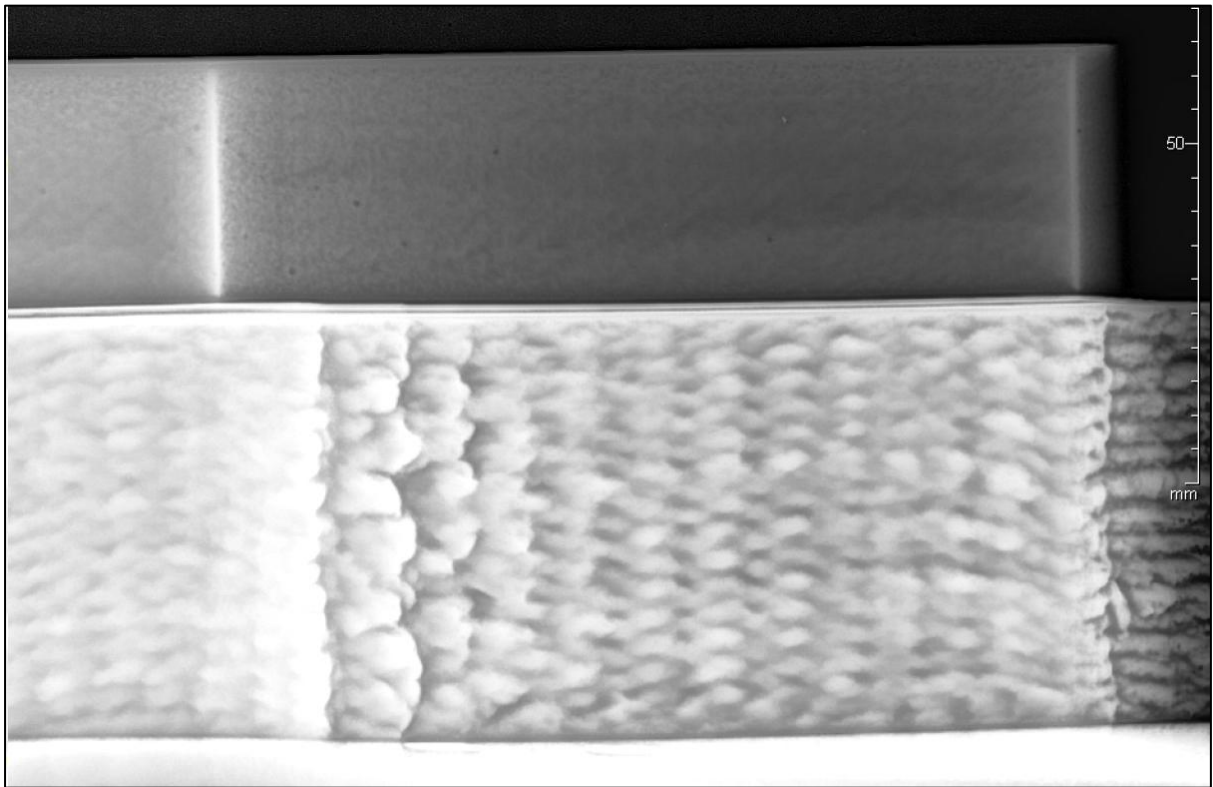


Figure 10: RX Ded-Arc printed part: only the machined (top part) can be interpreted

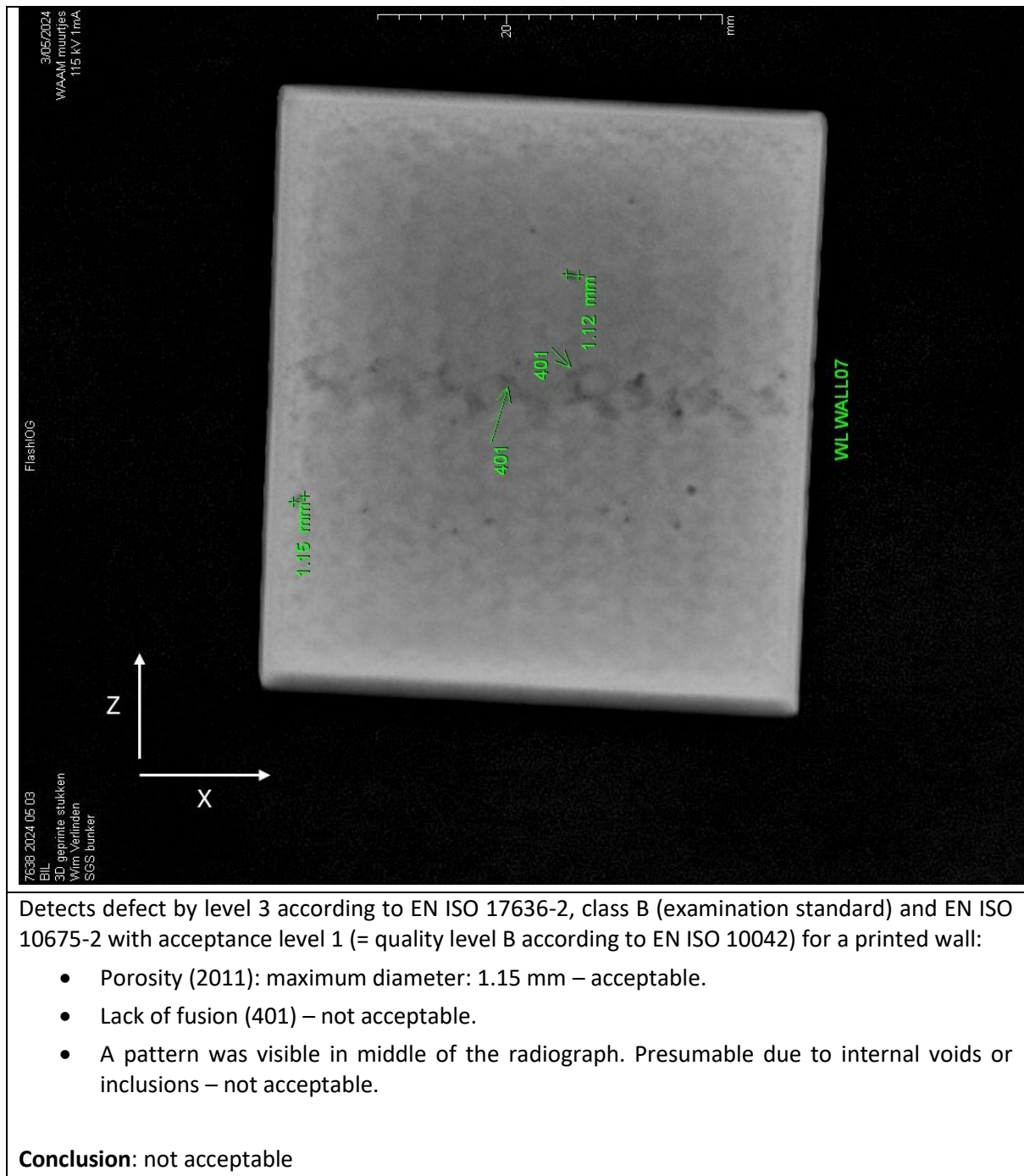


Figure 11: RT of printed wall with acceptance level 1 (ISO 10675-2)

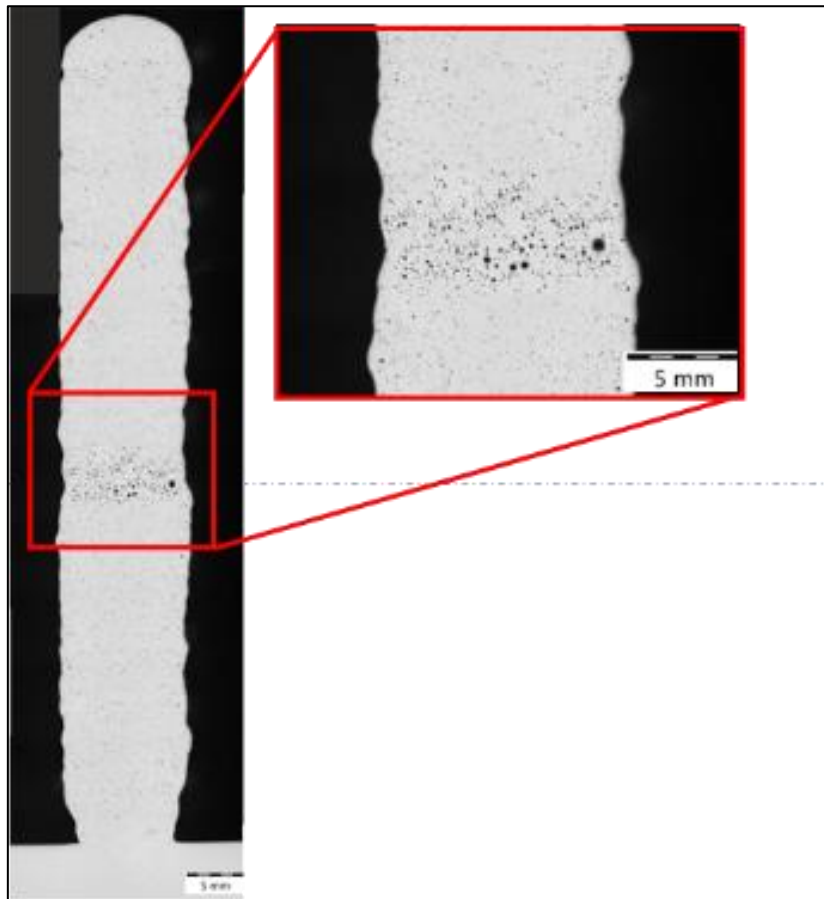


Figure 12: macro sectioning reveals the larger pores but also many small porosities can be detected (which were not detected by RX)

Tasks: Wire surface investigation by infrared spectrometry, measurement of the coefficient of friction, smoke test and microscopic analysis.

Abbreviations:

CH- Quantity – Hydrocarbons quantification via infrared spectrometry (*)

g - Total quantity of hydrocarbons soluble and insoluble (metal soaps) in CCl_4 [mg/m^2] (Trichlorotrifluoroethane) and CCl_3COOH (Trichloroacetic acid)

l - Amount of hydrocarbons soluble in CCl_4 (carbon tetrachloride) in [mg/m^2]

μ - Coefficient of friction with standard deviation (**)

(*) = With respect to the measurement of hydrocarbons (CH) on the wire surface by means of infrared spectrometry, we distinguish between those CH which are soluble in CCl_4 , and those which are not. The measurement procedures for these different types of CH are defined in our BE-standards 151 and 156 (see files annexed), which are available on request. Usually the "amount of soluble CH" or "l" should be equal to or, in case of a mixture of soluble and insoluble CH, smaller than the "total amount of CH" or "g". The difference between both values "g" - "l" represents the amount of non-soluble hydrocarbons (e.g. stearates).

However, it is possible that the measured value "amount of soluble CH" is higher than the "total amount of CH" if a part of the CH is soluble in water (e.g. emulsifiers).

(**) = The coefficient of friction test is performed following the BE-standard 153 (see file annexed).

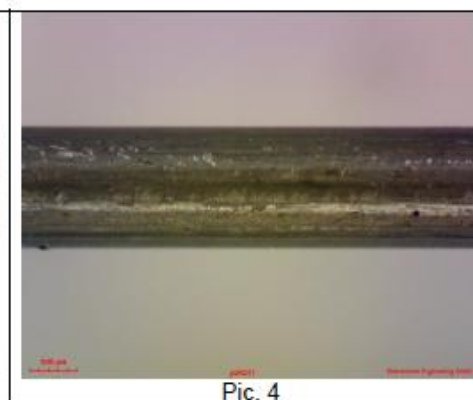
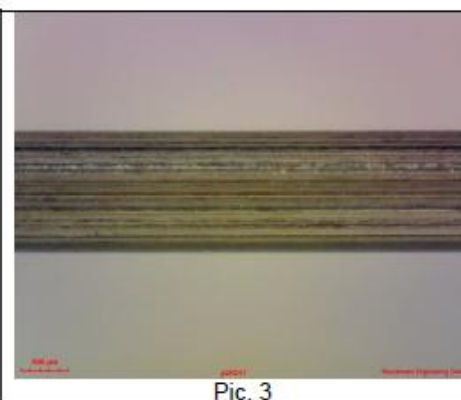
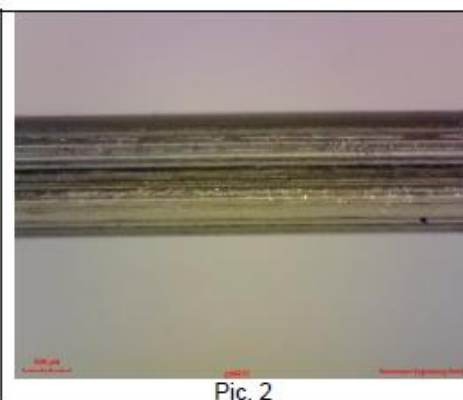
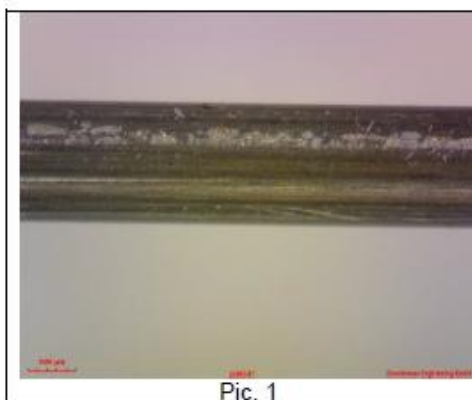
Overview of the wire tests - alloy ER7075:

Test no.	Short description of the treatment	CH-Quantity (mg/m^2)		$\mu \pm \Delta\mu$	Remarks
	Zone 1	l	g		
po643-01	Al-wire ER7075, $\varnothing$ 1.2 mm	52	56	0.36 $\pm$ 0.16	- The amount of hydrocarbons is very high. According to our experience with 5000 and 4000 Al-welding wire alloys, values bigger than 2 mg/m^2 can be likely to generate porosity in the welded material. The value of soluble and total hydrocarbons is more or less the same, for this reason we will perform on the wire po643-02 only the soluble hydrocarbons quantification. - Very high coefficient of friction with high standard deviation caused from the

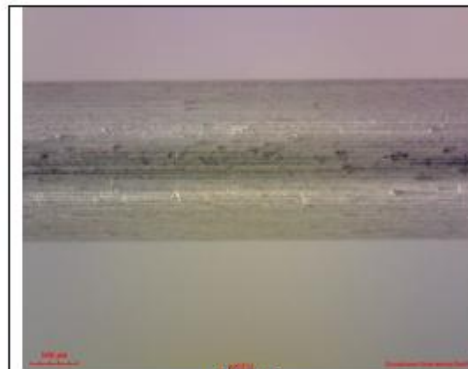
Test no.	Short description of the treatment	CH-Quantity (mg/m ²)		$\mu \pm \Delta\mu$	Remarks
	Zone 1	l	g		
					poor wire surface, very deep drawing marks observed under microscope (see pictures 1 to 4).
po643-02	Al-wire ER7075, Ø 1.6 mm	5	-	0.13±0.05	- The amount of hydrocarbons is slightly bigger than 2 mg/m² (values bigger than 2 mg/m² can generate porosity in the welded material). - Much better surface appearance compared to po643-01! - We observed light drawing marks (see pictures 5 to 8). - Much better coefficient of friction with lower standard deviation compared to po643-01.

Microscopic analysis:

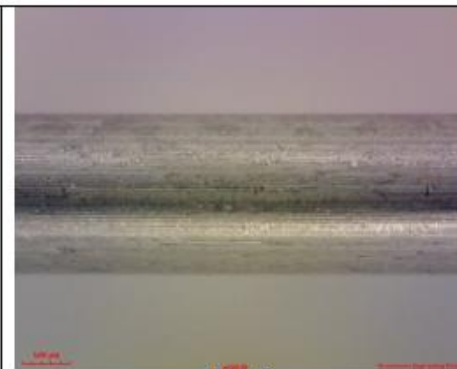
po643-01 – Al-wire ER7075, Ø 1.2 mm



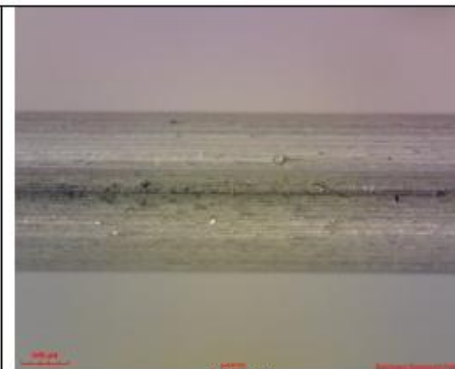
po643-02 – Al-wire ER7075, Ø 1.6 mm



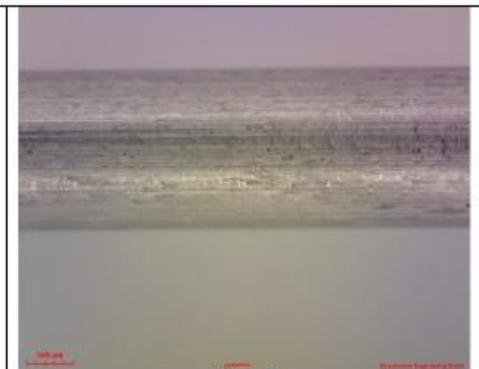
Pic. 5



Pic. 6



Pic. 7



Pic. 8

Smoke Test:

The smoke test will be performed fixing the wire between two screwable terminals and passing a short-circuit current through it until it burns up. Ideally, a reference wire with the same diameter and drawing process, but with a different amount of lubricant on the surface, should be used for comparison.

According to our experience, wires with less than 2 mg/m² of hydrocarbons don't generate visible smoke. As soon as residuals or lubricants are present on the wire surface, smoke will be visible. Currently, we are unable to quantify the amount of smoke using numbers, percentages or similar.

For wires po643-01 and po643-02, we can confirm a relationship between smoke formation and the amount of hydrocarbons on the wire surface (see the video sent via the WeTransfer link).

Test of feeding resistance respectively friction force in the liner (Newton)

To perform the feeding resistance test with a graphical presentation (see the example below), 1200 metres of wire wound on an SD300K spool is required. A reference wire should also be included for comparison with the others.

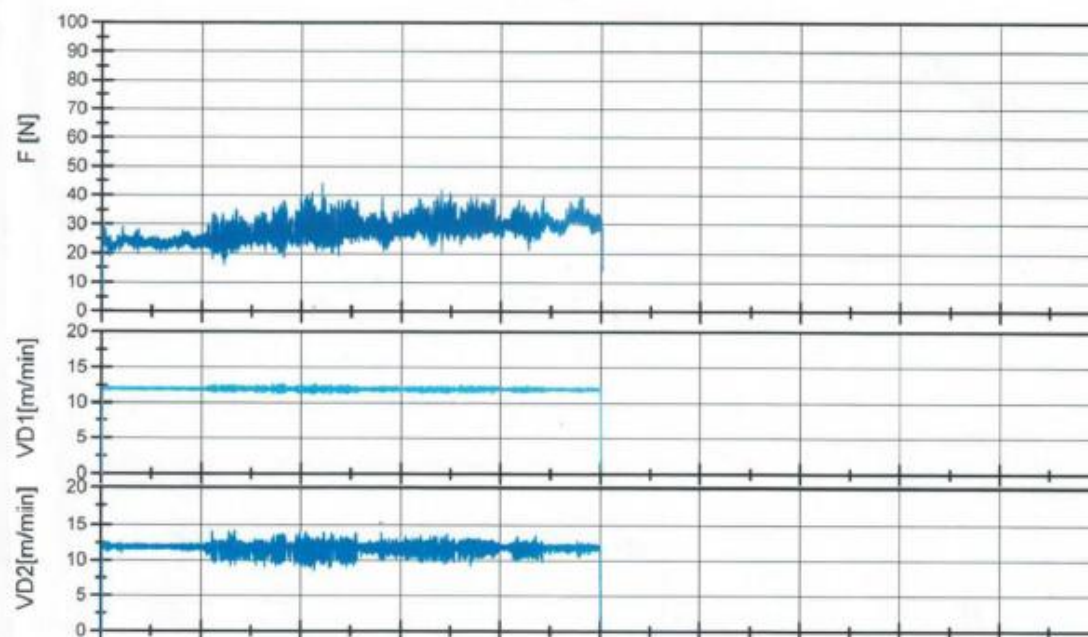
Abbreviations:

F - Feed resistance [N]

VD1 - Welding wire speed measured before liner - [m/min]

VD2 - Welding wire speed measured before contact tip - [m/min]

Example of feeding resistance test:



Final results:

According to our experience with 5000 and 4000 Al-welding wire alloys, an amount of hydrocarbons on the wire surface bigger than 2 mg/m^2 is likely to cause porosity in the welded material. The smoke test shows a relationship between the quantity of hydrocarbons and smoke formation; wires with a value bigger than 2 mg/m^2 generate visible smoke. Applying lubricant to the previously cleaned wire surface to improve feeding properties should also be performed respecting the 2 mg/m^2 target. To achieve this target, Boockmann Engineering GmbH has developed equipment (HELICORD[®] machine) and products designed for the aluminium welding wire industry.

Unfortunately, both wires po643-01 and po643-02 have a higher amount of hydrocarbons on the surface, especially po643-01. This wire has a very poor surface, which also causes a high coefficient of friction (see coefficient of friction value) and probably poor sliding performance. The surface of the po643-02 wire is better than po643-01, but still not as good as the 5000 and 4000 alloys. Some imperfections are also visible here. The smoke test also confirms the relationship with the quantity of hydrocarbons, po643-01 produces much more smoke than po643-02.

Unfortunately, we are unable to perform a full welding test with this special aluminium alloy. More wire is required for a feed resistance test.

Figure 13: report of wire surface investigation by infrared spectrometry, measurement of the coefficient of friction, smoke test and microscopic analysis

WIRE CAST AND HELIX



NS PREMIUM WELDING WIRE CHARACTERISTICS:

Consistent Cast and Helix Yield Weld Uniformity

Improper wire cast and helix reduces weld quality and adds to direct labor and factory overhead costs. Small cast and large helix causes the wire to exit the welding gun (contact tip) in constantly changing directions. It also causes downtime due to wire feeding problems. Too large a cast will cause downtime on some equipment due to inconsistent current pickup at the contact tip.

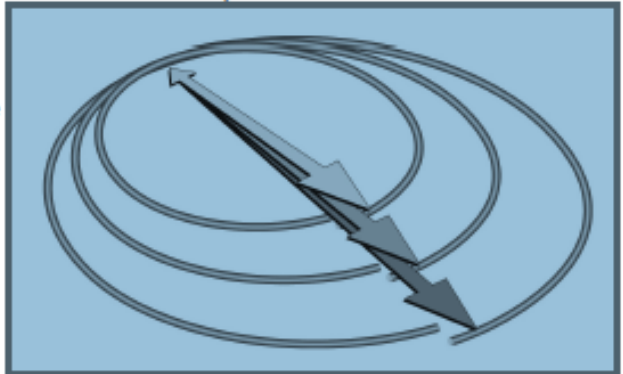
Helix is most detrimental when it is inconsistent and varies throughout the spool. This condition can result in arc wander. The amount of wire deflection due to excessive helix increases as cast decreases or as welding stick-out increases. This will result in weld joint tracking problems.

NS Cast and Helix Characteristics Exceed AWS Standards

	MINIMUM CAST	MAXIMUM CAST	MAXIMUM HELIX
NS PREMIUM CARBON WELDING WIRE	35"	55"	1"
NS SATIN GLIDE™ STAINLESS STEEL WELDING WIRE	30"	50"	1"
TYPICAL COMPETITIVE WELDING WIRES	Varies	Varies	Varies
AWS SPECIFICATION	15"		1"

- National Standard's controlled cast and helix helps eliminate excessive contact tip and liner wear, reduce arc wander and improve wire feedability.
- Manufactured in the USA according to ISO9001:2008 quality standards

CAST is the diameter of the circle formed by a length of wire thrown loosely on the floor. Cast is normally checked before it enters the wire feed system.



HELIX is the "pitch" of a single strand of weld wire measured as the distance one end of a strand of wire laying on a flat surface rises off that surface. Helix is normally checked before it enters the wire feed system.



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Figure 14: Cast and helix of welding wire

Sources

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 - b. Establishing best Practices in DED-Arc Manufacturing of High-Strength 7075 Aluminium Alloy Parts. [R. Nunes, W. Verlinde, K. Faes, M. Lezaack, W. De Waele, A. Simar] - Status: In preparation for submission.
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- 3) AWS A5.32M_A5.32 Welding Consumables Gases and Gas Mixtures for Fusion Welding and Allied Processes
- 4) TWI - <https://www.twi-global.com/technical-knowledge/job-knowledge/Avoiding-Porosity-When-Welding-Aluminium>
- 5) AWS Welding Handbook, VOL-5 - 9th Ed (2011) - Materials and Applications, Part 2 (page 33-36)

The Purpose of the elaborated Case Studies

Case studies are structured examinations of real-world situations or challenges designed to bridge theory and practice. They are developed both as a research method and as a learning tool to strengthen analytical and problem-solving skills. By engaging with authentic industrial scenarios, students gain practical insight into complex professional environments.

The purpose of this case studies is to encourage active, learner-centred engagement. They support approaches such as problem-based learning by enabling students to work independently or collaboratively, with or without instructor guidance. Through analysing theoretical concepts within realistic contexts, students learn to interpret data and test results, evaluate alternative courses of action, and develop well-reasoned, creative solutions.

This approach is particularly valuable in sectors such as aerospace, defence, and advanced manufacturing, where challenges are multifaceted and solutions are rarely singular. Because multiple valid solutions often exist, guided facilitation is frequently beneficial to help students structure their reasoning, assess trade-offs, and justify their decisions effectively

Competence unit coverage:

AILEEN competence units		Covered CU
AW_01	Welding: Advanced Metallic Materials in Aerospace and Defence Sectors	X
AW_02	Welding: Advanced Welding Processes and Equipment in Aerospace and Defence Sectors	X
AW_03	Welding: Advanced Welding Applications in Aerospace and Defence Sectors	X
AW_04	Welding: Introduction to brazing technology Knowledge for quality brazed joints	
AW_05	Welding: Fundamentals of Industrial Brazing: Main Processes, Quality Standards & Applications	
AI_01	Inspection: Non-Destructive Testing (NDT) in Additive Manufacturing for metals and polymers	X
AI_02	Inspection: Metrology in Additive Manufacturing for metals and polymers	
AI_03	Inspection: Inspection of AM parts. Material Quality	X
AAM_01	AM: Qualification, Certification and Standards for AM in A&D	
AAM_02	AM: Quality Assurance & Quality Control for AM in Aerospace & Defence	X
AAM_02/3	AM: Design of AM parts for A&D (2 courses - for DED & PBF)	
AD_01	Digital: Introduction to Digital Technologies in Advanced Manufacturing	
AD_02	Digital: Data Acquisition and Analysis	
AD_03	Digital: Industrial Internet of Things (IIoT) and Advantages in Advanced	
AD_04	Digital: Artificial Intelligence and Advantages in Advanced	
AD_05	Digital: Automation and Advantages in Advanced Manufacturing	
AD_06	Digital: Potentials of Advanced Simulation and Modelling in Advanced	
AD_07	Digital: Potentials of Digital Twins and Smart Factory Automation in Advanced Manufacturing	
AD_08	Digital: Unlocking the Potential of 3D Models Beyond Technical Drawings in the Aerospace and Defence Sector	
AG_02	Green: Sustainable Design and Environmental Compliance in Aerospace and Defence	