Experimental report

06/01/2020

Proposal: **1-02-273** **Council:** 4/2019

Title: Influence of temperature field on residual stresses in age hardened 6061 aluminium alloy prepared by wire-arc additive manufacturing

Research area: Materials

This proposal is a new proposal

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Samples: Wall n°4 (TS=40 ; Alternate vector)
Wall n°5 (TS=60 ; Alternate vector)
Wall n°6 (TS=80 ; Alternate vector)
Wall n°1 (TS=40 ; Unidirectional vector)
Wall n°3 (TS=80 ; Unidirectional vector)
Wall n°2 (TS=60 ; Unidirectional vector)

Instrument	Requested days	Allocated days	From	To
SALSA	3	1	10/09/2019	11/09/2019

Abstract:

Wire and Arc Additive Manufacturing (WAAM) offers a much high material deposition rate leading to the capability to manufacture large meter-scale components with lower cost. Age hardened aluminium alloys are widely used for this type of application because of their properties such as high specific strength combined with natural corrosion resistance. However, to date, no detailed studies on the residual stress development are available, especially as regard to AA6061.
Notwithstanding, the optimization of this technology necessarily requires an in-depth knowledge of the residual stresses being built in the parts produced by WAAM as a function of the process parameters in order to ensure reliable performance. The present proposal aims to relate process parameters, microstructural features, residual stresses and mechanical properties in additively manufactured AA6061 which has never been achieved so far. We are applying for an allocation of 3 days of beam time on SALSA in order to investigate the stress field in aluminium walls produced by WAAM.

<u>Experimental Report</u>: Influence of wire-arc additive manufacturing parameters on residual stresses in 6061 aluminium alloy analyzed by neutron diffraction

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Scientific background and context

Additive Manufacturing (AM) shows a great expansion due to the technologic stake it represents, allowing new developments structures lightening or complex architecture. Wire and Arc Additive Manufacturing (WAAM) offers a high material deposition rate leading to the capability to manufacture large components. Aluminium alloys are widely used for this type of application because of their properties such as high specific. However, these alloys are known for their poor weldability. The recent development of a MIG welding process based on a low-energy short-circuit transfer mode called CMT (Cold Metal Transfer) made the use of 6061 aluminium alloy (AA6061) possible by WAAM. Residual stresses developed during the WAAM building process have a critical influence on the mechanical performance of the part, leading to part distortion or crack formation[1,2,3]. It ensues from the high cooling rates, thermal gradients and volumetric changes occurring over the building process and is strongly reliant on the process parameters (heat input, welding speed, wire feed speed and welding trajectories)[4]. Although aluminium is one of the most widely used alloys for WAAM and other AM techniques, to date, no detailed studies on the residual stress development are available, especially as regard to AA6061[5]. The optimization of this technology necessarily requires an in-depth knowledge of the residual stresses being built in the parts produced by WAAM as a function of the process parameters in order to ensure reliable performance. Therefore, the present proposal aims to relate process parameters, microstructural features, residual stresses and mechanical properties in additively manufactured AA6061 which has never been achieved so far.

Proposed experiment

The aim of this present study intends to prove the feasibility of the experiment.
Experiments have been carried out on SALSA beamline. Measurements have been achieved on 3 wall-shaped samples ($5\times50\times180$ mm^3) directly deposited by WAAM from a 6061-wire filler drawn for the study on a 2 mm thick pure aluminium plate. A gage volume of $2\times2\times2$ mm^3 with the {311} diffraction peak of aluminium ($2\theta = 88.5°$ with a wavelength of 1.62 Å) are chosen. Samples have been produced using 2 welding trajectories (namely alternating (zigzag) and unidirectional vectors) an additional sample was machined and removed from the baseplate to understand how it impacts the equilibrium of residual stresses.

Experimental set-up

Experiments have been successfully achieved (on **10 Sept. 2019**) on three wall-shaped sample built by WAAM as-deposited.

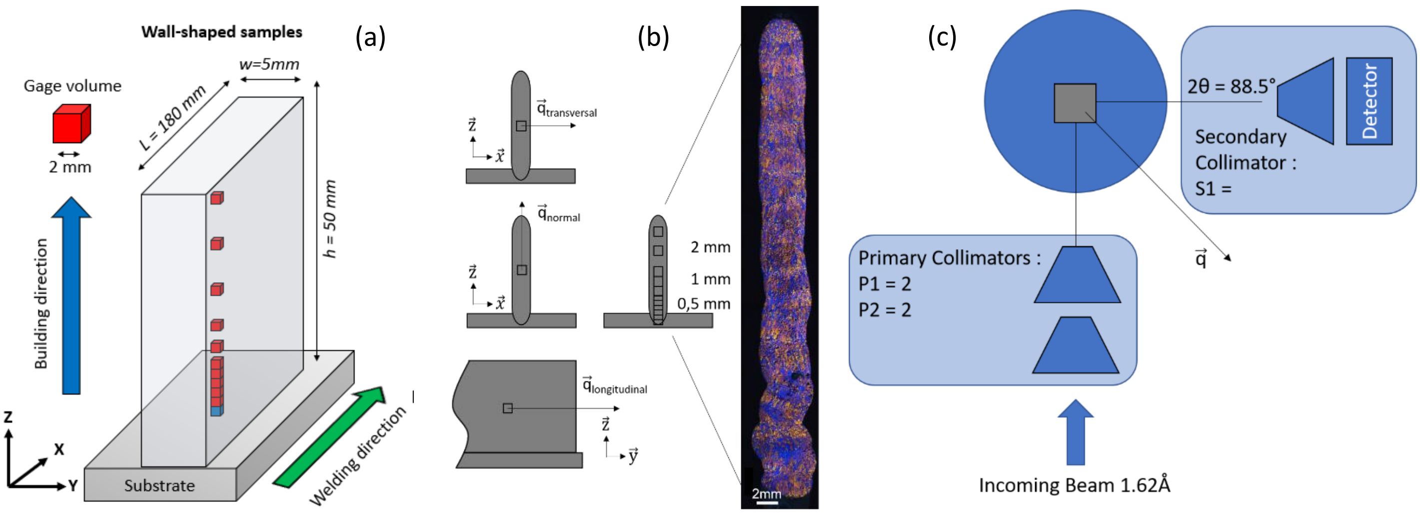

Figure 1: (a) Sample features; (b) gage position over the sample; (c) experimental set-up

The stress field investigation has been achieved along a column in the middle of the sample (Fig. 1.a). Position asymmetrically distributed over the height of the wall have been probed as shown on Fig. 2. Measurement points, as depicted in Fig. 1(b), ensure a reliable determination of the stress gradient. An additional point has been taken at the center of the base plate to understand its role in the residual stress equilibrium. Lattice strain will be measured along the three orthogonal directions matching the sample coordinate system at each measurement point to provide an assessment of the three normal strain components ε_{xx} ε_{yy}, and ε_{zz}.

Residual stress analysis has been achieved with experimental conditions describe below ({311} peak with a wavelength of 1.62 Å). A counting time of 10 min per point was sufficient to achieve a good intensity profile for the forty 2×2×2 mm^3 gauge volumes located along the vertical centerline and aligned with the three principal directions of the specimen. Fig. 2 presents a diffractogram to show the peak quality.

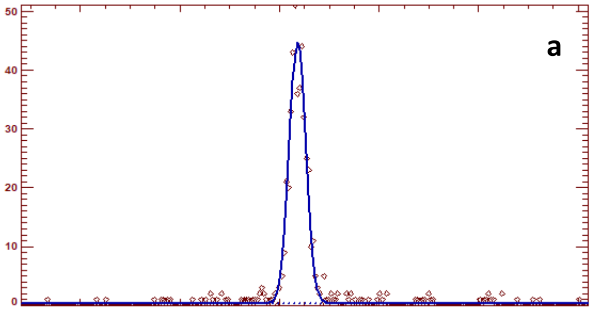

Figure 2: Example of neutron diffraction pattern

Intergranular rational deformations have been calculated from Bragg angle shift (Eq. *(1)*). For these experiments, the strain free θ_0 Bragg's angle has been estimated through an average of θ values over the sample height in the three principal directions (Eq. *(2)*). Strain evolution along the z axis in the longitudinal x-, transverse y- and normal z-directions for the sample obtained with an alternate strategy is presented on Figure 3.

$$\varepsilon = \ln\left(\frac{\sin\theta_0}{\sin\theta}\right) \qquad (1)$$

$$\theta_0 = \frac{\sum \theta_i}{N} \qquad (2)$$

This assumption which supposes that the stresses in the whole part is equal to zero because of the residual stress equilibrium does not take into account the possible evolution of microstructure.

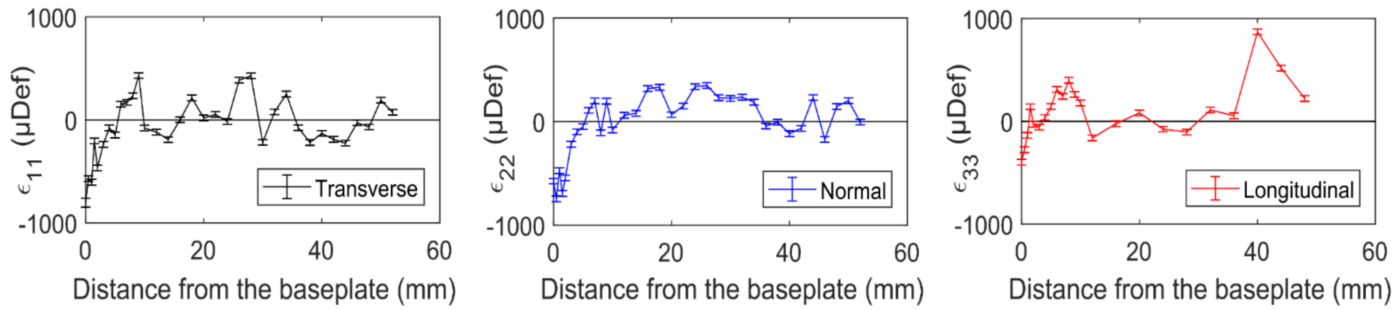

Figure 3 : strain evolution in the transverse, normal and longitudinal directions along z direction (height)

Residual stresses have been calculated from (Eq. *(3)*), where E_{hkl} is the Young's modulus and ν_{hkl} is the Poisson's ratio for a given {hkl} reflection.

$$\sigma_{xx} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_{xx} + \nu_{hkl}(\varepsilon_{yy}+\varepsilon_{zz})\right]$$

$$\sigma_{yy} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_{yy} + \nu_{hkl}(\varepsilon_{xx}+\varepsilon_{zz})\right] \qquad (3)$$

$$\sigma_{zz} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_{zz} + \nu_{hkl}(\varepsilon_{xx}+\varepsilon_{yy})\right]$$

Results

Figure 4 shows the residual stresses profiles along the height in the transverse, normal and longitudinal directions. These results show that experiments are perfectly feasible, the level of uncertainty associated with each measurement point is low. For each sample as depicted on Figure 4, the residual tensile stress has a slightly similar level over the walls. Stress values are low along the normal and transverse directions. For longitudinal direction, there is an increase of the residual stress magnitude in the penultimate layer. Alternate or unidirectional deposition strategies give the same stress levels. The sample called "Unidirectional + Machining" was remove from the baseplate and machined, it shows that machining only partially removes residual stresses obtained during manufacturing process. As expected, large compressive stresses are found in the baseplate. Important fluctuations can be found in the three samples, it could be explained by the assumption used for calculating the unstrained d_0 lattice spacing. Stress equilibrium means that over the whole solid the sum of stresses is equal to zero. Hence, this assumption does not take into account any microstructure evolutions and influence of heterogeneity.

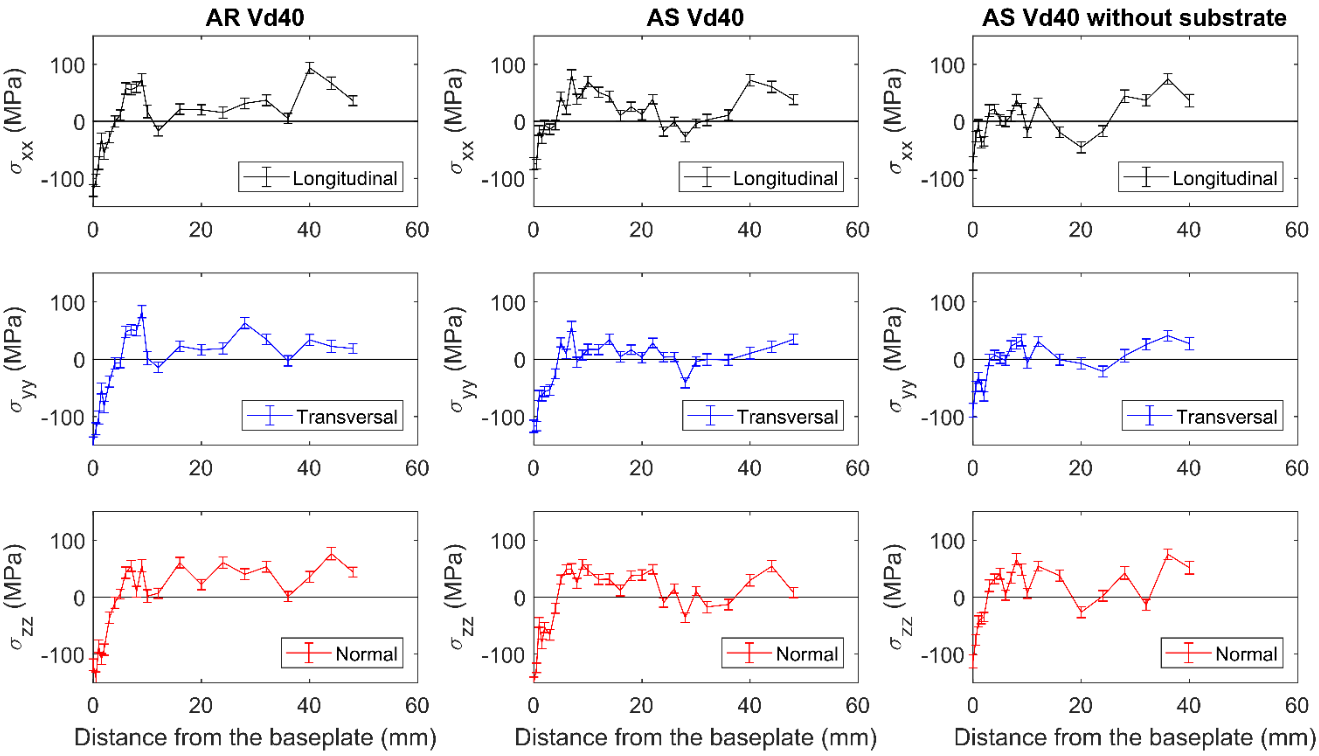

Figure 4 : Evolution of the residual stresses other the height within the three samples for each directions (transverse, normal and longitudinal)

As shown on Figure 5, the grains of the built part alternates from equiaxed to columnar structures, this could strongly influence the mechanical state locally. In order to ensure reliable d_0 (in particular regarding the evolution of the metallurgical state, chemical composition or microstructure), latter will have to be acquired thanks to measurements carried out on the same positions over each wall of 2×2×2 mm^3 cut from twin specimens of the walls through an Electro-Discharge Machine and whose extraction positions match the residual stress position measurements.

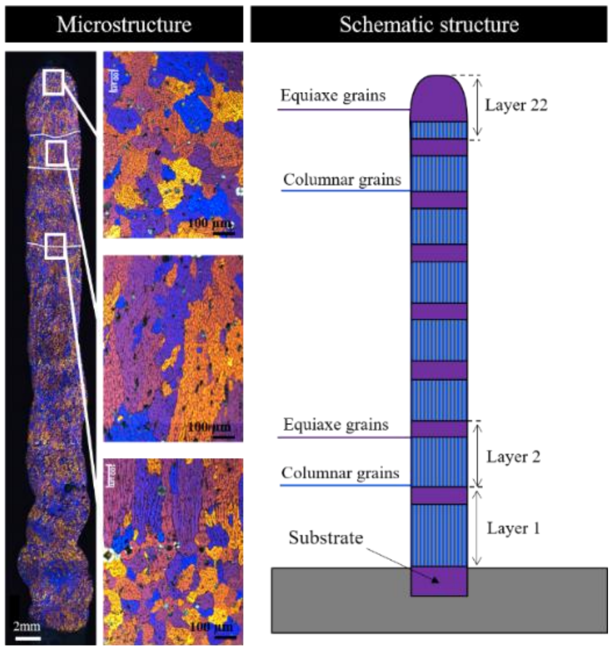

Figure 5 : Microstructure evolution over the built part

References

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