Porosity evolution in additively manufactured aluminium alloy during high temperature exposure

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Abstract. A 2319 aluminum alloy is deposited by the Wire+Arc Additive Manufacturing technology with Cold Metal Transfer process. Porosity that are both existing in the as-deposited and as-heat treated state metal are revealed by optical microscopy and quantitatively analyzed. It explains the reason why the newly initiated pores are easily tend to gather between each layer around the fusion line zone for the WAAM metal after heat treatment. The inner morphology of the pores are demonstrated by Scanning Electron Microscopy. Porosity evolution and distribution during high temperature exposure are demonstrated. Thus two porosity growth and number increase mechanisms are proposed eventually, providing theoretical basis for related material design and process optimization.

1. Introduction

Wire+Arc Additive Manufacture (WAAM) is a promising manufacturing process which offers near-net shape fabrication of complex components without dies or substantial machining, resulting in a reduction in lead-time, waste, and cost, as well as the ability to produce complex geometries which allows the manufacture of novel, light-weight structures from a low density alloy[1]. Nowadays, industry applications such as aerospace and automotive are normally applying aluminium alloys instead of steel due to their low density and low cost[2]. The production of such components is of great interest for large scale metallic parts[3]. However the implementation of additively manufactured aluminium is limited by its inferior physical properties and the hydrogen pores defect. It is reported by H. Toda[4] that the existing of micro pores will further reduce the mechanical properties of the alloy.

Hydrogen porosity are always hard to control during WAAM depositing process for two reasons. One reason is that aluminium alloys are the most susceptible to hydrogen due to the great difference in solubility between liquid and solid metal (0.036 against 0.69 cm³/100 g at a melting point of 660°C) [5]. Thus even small amount of hydrogen may exceed the solubility limit in solid state. The other cause of porosity is that the moisture, grease and other hydrocarbon contaminants on the wire, which is the raw material for WAAM process, are converted into atomic hydrogen which is then available for absorption into the molten pool[6].

During practical industrial manufacturing process, the metallic parts are always strengthened by solution treatment and subsequent aging process technology. However, some researches have been
carried out on casting and wrought aluminium alloys and have shown that the secondary porosity problem would be observed during high-temperature exposure[7]. Although the porosity number increase, formation and growth during homogenization were shown in these studies, the factors affecting those behaviors and the physical properties of those secondary pores in solid phase are not yet to be fully understood. Especially the porosity evolution of additively manufactured aluminium alloy have not been investigated before. The objective of the present research is to experimentally study the evolution of micro pores during high temperature exposure, thus to provide theoretical basis for related material design and process optimization.

2. Experimental
The compositions of ER2319 wire, which was applied in the present study as raw material for WAAM metal, is Al-6.3%Cu-0.3%Mn. 2219-T851 aluminium plate was used as substrate metal in this trail. The 1.2mm wire was feed at a constant wire feed speed (6m/min) by a wire feeder machine to deposit a wall dimensions in 230mm×50mm×6.5mm. The deposits were built by pulse advanced Cold Metal Transfer (CMT) process supplied by a Fronius CMT Advanced 4000R power source, connecting to an ABB robot IRB2400 at a fixed travel speed of 0.6m/min. Flow rate of the shielding gas of pure argon (99.99%) was kept at 25 L/min during the whole process. Half of the wall was solution treated in a furnace with a ramping speed at 200°C/h to 535°C and then held for 90min, followed by quenching in water at 20°C. Specimens for porosity observation were mechanically sectioned from the central region (20mm from the top surface) of the wall along the longitudinal-direction. They were prepared in epoxy mount and polished to a mirror finish. Microstructure of the alloy was etched and revealed by Keller reagent. Pictures for porosity observation were taken by an Olympus optical microscopy and quantitatively analyzed by Image-Pro Plus (IPP) software. The inner morphology of the pores was examined by Scanning Electron Microscopy (SEM).

3. Results and discussion
Figure 1(a) and (b) show the metallographic images of micro pores in as-deposited and as-heat treated additively manufactured 2319 aluminium alloy. There are various sized micro pores distributed in the two states of the WAAM alloys. In addition, it clearly shows that the pore numbers in the as-heat treated sample are greatly increased compared with the as-deposited one. The results analyzed by IPP have demonstrated that the number density of pores greater than 5 µm increases from 512 to 1667 per 100mm², which means that the number of pores increases by three times during high temperature exposure. Meanwhile the mean diameter of the pores just increases from 13.5mm to 15.5mm. Microstructure of the as-heat treated sample in figure 1(c) shows that the boundary between the dendrites and equiaxed grains is the fusion line between each layer. In other words, the newly initiated and grown pores (black points) are mainly distributed around the fusion line zone (partially melted zone).

Figure 1. Porosity in WAAM aluminum metal both in (a) as-deposited and (b) as-heat treated state, (c) is the microstructure of as-heat treated state
During the additive depositing process, when the liquid metal get into the molten pool, solidification begins to process as the dissolved atomic hydrogen are rejected from the newly formed solid into the surrounding liquids[8] due to the big gap of solubility between the two existing states. Along with the process of solidification, the continuously incremental hydrogen in the liquid will be gathered to surpass the solubility limit[9]. Thus pores will be nucleated and grew along the dendrite grain boundaries. If the newly initiated pore size and buoyancy force grow big enough, it may float to the upper part surface of the liquid metal[10]. Ultimately, the gas pores are usually distributed at the top of the solidified molten pool because they are always entrapped at the top layer of the fusion zone. In addition, the quickly formed oxide thin films are very easily absorbing molecular hydrogen and moisture in the air, which will further increase the amount of hydrogen in the top region of each layer[11]. Thus around the fusion line zone of each layer, there is always a higher amount of entrapped hydrogen and fine micro pores, which will be got together and grown to be bigger ones during high temperature exposure. That is why the greatly increased observable pores are mostly distributed around the fusion line zone between each layer.

Porosity of point A and point B in figure 1(a) are further magnified by SEM as shown in figure 2(a) and (b), as well as pore C and pore D in as-heat treated state are indicated in figure 2(c) and (d), respectively. There are distinctly different characteristics of inner morphology for these pores. Although the pores may be nucleated as spheres initially, as analyzed above and shown in figure 2(a) and (b), they will grow into various sized irregular hydrogen pores together with the primary eutectic phases along with the inter-dendritic grain boundaries and distributed in the dendritic arms and cells during the solidification process.

During heat treatment process, the pores evolution is obviously controlled by classical Ostwald Ripening effect[12] as characterized in that the pores have grown to be bigger and the sphericity of some individual pores are improved as shown in figure 2(c). During this process, hydrogen pores are governed by inter-pores coalescence in solid aluminum both from molecular hydrogen dominating in
micro pores or hydrogen entrapped in the other surrounding trap sites, such as precipitates, grain boundaries or lattice interstices. Intra-pore growth and coarsening is a local ripening of individual pores, which is controlled by increasing internal hydrogen pressure comparing with the surface tension.

However, another mechanism is also dominating the growth and initiation of gas pores, because there is one contrary observed phenomenon comparing with the classical Ostwald Ripening in that a prominent increase of number density of porosity is observed. It may be caused by the migration and combination of hydrogen and vacancies that originally existed after depositing or are induced by dissolving of primary eutectic phases (Al2Cu). In addition, the ample dispersion particles and abundant grain boundaries around the inter-layer region provide energetically favorablesites for the heterogeneous nucleation of hydrogen when supersaturated atomic hydrogen is precipitated as molecules. The hypothesis is in great accordance with the inner morphology as indicated in figure 2(d), where the eutectic phases are completely dissolved into the matrix metal. Besides, irregular pores are formed along the wall of inter-dendrites, exhibiting non-spherical shape characters.

4. Conclusions

Irregular shaped hydrogen pores are observed in the as-deposited 2319 aluminum alloy due to the solubility difference of the liquid and solid aluminum metal and the unavoidable hydrogen contaminants existing on the wire surface. During high temperature exposure, there is a great increase of number density as well as a slight increase of the mean size of porosity. The newly initiated pores are mostly gathered between each layer around the fusion line zone. In addition, the inner morphology of the pores both generated before and after heat treatment are demonstrated. It is illustrated that there are two related mechanisms in controlling the growth and number increase of porosity after heat treatment. They are the classical Ostwald Ripening effect and combination of hydrogen and vacancies effect, respectively.

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