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DEFECTS IN WIRE AND ARC ADDITIVE MANUFACTURED COMPONENTS: A REVIEW

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Abstract. *As a potential process for industry, the Wire and Arc Additive Manufacturing process has been probed for implementation in factory lines, once it has high deposition rates, material economy, feasible equipment and it can manufacture large and complex components. However, this process can present various defects if wrong parameters were used, causing high porosity, deformation, cracks and fractures, delamination, residual stress, and oxidation. Therefore, industrial companies and academic institutions has been studying these defects and its causes, to develop new methods to solve them and achieve higher quality in additive manufacturing parts. This article reviews the common defects found, for different materials deposited by different Wire Arc Additive Manufacturing processes, such as CMT-GMAW, GTAW, PAW and hybrid Laser processes. The main causes for each type of defect are presented followed by the methods that can be applied for solving them. Computer assisted simulations, its role in parameters optimization and its uses as forecasting defects method are also addressed. It was possible to notice that they can obtain good predictions for microstructure result, work temperature and which heat treatment can be done to solve problems with residual stress and cracks. Porosity and deformation can also be controlled with process technologies, as CMT-GMAW.*

Keywords: *WAAM, Defects, Parameters optimization, Quality improvement, Inspection methods.*

1. INTRODUCTION

Additive manufacturing (AM) process are becoming increasingly widespread in industrial segments due to the capability of doing parts with complex geometry with material and production economy. Many manufacturing methods can be applied in AM, such Laser Sintering, Directed Laser Deposition and Wire and Arc Additive Manufacturing (WAAM). The WAAM process has great potential, once the process has feasible equipment, compared with others AM deposition methods, and can manufacture large components with high deposition rates.

The WAAM process can be implemented in different industrial applications, such as: in automotive, aerospace, and civil construction. According to Wu *et al.* (2018) there are three main steps during fabrication: planning, deposition, and post processing. Planning step involves CAD model, 3D slicing, equipment setup, and programming the torch path and welding parameters for deposition. After deposition, post process can be applied to improve surface quality, like machining, and improve mechanical properties, like heat treatments or forging.

Recently Novelino *et al*. (2021a) mention different deposition methods used in WAAM processes such Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW) and Plasma Arc Welding (PAW). Furthermore, hybrid methods with laser deposition and variants from the conventional ones, as Cold Metal Transfer (CMT-GMAW) can also be implemented.

However, to be introduced into production lines WAAM methods needs to achieve high quality requirements, so it is important to study deposition process behavior and identify key factors that can generate defects and apply techniques to minimize them. Thus, this paper aims to make a review on the possible defects that can be present in WAAM parts and how they are generated during the process. As well, as which inspection and prediction methods can be applied to improve deposition and quality control on the manufactured components.

2. DEFECTS PRESENT IN WIRE AND ARC ADDITIVE MANUFACTURING

2.1. Cracks

Wire and arc additive manufacturing processes are susceptible to crack defects during the deposition, as observed in Fig. 1, which can harm mechanical properties of the final product. As an important effect to be studied, Seow *et al.* (2020) focus their research on crack defects and fracture behavior of Inconel 718 parts deposited by Plasma Arc Welding (PAW).

The authors mentioned that due to high energy density from plasma and path planning with oscillation movement, the border areas were submitted to high heat input and intense temperature gradient, which caused high thermal stresses and lead to crack formation at the middle points in the torch path. Added to it Wu *et al.* (2018) pointed those high thermal stresses causes high strain in the melt pool and obstruct solidified grain growth, which can result to solidification crack defects and lead to anisotropy.

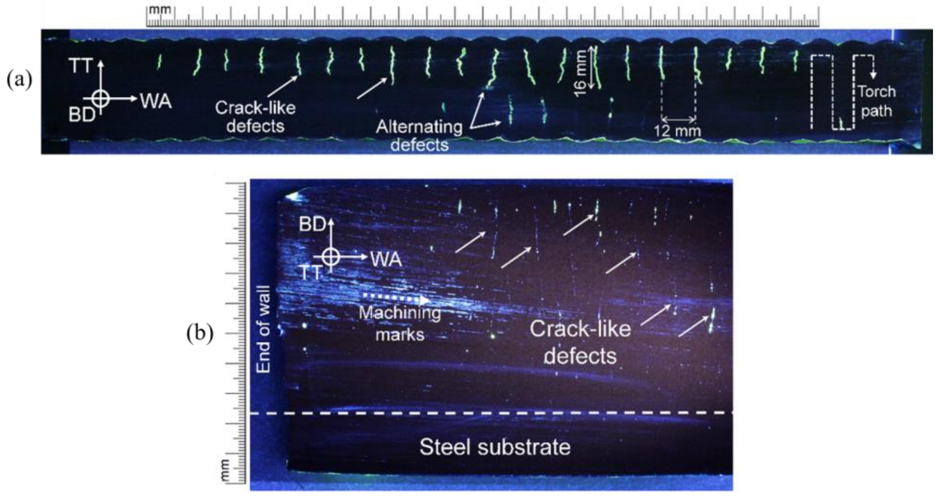

Figure 1. Crack-like defects in WAAM wall sections detected by fluorescent dye penetrant test in (a) build direction and (b) through thickness direction (adapted from Seow *et al.,* 2020).

Artaza *et al.* (2020) mentions small cracks presented in Mn4Ni2CrMo steel samples manufactured by GMAW deposition method, caused deleterious effect on the elongation once for the small diameter samples the elongation is sensitive to the internal state of the material. Meanwhile, when manufacturing with PAW there were no cracks, which influenced positively in the elongation values and mechanical resistance.

Clark *et al.* (2008) documented cracking problems during the deposition of Inconel 718 using GMAW deposition method. The authors mentioned that the orientation of the macro-scale cracks appears to be influenced by the stress field imposed during cooling process. This reinforces the high influence of residual stresses on crack defects and the importance of controlling interpass cooling to avoid chemical segregation that would worsen the mechanical properties.

Huang *et al.* (2021) focused their research on study the effect of wire feed speed parameter in solidification crack sensitivity and microstructure behavior of Al-Si alloys. The samples analyzed were deposited by CMT process, using ER4043 wire with a diameter of 1.2 mm. As process parameters, the wire feed speed ranged from 4.0 m/min to 7.0 m/min, a constant welding speed of 8 mm/s was adopted, pure argon flow at 8 l/min was applied as shield gas and no arc correction were used. As results, the authors mentioned that the increase of wire feed speed was directly related to the presence of cracks, until 5.5 m/min, with the crack solidification initiating at crater pipe region. The authors also mentioned that until 5.5 m/min, the increase in the feed was associated to a more irregular microstructure reducing both grains size and microstructural stability. However, for higher wire feed speed rates, the crack rate reduced from a maximum of 82.5% at 5.5 m/min to 28.67% at 6.0 m/min. The samples deposited with wire feed speed of 6.5 and 7.0 m/min did not present any solidification cracks. The microstructure from the samples submitted by wire speed rates of 4.5 m/min, 6.0 m/min and 7.0 m/min are represented in Fig. 2.

2.2. Delamination

Low bead penetration caused by wrong welding parameters as voltage, current or high weld torch velocity can generate weak interlayer region leading to delamination defects. According to Jafari *et al.* (2021), layers delamination occurs by lack of fusion, as the underlying material was not completely melted, which fragilize the region and leads to cracks failures. Wu *et al.* (2018) comments that delamination can also occur by material incompatibility with substrate and wire or bimetal material combinations, such as Al/Cu, Al/Ti and Al/Fe, once those materials have large differences in their chemical and solubility properties, making the intermetallic phase weak.

Xie *et al.* (2021) studied the defects of Al-Mg4.5-Mn Alloy samples deposited by GMAW with *in* situ micro-rolling process. The authors used a high-resolution X-ray tomography to analyze manufacturing defects and identify lack of fusion points, due to the quick solidification those points are relevant once they shrink and cannot fill the gaps, leading to stress concentration in interlayer region which possibly caused cracks nucleation and delamination.

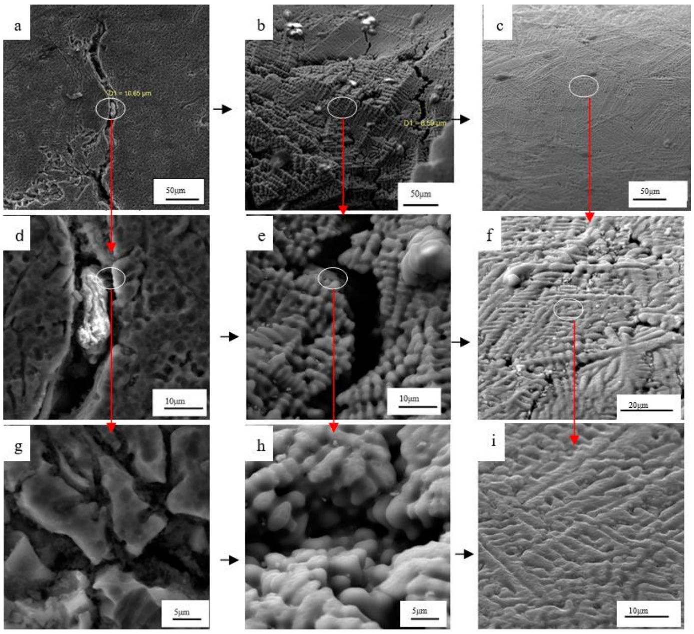

Figure 2. Influence of wire feeding speed on the microstructure near the solidification cracks: (a, d, g) 4,5 m/min; (b, e, h) 6.0 m/min and (c, f, i) 7.0 m/min (Huang *et al.*, 2021).

2.3. Oxidation

High exposition by rich oxygen atmosphere during deposition process can induce oxidation problems that weakens the metallic structure of the weld bead, affecting mechanical properties, once, according to Hauser *et al.* (2021), the oxides act like impurities and can contribute for porosity and cracks defects. Figure 3 highlights oxidation anomalies generated during wall deposition of AlSi5 with variable parameters.

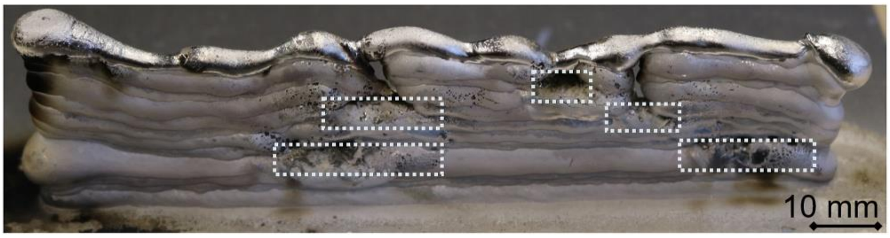

Figure 3. Oxidation anomalies present in second, fifth and seventh layer of twelve-layer wall (Hauser *et al.*, 2021).

During the manufacturing, Hauser *et al*. (2021) used CMT and pulsed CMT method, with the following parameters: shielding gas flow (4-10 l/min), nozzle-to-work distance (10-14 mm), wire feed rate (3-5 m/min) and travel speeds (350, 600 and 1500 mm/min). The monitoring of the oxidation anomalies during deposition was made by light emission spectroscopy, with the relativity intensity measurements of ultraviolet, visual, and infrared wavelength. Gas flow rate and nozzle-to work distance had the most impacted on shielding from oxidation anomalies. The pulsed CMT method presented more oxidation anomalies once higher heat input and pulses lead to disturbances of the shielding gas and thus a higher gas flow is necessary to avoid oxidation.

Liu *et al.* (2019) performed their study with the aim of minimize the oxidation defects in WAAM process, focusing on PAW deposition method, using ER70S-G wire. The experiment used different torch travel speed (15-95 mm/min) and gas flow (6-15 l/min**)** to analyze the weld bead quality and identify oxidation and surface finish defects. The experiment obtained an optimized gas flow rate of 9 l/min that prevented bead oxidation and did not cause turbulence, improving the morphology. When comparing CMT and PAW processes, lower gas flow (6 l/min) lead to oxidation in both methods, but in PAW process, the defects were more severe.

2.4. Porosity

Porosity on structure composition is another common defect in WAAM that needs to be controlled and minimized. According to Wu *et al.* (2018), high porosity rates affect mechanical properties and contribute to the generation of other defects such as: cracks and residual stress. It is worth mentioning that gas pore's formation is strongly associated with weld pool, which can be controlled by pulse frequency and arc current.

Pores can be caused by wire material and surface contamination, it also can be generated from poor path planning or unstable deposition process. Wu *et al.* (2018) mentions that aluminum alloys are most susceptible to this defect once hydrogen has significantly different solubility in solid and liquid phases, which can be absorbed into the melt pool and generate gas pores. According to Hirtler *et al.* (2020), to avoid mechanical resistance problems caused by high porosity, the porosity of all samples needs to stay below 1%, as recommended by VDI 3405.

Biswal *et al.* (2019) and Shamir *et al.* (2020) analyzed how porosity influenced on fatigue life on Ti-6Al-4V WAAM samples manufactured by plasma deposition method. The authors investigated the effects of gas pores defects on fatigue performance, and examined two groups of specimens, one as the reference group, building according to standard manufacturing procedure, and other group built with contaminated wires, using the same parameters. An X-ray computed tomography was used to determine porosity morphology and density. The density of the contaminated specimen was 99,96% and the reference group was more than 99,99%. The tensile test presented similar results for yield and ultimate tensile stress, but uniform elongation was 4% for contaminated group and 10% for the reference group. In fatigue life, the fatigue strength (10 million cycles and stress ratio 0,1) was 600 MPa and 400 MPa for the reference and contaminated specimens, respectively. In Figure 4 one can observe the fractures surfaces, in the image one can also note large gas pores for the contaminated specimen.

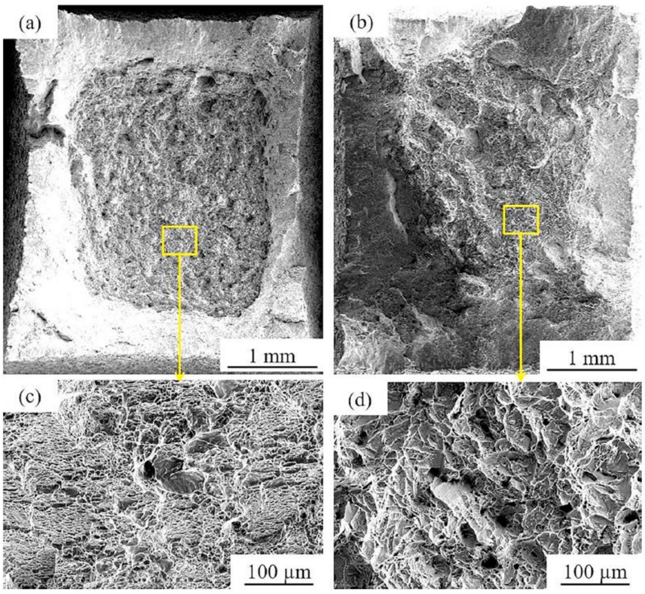

Figure 4. Tensile fracture surfaces from (a) reference and (b) contaminated specimens with respectively enlarged views on (c) and (d) (Biswal *et al.,* 2019).

Biswal *et al.* (2019) also applied a modified Kitagawa-Takashi diagram to predict fatigue strength limit for porosity defects diameters using Linear Elastic Fracture Mechanics theory, which shown to be effectively. Instead of using the monotonically decreasing relation of stress range with porosity size, a sigmoidal curve was used to determine notch fatigue limit. Using the modified diagram, the critical porosity diameter was found to be close to 100 µm for Ti-6Al-4V WAAM samples.

Shamir *et al.* (2020) continues the Biswal *et al.* (2019) previous research analyzing the relationship of defects-microstructure-crystallographic orientation as competing factors under fatigue life of Ti-6Al-4V. For the study, fatigue life was compared with the crack initiating pore size under different grain orientation. The authors concluded that the size of pores alone cannot be correlated with fatigue life, once crystallographic orientation of α phase of Ti-6Al-4V has high influence on cracks growing. If porosity defects cannot be eliminated in additive manufactured titanium alloys, then fatigue life also can be improved by reducing α lath width on crystallographic orientation. Recently Novelino *et al.* (2021b) mention that different simulation methods can be used in WAAM to optimize the process such as computational thermal models that can help in predicting the microstructure of the material, due to the precise characterizations of the temperature fields presented. With those simulations it becomes possible to optimize the parameters and obtain the product with the correct mechanical characteristics and microstructural composition for the desired application.

In other study, Wang *et al.* (2018) obtained porosity reduction and grains refinement of aluminum alloy Al-5Si using pulsed GTAW method with variable pulse frequency (2-500 Hz). When increasing the frequencies, the authors verified that 50 Hz was an optimal value in terms of pore reduction. However, for pulse frequency above 50 Hz, the material density decreases with the increase of pulse frequency. The authors explains that despite that high pulse frequency increase gas pores capacity to detach from the melt pool and escape for the atmosphere, for pulse frequency above 50 Hz, the pores nucleation will overcome that, and more gas pores will be formed.

2.5. Deformation and surface finish

Deformation and surface finish problems in manufactured parts can be caused by arc instability, wrong deposition parameters and technologies, as showed by Ji *et al.* (2018) in one of their examples using GTAW-based process of TC4 titanium alloy, shown in Fig. 5. The samples 3 (a) and 4 (b) were manufactured using not optimized parameters and resulted in bead collapse. The Sample 5 used optimized parameters and presented better surface quality without high deformation.

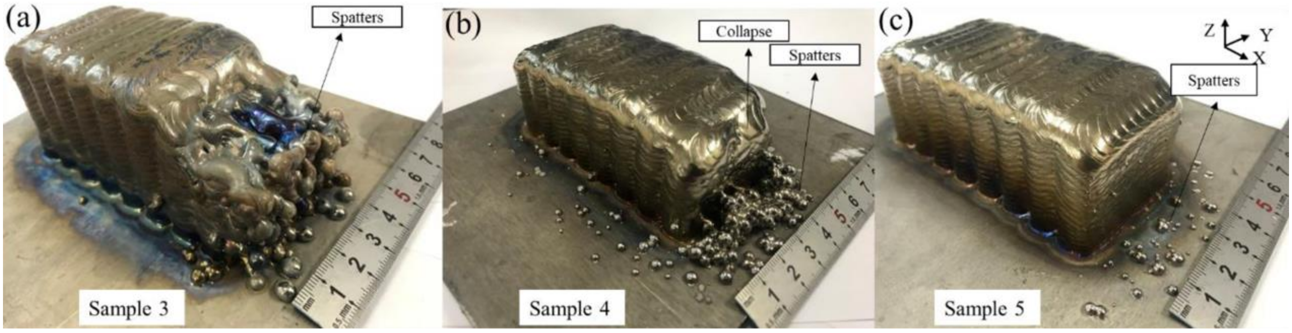

Figure 5. Macrostructure images of samples 3, 4 and 5 with layer thicknesses of (a) 1.10 mm, (b) 1.05 mm and (c) 1.05/1.10 mm (Ji *et al.*, 2018).

Humping is another type of surface defect that is caused by irregular material flow in melt pool, shown in Fig. 6. Yamba *et al.* (2019) studied hump formation process of AISI 1018 carbon steel deposited by Laser-GMAW method and the influence of travel speed on the defect generation.

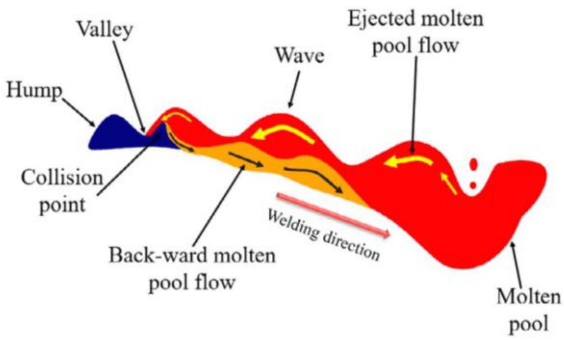

Figure 6. A schematic illustration of hump formation process (Yamba *et al.*, 2019).

In the experiment, Yamba *et al.* (2019) used different torch travel speeds on various weld beads to analyze the turn point for humps formation. Under low travel speeds (2.5 m/min), the droplet impacts the molten pool and create a non-turbulence flow, totally direction in a main direction, resulting in a weld bead with no defects. For travel speed of 3.5 m/min, the length of the weld pool is stretched and material flow in molten pool presented two dominant directions, retreating material flow, and affecting arc stability, resulting in a tail end and pre humping defects along some weld bead sections. For travel velocities above 3.5 m/min, the experiment shown that heat input became insufficient and lead to less melting of molten metal area. The material flow at this travel velocity became turbulent in result of the retreating molten pool, leading to a material transfer instability which resulted in hump defects along all weld bead (Yamba *et al.*, 2019).

2.6. Residual Stress

Residual stresses are common in WAAM processes once it generates high thermal gradients. Wu *et al.* (2018) mention that residual stress can be a critical influential factor in the mechanical properties and fatigue performance. The defect is associated with many process parameters, such as welding current and voltage, wire feeding speed, ambient temperature and shielding gas flow rate. The authors also mentioned that bimetal components normally exhibit higher level of residual stresses once the materials have different thermal expansion rates. For that reason, bimetal materials need an even more accurate interpass temperature control to minimize the residual stresses.

As an attempt to fully predict the residual stress behavior, Wu *et al.* (2020) uses Machine Learning techniques and a computer model, present in Fig. 7, which measured normal tensions values, being able to set over 243 data points simulated using neural links and random forest methods.

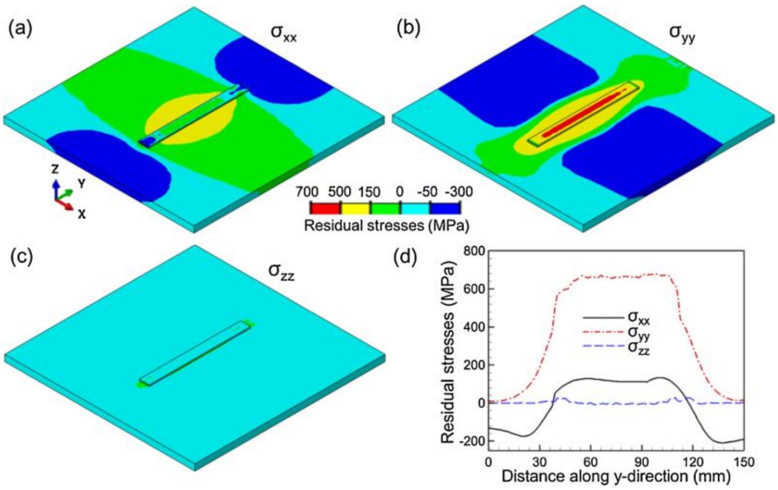

Figure 7. Computational model used to predict and analyzed residual stress values in which direction in (Wu *et al.*, 2020).

In order to minimize or even mitigate the residual stresses, post-processing treatments have been proven to effective, highlighting heat treatments, interpass cooling and interpass cold rolling, which helps recrystallization process, refining microstructure and brings more homogenous material properties (Wu *et al.*, 2018).

Sun *et al.* (2021) also used numerical models to analyze distribution characteristics of residual stresses in Al-5356 alloy samples fabricated by CMT-WAAM process with Al-6082 alloy as substrate. The experimental procedure consisted by deposition of 20 layers into a 100ºC preheat substrate with thermocouple applied to measure the thermal cycle and compare with simulation results. The simulation used finite element method and 8 models were analyzed, each one representing a different number of layers deposited. The objective was to identified residual stress level in longitudinal (along deposited direction, x axis) and transversal (y axis) directions and how consecutive layers deposition affects it. The authors also used different models to analyze other possible influent factors, such as models with and without substrate clamping, larger substrate and considering bending deflection effect. The results are presented in Fig. 8. Both deflection distribution and thermal cycle obtained from simulation results matched with the experimental data of case 5, which was the experimental configuration. The simulation model shown to be reliable and capable to reasonably predict residual stresses and helped on WAAM process optimization.

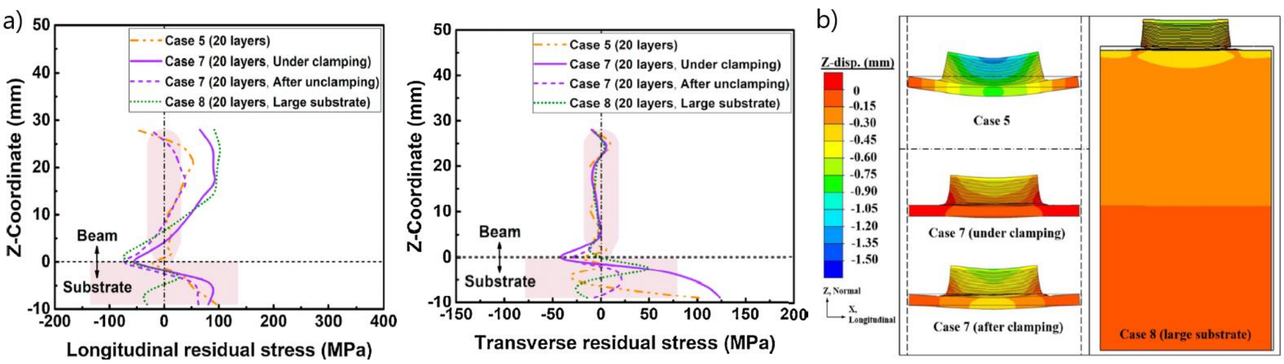

Figure 8. (a) Distribution of longitudinal (σ_{yy}) and transverse (σ_{xx}) stress along WAAM deposited wall height and (b) Longitudinal bending deflection in the longitudinal middle-cross section (adapted from Sun *et al.*, 2021).

Yang *et al.* (2018) focused the research on reducing residual stresses of Ti-6Al-4V WAAM samples, manufacturing by GTAW method, using Ultrasonic Impact Treatment (UIT). The UIT consists in create severe surface plastic deformation by high frequency oscillation of an impact head and, according to the authors, has been proved to be useful on residual stress reduction and fatigue performance improvement. For the experiment, the authors applied UIT twice just after the deposition process of the samples and compared with samples without the post treatment. Compared with the original samples, the samples submitted to UIT process presented 2 to 4 times lower residual stresses values, the Von Mises Residual Stress reduced from 250 MPa to 56 MPa approximately, for the sample with seven layers, and from 96 MPa to 54 MPa for the single layer sample.

Shen *et al.* (2019) focused on measure residual stress for Fe_3Al based iron aluminide components fabricated by GTAW process using neutron diffraction analysis. A 50-layer wall was fabricated using single deposition direction and interpass temperature of 400ºC to prevent cold cracks. The experiment consisted in the analysis of samples as-fabricated, heat-treated and cut-off samples, comparing residual stress level between samples.

The heat treatment applied was 500ºC for 6 h and the cut-off sample was extracted from 5 mm above the substrate to remove the region induced by the element diffusion from substrate material. The neutron diffraction method determined the stress level upon the measure of lattice spacing of microstructure and divided the measure points in three groups at the start, middle and end layer deposition direction. When comparing the heat-treated sample with the as-fabricated one, the residual stresses turning points from tensile to compressive were mainly distributed near to the balanced points. The cut-off sample presented tensile and compressive stresses points in all three sections, moved upwards compared with as-fabricated sample and indicates residual stress relief in the sample. It also can be observed that the longitudinal and transverse were significantly relief while the normal direction stayed significantly tensile. According to the authors, it happened because the constraint from the substrate was entirely released after the cut, releasing longitudinal and transverse directions, but the residual stresses in the normal direction was mostly induced by layers interaction during deposition and were not related with the substrate (Shen *et al.,* 2019).

3. CONCLUSIONS

Industry segment has great interest in additive manufacturing field once it reduces material waste and expand geometry possibilities. WAAM processes are highlighted compared to other technologies due its feasible equipment and easy application. However, quality control is one of the essential requirements from the industry, so it is important to understand defects generation and optimize the process to obtain more predictable results. This paper reviews some of the techniques to inspect and prevent the appearance of those defects. After the literature review and analyzes, the following conclusions could be drawn:

- Cold Metal Transfer is the most explored process in the recent researches, since it has low heat input and high arc stability, which makes deposition less susceptible to defects. Components fabricated by CMT technology also tends to present good surface finish quality.
- Control WAAM components porosity level is one of the challenges of process optimization. Due to the complex thermal cycle and various weld parameters, the path planning needs to be optimized to guarantee a regular molten pool flow and to reduce hydrogen concentration, which causes pores formation. High porosity also leads to cold cracks formation, since the hydrogen concentration inside molten pool causes high residual stress levels and, consequently, reduces mechanical resistance of the component.
- As prevent methods, numerical models shown to be highly effective to prevent heat stresses and hot cracks formation. Several researchers achieved computational results in accordance with the experimental analysis. Also, thermal analysis can be used to optimize heat input during the deposition, reflecting to weld parameters adjust, and can even indicates the right cooling rate in order to control the thermal cycle and guarantee the desirable mechanical properties. On the other hand, CFD analysis are used to study flow dynamics and help on the control of the molten pool, leading to parameters optimization in terms of wire feed and weld speed, mainly, and to optimize shield gas flow to prevent oxidation defects.
- Inspection methods are also important to comprehend those complex effects, like residual stress levels, which can be obtained by neutron diffraction. The X-ray tomography method can be used to measure fabricated components density and identify which defects are present on structure without the necessity of making a destructive analysis. Finally, light emission spectroscopy is another inspection method that can be used to monitoring oxidation anomalies during deposition process and can help in the gas flow rate optimization.

4. ACKOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

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