35th International Manufacturing Conference (IMC35) 2018

DEVELOPMENTS IN LARGE SCALE ADDITIVE MANUFACTURE – THE POTENTIAL AND LIMITATIONS OF WIRE ARC ADDITIVE MANUFACTURE AND ASSOCIATED TECHNOLOGIES

Richard Ward,Shaun Mc Fadden,Justin Quinn

"School of Computing, Engineering & Intelligent systems; Ulster University, Magee Campus Londonderry,UK"
Ward-r14@ulster.ac.uk

Abstract

Additive manufacturing (AM) is different from traditional subtractive or formative manufacturing processes. Building from the 'bottom up' layer by layer as opposed to forming by machining, removing material from a billet, or casting AM offers a high material utilization rate. This paper reviews recent developments in AM technologies, focusing on those techniques which have the capability of producing medium to high complexity larger scale parts within reasonable cycle times. Wire arc additive manufacturing (WAAM) is an AM method which uses a metal wire feedstock and an electric arc heat source to form the component. WAAM can offer a relatively high deposition rate (>10kg /hr) with resolution ≈ 1mm. The paper examines current WAAM technologies, exploring the parameters required to achieve process efficacy, including, management of stresses, deposition orientation and sensor inclusion for process control. It will be demonstrated that WAAM offers a realistic alternative to traditional manufacturing methods due to the potential for high deposition rates, relatively low equipment costs and ability to produce components with good mechanical properties.

Introduction

Additive manufacturing (AM), also referred to as 3D printing, is a term used to cover a range of processes for the manufacture of three-dimensional components. AM technologies use data from a digital model generated by computer aided design (CAD) software to build the part. The 3D CAD model is sliced into 2D layers. Feedstock material is then deposited layer by layer, fusing together to create consolidated components. Materials suitable for AM include polymers, metals and ceramics. The resulting 3D components may possess intricate geometrical features that are otherwise impossible to achieve using traditional subtractive manufacturing processes, such as complex internal features or lattice structures which can be useful for part weight reduction. (Gibson, Rosen, & Stucker, 2010).

As AM techniques develop companies seek to attach their own name to a process, often trademarking the result. This has led to many different names being attributed to fundamentally the same processes. In an attempt to standardise AM terminology, the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) collaborated to develop the ISO/ASTM standard 52900:2015 (E).

According to the standard, AM is defined as a 'process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies' see Table 1 (52900:2015, 2015).Table 1. identifies the ISO /ASTM standard technologies and the materials associated with each discipline.

Table 1. Additive Manufacturing Process / Material Combinations. (Wohler, 2012).

	Material extrusion	Material jetting	Binder jetting	Vat photopoly-merization	Sheet lamination	Powder bed fusion	Directed energy deposition
Polymers and polymer blends	x	x	x	x	x	x	
Composites		x	x	x		x	
Metals		x	x		x	x	x
Graded/hybrid metals					x		x
Ceramics			x	x		x	
Investment casting patterns		x	x	x		x	
Sand molds and cores	x		x			x	
Paper					x		

Each has strengths and weaknesses and AM process selection should be specified based on the particular application required. As such, the techniques are not necessarily in competition but should be selected based on their suitability for a particular function.

(Assuncao, E., A. Cereja, Martina, F., Williams, 2017) state that the current AM processes capable of producing engineering components, i.e., with suitable mechanical properties for the relevant application, are;

- Powder bed fusion (PBF)
- Blown powder systems (BPS)
- High deposition wire based systems (EBD) and
- Wire and arc additive manufacture. (WAAM)

To illustrate the relative strengths and weakness of these processes a spider diagram was developed (Figure 1)

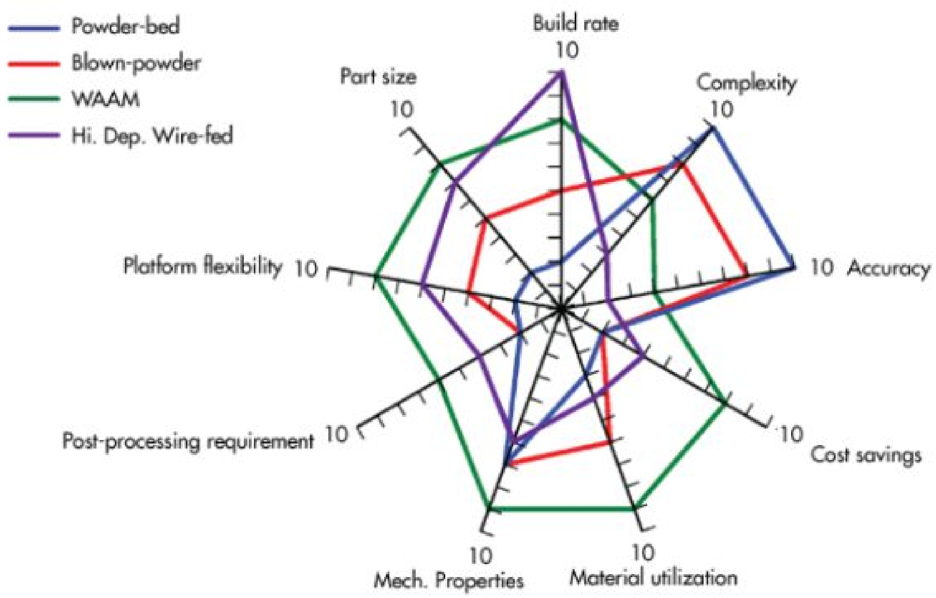

Figure 1. Metallic AM process comparison diagram (Assuncao, E., A. Cereja, Martina, F., Williams, 2017)

For larger engineering components (Williams et al., 2016) reported that the most important requirements of the process include:

- Mechanical properties
- Deposition rate
- Deposition envelope and
- Cost reduction

Wire arc additive manufacturing

Wire arc additive manufacturing (WAAM) utilises an electric arc as the source of heat and a fed wire as feedstock, as opposed to the powder used by Selective laser sintering (SLS) or direct metal laser sintering (DMLS). A WAAM system will typically consist of a Cartesian work frame or robotic arm, a power source, a wire feed and a welding torch (Ding et al., 2015).

(Almeida & Williams, 2010) carried out a series of experiments using four WAAM systems to deposit a series of single and multi-layer depositions and concluded that Gas Metal Arc Welding (GMAW), otherwise known as metal inert gas (MIG), is generally the most appropriate technology for WAAM. They reported that the Fronius™ Cold Metal Transfer (CMT), a novel GMAW process that achieves greater process stability and control while minimising heat transfer during deposition, overcomes many common issues associated with WAAM processing, such as spattering and arc wander, creating high quality results demonstrating a high deposition rate.

(Williams et al., 2016) stated that MIG, with the feed wire as the consumable electrode, is generally the preferred option, due in part, to the co-axiality of the wire and torch simplifying tool path calculations. However, they further found that while the Fronius™ CMT delivered excellent results when depositing Aluminium and steel, Titanium deposition could be affected by arc wandering leading to an increase in surface roughness with the result that TIG is a more suitable process for Titanium deposition.

Capital Cost

As the components of a WAAM system are 'off the shelf' the initial capital cost can be controlled with the user specifying the power source, manipulator, and associated tooling depending on budget and specific technical requirements. It has been reported that a WAAM system suitable for Aluminium and Steel deposition could be purchased for £90,000.00. (Williams et al., 2016)

Material Utilisation

WAAM technology can significantly reduce the buy to fly ratio of traditional formed components.(Yilmaz & Ugla, 2016). The buy to fly ratio gives a comparison between the amount of raw material acquired and the weight of the final component. Traditional subtractive processes can require the removal of as much as 95% of the initial stock. A typical BTF ratio for conventional manufacturing would be 5/6:1 but could be as much as 20/25:1 depending on the complexity of the finished component. (Yilmaz & Ugla, 2016) reported a reduction from 20:1 to 2:1 comparing a traditional machining regime to shaped metal deposition (SMD), otherwise known as WAAM processing.

Deposition envelope

Aluminium and Steel require only local gas shielding. The maximum deposition area is determined, initially, by the range of motion of the robotic arm manipulator. This can be extended, indefinitely, by the addition of running rails. Researchers at Cranfield University have deposited a 6m long, 300 kg double sided spar from aerospace grade aluminium on a 10m WAAM rig(Cranfield University, 2017)

A second manipulator arm can further extend deposition envelope and subsequently results in an increased deposition rate. For more volatile materials, such as Titanium, which require more stringent shielding the development of flexible tent like chambers has enabled larger Titanium structures to be produced.

Deposition Rate

(Williams et al., 2016) found that with comparatively high deposition rates, ranging from 1kg/hr to 4 kg/hr for aluminium and steel, compared to 0.1-0.2kg/hr for powder bed fusion (PBF) WAAM can form large components within an acceptable time frame. They further stated that deposition rates of 10 kg/hr can be achieved, however the fidelity of the component may be compromised thus increasing the amount of material requiring removal during post processing increasing the BTF ratio.

Challenges

In order to achieve engineering tolerances and improve mechanical properties it is generally required to carry out some post processing and finishing operations to AM produced components. Whilst WAAM usually has a greater surface roughness than powder bed fusion (PBF) type processes the superior deposition rate compensates. (Mereddy, Bermingham, StJohn, & Dargusch, 2017) found that the addition of silicon could affect grain size allowing for modification and a degree of control over mechanical properties.

With WAAM the quality of deposition is dependent on the ability to repeat and accurately control all the critical parameters. The development of bespoke WAAM wire to replace the welding wire currently widely used will allow for the selection of the most appropriate feed stock. Further work controlling shielding gases, arc control and deposition profile will all help to ensure the quality of the deposition.

Real time 'on the fly' monitoring of system parameters, such as, weld pool temperature, weld pool dimension, needs to be developed to allow the ability for process optimisation giving real time feedback and closed loop control to maintain parameters and minimise discontinuities. (Everton, Hirsch, Stravroulakis, Leach, & Clare, 2016) proposed a number of different methods of feedback, including high speed cameras, pyrometers and IR monitors, concluding that in situ control is imperative to ensure quality.

The substantial cyclical heat input associated with WAAM, and other AM processes, can lead to a high level of residual stress within the component resulting in distortion of the component once released from clamps.(Ding et al., 2015). Post processing heat treatments can reduce these stresses. (Filomeno Martina, Matthew Roy, Paul Colegrove, 2014) found that 'in process' high pressure rolling reduced but did not eliminate these stresses.

Further Work

Further work on the development of deposition profiling, and real-time system feedback for the control of critical system parameters to achieve an appropriate deposition strategy depending on feedstock may be beneficial. An examination of techniques to reduce stress inputs during deposition, such as deposition path profiling, heat reduction, or substrate heating could lead to a reduction in post processing requirement.

References

52900:2015, A. (2015). Standard Terminology for Additive Manufacturing – General Principles – Terminology. *ASTM International*, *i*, 1–9. https://doi.org/10.1520/F2792-12A.2

Almeida, P., & Williams, S. (2010). Innovative process model of Ti–6Al–4V additive layer manufacturing using cold metal transfer (CMT). *Solid Freeform Fabrication Symposium*, (June), 25–36.

Assuncao, E., A. Cereja, Martina, F., Williams, S. (2017). All-in-One Machine Manufactures Large Metal Parts, 1–9.

Ding, J., Colegrove, P., Martina, F., Williams, S., Wiktorowicz, R., & Palt, M. R. (2015). Development of a laminar flow local shielding device for wire + arc additive manufacture. *Journal of Materials Processing Technology*, *226*, 99–105. https://doi.org/10.1016/j.jmatprotec.2015.07.005

Everton, S. K., Hirsch, M., Stravroulakis, P., Leach, R. K., & Clare, A. T. (2016). Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing. *Materials and Design*, *95*, 431–445. https://doi.org/10.1016/j.matdes.2016.01.099

Filomeno Martina, Matthew Roy, Paul Colegrove, S. W. W. (2014). Residual Stress Reduction in High Pressure Interpass Rolled. *Solid Freeform Fabrication Proceedings*, 89–94.

Gibson, I., Rosen, D. W., & Stucker, B. (2010). Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, 1–459. https://doi.org/10.1007/978-1-4419-1120-9

Mereddy, S., Bermingham, M. J., StJohn, D. H., & Dargusch, M. S. (2017). Grain refinement of wire arc additively manufactured titanium by the addition of silicon. *Journal of Alloys and Compounds*, *695*, 2097–2103. https://doi.org/10.1016/j.jallcom.2016.11.049

University Cranfield. (n.d.). Have we 3d printed the biggest metal part ever? — WAAMMat. Retrieved May 10, 2018, from https://waammat.com/blog/have-we-3d-printed-the-biggest-metal-part-ever

Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire + Arc Additive Manufacturing. *Materials Science and Technology*, *32*(7), 641–647. https://doi.org/10.1179/1743284715Y.0000000073

Yilmaz, O., & Ugla, A. A. (2016). Shaped metal deposition technique in additive manufacturing: A review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *230*(10), 1781–1798. https://doi.org/10.1177/0954405416640181

The North West Centre for Advanced Manufacturing (NWCAM) project is supported by the European Union's INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB). The views and opinions in this document do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB). If you would like further information about NW CAM please contact the lead partner, Catalyst Inc, for details.