Wire + arc additive manufacturing :
the challenge of distortions and residual stresses.

20 years NeT
The European Network on Neutron Techniques Standardization for Structural Integrity
2002 - 2022

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20th anniversary NeT workshop, 23rd November 2022

OUTLINES

What is WAAM ?

Why measuring residual stresses ?

How do we measure residual stresses ?

Neutron stress measurements made on our specimens

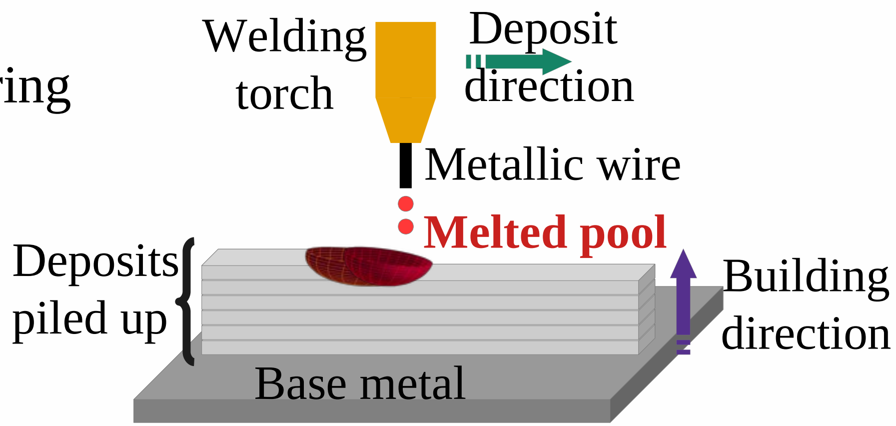
Outcomes

What is WAAM ?

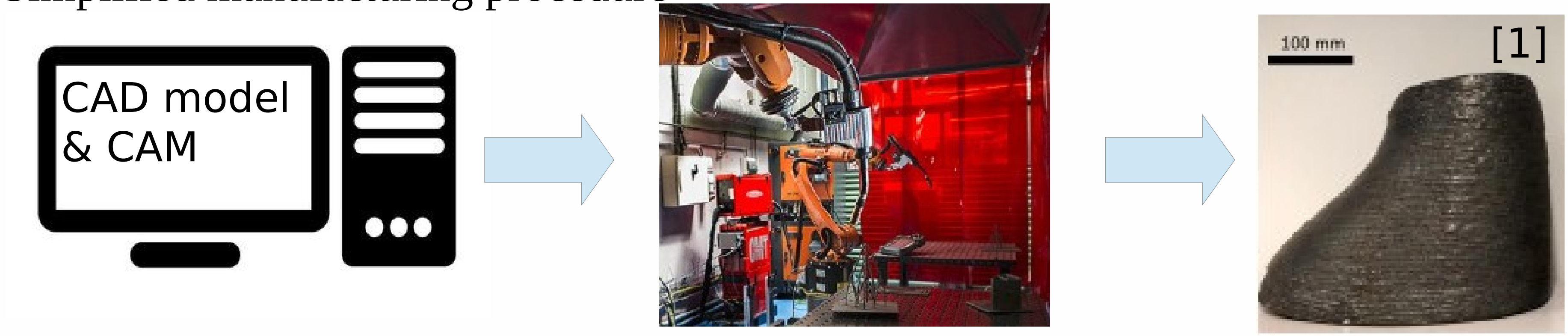
WAAM = Wire + Arc Additive Manufacturing

Layer by layer deposition of metallic wire

Arc welding source (GMAW-CMT)



Simplified manufacturing procedure



[1] Diourte A, PhD thesis, Génération et optimisation de trajectoire dans la fabrication additive par soudage à l'arc, Institut Clément Ader, Université de Toulouse 3, 2021.

Advantages:

✔ Require less raw material (vs traditional machining)

✔ Optimisation of part geometry for reducing part weigh and/or improving mechanical strength

✔ high deposition rate & possibility to make large mechanical parts (>0,5 m)[2]

Drawbacks:

✗ Microstructure with large grains

✗ Distortions

✗ Residual stresses.

→ Reduce mechanical strength

Our Objectives: (C. Cambon PhD Thesis 2017-2021)

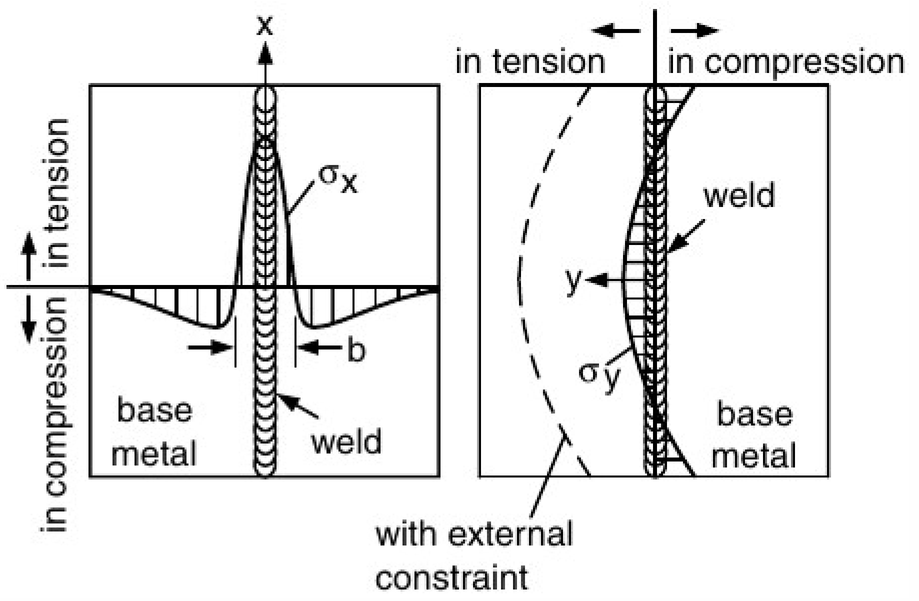
➔ Set-up a WAAM benchmark:

- ➔ For studying the effects of operating parameters
- ➔ For establishing a simple thermal-mechanical simulation

[2] D. Ding, Z. Pan, D. Cuiuri, H.L. School. A multi-bead overlapping model for robotic wire and arc additive manufacturing, *Robotics and Computer-Integrated Manufacturing* 31 (2015).

Why measuring residual stresses?

« Residual stresses are stresses that would exist in a body if all external loads were removed. ... Residual stresses that exist in a body that has previously been subjected to nonuniform temperature changes, such as those during welding, are often called thermal stresses. »[3]



High residual tensile stresses can cause:

- hydrogen-induced cracking,
- reduce cycle to failure tests (due to cracking)
- stress corrosion cracking.

Structural integrity

Post weld heat treatment is often used to produce stress relief.

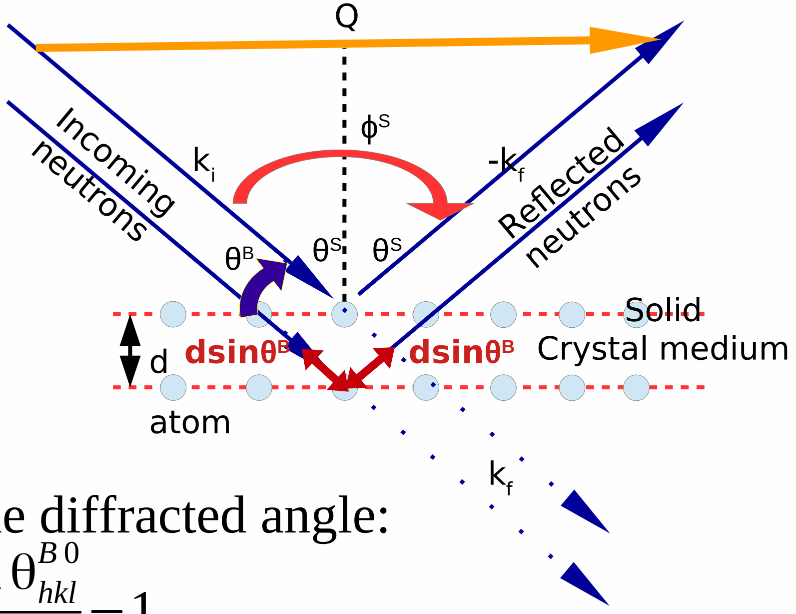
[3] S. KOU. Welding Metallurgy, 2nd edition, Wiley interscience, ISBN 0-471-43491-4 (2003).

How to measure residual stresses?

Few techniques:

- Destructives: deep hole drilling, contour method
- Non destructives: strain gauges, x-ray diffraction, neutron diffraction, ...

Neutron diffraction phenomena in solid crystal medium[4].



Bragg's law : $\lambda = 2d_{hkl} \sin\theta^B_{hkl}$ where λ is the wavelength with incident angle θ^S

The elastic strain of crystal lattice is related to the diffracted angle:

$$\epsilon^{hkl} = \frac{d_{hkl} - d^0_{hkl}}{d^0_{hkl}} = \frac{\sin\theta^{B0}_{hkl}}{\sin\theta^B_{hkl}} - 1$$

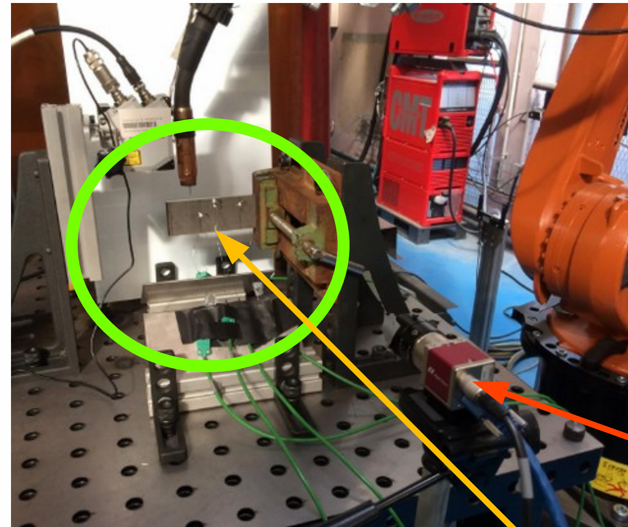
Stress is deduced by applying Hooke's law:

$$\sigma_{ij} = \frac{E}{(1+\nu)}\left[\epsilon_{ij} + \frac{\nu}{(1-2\nu)}(\epsilon_{11}+\epsilon_{22}+\epsilon_{33})\right]$$

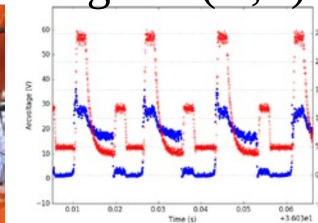
[4] M.T. Hutchings, P.J. Withers, T.M. Holden, T. Lorentzen. Introduction to the characterization of residual stress by neutron diffraction, Taylor & Francis (2004).

SS316L specimens built with GMAW-CMT welding source

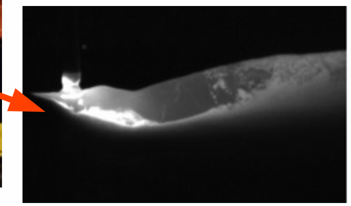
Parameters	Set 1 layer 1	Set 1 layer n
U (V)	13.5	13
I (A)	119	99
S_w (m/s)	0.007	0.007
E (J/mm)	183.6	147.1
S_f (m/min)	3.2	2.5



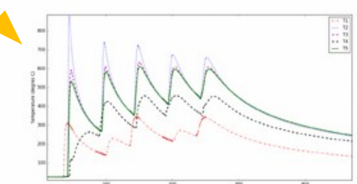
Electric signals (U, I)



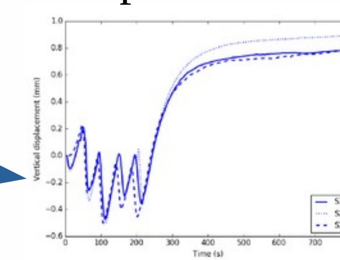
Melted pool images

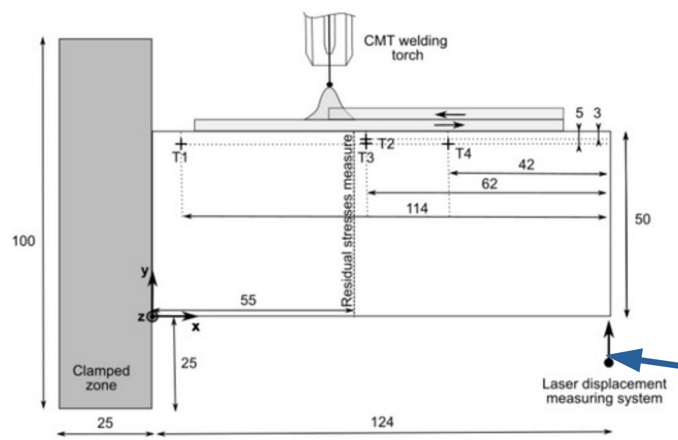


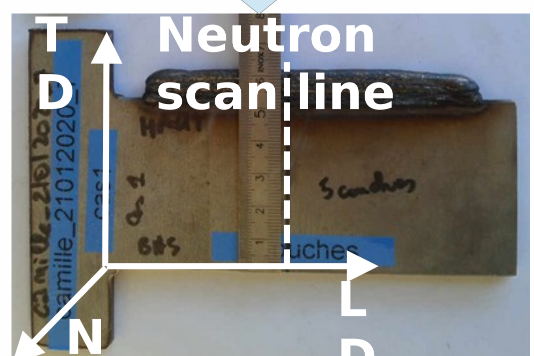
Temperatures



Displacement

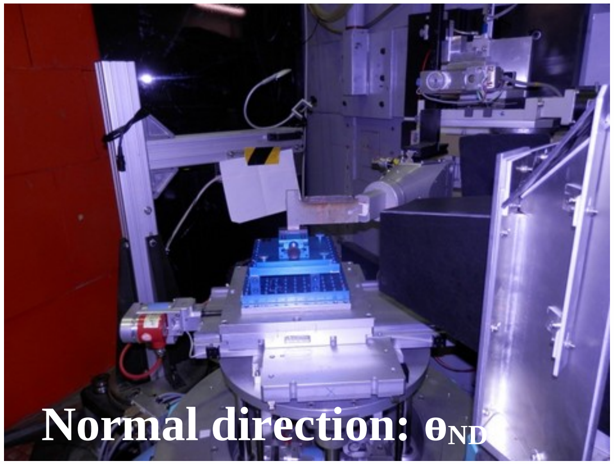


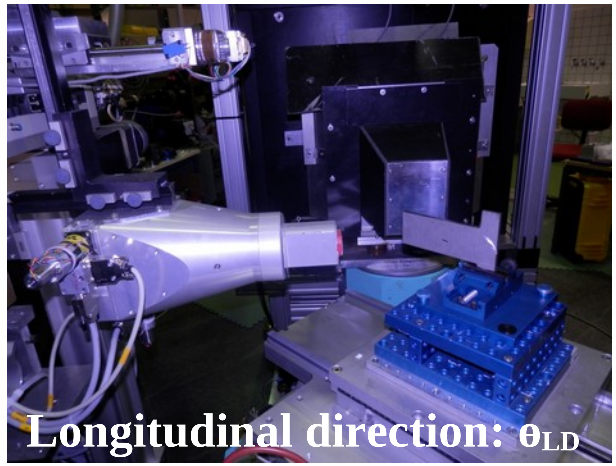


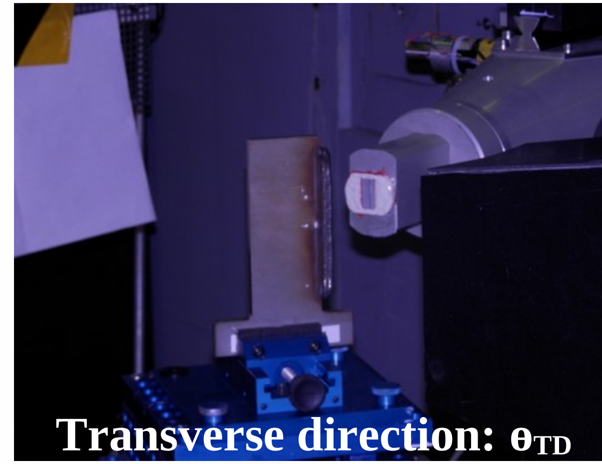


What about the residual stresses?

Measured residual stresses at Helmotz Berlin Zentrum, Berlin (thanks to Robert Wimpory, member of NeT).


Normal direction: θ_{ND}


Longitudinal direction: θ_{LD}


Transverse direction: θ_{TD}

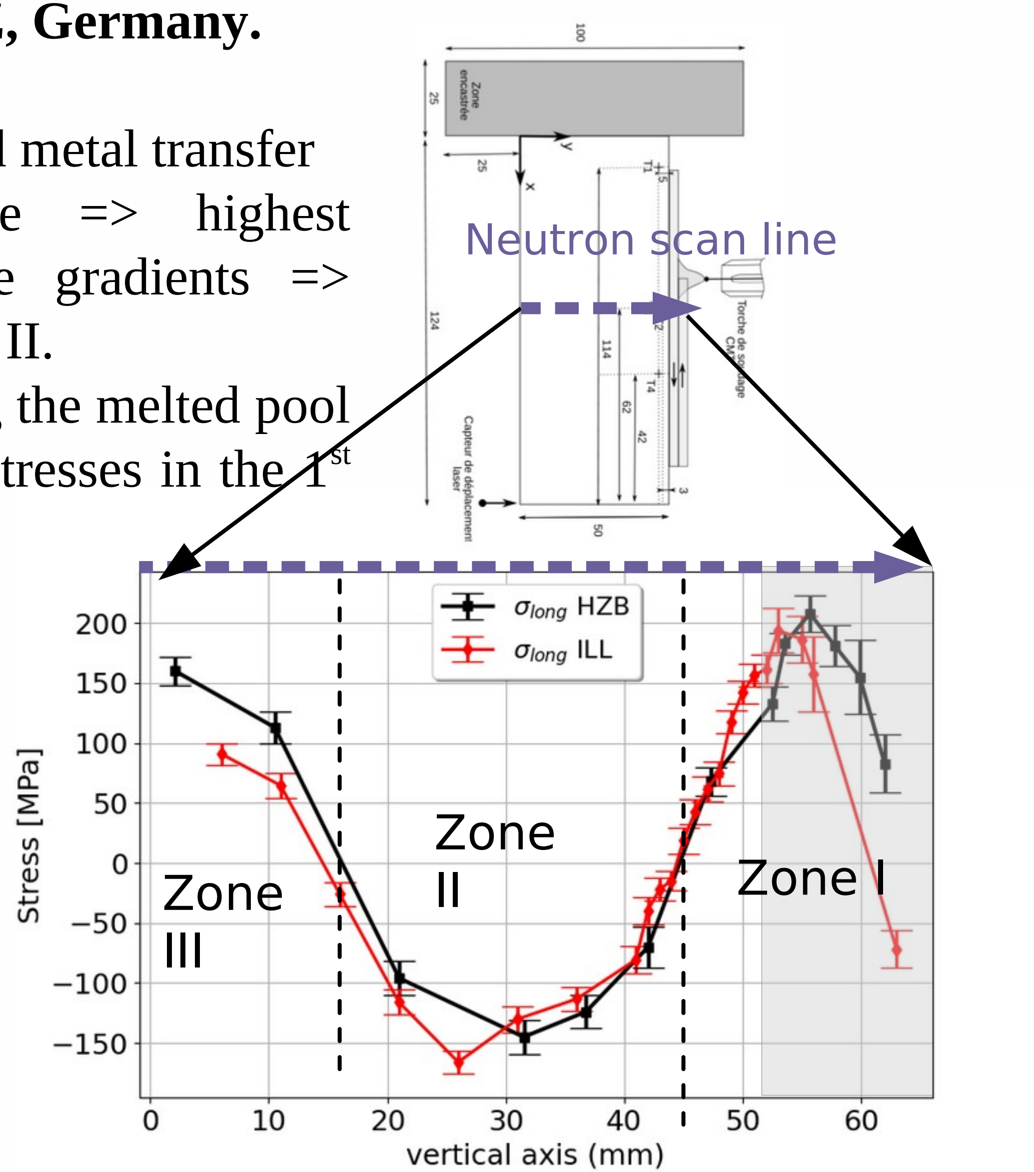
Measured (θ_{ND}, θ_{LD}, θ_{TD}) + plane stress ($\sigma_{ND} = 0$) gives θ_0 => ε_{ND}, ε_{LD}, ε_{TD} and σ_{LD} & σ_{TD}

Neutron diffraction experimental parameters:

Crystal plane	wavelength	2ɵ angle	GV – LD (mm)	GV _ TD (mm)	GV – ND (mm)
Fe-311	1.471 Å	85.587°	2x2x2	2x2x2	10x2x2

Measured residual stresses at HBZ, Germany.

Zone I: place of the electrical arc and metal transfer
Local melting of the substrate => highest temperatures => high temperature gradients => strong thermal compression => zone II.
During the solidification and cooling the melted pool shrinks and it leads to high tensile stresses in the 1st layer.



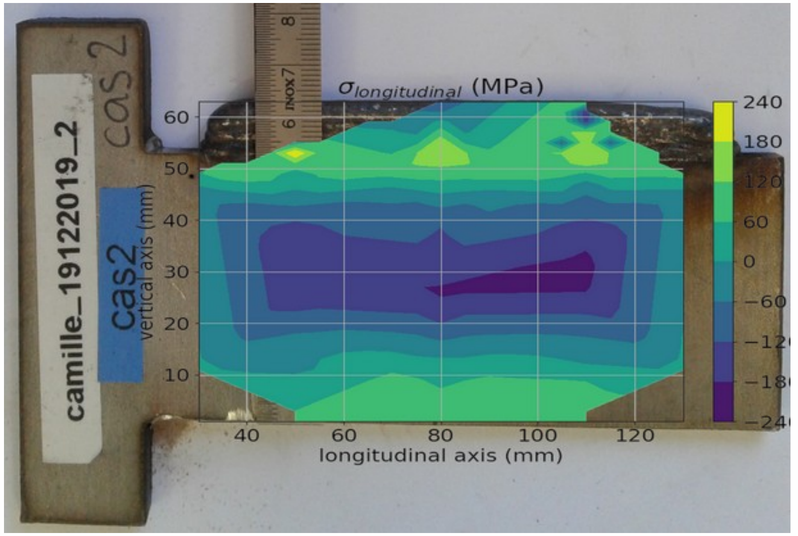
Zone II: compression stress due to the dilatation of zone I during the heating. The thermal stress was enough to plasticize the material.

Zone III: due to shrinkage of Zone I (during cooling) the substrate bent slightly upward leading to tensile stress.

Camille Cambon, Issam Bendaoud, Sébastien Rouquette et Fabien Soulié. A WAAM benchmark: From process parameters to thermal effects on weld pool shape, microstructure and residual stresses published in Materials today communications V33 (2022).

Outcomes

- Operational WAAM mock-up
- Online monitoring of the building procedure (electric signals, temperature, weld pool, displacement)
- Lots of neutron diffraction measurements from other facilities: ILL (Grenoble, France) and ISIS (Didcot, UK)… still under processing



Perspectives

- Investigate the effect of other operating parameters such as dwell time, path deposition strategy to mitigate the residual stresses and microstructure.
- Characterization of the specimen's mechanical properties.
- Seeking for research collaboration (e.g. PhD, numerical simulations ...)

This research work is related to Net TG9 “Additive Manufacturing”.
We thank EDF (Vincent Robin & Josselin Delmas) for connecting us.
=> valuable scientific exchanges both on numerical and experimental sides,
=> thanks to R. Wimpory, we got our 1st residual stress measurements in 2020,
=> we are keen on sharing all the data (published) on our various specimens.

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Thank you for your attention