EPFL

PAUL SCHERRER INSTITUT PSI

Empa Materials Science and Technology

Strategic Focus Area
Advanced Manufacturing

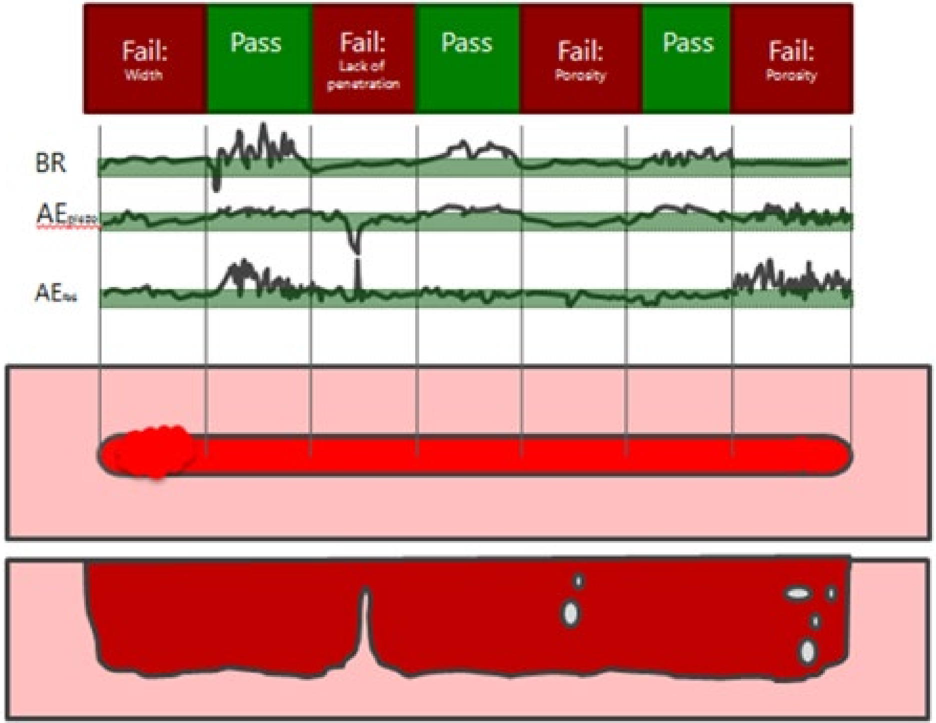
MOnitoring and CONtrol of AM metal process (MOCONT)

Revolutionizing in situ and real-time control by combining state-of-the-art sensors (acoustic) and artificial intelligence (AI)

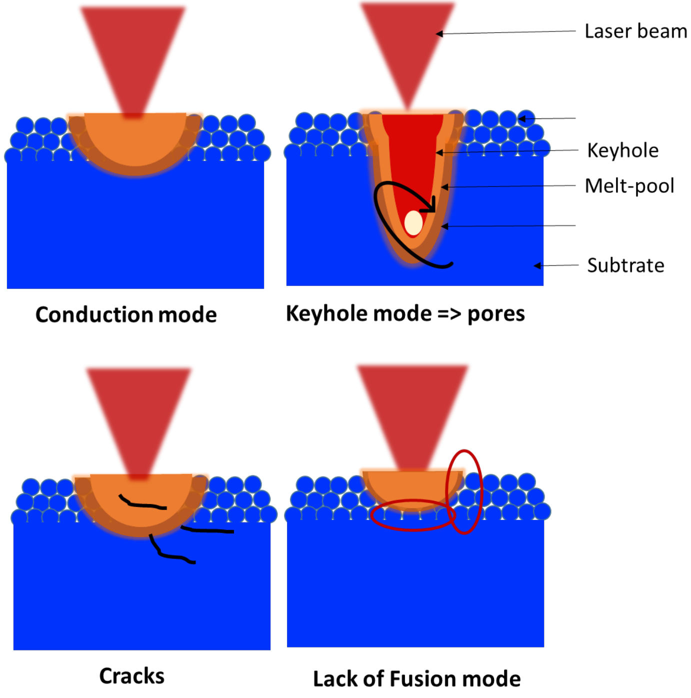
Dr Kilian Wasmer

Project : technology, key challenges & objectives

Objectives: Monitor and control defects in real-time



Key challenges: defect to be monitored



The reality

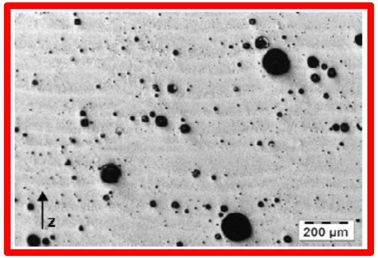
Starting the laser process

The reality

The laser process itself

the is sample good

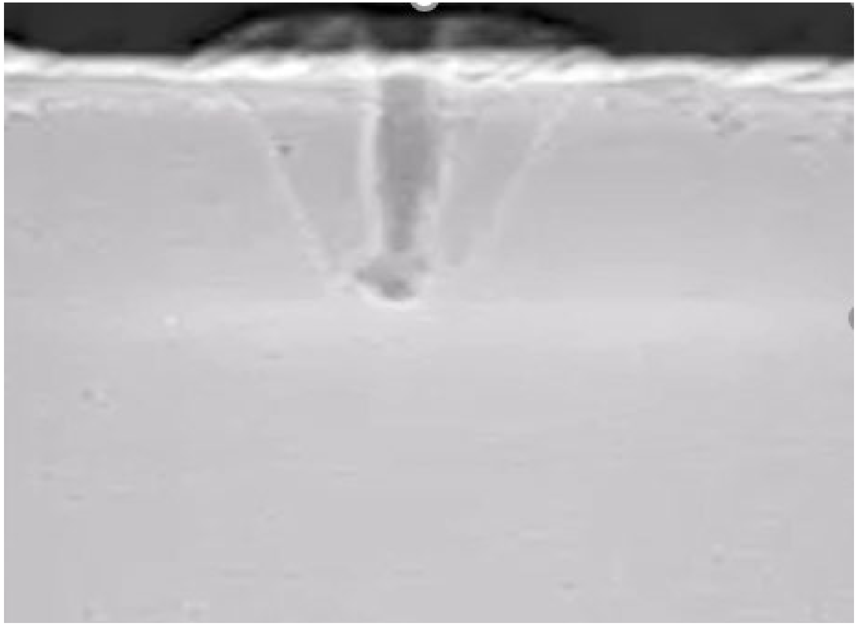
The sample break after the process end



Defect occuring during the process

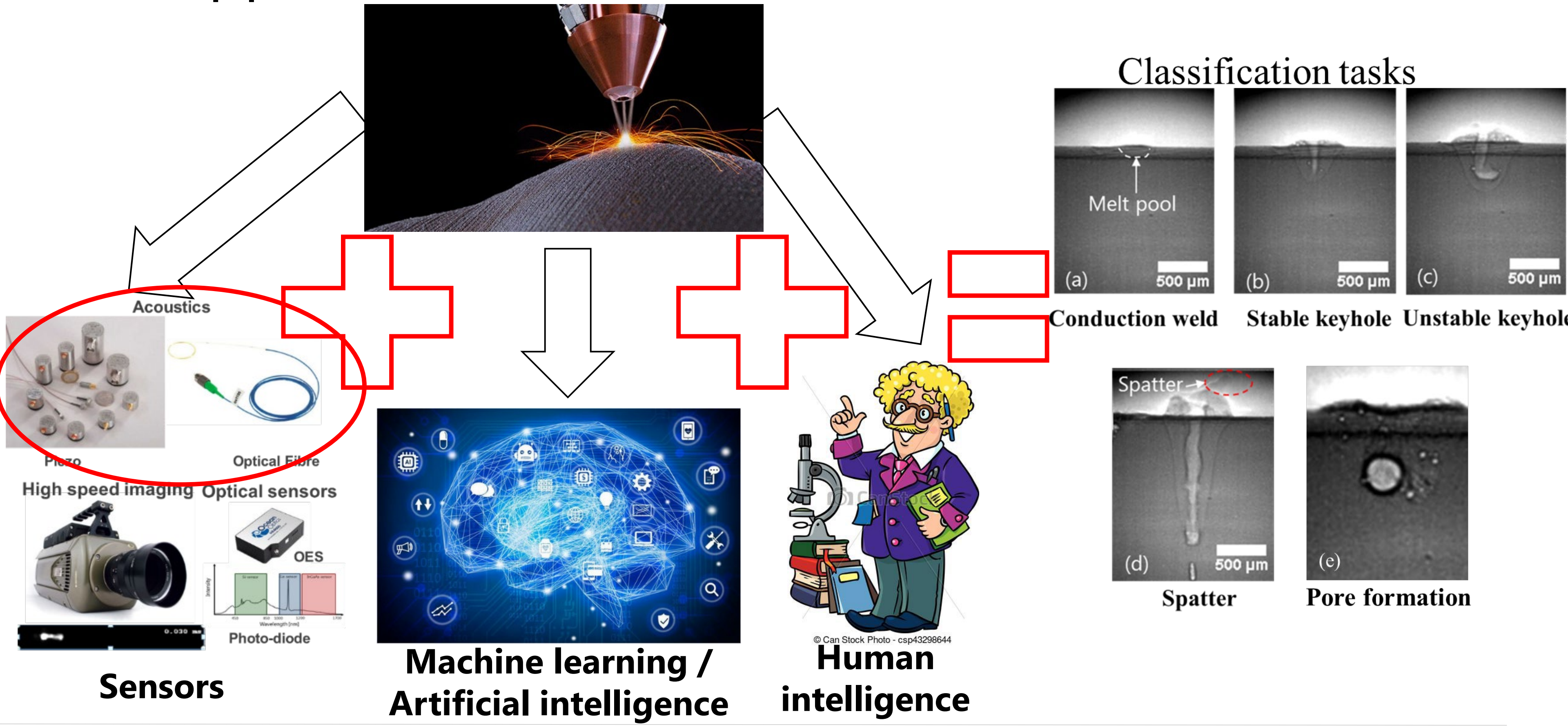
The problems: Maybe why?

Extreme keyhole case



Aluminum plate 2mm thick,
no gas shielding,
room temperature
keyhole experiment with defects
Laser 1070 nm,
pulse length 10 ms,
laser spot ∅ 30 μm
ESRF experiment at the ID19 X-ray beam

Our approach



The team

EPFL

LPBF specialist

Empa Materials Science and Technology

ML specialist

X-ray specialist

PAUL SCHERRER INSTITUT PSI

Neutron imaging specialist

Empa Materials Science and Technology

ML consultants

Main players

Mrs Rita DRISSI DAOUDI

Dr Vigneashwara PANDIYAN

Dr Annapaola PARRILLI

Dr Pavel TRTIK

Mr Giulio MASINELLI

Dr Sergey SHEVCHIK

Shadow players

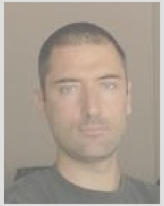
Prof. Dr Roland Logé

Dr Kilian Wasmer

Dr Robert Zboray

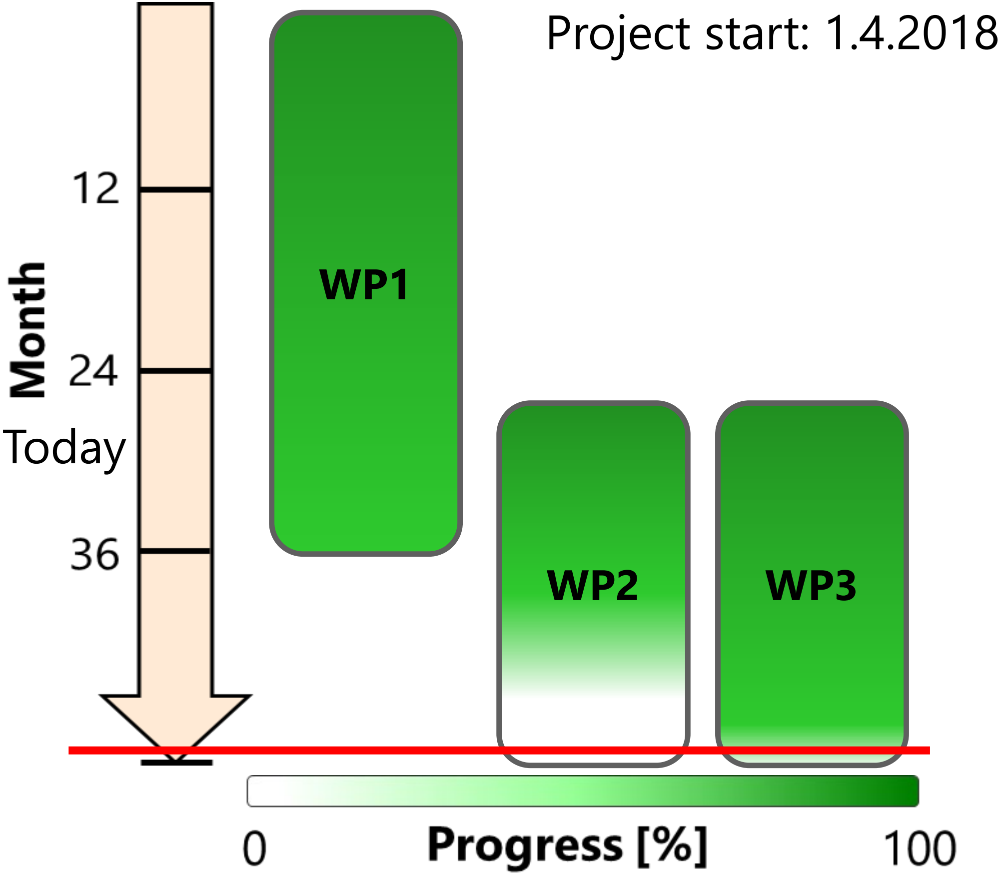
Prof. Dr Markus Strobl

UNIVERSITE DE GENÈVE



Prof. Dr François Fleuret

Status of the tasks



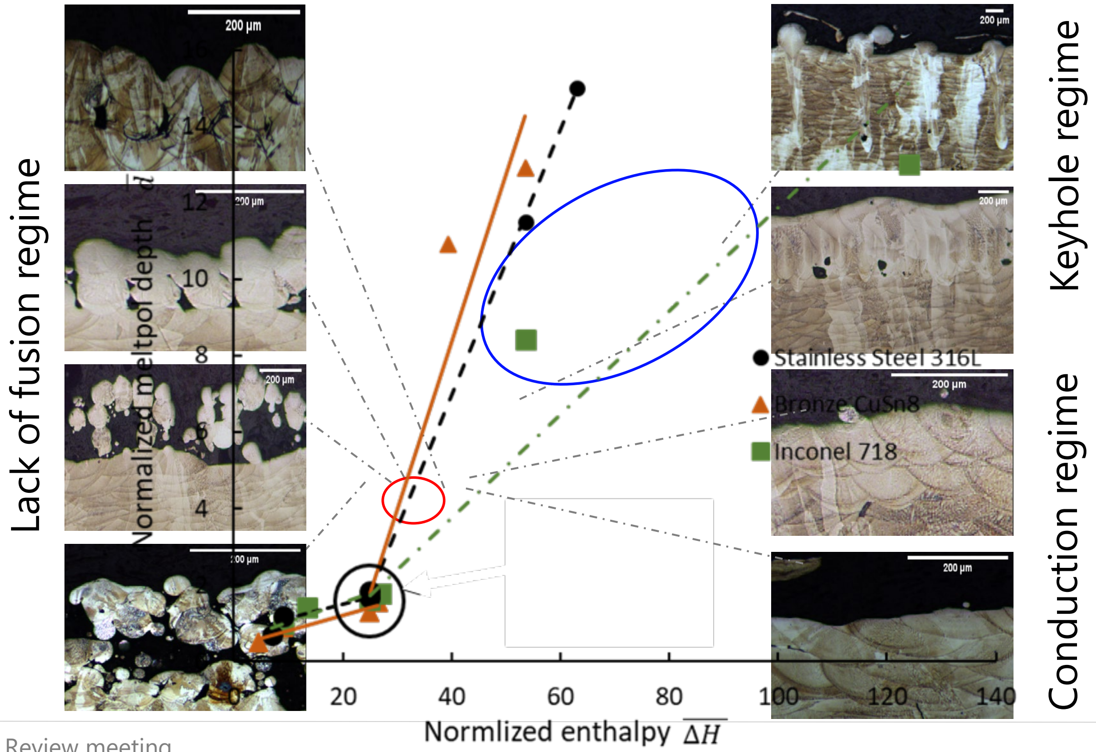
Task 1 Develop a signal processing unit able to classify with high confidence the type of defects, including various contents of porosity

Task 2 Localise cracks due to residual stresses

Task 3 Develop a universal regressor model able to predict the creation of a defect

Process regimes

Image of stainless steel (SS)



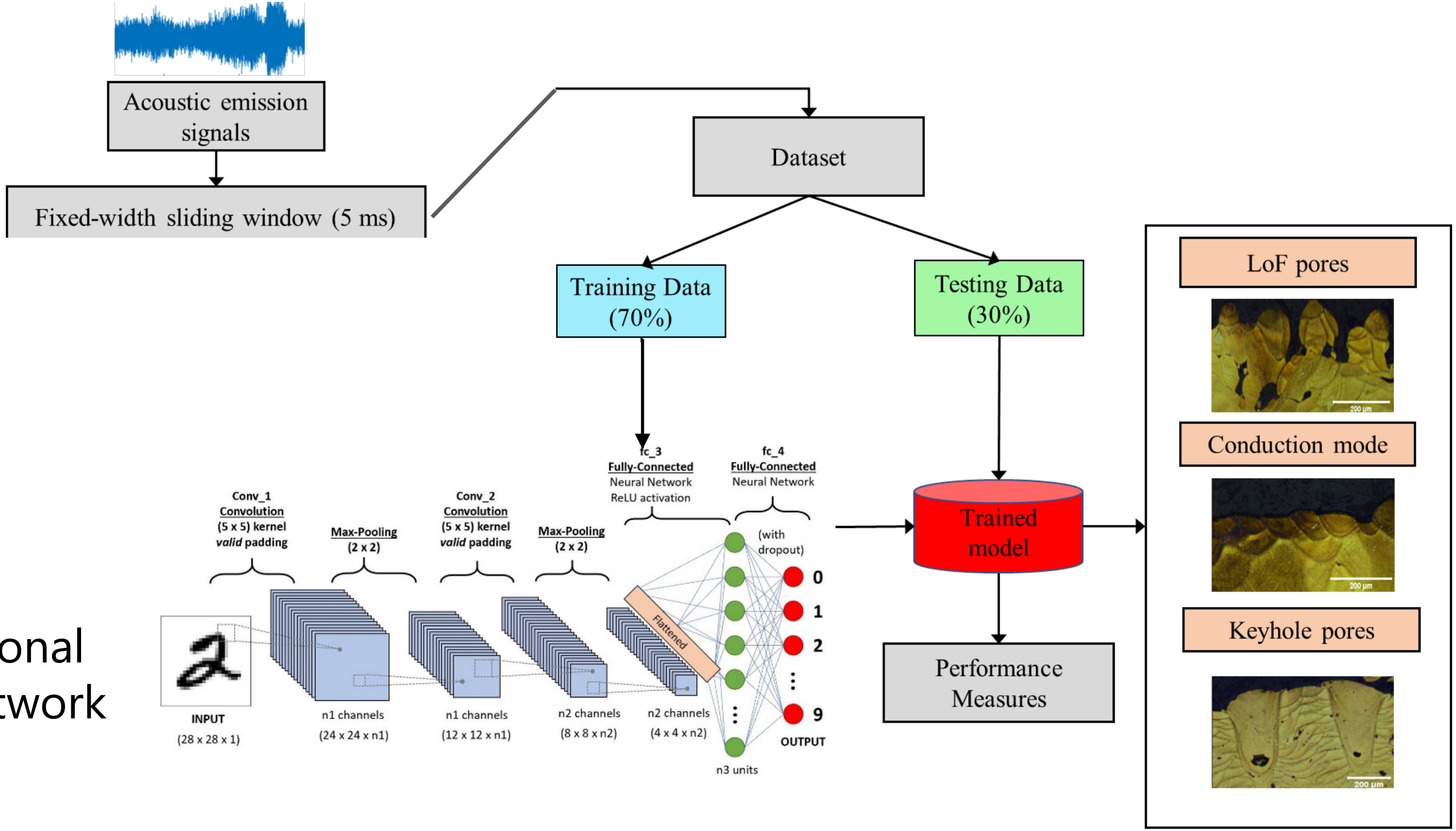
- Elaborated process maps for 3 **materials** (SS, bronze, and Inconel)
- Performed specific experiments for all three materials and **recorded AE signals**
- **Have databases** for features analyses and ML algorithm developments

Process parameters

Regimes	Stainless steel			Bronze			Inconel		
	Laser power (W)	Scan speed (mm/s)	Normalized enthalpy	Laser power (W)	Scan speed (mm/s)	Normalized enthalpy	Laser power (W)	Scan speed (mm/s)	Normalized enthalpy
LoF pores	**50**	**350**	7	**50**	**350**	4.4	**50**	**350**	13.4
	70	400	*9.2*	110	400	*9.2*	36	400	*9.2*
Conduction mode	180	350	**25**	300	350	**26.5**	100	350	**27**
	135	200	**25**	215	200	**25**	69	200	**25**
Keyhole pores	**450**	**350**	63	**450**	**350**	39.4	**450**	**350**	124
	250	150	*53.5*	396	150	*53.5*	127	150	*53.5*

Drissi-Daoudi R., Pandiyan V., Logé R., Shevchik S.A., Masinelli G., Ghasemi-Tabasi H., Parrilli A., and Wasmer K., "Differentiation of Materials and Laser Powder Bed Fusion Processing Regimes from Airborne Acoustic Emission Combined with Machine Learning", VPP, 17(2), 2022, https://doi.org/10.1080/17452759.2022.2028380

Schematic flow for classification



Convolutional neural network

Drissi-Daoudi R., Pandiyan V., Logé R., Shevchik S.A., Masinelli G., Ghasemi-Tabasi H., Parrilli A., and Wasmer K., "Differentiation of Materials and Laser Powder Bed Fusion Processing Regimes from Airborne Acoustic Emission Combined with Machine Learning", VPP, 17(2), 2022, https://doi.org/10.1080/17452759.2022.2028380

Classification results

Origin of the acoustic emission features

LR (**Bold**), SVM (Normal), RF (*Italics*), and CNN (***Bold Italics***). All values in %.

Ground truth / Classification accuracy [%]	*LoF pores*			*Keyhole pores*		
	Stainless steel	*Bronze*	*Inconel*	*Stainless steel*	*Bronze*	*Inconel*
Stainless steel	**99** 98 *100* ***100***	**1** 1 *0* ***0***	**0** 1 *0* ***0***	**95** 96 *97* ***97***	**0** 0 *0* ***3***	**5** 4 *3* ***0***
Bronze	**0** 0 *1* ***1.5***	**98** 96 *99* ***97***	**2** 4 *0* ***1.5***	**0** 0 *0* ***5***	**100** 100 *100* ***95***	**0** 0 *0* ***0***
Inconel	**1** 1.5 *1* ***0***	**0** 1.5 *1* ***1***	**99** 97 *98* ***99***	**5** 9 *11* ***1***	**1** 1 *1* ***0***	**94** 90 *88* ***99***

One on one alloy classification

LR (**Bold**), All values are in %.

Ground truth / Cassif. accuracy [%]	Stainless steel: *LoF pores*	Stainless steel: *Conduction mode*	Stainless steel: *Keyhole pores*	Bronze: *LoF pores*	Bronze: *Conduction mode*	Bronze: *Keyhole pores*	Inconel: *LoF pores*	Inconel: *Conduction mode*	Inconel: *Keyhole pores*
LoF pores	**92**	**0**	**8**	**100**	**0**	**0**	**99**	**0**	**1**
Conduction mode	**0**	**91**	**9**	**0**	**99**	**1**	**2**	**98**	**0**
Keyhole pores	**5**	**7**	**88**	**1**	**2**	**97**	**1**	**2**	**97**

Cross alloy classification

RF. All values in %.

Stainless steel + Bronze on Inconel
Good case (80%)

Ground truth / Classif. accuracy [%]	*LoF pores*	*Conduction mode*	*Keyhole pores*
LoF pores	61	0	39
Conduction mode	0	93	7
Keyhole pores	6	6	88

One on all alloy classification

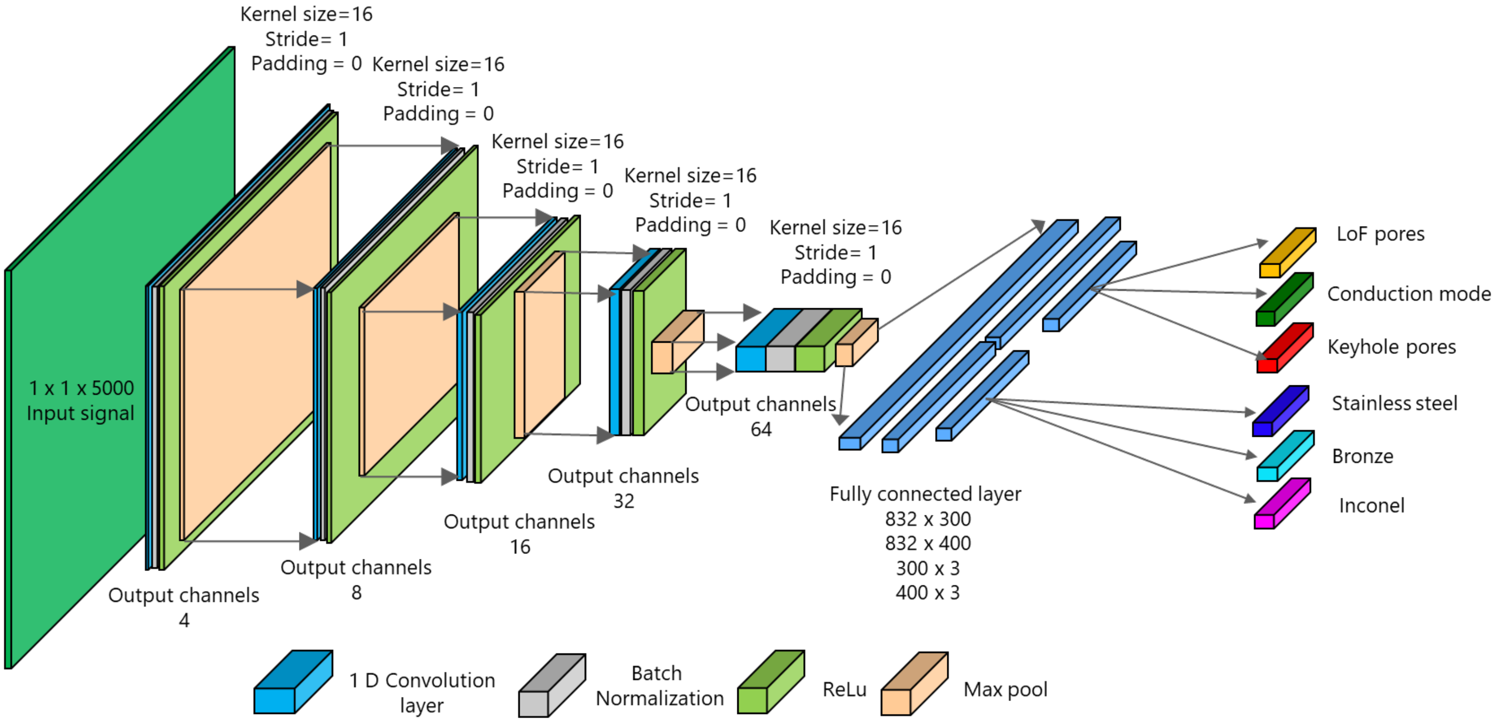
LR (**Bold**). All values are in %.

Ground truth / Classif. Accuracy [%]	*LoF pores*	*Conduction mode*	*Keyhole pores*
LoF pores	**97**	**3**	**0**
Conduction mode	**3**	**92**	**5**
Keyhole pores	**2**	**5**	**93**

Drissi-Daoudi R., Pandiyan V., Logé R., Shevchik S.A., Masinelli G., Ghasemi-Tabasi H., Parrilli A., and Wasmer K., "Differentiation of Materials and Laser Powder Bed Fusion Processing Regimes from Airborne Acoustic Emission Combined with Machine Learning", VPP, 17(2), 2022, https://doi.org/10.1080/17452759.2022.2028380

Classification results

CNN architecture for multi-label classification



Drissi-Daoudi R., Pandiyan V., Logé R., Shevchik S.A., Masinelli G., Ghasemi-Tabasi H., Parrilli A., and Wasmer K., "Differentiation of Materials and Laser Powder Bed Fusion Processing Regimes from Airborne Acoustic Emission Combined with Machine Learning", VPP, 17(2), 2022, https://doi.org/10.1080/17452759.2022.2028380

Classification results

Multi-label classification

Left table: classification accuracy on the regimes. *Right table*: classification accuracy on the materials.

All values are in %.

Process regimes (93.3%)

Classif. accuracy [%] \ Ground truth	*LoF pores*	*Conduction mode*	*Keyhole pores*
LoF pores	93.0	6.5	0.5
Conduction mode	6.0	91.0	3.0
Keyhole pores	0.5	3.5	96.0

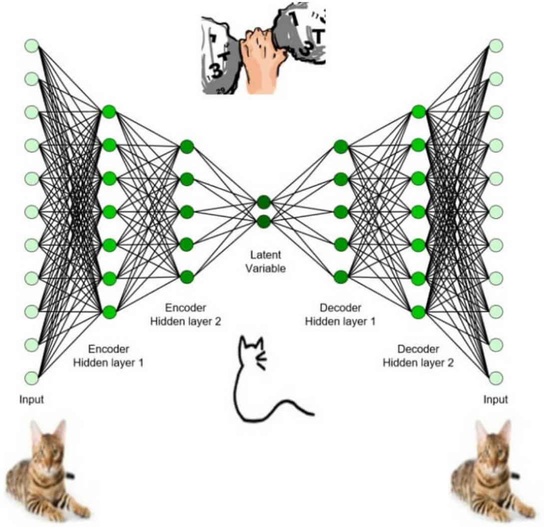
Materials (94.0%)

Classif. accuracy [%] \ Ground truth	*Stainless steel*	*Bronze*	*Inconel*
Stainless steel	97.0	2.0	1.0
Bronze	2.0	91.0	7.0
Inconel	0.5	5.5	94.0

Drissi-Daoudi R., Pandiyan V., Logé R., Shevchik S.A., Masinelli G., Ghasemi-Tabasi H., Parrilli A., and Wasmer K., "Differentiation of Materials and Laser Powder Bed Fusion Processing Regimes from Airborne Acoustic Emission Combined with Machine Learning", VPP, 17(2), 2022, https://doi.org/10.1080/17452759.2022.2028380

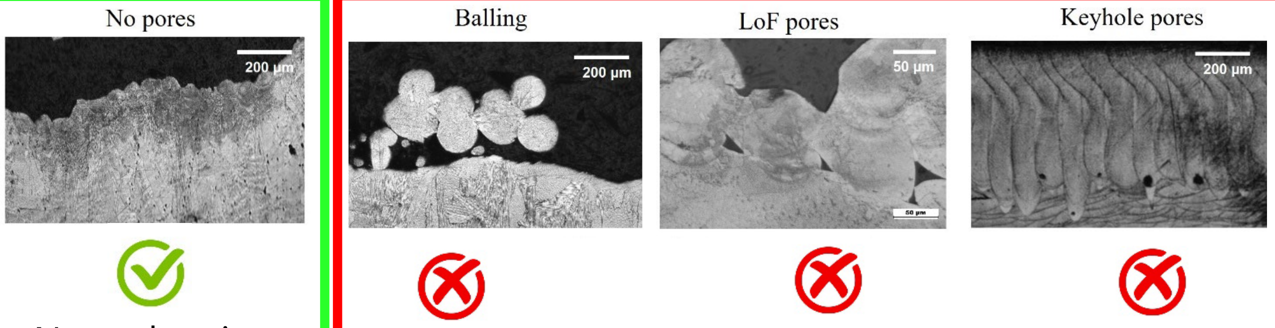
Semi-supervised approach

Autoencodeur principle



The trained CNN model based on GANomaly classified 2’800 signals with an accuracy higher than 97%.

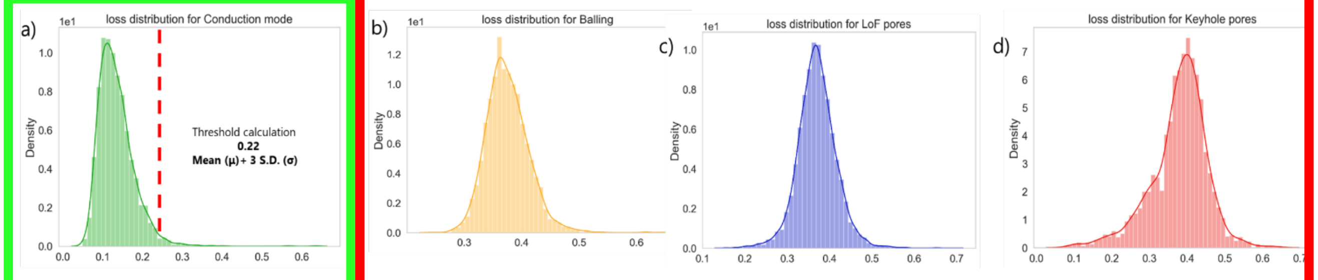
Process regimes



Normal regime

Abormal regimes

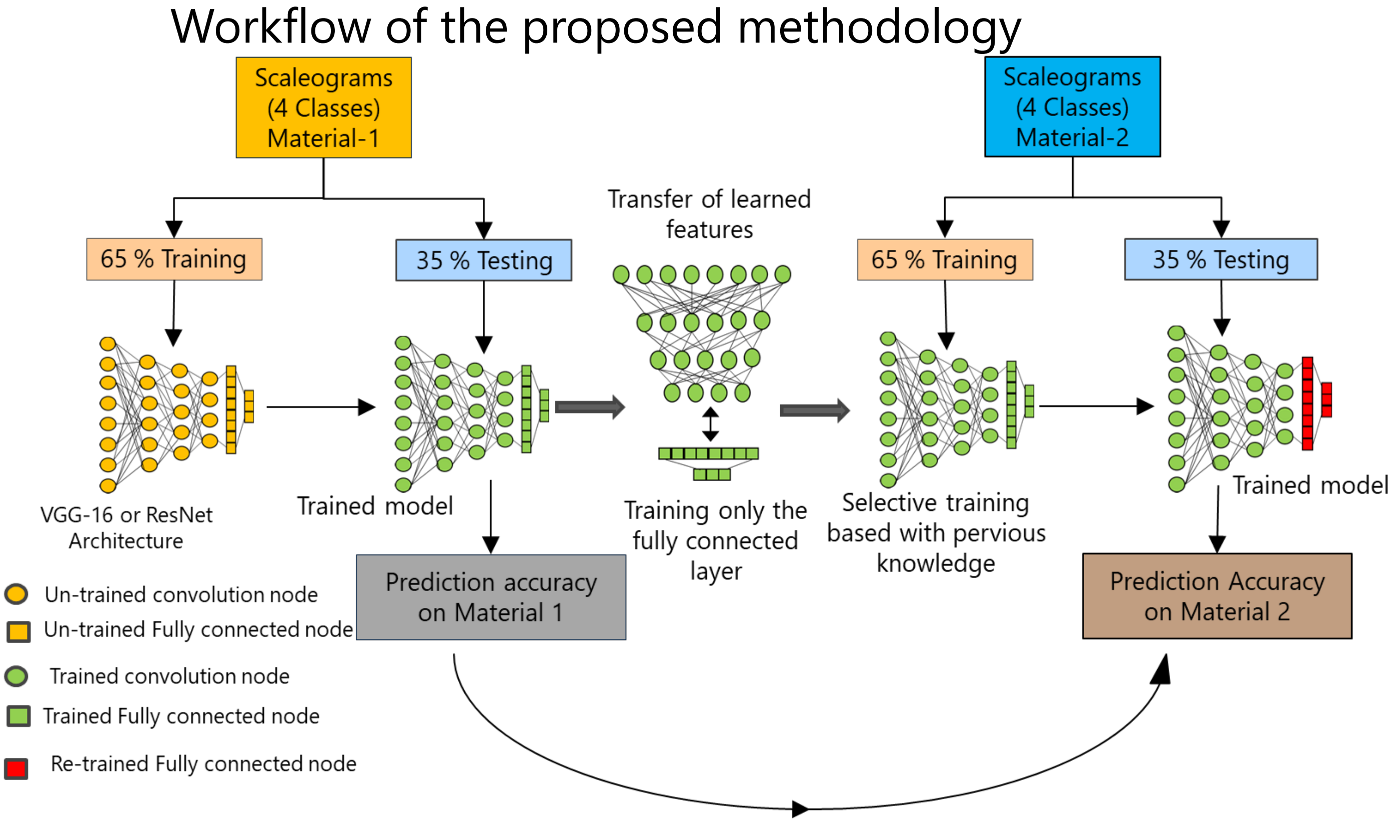
Loss distribution of the regimes



Loss values higher than 0,22 (Mean + 3S.D) are considered as anomaly

Pandiyan V., Drissi-Daoudi R., Shevchik S.A., Masinelli G., Quang-Le T., Logé R., and Wasmer K., "Semi-Supervised Monitoring of Laser Powder Bed Fusion Process Based on Acoustic Emissions", Virtual and Physical Prototyping, Vol. 16, Issue 4, pp: 481-497, 2021, https://doi.org/10.1080/17452759.2021.1966166

Deep transfer learning approach



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Deep transfer learning approach

One on one alloy classification

Classif. accuracy [%] \ Ground truth	*Balling*	*LoF pores*	*Conduction mode*	*Keyhole pores*
Balling	97.75	0.00	1.75	0.50
LoF pores	3.00	95.00	1.50	0.50
Conduction mode	0.75	0.25	96.75	2.25
Keyhole pores	0.75	0.25	4.25	94.75

Deep transfer leaning to bronze classification

a) Full dataset (Mode I)

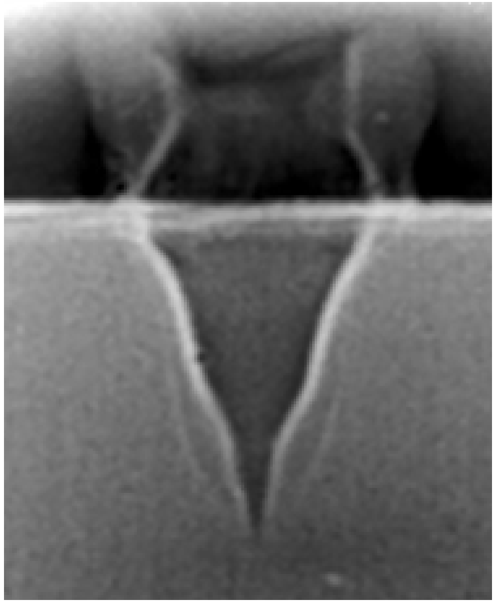
Classif. accuracy [%] \ Ground truth	*Balling*	*LoF pores*	*Conduction mode*	*Keyhole pores*
Balling	94.00	3.50	2.50	0.00
LoF pores	2.00	76.5	21.00	0.50
Conduction mode	3.00	17.75	75.75	4.00
Keyhole pores	0.00	1.50	5.00	93.50

b) 50% of the dataset (Mode II)

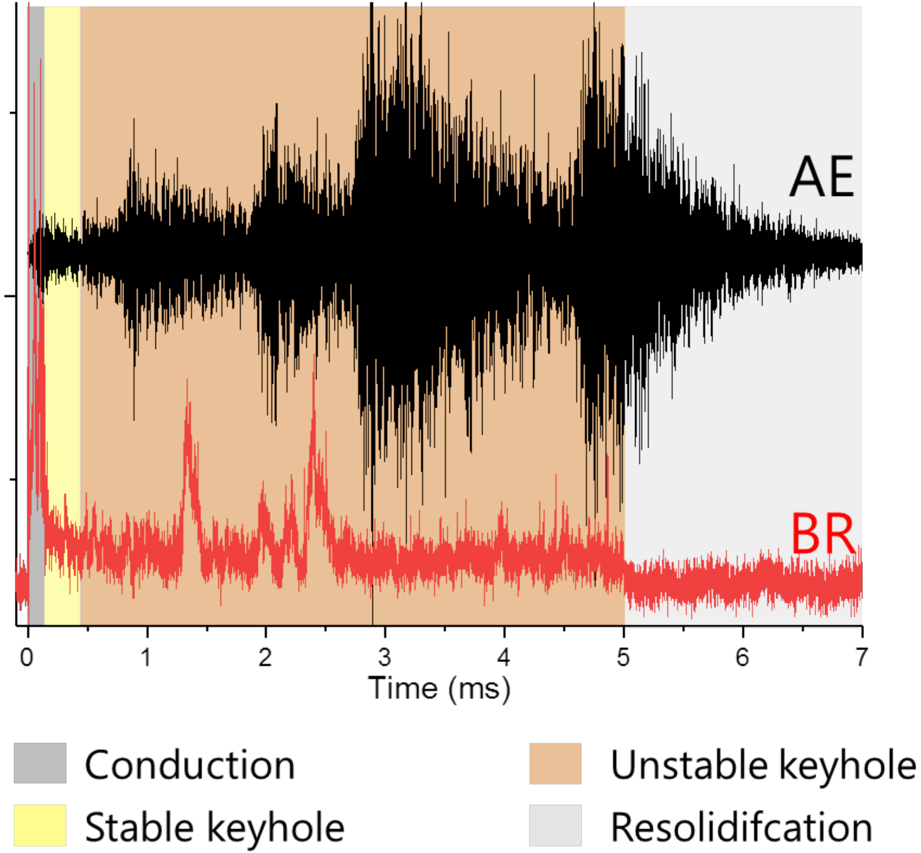
	Balling	*LoF pores*	*Conduction mode*	*Keyhole pores*
Balling	89.00	5.50	5.25	0.25
LoF pores	3.00	74.50	20.75	1.75
Conduction mode	2.50	21.25	72.00	4.25
Keyhole pores	0.00	1.75	7.25	91.0

Pandiyan V., Drissi-Daoudi R., Shevchik S.A., Masinelli G., Quang-Le T., Logé R., and Wasmer K., "Deep Transfer Learning of Additive Manufacturing Mechanisms Across Materials in Metal-Based Laser Powder Bed Fusion Process", JMPT, 303, May 2022, Paper ID: 117531, 2022, https://doi.org/10.1016/j.jmatprotec.2022.117531

High-speed X-ray observation



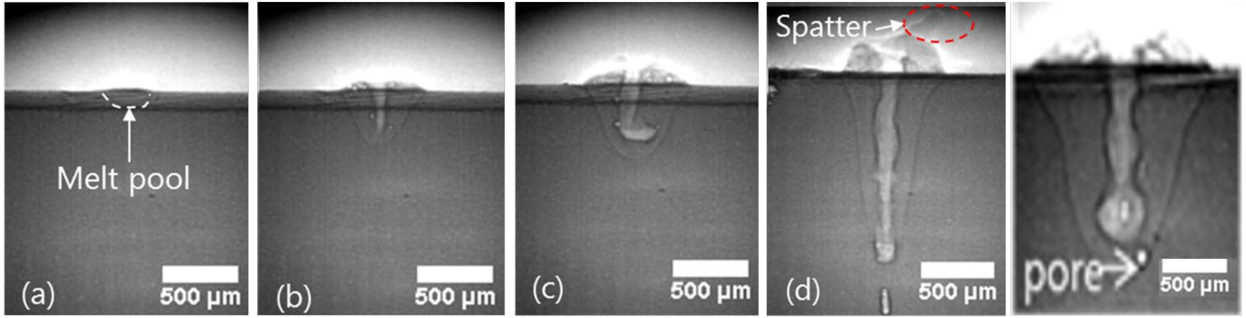
Aluminum plate 2mm thick,
no gas shielding, room temperature
Keyhole experiment with defects
Laser 1070 nm, pulse length 10 ms,
laser spot ∅ 30 μm
ESRF ID19 X-ray beam



Shevchik S.A., Le-Quang T., Meylan B., Vakili-Farahani F., Olbinado M.P., Rack A., Masinelli G., Leinenbach C., and Wasmer K.,
“Supervised Deep Learning for Real-Time Quality Monitoring of Laser Welding with X-Ray Radiographic Guidance", Scientific Report,

X-ray classification of process regimes and repair

Laser process regimes classified

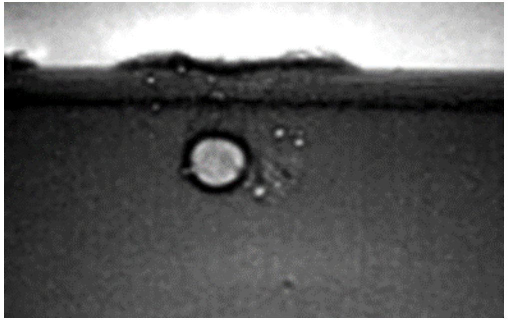


Conduction weld | **Stable keyhole** | **Unstable keyhole** | **Blowout** | **Pore**

Ground truth / *Classification*	**Cond. welding**	**Stable keyhole**	**Unstable keyhole**	**Blowout**	**Pore**
Conduction welding	(88/99) 99	(7/1) 1	(5/0) 1	(0/0) 0	(0/0) 0
Stable keyhole	(5/1) 0	(82/91) 93	(13/8) 6	(0/0) 1	(0/0) 0
Unstable keyhole	(4/0) 0	(5/2) 6	(87/92) 94	(4/6) 0	(0/99) 0
Blowout	(0/0) 0	(0/0) 0	(5/1) 1	(95/99) 99	(0/99) 0
Pore	(0/0) 0	(10/8) 12	(10/7) 0	(7/0) 0	(73/99) 88

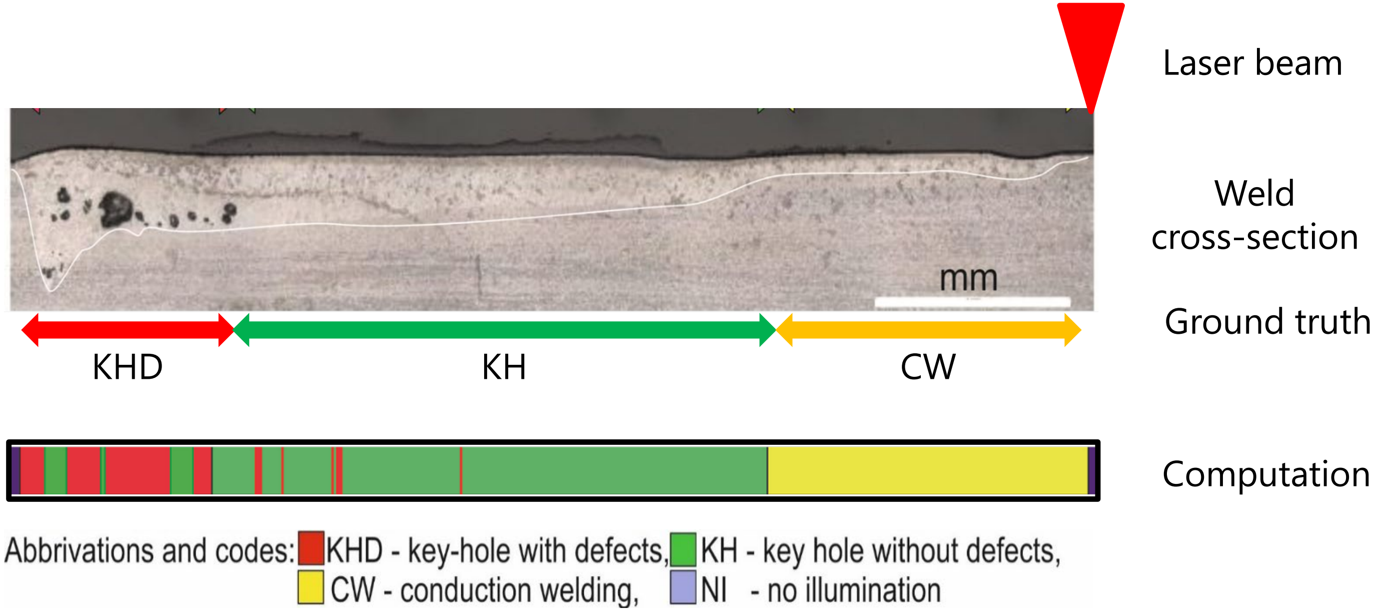
Table of classification results for the different quality categories.
(optical sensor / *acoustic sensor*) **Both sensors together**

Repair of large defect



Ground truth / *Classification*	**Pore formation**	**Pore removal**
Pore formation	87	13
Pore removal	23	73

Today’s available at Empa for welding & AM in Dübendorf



Today, time resolution is around 25 ms and so the spatial resolution for defects is around 30 µm.
For the time resolution, we are working to go down in tens of us

Summary & outcome of this project

- Laser processing: combining sensors (AE, optical), and ML, we have:
  - Detected and classified process regimes terms of quality with high confidence
  - Could not develop a universal data driven ML models
  - Develop alternatives strategies in development of ML models
    - Used semi-supervised methods to save data acquisition and computer time
    - Developed transfer know-how methods across material and machine
  - Detected and classified stable and unstable process (important for control loop)
  - Demonstrated potential for monitoring of repair of AM parts
  - Develop a new approach for 3D crack reconstruction in mechanical workpieces
- 6 peer-reviews papers, 11 conferences (5 invited)
- New SFA-AM project SMARTAM => move from data driven to physics driven ML models (Combining PREAMPA and MoCont)
- Several new projects on monitoring and control for other laser processes

Thank You For Your Attention!