

# WIRE+ARC ADDITIVE MANUFACTURING OF ALUMINIUM

Jianglong Gu<sup>a,b</sup>, Baoqiang Cong<sup>a,c</sup>, Jialuo Ding<sup>a</sup>, Stewart W. Williams<sup>a</sup>, Yuchun Zhai<sup>b</sup>

a Welding Engineering and Laser Processing Centre, Cranfield University, MK43 0AL, UK

b School of Materials and Metallurgy, Northeastern University, 110819, China

c School of Mechanical Engineering and Automation, Beihang University, 100191, China

## Abstract

Wire+Arc Additive Manufacturing is very suitable for the production of large scale aluminium parts. However implementation is currently limited by issues such as porosity and low mechanical properties. We have studied the utilization of new deposition processes such as pulsed advanced cold metal transfer which allows modification of the thermal profile resulting in refined equiaxed microstructure and elimination of porosity. Standard and new feedstock compositions are being evaluated and developed with ultimate tensile strengths of up to 260 MPa with 17% elongation being obtained in the as-deposited condition. Post build heat treatments compositional changes and high-pressure inter-pass rolling are being investigated in order to increase the strength further.

Key words: Wire+Arc Additive Manufacturing (WAAM), Cold Metal Transfer (CMT), aluminium, porosity, microstructure, mechanical property

## Introduction

Wire+Arc Additive Manufacturing(WAAM) is a promising solid freeform fabrication manufacturing technology in reducing the time of products from concept to production, as well as its advantages in rapid processing times, perfect density, materials-saving, flexibility in materials and easy adaptability to automation [1]. However most current research and production in WAAM are focused on titanium and steel [2]. Aluminium alloys, especially high strength ones, have become more and more important in industries such as aerospace and transportation. Therefore research and development of WAAM technology for aluminium is urgently needed. Cranfield University has begun to apply WAAM technology to aluminium and large functional components of ribs and cones in aluminium alloy have been built. It was found that the WAAM process is very suitable for the production of large scale aluminium parts [3]. However the implementation of traditional welding process for WAAM aluminium is currently limited by solidified defects such as porosity and solidification cracks [4], which will exert negative effects on the mechanical properties to some extent. Porosity is the main problem in aluminium alloys, which are far more susceptible to this defect than all other structural metals. This is because merely trace levels of hydrogen usually exceed the threshold concentration needed to nucleate bubbles in the molten pool [5]. Low dilution cladding and welding of aluminium alloy have been

studied using the Cold Metal Transfer (CMT) process [6, 7], which is a modified Gas Metal Arc Welding (GMAW) variant based on a controlled dip transfer mode mechanism. The process delivers excellent performance with excellent welding quality, low thermal heat input (HI) and is nearly spatter-free [8]. A variant of this process is where conventional spray is mixed with the dip transfer mode and this is referred to as CMT pulsed (CMT-P). A further development is the advanced variant of both these processes (CMT-ADV and CMT-PADV). This variant allows for polarity reversal and therefore AC operation. This process has been studied for the WAAM process for aluminium in the present research. This allows modification of the thermal profile resulting in refined equiaxed microstructure and elimination of porosity. Furthermore, neither hot nor cold cracks were observed in the deposited parts.

### **Experimental**

In the present study, aluminium walls were made from ER2319 aluminium alloy wire by the WAAM fabrication system which is shown in Fig.1. 2219-T851 aluminium plates were used as substrates. A Fronius CMT Advanced 4000 R was employed as the power source, which was connected to the ABB robot IRB2400. A home built Cranfield University rolling rig [9] was applied to the inter-pass rolling experiments. Pure argon (99.99%) was used as the shielding gas with a constant flow rate of 25 L/min. The contact tip to work distance (CTWD) was kept constant at 15 mm. Walls dimensions were 500mm long and 200mm high and were built by all four variants of the CMT process using variable wire feed speed (WFS) and deposition travel speed (TS).

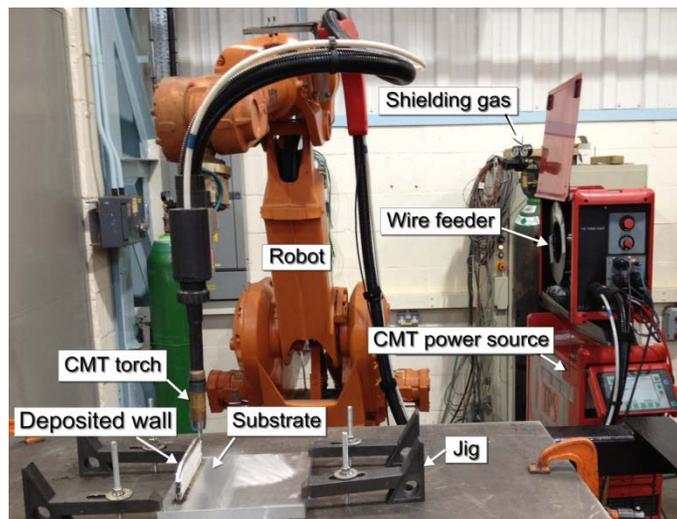


Fig.1 CMT WAAM experimental system

All specimens were naturally aged prior to tests for a minimum of 30 days after deposition. Specimens for porosity and microstructure tests were mechanically taken from the middle part of the wall, then ground and polished to a mirror finish. Specimens were etched with Kroll's reagent

solution to reveal the microstructure. A light optical microscope (OPTIPHOT, Nikon, Japan), scanning electron microscope (SEM) (XL30ESEM, PHILIPS), energy dispersive spectrometry (EDS) were employed for microstructures and porosity analysis. The Vickers micro hardness was tested by auto-C.A.M.S. of Zwick Roell using a load of 200 g for 15 s. Tensile test samples were prepared according to BS EN ISO 6892-1:2009 Standard. Tensile tests were carried out at ambient temperature by an electro-mechanically controlled universal machine at a rate of 0.1 strain min<sup>-1</sup>.

## Results and discussion

### Porosity and microstructure

Fig 2 (a) shows that the CMT-PADV process effectively eliminated porosity compared to a wall built by pulsed CMT (CMT-P) process (Fig.2 (b)) where there are many small pores (less than 50 $\mu$ m in diameter).



Fig.2 Longitudinal porosity of WAAM 2319 deposited by (a) CMT-PADV process, WFS=6m/min, TS=0.6m/min, HI=112.2J/mm, (b) CMT-P process, WFS=6m/min, TS=0.8m/min, HI=189.1J/mm

The narrow finger-shaped molten pool during the CMT-P process or other conventional arc welding processes prevents the escape of gas pores. In addition to that there is a competition correlation between dendrite growth and pore nucleation rate, so the porosity has a close

relationship with the grain size [10, 11]. Fig.3 (b) shows the growing direction of the coarse columnar grain structures of the CMT-P process during solidification, which is normal to the solid/liquid interface and is aligned to the heat-flow direction. Porosity will be increased because cellular dendrite, dendritic solidification interface and some inclusions can be used as heterogeneous nucleation particles for pores. Due to decreased pressure, during solidification small pores float up and can combine into larger ones that were observed at the top part of each deposit layer. Thus, a large number of pores were observed. Grain sizes and morphology are predominantly affected by the HI level. A lower HI can effectively refine the grain structure [12]. The CMT-PADV process was observed to have low dilution and a fine equiaxed grain structure (as shown in Fig.3 (a)). This was due to its lower HI, which is beneficial in eliminating porosity. The alternating polarity of the arc of the advanced CMT process is also beneficial in that it has a significant oxide cleaning effect of the end of the aluminium wire [13]. This reduces the hydrogen content which is contained in the oxidation layer, entering into the molten pool.

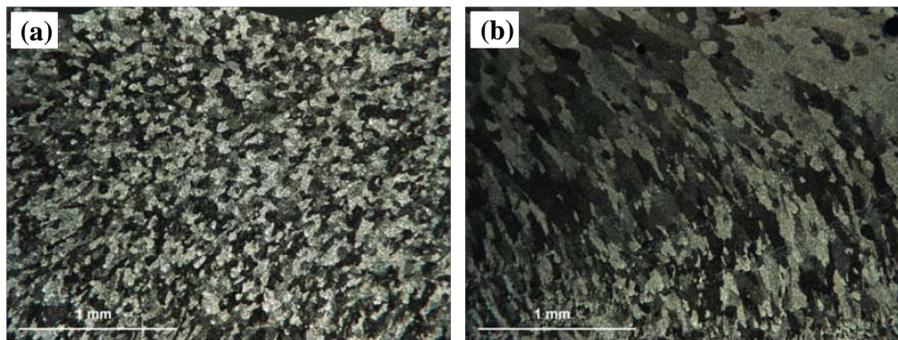


Fig.3 Microstructure of WAAM 2319 deposited by (a) CMT-PADV process, (b) CMT-P process

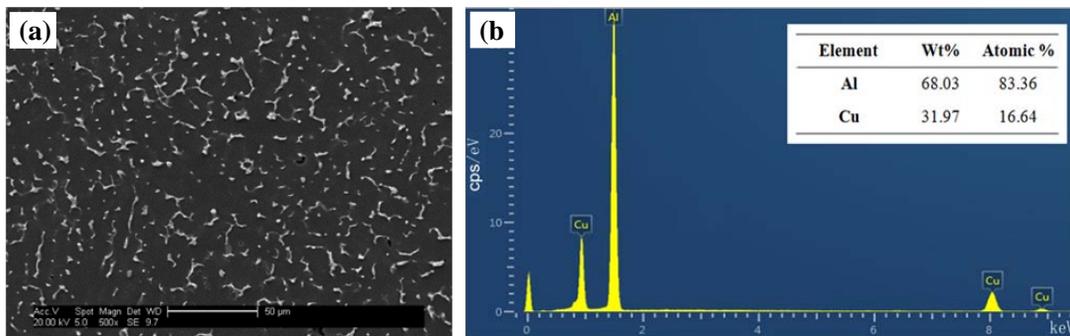


Fig.4 Micro analysis of WAAM 2319 deposited by CMT-PADV process (a) SEM morphology, (b) EDS analysis of the white phases

The precipitated microstructure of the CMT-PADV process is shown in Fig.4 (a). It is composed of a refined dendritic network, where some white phases exist between them. According to EDS analysis in Fig. 4 (b), it indicates that the white particles contain 68.03% Al-31.97% Cu (wt. %). Referring to the Al–Cu binary diagram and a previous study [14], they are identified as  $\alpha$ -Al +  $\theta$ -Al<sub>2</sub>Cu eutectics, which were uniformly formed along grain and sub-grain

boundaries. They are caused by dendritic solidification of the non-equilibrium cooling process. During the wire production process most of the Ti, Zr elements will have existed as  $Al_3Ti$ ,  $Al_3Zr$  or  $Al_3(Ti, Zr)$  phases. The exception is that some of them will have been dissolved into the aluminium wire matrix. Because of the high melting point of the particles and the low HI of the CMT-PADV process it is likely that there will be more particles retained in the solidified molten pool than other traditional arcing processes. Consequently these particles become to be near perfect heterogeneous nucleation particles due to their similar crystal structures and lattice parameters compared with aluminium matrix, therefore the grain sizes were effectively refined.

### Mechanical properties

The experimentally evaluated vertical and horizontal tensile properties of WAAM deposited 2319 aluminium alloy and wrought 2219 alloy are presented in Table 1. The vertical (V) direction refers to samples taken across the build layers whilst the horizontal (H) direction refers to those taken along the layers. Yield strength (YS), ultimate tensile strength (UTS) and elongation of the WAAM alloy are evenly distributed in the whole as-deposited wall. Average YS and UTS are 110 MPa and 260 MPa respectively. Although the strength values are lower than those of the T851-tempered alloy, they are 50% higher than those of the O-tempered alloy. Meanwhile, the excellent 17% plastic elongation is higher than the T-tempered alloy, which will expand their application in the industry to some extent.

Table 1 Tensile properties of WAAM deposited 2319 alloy and wrought 2219 alloy

Property	WAAM alloy						Wrought alloy	
	V1	V2	V3	H1	H2	H3	2219-O	2219-T851
Yield strength /MPa	105	106	107	112	110	121	76	350
Ultimate tensile Strength/MPa	257	261	256	262	263	263	172	455
Elongation /%	15.4	16.8	14.4	18.3	19.0	17.8	18	10

(V-Vertical; H-Horizontal)

### Further development of WAAM for aluminium

The strength of T851-tempered 2219 wrought alloy is improved by solution treatment, cold working and artificial aging of O-tempered alloy. In the future developments WAAM built aluminium components will be heat treated to enhance their strength. Although the strength property of the alloy will be definitely improved after heat treatment, the key problem is to control distortion. Therefore inter-pass cold rolling will be applied to the process too, which can significantly reduce the peak residual stress in a straight WAAM wall, thus distortion will be reduced, even eliminated [15]. Furthermore the rolling process also induces additional grain

refinement as well as increased hardness (See Fig.5), therefore mechanical properties of WAAM alloy will be further improved. In addition, compositional changes to the current standard aluminium wires or production of novel aluminium alloy wires are being investigated. For example, strength-enhancing elements such as Magnesium which will react with aluminium-copper alloy to form S phase, will be added into the smelting process of the wire production. Consequently new aluminium wires with advanced compositions will be applied to WAAM to obtain high strength eventually.

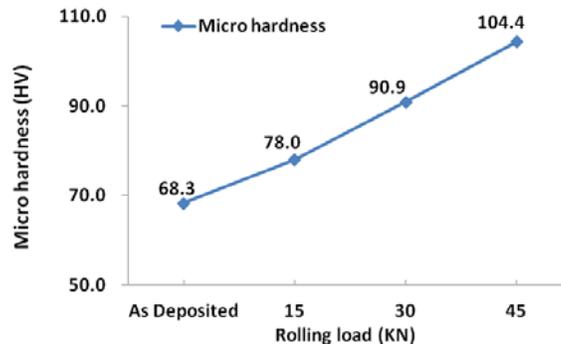


Fig.5 Average micro hardness of WAAM 2319 rolled by increasing rolling load

### **Conclusion**

Conventional processes, which generate high levels of porosity due to their high thermal heat input level, the narrow finger-shaped molten pool and the coarse grain structure, are considered not suitable for the WAAM process for aluminium. Due to its lower heat input, CMT-PADV process is an efficient deposition process in terms of reducing and even eliminating the porosity. In addition fine equiaxed grain structures and uniformly distributed  $\theta$ -Al<sub>2</sub>Cu phases were observed in the WAAM deposits. Consequently, the application of WAAM aluminium alloy deposited by CMT-PADV process will be widened for its perfect strength and excellent plastic elongation. In the near future, new compositional wires, inter-pass rolling and post build heat treatment will be applied to WAAM aluminium alloys to improve their comprehensive properties further.

### **Acknowledgements**

The authors would like to give their gratitude to all the technician members in Welding Engineering and Laser Processing Centre in Cranfield University. The work was supported by the WAAMat programme industry partners.

### **References**

1. Zhang, Y., et al., *Weld deposition-based rapid prototyping: a preliminary study*. Journal of

- Materials Processing Technology, 2003. **135**(2-3): p. 347-357.
2. Wang, H. and R. Kovacevic, *A novel welding-based solid freeform fabrication technology for aluminum*, 84<sup>th</sup> Annual AWS Convention, 2003: Detroit, Michigan, USA. p. 2.
  3. Ding, J., et al., *Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts*. Computational Materials Science, 2011. **50**(12): p. 3315-3322.
  4. Ouyang, J.H., H. Wang, and R. Kovacevic, *Rapid prototyping of 5356- aluminium alloy based on variable polarity gas tungsten arc welding: process control and microstructure*. Materials and Manufacturing Processes, 2002. **17**(1): p. 103-124.
  5. Devletian, J.H. and W.E. Wood, *Factors affecting porosity in aluminum welds - a review*. 1983, New York: Welding Research Council. 18.
  6. Pickin, C.G., S.W. Williams, and M. Lunt, *Characterisation of the cold metal transfer (CMT) process and its application for low dilution cladding*. Journal of Materials Processing Technology, 2011. **211**(3): p. 496-502.
  7. Pickin, C.G. and K. Young, *Evaluation of cold metal transfer (CMT) process for welding aluminium alloy*. Science and Technology of Welding and Joining, 2006. **11**(5): p. 583-585.
  8. Sequeira Almeida, P.M. and S.W. Williams, *Innovative process model of Ti-6Al-4V additive layer manufacturing using Cold Metal Transfer (CMT)*, 21<sup>th</sup> International Solid Freeform Fabrication Symposium. 2010: Austin, Texas, USA. p. 25-36.
  9. Martina, F., S.W. Williams, and P.A. Colegrove, *Improved microstructure and increased mechanical properties of additive manufacture produced Ti-6Al-4V by interpass cold rolling*, 24<sup>th</sup> International Solid Freeform Fabrication Symposium. 2013: Austin, Texas, USA. p. 490-496.
  10. Li, Z., M. Zhu, and T. Dai, *Modeling of microporosity formation in an Al-7%Si alloy*. Acta Metallurgica Sinica, 2013. **49**(9): p. 1032-1040.
  11. Lee, P.D. and J.D. Hunt, *Hydrogen porosity in directionally solidified aluminium-copper alloys: a mathematical model*. Acta Materialia, 2001. **49**(8): p. 1383-1398.
  12. Pal, K. and S.K. Pal, *Effect of Pulse Parameters on Weld Quality in Pulsed Gas Metal Arc Welding: A Review*. Journal of Materials Engineering and Performance, 2010. **20**(6): p. 918-931.

13. Harwig, D.D., et al., *Arc behavior and melting rate in the VP-GMAW process*. Welding Research, 2006. **3**: p. 52-62.
14. Zhang, C., et al., *Strength improving mechanism of laser arc hybrid welding of wrought AA 2219 aluminium alloy using AlMg5wire*. Science and Technology of Welding and Joining, 2013. **18**(8): p. 703-710.
15. Colegrove, P.A., et al., *Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling*. Journal of Materials Processing Technology, 2013. **213**(10): p. 1782-1791.