

**RELATIONSHIP BETWEEN POROSITY AND SURFACE DEPOSIT COVERAGE FOR WIRE AND ARC  
ADDITIVE MANUFACTURED ALUMINIUM ALLOY 2319**

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**ABSTRACT**

Wire and Arc Additive Manufacturing (WAAM) has the potential to enable a very significant reduction in buy-to-fly ratio compared to conventional manufacturing through the ability to build near-net shape components. Components manufactured from AA 2319 by WAAM can exhibit significant levels of porosity. There is also a variation in the physical appearance of the surface deposit sometimes found on such components. This deposit is similar to those observed on aluminium joined by MIG and TIG welding processes. It has been suggested that both the bulk porosity and the surface deposit are caused by hydrocarbon-based lubricant on the feedstock wire. An established correlation between surface deposit and porosity would offer valuable insight into WAAM products and enable early interventions in quality control or process monitoring based on visual examination. The relationship between the nature of the surface deposit and porosity has been studied for AA 2319 WAAM components manufactured using different wire batches. Evidence is presented to support the assertion that (i) there does not appear to be a relationship between surface deposit coverage and porosity, (ii) batch-to-batch variability in feedstock wire affects porosity. This study has led to a better understanding of the cause of porosity in WAAM components.

**KEYWORDS**

Additive manufacture, Cold metal transfer, AA 2319, Weld smut

## INTRODUCTION

There is a high cost associated with conventional, subtractive manufacturing because of the high 'buy-to-fly' ratio, a measure of the initial material bought compared to the material found in the finished part (Allen, 2006; Yilmaz & Ulga, 2016). A typical aerospace product may have up to 90% of the purchased billet of forging machined away which is cost inefficient and high in material waste. Wire and Arc Additive Manufacturing (WAAM) has the potential to reduce costs and lead time. Robotically controlled weld torches rapidly deposit feedstock wire in layers to build large near-net shapes with mechanical properties similar to those of conventional manufactured parts (Sequeira Almedia & Williams, 2010; Martina et al., 2012; Ding et al., 2015; Williams et al., 2015).

A high level of porosity variation has been observed in aluminium WAAM parts (Cong, Ding & Williams, 2014; Gu et al, 2016) which can result in a range of material properties (Rudy & Rupert, 1970). This leads to difficulties in regards to standardisation and qualification of process and parts. In order for WAAM to be used commercially, porosity will need to be understood, monitored and reduced to a reproducible acceptable level or eliminated.

Porosity formation during WAAM and welding, on which WAAM is based, is commonly attributed to hydrogen entrapment (Harris, 1988; Toda et al., 1999; Gu et al., 2016). The solubility of hydrogen has been reported as 0.65 mL per 100 g in molten aluminium and 0.034 mL per 100 g in solid aluminium (Boeira et al., 2009). The difference in solubility results in the evolution of hydrogen gas as the weld pool solidifies which is then trapped in the solid metal, causing porosity. One principal source of the hydrogen is hydrocarbon-based lubricants on the surface of the feedstock wire (Harris, 1988; Gingell & Gooch, 1998).

It has been suggested that a deposit that is often observed on the surface of aluminium WAAM parts and aluminium welds is caused by dissociation of hydrocarbon-based lubricants (Ryazantsev, Fedoseev & Savostikov, 1998; Gu et al., 2014; Lee, Park, & Kang, 2015). It has therefore been hypothesised that there is a correlation between surface deposit coverage and porosity of aluminium WAAM parts; the higher the surface deposit coverage, the higher the porosity of the part. The purpose of this work is to analyse the relationship between surface deposit coverage and porosity of aluminium WAAM parts to develop early interventions in quality control or process monitoring based on visual examination. This paper presents porosity measurements of WAAM parts that had different levels of surface deposit coverage. Possible mechanisms of porosity generation are discussed.

## EXPERIMENTAL

Sets of truncated cones and panels were manufactured from 1.2 mm diameter AA 2319 wire using different build parameters and wire batches to obtain different levels of surface deposit coverage. The nominal composition of AA 2319 is shown in Table 1.

Table 1. Nominal composition of AA 2319 (wt%)

Cu	Mg	Mn	Ti	Zr	V	Zn	Si	Fe
5.8-6.8	≤0.02	0.2-0.4	0.1-0.2	0.1-0.25	0.05-0.15	≤ 0.1	≤ 0.2	≤ 0.3

The amount of surface deposit seen on each part was graded by four operators on a qualitative scale, ranging from 1 for no evident deposit to 5 to complete coverage. The colour of the surface deposits was also visually assessed as grey, brown or black. Figure 1 shows examples of surface deposit coverage.

The parts were manufactured using a Fronius Cold Metal Transfer (CMT) power source on an ABB robot. CMT, a modified Metal Inert Gas (MIG) welding process, is a controlled dip metal transfer technique where single droplets of feedstock wire are detached using short circuiting (Fronius International GmbH, 2014). There are different CMT modes: CMT-P, CMT-ADV and CMT-PADV. 'P' refers to pulsing the current to control the detachment of single droplets from the wire. 'ADV' involves a reversal of polarity of the welding current in the short circuit phase of the CMT cycle. 'PADV' describes the polarity

difference of the pulse cycle (positively poled) and the CMT cycle (negatively poled). All three modes have been used in this study.

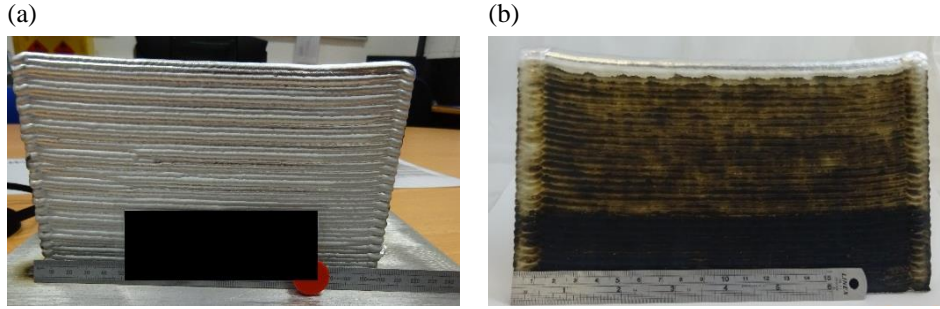


Figure 1. Photographs of (a) a panel that has a surface deposit coverage of 1: no coverage and (b) a panel that has a surface deposit coverage of 5: complete coverage.

The truncated cones were manufactured to a height of 160 mm, a bottom diameter of 125 mm and a top diameter of 230 mm. Two different batches of wire from two different wire manufacturers were used: A and B. The panels were manufactured to a length of 200 mm and a height of 120 mm by depositing alternating single pass layers in opposite directions. Six different batches of wire from three manufacturers A, B and C were used. For all of the builds, the shielding gas was 99.99% argon and the gas flow rate was 15 L min<sup>-1</sup>. The parameter details for each build are shown in Table 2. Wire feed speed (WFS) refers to the rate at which the wire is fed through the torch and travel speed (TS) refers to rate at which the torch moves. Resulting surface deposit scores are also presented in Table 2.

Table 2. Details of the wire, CMT mode, WFS and TS used for manufacture of parts and the resulting surface deposit.

Part Label	Wire	CMT mode	WFS (m min <sup>-1</sup> )	TS (m min <sup>-1</sup> )	Surface Deposit Scale	
					Coverage	Colour
Cone A	A1	PADV	2.5	0.5	1	N/A
Cone B	A1	PADV	4.0	1.0	2	Brown
Cone C	A1	PADV	5.0	0.5	1	N/A
Cone D	A1	PADV	6.0	1.5	3	Brown, Black
Cone E	B1	PADV	8.0	0.5	5	Black
Cone F	A1	PADV	8.0	1.0	5	Black
Cone G	A1	PADV	8.0	1.5	4	Brown, Black
Panel A	A2	P	6.0	0.6	5	Black
Panel B	A2	P	4.5	0.6	4	Black
Panel C	A3	ADV	3.5	0.3	1	N/A
Panel D	B2	PADV	3.5	0.3	1	N/A
Panel E	B2	P	6.0	0.6	3.5	Brown, black
Panel F	B2	P	4.5	0.6	3	Brown
Panel G	B2	PADV	6.0	0.6	2	Brown
Panel H	B2	PADV	3.5	0.3	2	Brown
Panel I	B2	PADV	3.5	0.3	1	N/A
Panel J	B1	PADV	6.0	0.6	3	Brown, black
Panel K	C1	PADV	3.5	0.3	2	Black
Panel L	C1	P	6.0	0.6	2	Black
Panel M	C1	P	4.5	0.6	1	N/A
Panel N	C2	P	6.0	0.4	2.5	Black
Panel O	C2	P	4.5	0.6	3	Black
Panel P	C2	PADV	3.5	0.3	3	Brown, Black

All samples for porosity measurements were extracted from the parts after a T6 heat treatment. Samples from the cones were extracted from a region 25 mm from all as-built edges. Samples from the panels were extracted from a region 40 mm from the edge at half height. Samples were mounted perpendicular to the WAAM layers through the thickness of the parts and polished for metallographic examination. Two different operators each measured the porosity over an area of 84 mm<sup>2</sup>, covering approximately 20 layers in height, on at least two independent polished planes using a Nikon Eclipse LV150 light microscope with Leica Analysis software.

## RESULTS

### Porosity of Cones

Figure 2 shows the distribution of pores in cones manufactured using wire from different manufacturers and different build parameters. A variety of pores was observed in the cones including: spherical pores ranging in size from 20 μm<sup>2</sup> to over 5000 μm<sup>2</sup>, very fine pores of size less than of size 20 μm<sup>2</sup> and irregularly shaped pores with a range of sizes. Fine pores were the most commonly observed in all of the cones except for A. For Cone A, nearly all the pores were over 50 μm<sup>2</sup> and most were between 100 and 1000 μm<sup>2</sup> in size. Cone E and G contained more very large pores, over 2000 μm<sup>2</sup> in size, compared to the other cones.

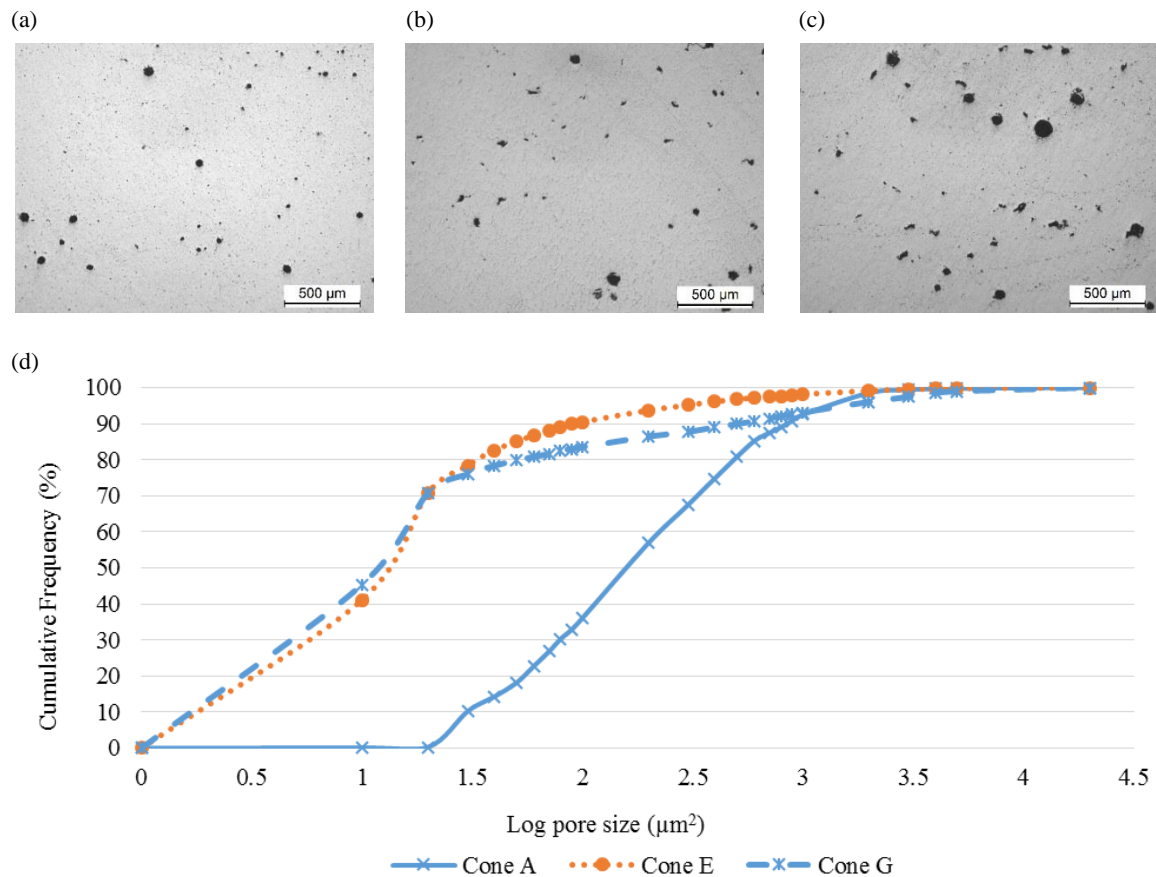


Figure 2. Optical micrographs of (a), Cone A, (b) Cone E, (c) Cone G and (d) a cumulative frequency histogram of pore size distribution for Cones A, E and G for 42 mm<sup>2</sup> across one cross section.

Figure 3a shows the average area fraction of porosity for each of the cones. Cone A contained less porosity than the majority of the other cones, less than 1% area fraction compared to 1.7–3.2%. Cone A was built with a different spool of wire batch A1 to the rest of the cones built from A1. Cone E was built

with wire from a different manufacturer. Cone E also contained significantly less porosity than Cone F and G, which were built with similar build parameters, 1.1% compared to more than 2%. Figures 3b illustrates variation of porosity with surface deposit coverage.

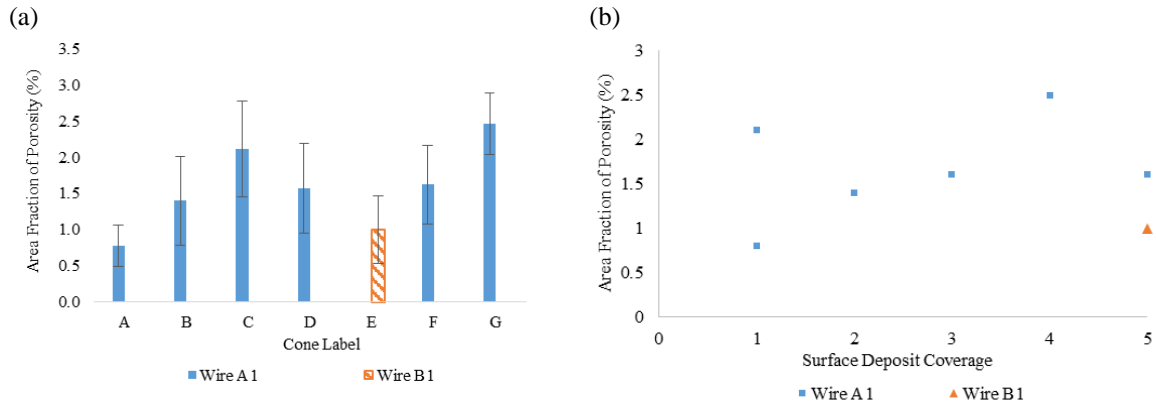


Figure 3. (a) The average area fraction of porosity across 84 mm<sup>2</sup> of two independent cross sections of the cones. The error bars indicate the standard deviation. (b) Variation of porosity with surface deposit coverage of the cones

Least squares fitting showed no statistically significant correlation between coverage and porosity. The R<sup>2</sup> value was 0.007. Single factor Anova analyses were performed to determine if there was statistically significant differences in porosity between different wire batches and different surface deposit coverage scores. The P values showed that there was not sufficient evidence to determine if the differences in porosity for different wire batches and surface deposit coverage scores were statistically significant.

### Porosity of Panels

The distributions of pores in typical panels manufactured using different wire manufacturers and build parameters are illustrated in Figure 4. Spherical pores of size 20 μm<sup>2</sup> to over 5000 μm<sup>2</sup>, fine pores that were less than 20 μm<sup>2</sup> and irregular shaped pores with a range of sizes were observed in the panels in different quantities. Panels built with wire from Manufacturer A had some large spherical pores, of over 1000 μm<sup>2</sup> in size, but most pores were less than 20 μm<sup>2</sup> in size. Panels built with wire from Manufacturer B again contained mostly fine pores but contained very few large spherical pores and none over 5000 μm<sup>2</sup> unlike panels built wires from A and C. The porosity in panels built with wire from Manufacturer C was dominated by large spherical pores, the majority of them exceeding 20 μm<sup>2</sup> in size and many were more than 1000 μm<sup>2</sup> in size.

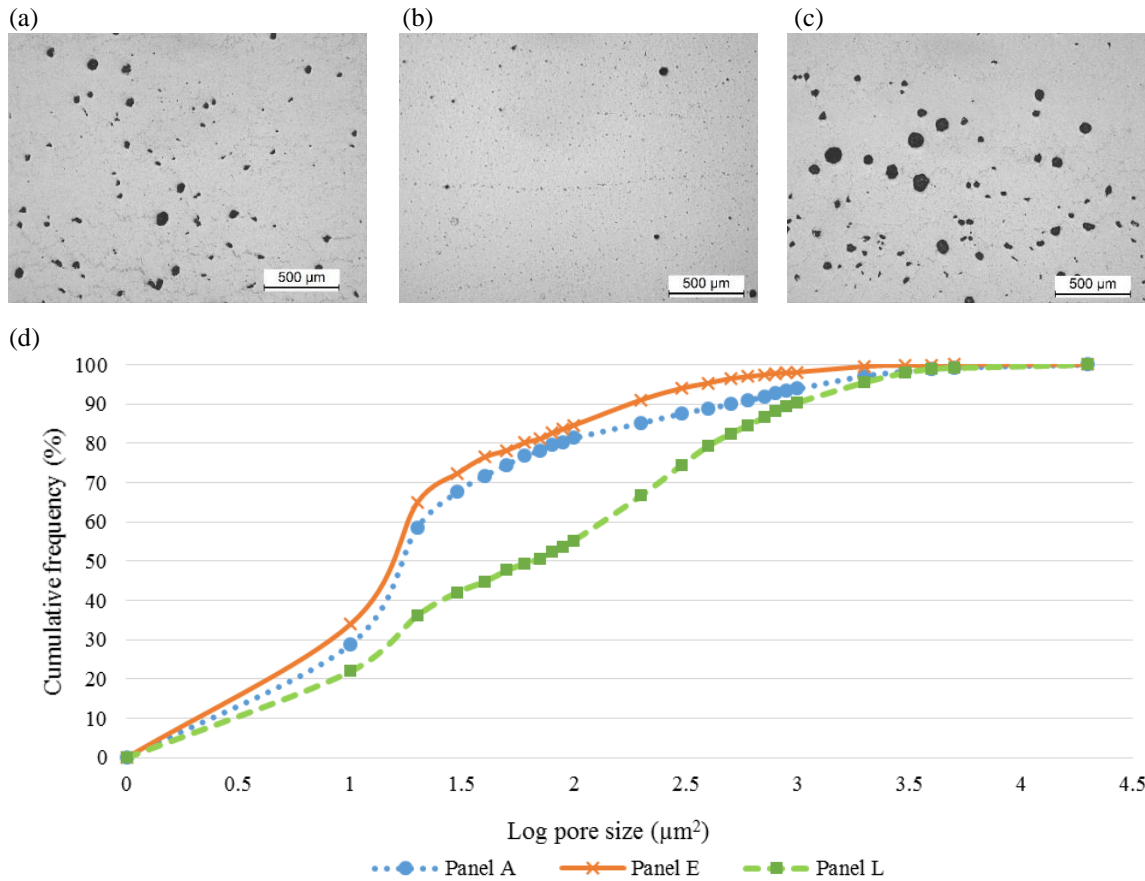


Figure 4. Optical micrographs of (a) Panel A, (b) Panel E, (c) Panel L and (d) a cumulative frequency histogram of the pore size distribution for Panels A, E and L for 42 mm<sup>2</sup> across one cross section.

Figure 5 shows the average area fraction of porosity for all of the panels and illustrates the variation of porosity with surface deposit coverage. The critical factor that affected porosity appears to be the wire manufacturer used. Panels that were manufactured using wire from Manufacturer B had far lower area fractions of porosity than most of the panels from Manufacturer A or all of the panels from Manufacturer C regardless of build parameters used: less than 1.0% compared to 2.0–3.5% area fraction. Panel C, made from Manufacturer A wire, had significantly lower porosity than Panels A and B; the area fraction of porosity was more similar to panels built from Manufacturer B wire. Panel C was manufactured from Wire A3, which was produced using a different process to Wire A1 and A2.

Least squares fitting showed no statistically significant correlation between surface deposit and porosity. The  $R^2$  value was 0.03. Single factor ANOVA analyses were performed to determine if there was statistically significant differences in porosity between different wire batches and different surface deposit coverage scores. Panel C was omitted from the analyses as it appeared to be an anomaly, caused by the use of wire from Manufacturer C produced using a different process. The P value showed that there was a statistically significant difference in porosity between different wire batches for a confidence level of 0.05. There was not sufficient evidence to determine if the differences in porosity for different surface deposit coverage scores were statistically significant.

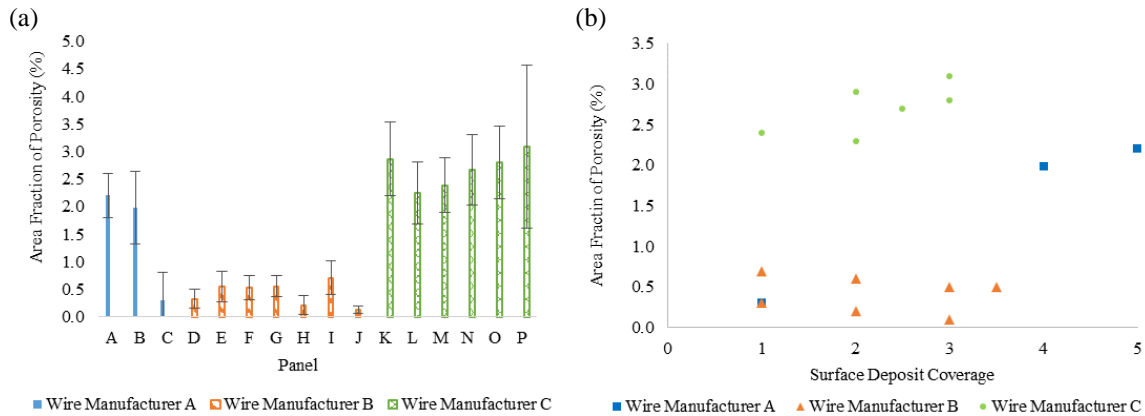


Figure 5. (a) Average area fraction of porosity across 84 mm<sup>2</sup> of two independent cross sections of the panels. Error bars indicate the standard deviation. (b) Variation of porosity with surface deposit coverage of the panels.

## DISCUSSION

The results refuted the hypothesis that there was a correlation between surface deposit coverage and porosity for both the cones and panels. The hypothesis was based on literature suggesting that hydrocarbon lubricant on the surface of the wire was a principal source of both surface deposits and porosity. The results suggest that lubricant on the surface of the wire is the source of the surface deposit but not the porosity. Panels K, L and M were built from wire with reduced lubricant, C1, and scored consistently low for surface deposit coverage but had relatively high area fractions of porosity: between 2.3 and 2.9%. The porosity measurements were comparable to the porosity in Panels N, O and P which made with standard lubricant wire from the same manufacturer.

The results showed that the wire was the source of the porosity as there was significant variation in porosity between parts built with wire from different wire manufacturers and batch to batch variation with wire from the same manufacturer. Cone E, built with wire from Manufacturer B, contained less porosity than most of the cones built with wire from Manufacturer A. Cone A, built with wire from Manufacturer A, had similar porosity as Cone E but was built with vastly different build parameters: a WFS of 2.5 m min<sup>-1</sup> compared to 8.0 m min<sup>-1</sup>. Panels built with wire from Manufacturer B contained area fractions of porosity less than half that of Manufacturer A and C. There were notable differences in the pore size distribution. Panels built with wire B contained no pores over 5000 μm<sup>2</sup> in size and very few over 1000 μm<sup>2</sup> in size, unlike panels built from wire A and C. Panel C was built from Wire A3 and contained significantly lower porosity than other panels built with wire from Manufacturer A. Wire A3 was manufactured using a different process to Wire A1 and A2 which may have influenced porosity formation.

The observed variation in area fraction of porosity, pore size and shape could be attributed to features of the wire. Hydrogen entrapment appeared to dominate as the primary mechanism for porosity formation in the parts as spherical porosity was the most common, caused by hydrogen segregation and Ostwald ripening (Toda et al. 2009). It does not appear that the source of the hydrogen was lubricant on the surface of the wire as Panel K, L and M had high area fractions of porosity. It is not possible to state this for certain however as claims that wire C1 had less lubricant have not been tested independently of the wire manufacturer. Also, different wire manufacturers may use different lubricant so it is possible that wire Manufacturer B used a silicone-based lubricant, for example, rather than a hydrocarbon-based lubricant. Hydrogen can also be found in the oxide layer on the surface of the wire or within the bulk of the wire (Gingell & Gooch, 1998). Characterisation of the wire is required to determine the most likely source of the hydrogen.

It has been demonstrated that different alloying elements could affect porosity formation for aluminium alloys (Gingell & Gooch, 1998, Toda et al., 2009; Gu et al., 2016). Slight differences in alloying elements could change the solidification characteristics, hydrogen solubility and hydrogen nucleation sites of the material all of which would influence porosity. Wire composition will need to be analysed to determine if there are any noticeable differences that could cause differences in porosity.

Wire A3, which resulted in significantly lower porosity than panels built with wire from the same manufacturer, was manufactured using different dies, a different cleaning process and a different spooling process. These factors could have influenced the amount of contamination of the surface of the wire, which is often a source of hydrogen. Improved surface finish from different dies may also affect arc stability and metal transfer behaviour, both of which could impact porosity formation (Woods, 1974; Harris, 1988; Gingell & Gooch, 1998; Modenesi & de Avelar, 1999; Gu et al., 2014). In addition to wire characterisation, WAAM should be monitored to determine likely mechanisms for deposit and pore formation. The monitoring process should include a high speed camera for capturing weld bead behaviour and measuring the current and voltage to determine arc stability to analyse the effect of metal transfer on deposit and pore formation.

The relatively low porosity observed in Cone A could be attributed to low WFS. Low WFS would cause less wire fed to the weld pool and thus result in less hydrogen and reduce the distance hydrogen bubbles travel to escape to the surface (Harris, 1988). Although no correlation was observed between porosity and WFS,  $2.5 \text{ m min}^{-1}$  may be the optimal WFS for hydrogen to escape. It is also of note that cone A was made from a different spool of Wire A1 compared to the other cones. It is possible that there was spool to spool variation in addition to manufacturer to manufacturer variation. Again, characterisation of the wire will be required to determine any significant differences. It may also be of use to build a part with a different spool of wire and a WFS of  $2.5 \text{ m min}^{-1}$  to further elucidate the effect of very low WFS on porosity.

## CONCLUSIONS

There appears to be no correlation between surface deposit and porosity for WAAM AA 2319 parts. Panels with high levels of surface deposit did not correspond with panels that contained large amounts of porosity and vice versa. Panels built with reduced lubricant wire resulted in lower surface deposit coverage but not lower porosity. These results suggest that hydrocarbon-based lubricant is not a principal source of porosity in WAAM AA 2319 parts as proposed in previous studies.

While this paper does not offer a simple visualisation technique for characterising porosity of AA 2319 WAAM parts, it does show that porosity varies significantly with wire batch used. It would be of use to characterise the wires used in this study to determine likely sources of the porosity in order to improve understanding of porosity variation in WAAM, so that it can be reduced or eliminated.

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