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Review

Invited review article: Strategies and processes for high quality wire arc additive manufacturing

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ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is attracting significant attention in industry and academia due to its ability to capture the benefits of additive manufacturing for production of large components of medium geometric complexity. Uniquely, WAAM combines the use of wire and electric arc as a fusion source to build components in a layer-by-layer approach, both of which can offer significant cost savings compared to powder and alternative fusion sources, such as laser and electron beam, respectively. Meanwhile, a high deposition rate, key for producing such components, is provided, whilst also allowing significant material savings compared to conventional manufacturing processes. However, high quality production in a wide range of materials is limited by the elevated levels of heat input which causes a number of materials processing challenges in WAAM. The materials processing challenges are fully identified in this paper to include the development of high residual stresses, undesirable microstructures, and solute segregation and phase transformations at solidification. The thermal profile during the build poses another challenge leading to heterogeneous and anisotropic material properties. This paper outlines how the materials processing challenges may be addressed in WAAM by implementation of quality improving ancillary processes. The primary WAAM process selections and ancillary processes are classified by the authors and a comprehensive review of their application conducted. Strategies by which the ancillary processes can enhance the quality of WAAM parts are presented. The efficacy and suitability of these strategies for versatile and cost effective WAAM production are discussed and a future vision of WAAM process developments provided.

1. Introduction

In recent years, Directed Energy Deposition (DED) techniques have enabled cost effective additive manufacturing of large, medium complexity metallic components. The effectiveness of DED in manufacturing these part types can be attributed to unconstrained build volumes and substantially higher deposition rates than alternative approaches such as Powder Bed Fusion. The lower resolution and need for post finish machining in DED is readily offset by the enhanced processing efficiency. Meanwhile significant raw material savings are possible in comparison to conventional approaches such as CNC machining and forging [1].They do not require specific tooling, as in casting and forging, therefore, manufacturing costs are significantly lower specifically for low production volumes and significant reduction in cycle time can be expected [2]. Complementary to this, is the ability to use wire as feedstock in DED, which offers high efficiency material deposition eliminating the need for peripheral powder recycling processes [3], reducing health and safety concerns and offering a significant reduction in price per kilogram compared to powder in a range of engineering materials including aerospace alloy Ti-6Al-4 V [4], stainless steel and nickel based superalloys as shown in Table 1.

Wire arc additive manufacturing (WAAM) is a wire-based DED approach that uses an electrical arc as a source of fusion to melt the wire feedstock and deposit a part preform, layer by layer. Use of an electrical arc as a fusion source provides a number of processing advantages, compared to electron beam and laser which are the alternative sources of fusion in DED outlined in the "Standard Guide for DED of Metals," part of the ASTM F3187 - 16 standard series [5]. A major benefit of the WAAM process relates to the low capital investment, as the components of a WAAM machine may be derived of open source equipment, sourced from an array of suppliers in the mature welding industry [6]. The processing characteristics may also make the WAAM process preferable compared to the alternative fusion sources. For example, WAAM does not does not need a vacuum environment to operate as required in electron beam based methods [7]. As such, prolonged set up and ramp down times which can lead to over-aging in precipitate hardened

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Table 1
Approximate cost per kilogram in wire and powder compiled from supplier quotes sourced in 2016.

Feedstock	Cost per kilogram (£/kg)			
	Ti-6Al-4V	Inconel 718	Inconel 625	Stainless Steel 316 L
Wire	120	58	49	12
Powder	280	80	80	40

materials can be avoided [8]. Whilst inert shielding gas may not be required in electron beam DED to avoid atmospheric contamination, there is an elevated susceptibility to element depletion and evaporation during processing [9]. In comparison to laser based methods, the use of the electrical arc offers a higher efficiency fusion source [10]. This is of benefit from an energy consumption perspective, in particular, for reflective metal alloys of poor laser coupling efficiency such as aluminium, copper [11] and magnesium [12]. With typical layer heights of 1–2 mm, surface waviness of 500 μm [13] and deposition rates up to 10 kg/hr, WAAM productivity and material removed is similar to laser-based and electron beam-based DED approaches.

Research and developments have allowed the WAAM process to become highly capable in a number of materials, including aerospace titanium alloy Ti-6Al-4 V [14] and nickel bronze [15], where static mechanical properties close to those found in wrought and cast can be produced [16]. As shown in Table 2, at present there are several commercial WAAM machine manufacturers and/or service providers able to produce WAAM components in a number of materials. However, high quality production of WAAM parts is only achievable when the specific materials processing challenges related to the high-levels of heat input of the WAAM process are addressed.

Williams, et al. [13] and Ding et al. [22] regarded the management of the high levels of residual stress and distortion as the primary heat-related material processing challenge in WAAM. Ding et al. [22] considered the surface finish of WAAM parts another major concern to dimensional compliance as well as premature part failure. Practical methods of mitigating these issues were presented, but were limited in scope primarily to build strategies for the management of residual stress. Pan et al. [16] summarised of static mechanical properties achieved in WAAM research, reporting the welding technology and processing condition, e.g. heat treated, interlayer cooling etc. however, the mechanisms of material property improvements were not discussed. This paper identifies the full range of materials processing challenges in WAAM. The primary process selections and ancillary processes that may be used in WAAM are classified by the authors and the strategies in which they may be deployed to overcome these challenges are presented. Finally, future challenges and opportunities in the area of WAAM are identified.

Table 2
Commercial WAAM DED technologies categorised by energy source and feedstock.

Commercial WAAM machine manufacturers and/or service providers	Deposited Material
Norsk Titanium AS [17]	Ti6Al4V
Gefertec [18]	Inconel 718, 625, Ti6Al4V, invar and range of mild steels, stainless steels & aluminium alloys.
Prodways [19]	Ti6Al4V
Mazak [20]	Not specified
Glenalmond Technologies [21]	Not specified

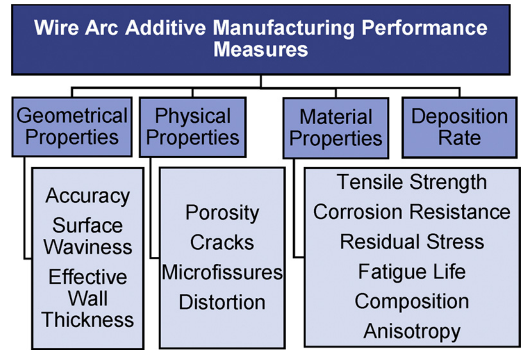

Fig. 1. Performance measures in WAAM.

2. Materials processing challenges in WAAM

The materials processing challenges in WAAM relate to the achievement of the performance measures related to geometric, physical and material properties as shown in Fig. 1 with several examples of possible requirements presented. The deposition rate of the process is essential to commercial adoption of WAAM as a high deposition rate DED process. This consequently comprises the final performance measure, which the aforementioned performance measures must be sustained relative to. Depending on material and the application, typical deposition rates for WAAM are reported in region of 1–10 kg/h.

In WAAM, solidification presents a major materials processing challenge due to the promotion of a microstructure containing large columnar grains. Although this is beneficial for applications requiring high temperature creep resistance [23], at regular operating temperatures it provides lower strength, toughness and corrosion resistance compared to a fine equiaxed microstructure [24]. A fine equiaxed microstructure tends to be difficult to develop in WAAM and other additive manufacturing technologies, as beyond an epitaxial growth zone close to the substrate, grains tend to grow in a competitive grain growth process in which the total number of grains reduce leading to grain enlargement [25]. The most dominant grain growth occurs in the preferred crystallographic orientations that correspond with the maximum thermal gradient. Due to the relatively low energy density of the electrical arc which results in low thermal gradient and low solidification rate [26], the heat sink effect of the substrate [27] can result in pronounced columnar grain growth aligned transverse to the weld direction as shown in Fig. 2 [28]. This grain growth can progress without interruption due to minimal grain nucleation mechanisms in WAAM, and consequently provides conditions for development of substandard and anisotropic mechanical properties which occur as shown in Table 3.

There is a lack of driving force in the solidified WAAM deposit for

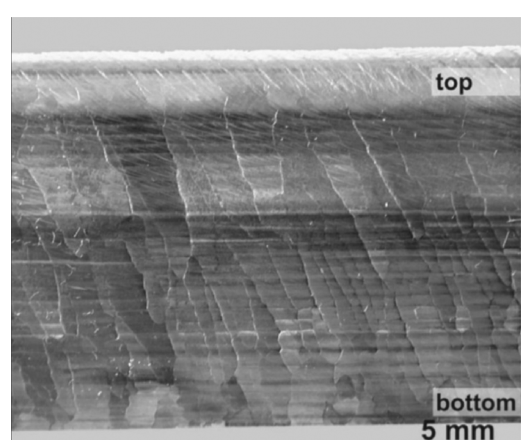

Fig. 2. Large columnar WAAM grain growth shown in Ti-6Al-4 V [28].