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Oxide accumulation effects on wire + arc layer-by-layer additive manufacture process

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ABSTRACT

A maraging steel wall structure was built layer-by-layer to study oxide accumulation mechanisms and the influence of oxides on the subsequent deposition. An online arc welding camera was also applied to investigate the wetting and spreading behaviour of the deposition on different surface conditions. Two maraging steel walls were deposited under torch shielding only and torch plus tent shielding conditions respectively to study the effect of oxides on the mechanical properties. Upon deposition a mixture of Fe, Al and Ti oxides formed, floated to the weld pool surface and accumulated layer by layer, deteriorating the surface condition such that it was rough and porous, which adversely affected the stability of arc and the wetting and spreading process of the weld pool in subsequent layers. The accumulation of oxides added to the uncertainty of the layer dimension and worsened the surface finish to reduce the structural integrity. Despite that the majority of the oxides floated to the weld pool surface, oxides (up to a few hundred nanometers in diameter) were found to be dispersed in the additively manufactured structure and might be one of the strengthening sources resulting in a 11% increase in UTS and a 19% decrease in elongation compared to the structure built in the torch plus tent shielding condition.

1. Introduction

Herzog et al. (2016) explained that additive manufacturing (AM) was initially developed for rapid prototyping to allow greater design freedom, less material wastage, and shorter lead-time in a layer-by-layer manner. Extensive research was devoted to plastic parts initially and as Atzeni and Salmi (2012) summarised, AM technology makes the economic production of small quantities of final plastic parts more feasible. After decades of development, the research interest has now moved to metals, which is attractive to many industrial sectors such as aerospace, shipbuilding and oil and gas where massive large-scale metallic structures are fabricated.

Almeida and Williams (2010) developed the wire + arc additive manufacture (WAAM) process, aimed at producing massive (meter scale) metallic structures with full density, high deposition rate, and low equipment cost. Ding et al. (2015) described that in WAAM the commercial welding power source is utilised to generate the electric arc as the heat source and an external wire is fed as the feedstock; usually, a preprogrammed robot arm is applied to control the deposition path to build a functional part in a layer-by-layer manner. So far, WAAM has been proved feasible for a broad range of materials from steel, titanium, Inconel superalloy, high strength aluminium to refractory metals, as stated by Williams et al. (2015).

Ever since WAAM has been proposed, various researches have been carried out to fully understand this process. Cong et al. (2014) investigated the effects of power source mode on the porosity characteristic of additively manufactured high strength aluminium alloy with cold metal transfer (CMT) process and studied the relationship between deposition mode and WAAM materials properties (Cong et al. (2017)). The interpass rolling technology has been applied by Gu et al. (2016) and Colegrove et al. (2013) to WAAM for aluminium and steel to induce recrystallization and eliminate porosities in aluminium and to reduce distortion and residual stress in steel, respectively. Various in-situ inspection of metal AM processes has been applied as well. For example, Berumen et al. (2010) utilised an in-line camera based set-up to measure the dimensions of the melt pool and the mean radiation emitted; Furumoto et al. (2012) assembled a high-speed camera to monitor the consolidation of the metal powder during irradiation. Similar technologies are also being investigated in WAAM now.

In WAAM, two aspects are of most concern: surface finish and mechanical properties, which represents the surface and interior qualities, respectively. A component built by WAAM is built up on a layer by layer basis. Each layer except the first, is formed by solidifying the liquid weld pool on the surface of the previously solidified layers. Therefore, the surface condition and the wetting and spreading behaviour of the weld pool play a dominant role in controlling the surface

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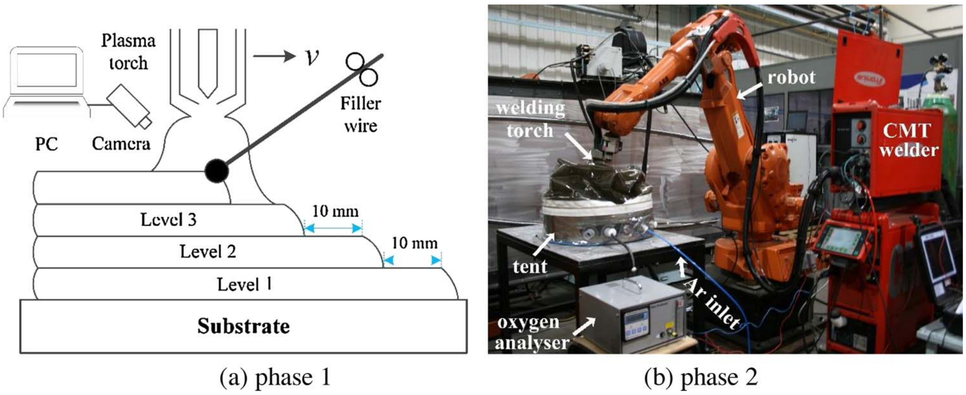

Fig. 1. Experimental setups of the WAAM process. (a) phase 1 (b) phase 2.

finish of WAAM parts. The commercial wire used for WAAM is designed for welding with deoxidizing alloying elements (Si, Mn, Al, Ti, etc.) added deliberately to prevent porosity and to minimise the oxygen content remaining in the solidified bead, as described by D.J.Widgery (1976). In conventional welding, these elements combine with oxygen and float to the surface to form scales or slags covering and protecting the inner bead; such scales or slags could be easily removed during multi-layer and multi-pass welding and will not affect the final weld quality.

As reported by Cáceres and Selling (1996), defects such as inclusions, entrapped dross and gas porosity could lead to a decrease in tensile ductility and strength which can be correlated with the area fraction of defects in the fracture surface. In another AM process, selective laser melting (SLM), experiments are carried out in an inert atmosphere in a sealed chamber. Despite this, Kempen et al. (2011) and Yasa et al. (2010) reported that in their research on 18Ni-300 maraging steel Ti and Al combined oxides (TiO_2: Al_2O_3) were present as large inclusions (in the size of 10–20 μm) in the matrix. These inclusions reduced the toughness especially in the aged condition when the material was brittle. Thijs et al. (2011) applied microscopy and spectroscopy to investigate the initiation of these oxides (size ranging from 10 to 120 μm). It was found that an oxide layer containing Al and Ti was created on top of each layer; upon depositing the next layer, the oxide layer was broken and dragged further. Such accumulation of oxides in the bulk resulted in the large and irregularly shaped inclusions inside the final component.

Similarly to SLM, WAAM is also a layer-by-layer process so oxide accumulation could be an issue, the only difference being that the main source of oxide in the SLM process is the powder (oxide surface, humidity, entrapped gas and so on) while in the WAAM process the atmosphere is the most significant source of oxygen. Thus, oxides formation mechanism and how oxides will affect the surface finish and mechanical properties of WAAM parts have been studied in this research. Furthermore, WAAM is characterised by a much larger weld pool and a much slower cooling rate compared to SLM. Therefore for WAAM wetting and spreading of the liquid weld pool on the as-solidified surface will be a significant issue determining the surface finish. Furthermore, the slow cooling rate allows enough time for the low-density oxides to escape from the inner weld pool and float to the surface. Successive thermal cycles lead to the part being built being kept at a high temperature for long periods, increasing the likelihood of forming more undesirable oxides on the surface.

A common practice in AM is to melt the metallic powder or wire in an inert atmosphere; however few researches have been carried out to investigate the benefits of this. Customising an inert atmosphere and reducing the oxygen level to a certain low level is not always practical and economic and could be time-consuming especially when manufacturing large-scale parts. The preceding inclusions issue found in SLM showed that it is hard to eliminate oxides through the use of a low oxygen atmosphere so more understanding needs to be gained on how these oxides could affect the AM process.

AM research has been very focused on achieving mechanical properties comparable to the wrought materials, with relatively few studies specifically on understanding the influence of surface conditions on subsequent layer deposition and the resultant surface finish and mechanical properties of the components. Therefore, this paper aims to investigate the formation and accumulation mechanisms of oxides and effect of oxides on the wetting and spreading of the deposition, arc stability and structure integrity and mechanical properties of the WAAM products.

2. Materials and methodology

The WAAM system comprises a welding power source, a wire feeding system, a tent (filled with pure Ar when required, as shown in Fig. 1b), a 6-axis ABB robot with a welding torch mounted, and a working platform. A 10 mm thick mild steel plate was used as the substrate, and the 1.2 mm maraging steel wire (MARVAL 18S, equivalent to maraging 250-grade steel) was used as the feedstock. The chemical composition of the wire is listed in Table 1.

The experimental procedure consists of two phases to represent two different WAAM processes. In phase 1, a plasma power source and a plasma torch were assembled to the robot arm to apply the plasma-WAAM process in an open atmosphere (Ar for plasma gas: 0.8 l/min, Ar for shielding gas: 10 l/min). A 9-layer wall structure was built in the form of stairs (see Fig. 1a) in which the length of each layer was reduced by a pre-determined value (10 mm) to investigate oxides accumulation process. An online arc welding camera (Redman MC500) was attached to the torch to investigate the formation of oxides and monitor the wetting and spreading behaviour of the deposition on different layers (as shown in Fig. 1a). Meanwhile, an AMV 5000 arc monitor was deployed to monitor the arc voltage variation pattern in real time. In phase 2, a CMT power source and a CMT torch were fixed to the set-up to perform the CMT-WAAM process. Two 6-layer walls were built in comparison: one in the open atmosphere with standard torch shielding only and the other one in an argon-filled tent (where oxygen level was controlled below 300 ppm by using Z230 Oxygen Analyser, Hitech Instruments and the measurement was taken at the bottom of the tent) to investigate the influence of the ambient condition on the surface finish and structure integrity of the WAAM structures, as shown in Fig. 1b. Two additional walls were built under identical conditions and tensile samples were sectioned across the layers to study the effect of oxides on the mechanical properties of the WAAM products. Three samples in

Table 1
Chemical composition of the MARVAL 18S filler wire (wt.%).

Ni	Mo	Co	Ti	Al	C	Si	Mn	Fe
18.28	4.69	8.21	0.44	0.11	< 0.01	< 0.1	< 0.1	Balance