PAS 6012:2020

Additive manufacturing – Wire arc – Guide

Publishing and copyright information

Published by BSI Standards Limited 2020.

ISBN 978 0 539 03316 8

ICS 29.060.10

Publication history

First published November 2020

Contents

Foreword

This PAS was sponsored by Innovate UK. Its development was facilitated by BSI Standards Limited and it was published under licence from The British Standards Institution. It came into effect on 30 November 2020.

Acknowledgement is given to Dr Chloe Cunningham of the University of Bath, as the Technical Author and to the following organizations that were involved in the development of this PAS as members of the steering group:

- Airbus
- GKN Aerospace
- Hybrid Manufacturing Technologies
- Nuclear AMRC
- The Manufacturing Technology Centre
- TWI Ltd
- UKAEA
- WAAM3D Ltd
- Welding Alloys Group
- Yamazaki Mazak Ltd

Acknowledgement is also given to the members of a wider review panel and ASTM who were consulted in the development of this PAS.

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The PAS process enables a Guide to be rapidly developed in order to fulfil an immediate need in industry. A PAS can be considered for further development as a British Standard, or constitute part of the UK input into the development of a European or International Standard.

Relationship with other publications

PAS 6010, *Additive manufacturing – Wire for directed energy deposition (DED) processes in additive manufacturing – Specification*

PAS 6011, *Additive manufacturing – Non-destructive testing for use in directed energy deposition – Guide*

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Use of this document

As a guide, this PAS takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice.

Presentational conventions

The provisions of this PAS are presented in roman (i.e. upright) type. Its requirements are expressed in sentences in which the principal auxiliary verb is "shall".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Where words have alternative spellings, the preferred spelling of the Shorter Oxford English Dictionary is used (e.g. "organization" rather than "organisation").

Contractual and legal considerations

This Publicly Available Specification does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a Publicly Available Specification cannot confer immunity from legal obligations.

Introduction

In recent years, Additive Manufacturing (AM) has become an established manufacturing route alongside casting, forming, machining, joining and surfacing processes. Defined in BS ISO/ASTM 52900:2015 as "a process of joining materials to make objects from 3D model data, usually layer upon layer", AM is often cited as offering direct and decentralized production, with reduced dependency on expensive and dedicated tooling.

Whilst the field of AM has been subject to many technical advancements in the past three decades, the high cost (purchase, operation, maintenance and depreciation) of AM machines and materials present major challenges to AM progression [1]. There has been limited ability to replace conventionally made parts economically, particularly large parts. The application of AM has therefore been primarily focused on niche, high-value and technically-demanding parts of small-build volume, where the benefit of greater design freedom offsets the high cost.

Wire Arc Additive Manufacturing (WAAM) is a directed energy deposition (DED) additive manufacturing technology that is broadening the applicability of AM. Using an electric arc as a fusion source to melt wire feedstock, metallic end-use parts of medium-to-large build volume and low-to-moderate levels of complexity can be cost-efficiently produced. This capability can be attributed to the low cost of wire relative to metal powder used for powder-based AM for many materials, low capital expenditure, and a high deposition rate achievable within a flexible build envelope. Moreover, by lowering the barrier to entry, the non-tangible benefits of AM and DED may be accessible to more cost-sensitive manufacturers for the first time.

A compromise of the high deposition rate is that an as-built surface can be uneven and within a wide manufacturing tolerance. This means that WAAM is often reliant on post-process finishing to meet dimensional and geometric requirements. However, even with post-processing accounted for, substantial raw material and cost savings have been demonstrated in comparison to CNC machining and forging processes. Besides new part manufacture, as a DED process, WAAM can also be readily applied to feature addition and repair applications.

Recently, WAAM is becoming increasingly industrialized, with growth in both numbers of end users and equipment suppliers. The aerospace industry, as an early adopter of WAAM, has seen the process mature significantly for production of large titanium alloy aerospace components previously conventionally forged and machined. For example, WAAM parts produced by Norsk Titanium achieved US Federal Aviation Authority certification for production of WAAM parts for the Boeing 787 Dreamliner in 2015 [2]. Other applications of WAAM have been demonstrated in space, nuclear, automotive and marine industries, as well as in design, architecture and art.

NOTE *The Military Aviation Authority, UK MASAAG Paper 124 Issue 1 and DNVGL-CG-0197 provide guidance for qualification and certification of WAAM for military and marine applications, respectively. General certification guidance for AM, including recommendations applicable for WAAM is provided in guidance documents by ABS 299 and Lloyds Register. Information on materials, material tolerances, and quality control procedures and processes for the aerospace sector for Wire Fed Plasma Arc DED is provided by SAE AMS-7004, and for Titanium alloy preforms, SAE AMS-7005.*

Despite the growing interest and application, there is limited information to aid prospective users in effective implementation of WAAM. This PAS is intended to fulfil this need through providing practical guidance to enable organizations to embrace the technical and economic opportunities associated with WAAM.

1 Scope

This PAS provides an overview of the wire fed arc directed energy deposition, more commonly known as wire arc additive manufacturing (WAAM), process characteristics, benefits and limitations relative to other DED and conventional processing routes. This is intended to aid potential users in evaluating the suitability of adopting WAAM for a given application. It also covers:

- the general architecture and sub-systems that constitute a WAAM machine and their effect on WAAM capability;
- key process parameters and their influence on the WAAM process;
- considerations for effective WAAM path-planning, monitoring and control, and post-processing; and
- terminology relevant to WAAM.

This PAS does not cover other additive manufacturing processes, process qualification or quality assurance, nor does it provide guidance for a specific user application or material.

This PAS is aimed at WAAM machine developers and process parameter developers.

This PAS may also be of interest to potential end users of WAAM technology.

This PAS does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes provisions of this PAS. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 841:2001, *Industrial automation systems and integration – Numerical control of machines – Coordinate system and motion nomenclature*

PD ISO/TR 25901-1:2016, *Welding and allied processes – Vocabulary – Part 1: General terms, Welding and allied processes – Vocabulary – Arc welding*

PD ISO/TR 25901-3:2016, *Welding and allied processes – Vocabulary – Welding processes*

PD ISO/TR 25901-4:2016, *Welding and allied processes – Vocabulary – Arc welding*

BS ISO/ASTM 52900, *Additive manufacturing – General principles – Terminology*

BS EN ISO/ASTM 52921:2016, *Standard terminology for additive manufacturing – Coordinate systems and test methodologies*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this guide, the terms and definitions given in ISO/ASTM 52900:2015(EN), BS EN ISO/ASTM 52921:2016, ISO/TR 25901-1:2016(EN), ISO/TR 25901-3:2016(EN), ISO/TR 25901-4:2016(EN), ISO 841:2001 and the following apply.

3.1.1 additional processes

procedures carried out in-situ of WAAM deposition to directly affect the dynamics of the melt pool, an intra-layer basis during WAAM deposition or an interlayer basis between WAAM deposition periods

3.1.2 as-built

state of components made by DED before any post-processing except where removal from a build platform is necessary

3.1.3 build platform

base which provides a surface upon which the building of the part is started and supported throughout the build process

3.1.4 feature addition

deposition of material to a part made by an alternative manufacturing process to produce a preform in accordance with the design specification

3.1.5 preform

geometry of the WAAM deposition before post-processing

3.1.6 WAAM equipment

individual apparatus used in a WAAM machine

3.1.7 WAAM operator

person who sets up, maintains, and runs WAAM equipment

3.1.8 WAAM process planner

person who specifies process parameters, tool paths, and build procedures for production of WAAM parts using WAAM equipment

3.1.9 wire arc additive manufacturing (WAAM)

DED approach that uses an electric arc as a source of fusion to melt wire feedstock and preceding material to build a part or feature preform, layer by layer

3.2 Abbreviations

AM	additive manufacturing
CNC	computer numerical control
CTD	contact tip distance
DED	directed energy deposition
EB-DED	electron beam directed energy deposition
EWW	effective wall width
GMA	gas metal arc
GTA	gas tungsten arc
LB-DED	laser beam directed energy deposition
MAG	metal active-gas
MIG	metal inert-gas
PA	plasma arc
TAG	tungsten active-gas
TIG	tungsten inert-gas
TWW	total wall width
WAAM	wire arc additive manufacturing

4 WAAM suitability considerations

4.1 An evaluation of WAAM suitability for adoption for a given application should consider the following:

a) the potential for manufacturing cost reduction compared to conventional manufacturing processes;

b) the value that might be provided by incorporating a cost-efficient AM process, such as greater responsiveness, design freedom and material capability; and

c) the value of the unique processing characteristics in WAAM relative to other AM processes.

NOTE *For any one application, it is possible that only one of these considerations, or a combination, form the drivers relevant to adoption.*

4.2 Adoption for cost reduction relative to conventional manufacture

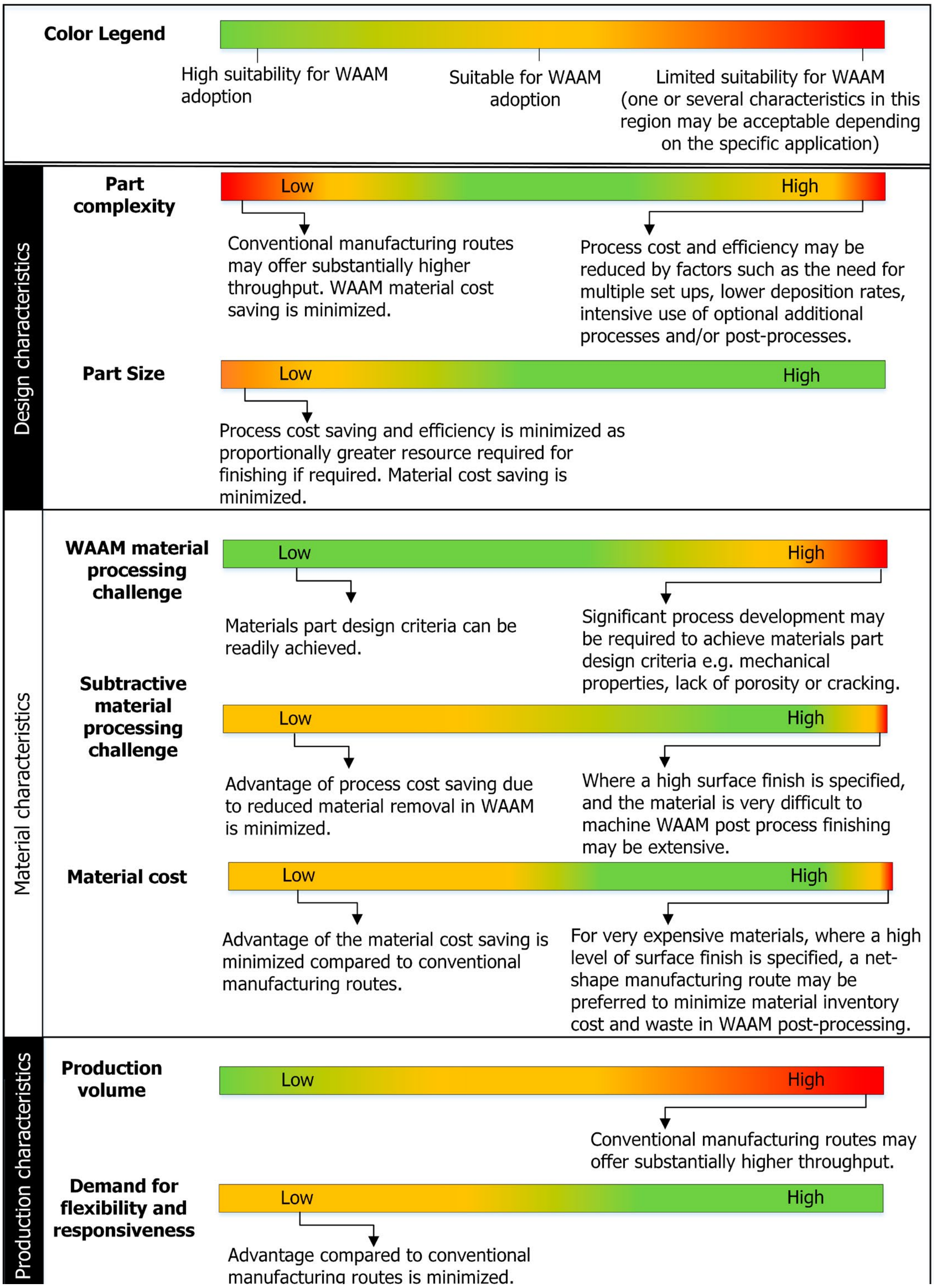
4.2.1 Case studies have shown that WAAM can be cost-effective for parts previously produced by CNC machining or forging routes [3, 4]. One reason for this is the resultant part mass for conventional manufacturing routes comprises only a fraction of the raw material supplied. In forging, to promote material flow and maintain processing temperature, extra stock material is added, and several millimeters or more of material is machined away to remove superficial residual stresses and oxide layers from the surface. In contrast, the near-net shape deposition in WAAM results in efficient use of raw material which can lead to reduction in energy consumption as well as material [5]. As the wire feedstock used in WAAM is, in many cases, widely available from the welding supply chain, the cost/kg of the raw material is generally comparable to billet. This allows significant material cost saving to be possible for the production of net-shape parts.

NOTE *Materials and wire diameter sizes not commonly available as welding filler material can incur a price premium and extended lead times. Materials of low ductility may be difficult to be wire drawn and therefore can be more expensive, difficult to source, or require specific research & development to produce. It is possible to feed multiple wires of different composition to the melt pool to generate a WAAM metal of tailored composition in-situ (see **5.3**).*

4.2.2 The suitability of WAAM adoption for a cost-driven application is dependent on the part design, material and production characteristics as shown in Figure 1.

NOTE *Figure 1 allows users to understand the key factors driving suitability of WAAM from a cost perspective and is not intended as a conclusive decision tool.*

Figure 1 – WAAM suitability scale based on production, material and part design characteristics for cost-driven applications

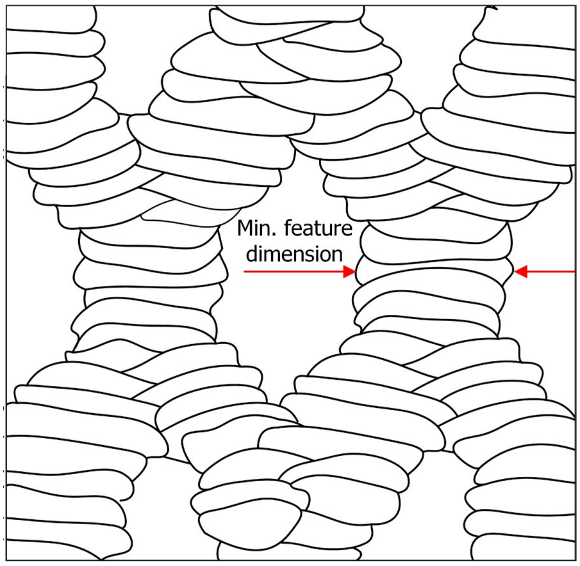


4.2.3 The size and complexity of parts should be considered when evaluating WAAM competitiveness compared to conventional manufacturing routes. The potential saving on materials and tooling, and machining time relative to CNC machining and forging is maximized for parts of larger size and medium to high level complexity. Due to the uneven surface finish and tolerance of WAAM, post-process finishing where required comprises a greater proportion of the overall manufacturing time for smaller parts. Additionally, highly complex parts can require more intensive additional or post-processing, or multiple set up routines. Whilst a high substantial buy-to-fly ratio or strong feature aspect ratios indicate great potential for material cost saving, as parts become more complex, factors such as reduced minimum feature size and the need for a greater number of set-ups might decrease manufacturing efficiency.

4.2.4 Part designs with complex geometry, such as lattice structures shown in Figure 2, or contoured surfaces, are possible to manufacture through WAAM. Similarly, features such as overhangs are possible to manufacture without support structures. However, the minimum feature size of the part, relative to WAAM minimum feature size and the level of surface finish required, is critical to the suitability of production of parts containing complex geometry. Post-process finishing becomes increasingly challenging for complex geometries as the minimum feature dimension becomes lower than the WAAM minimum feature size. In addition, the need for freedom in multiple rotary axes, or multiple set-ups may also increase the WAAM machine and process cost respectively.

4.2.5 Parts of lower complexity levels are less suited to WAAM, as the reduced material removal and tooling cost through conventional processing limits the cost benefit. The competitive benefits of using WAAM are reduced especially if the throughput required is high, as conventional manufacturing processes tend to have more rapid processing time than WAAM, once the tooling has been obtained.

Figure 2 – Schematic example of a WAAM lattice structure showing the minimum feature size equivalent to a singular WAAM bead width



4.2.6 In evaluating the suitability of the part complexity for WAAM adoption, feature addition applications should also be considered for parts containing geometry that can be separated into large volumes of low complexity and small volumes of higher complexity. An example of this is the manufacture of a part where the features consist of a large cylinder with a boss extruded from the radius. The smaller detail, of greater complexity, i.e. a boss, may be added by WAAM feature addition onto a cast or forged cylinder. This approach can reduce manufacturing cost and time substantially compared to conventional manufacturing or stand-alone WAAM production.

4.2.7 An assessment of the suitability of adopting WAAM should take into consideration the range of materials required to be manufactured and their ability to be processed by WAAM. WAAM can be more readily implemented in accordance with material, geometric and physical specification for materials of high levels of weldability or those that have been subject to significant WAAM research and development.

4.2.8 The material-saving opportunity is maximized for materials of high cost per kilogram. For less expensive materials, the potential to achieve reduction in overall processing times and associated cost saving through this route might also drive adoption. This is especially the case in difficult-to-machine materials that pose a significant subtractive material processing challenge.

4.2.9 The production factors that should be considered include the production volumes and the demand for flexibility. Cost of tooling can also be reduced substantially in comparison to casting and forging, where dies can be costly in terms of material and lead times can exceed a year. For very large production volumes, where there is limited requirement for part customization or design changes, the disadvantage of the high cost of tooling and lengthy lead times are readily overcome by rapid processing times and tooling amortization. However, lead times for forging blanks can be extensive, and forging equipment can incur higher recurring costs than WAAM.

4.3 Adoption for a cost-effective route to AM

4.3.1 The cost-effectiveness of WAAM allows the many value-adding benefits of AM to be accessible to a wider, more cost-sensitive audience. Prospective advantages of AM which may drive adoption include the following:

a) localized, responsive manufacture which might reduce transportation and inventory cost;

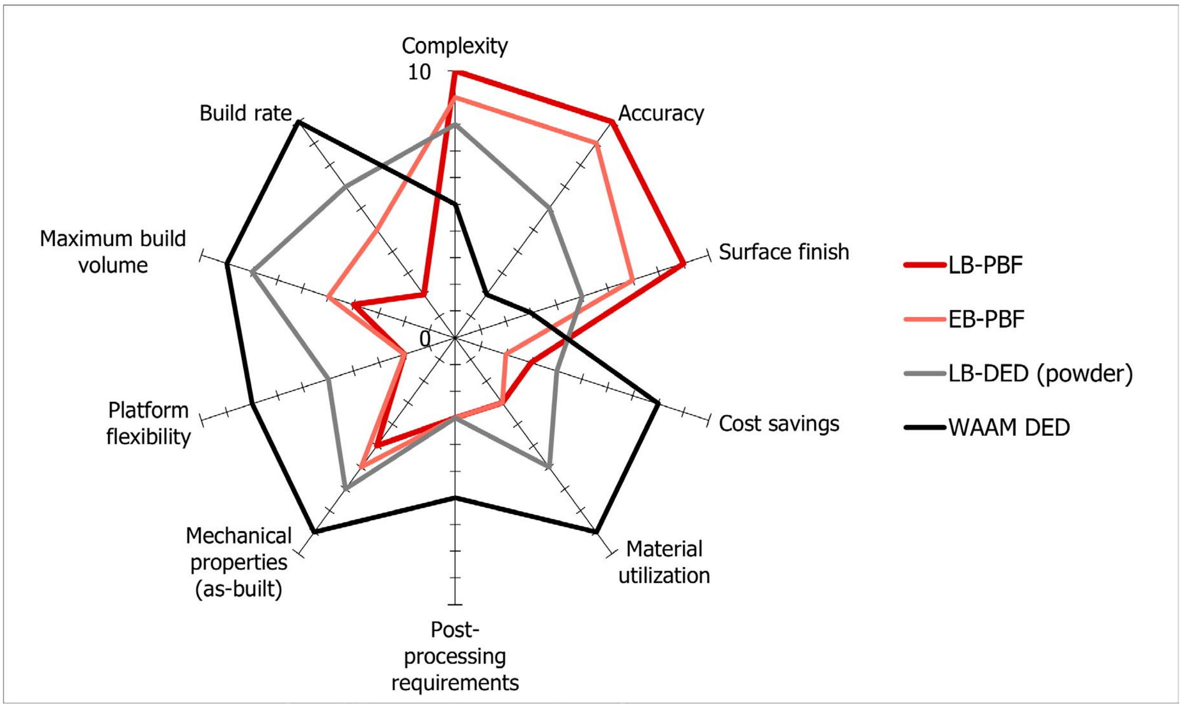
b) greater control over the manufacturing process; and

c) improved part functionality, including design or materials properties.

4.3.2 The cost effectiveness of WAAM can primarily be attributed to the low cost of wire relative to metal powder used for powder-based AM for many materials, comparatively low capital expenditure, and high deposition rate. WAAM may therefore be adopted as the least costly route to obtaining operational advantage associated with AM, even if WAAM is less cost-effective per part than conventional manufacturing processes.

4.3.2.1 Evaluation of the comparative cost effectiveness of WAAM should consider its performance in relation to the process characteristics which comprise the major cost drivers for a particular application. The comparative performance of several metal AM technologies for the important process characteristics from an aerospace industry perspective is shown as an example in Figure 3. The improved as-built mechanical properties, although dependent on the material being processed, can be related to typically low levels of porosity in WAAM and greater platform flexibility that allows additional processes (see **5.6**) to be carried out in-situ of deposition or on an intra-/inter-layer basis to enhance the as-built material performance. All wire based DED approaches benefit from much reduced complexity of feedstock handling and safety related equipment and improved material utilization than powder based additive manufacturing.

Figure 3 – The comparative performance of several metal AM technologies for the important process characteristics from an aerospace industry perspective (1=low 10=high) adapted from [6]



4.3.3 Compared to other wire based DED processes, WAAM productivity and geometric resolution lies within the region of that produced by LB-DED (laser beam DED) and EB-DED (electron beam DED) approaches; typical layer heights are in the region of (1-3) mm, minimum deposition width of (2-6) mm and surface waviness mean surface height of 500 µm. Deposition rates between (1-4) kg/hr are common, although up to 10 kg/hr has been reported for multiple wire feed systems.

4.3.4 For small, complex or hard-to-machine parts where low surface roughness is specified, the additional material removal in post-processing in WAAM should be considered and balanced against powder based DED or powder bed fusion approaches of improved geometric resolution.

In addition, wire LB-DED and EB-DED may be considered due to greater ability to vary the spot size of the energy source and may produce features that require less extensive finishing.

Depending on the material selection, the cost-effectiveness of WAAM may also be reduced. For example, materials that demand a high cooling rate to achieve the desired material properties may be produced more rapidly with less additional and post-processing with LB-DED than WAAM. Although the capital expenditure is reduced relative to other DED approaches, the material compatibility should also be evaluated before proceeding with WAAM adoption as a cost-effective route to AM.

NOTE *The processing characteristic may also provide value adding benefit to the functionality of the material (see **4.4**).*

4.3.5 The key attraction of WAAM compared to wire LB-DED and wire EB-DED is that the electric arc, as a fusion source, achieves a high deposition rate at comparatively low levels of capital investment. This is because a WAAM machine is assembled from open architecture equipment, from a wide range of suppliers in the arc welding industry. Other factors that should be considered in the selection of an electric arc as a fusion energy source include:

a) the higher energy efficiency of the electric arc compared to LB-DED which might allow it to be more effectively scaled to high power levels;

   NOTE *This can benefit processing of metals or metal alloys of high melting point or high reflectivity.*

b) the elimination of chamber evacuation and cool down times in comparison to EB-DED;

   NOTE *This can benefit high deposition rate production.*

c) the availability of a skilled workforce;

   NOTE *Many of the skills required are transferable from the arc welding industry.*

d) the viability of integration with legacy infrastructure and production systems; and

e) less complex and costly protection equipment and facilities to manage health and safety risk compared to EB-DED and LB-DED.

   NOTE *Health and safety varies between countries and therefore be observed respectively.*

4.4 Adoption for the specific value adding characteristics of WAAM

4.4.1 The material properties in AM parts depend strongly on the heat input of the fusion source and thermal cycling experienced post-deposition, with different fusion sources subsequently providing unique processing capabilities.

4.4.2 The source of fusion should be selected with consideration given to the end-user application and material selection. The electric arc used in WAAM provides lower heat source intensity than LB-DED and EB-DED as shown in Table 1.

Table 1 – Adapted from weld data provided by Lancaster [7]

DED fusion source		Heat source intensity (W/cm³)
Laser		10^{10} – 10^{12}
Electron beam		10^{10} – 10^{12}
Electric arc	Plasma arc	5×10^{6} – 5×10^{10}
	Gas metal arc	5×10^{6} – 5×10^{8}

4.4.3 WAAM promotes lower cooling rates and a larger melt pool than LB-DED, as the fusion source moves more slowly to provide the heat for melting. In contrast, WAAM typically offers higher cooling rates and lower build temperatures than EB-DED where heat dissipation is slow due to the need to process in a high vacuum environment which can lead to substantial heat accumulation during a build.

NOTE *The cooling rate also depends on the deposition tool path and processing parameters employed. A weaving tool path, high current setting and continuous deposition without cooling may lead to reduced cooling rates.*

4.4.4 The process-microstructure-properties relationship in WAAM might be beneficial to manufacturing parts more efficiently or at higher quality depending on the material and design specification. This advantage should be considered in particular for production of functionally graded materials or microstructures, where thermal gradient and cooling rate are required to be closely controlled within a certain range. The value-adding potential can be categorized by the improved functionality in relation to the material, physical, and geometrical capability.

4.4.5 Characteristics that may be investigated to establish value-added potential include:

a) microstructural texture and grain size;

b) phase development;

c) composition and contamination;

d) residual stresses; and

e) aesthetic for design and art related applications.

4.4.6 For smaller build envelopes that are contained within an enclosure, interlocking and guarding systems can minimize the health and safety hazard to the operator for all DED approaches. For production of large parts or remote manufacturing, out-of-chamber production is more common, using large gantry or robotic arm systems also with interlocking and guarding systems.

NOTE 1 *For guidance on general principles of design involving risk assessment and risk reduction for safety of machinery, see BS EN ISO 12100.*

NOTE 2 *For guidance on safety-related parts of control systems for safety of machinery, see BS EN ISO 13849-1.*

NOTE 3 *For guidance in managing the hazards of industrial robotics, including emergency stops for the system and operating the system in a separate area clearly marked with the possible hazards, see BS EN ISO 10218.*

4.4.7 Remote manufacture, directly or close to the end-use location, may provide operational advantage by reducing transport and inventory cost. For out-of-chamber systems, the use of an electric arc includes hazards such as arc eye flash and fume exposure. However, the risk might be reduced more effectively than for LB-DED due to reduced hazard severity and the tendency for the energy source to self-extinguish or fail to arc in case of a positional build error.

5 WAAM Machine

5.1 General

5.1.1 There are several commercial WAAM machine providers and WAAM service providers, however, a WAAM machine might also be assembled from readily available hardware, where the key elements of a WAAM machine can comprise equipment from different suppliers and manufacturers, provided integration is possible. This can reduce capital expenditure compared to off-the-shelf WAAM systems and maximize the ability to specify the machine to meet the application requirements. However, a greater level of expertise is required to integrate WAAM hardware and process parameter development.

5.1.2 WAAM equipment hardware should comprise of motion system, arc technology (which determines the torch, power and wire supply configuration), shielding gas and extraction, and fixtures.

5.1.3 A control system should automate and synchronize the motion system and arc technology, and might include the use of sensors for process monitoring and control (see **6.4**).

5.1.4 The shielding gas and extraction function might also be automated by the control system, although this may also be controlled manually. Computer Aided Manufacture (CAM) software should be used for complex parts, as it is essential in generating appropriate tool paths (see **6.2**). In addition, the process parameter development may be guided by Computer Aided Engineering (CAE) tools (see **6.3**).

NOTE 1 The minimum capability of DED control system hardware and software is outlined in ASTM F3187.

NOTE 2 Guidance in the safe installation and use of equipment for arc welding and allied processes is provided in BS EN IEC 60974-9:2018.

5.2 Motion system

5.2.1 The relative motion between the WAAM head and the build surface can be achieved with linear or rotary drives, articulated robotic arms or a combination of these. The range of travel of the motion system should be specified considering part dimension, substrate thickness, torch stand-off, and any additional process stand-off if used.

5.2.2 Linear and rotary drives are typically stiffer and more accurate in terms of position and speed than articulated robotic arm systems. In specifying a motion system, the tendency to incur travel speed errors at corners should be considered as this can result in systematic build-up of material where a change of direction has occurred.

5.2.3 The accuracy, precision, and repeatability on WAAM quality should also be considered and compensatory path-planning or calibration procedures may also be introduced. Reproducibility may also be important for consistent production across multiple WAAM machines and if deposition is influenced by the WAAM operator. These factors are important as they influence the arc length. Combined with the arc power supply parameters and relative position of the wire (see **5.3**) this strongly affects the arc heat input, metal transfer mode and arc stability, as well as the geometrical, physical, and material properties of the WAAM deposit.

5.2.4 Accuracy, repeatability and reproducibility of the deposition can also be affected by the interface between the substrate or torch to the motion system. The interface should be designed so that the positioning of the torch, including torch angle and contact tip distance (CTD), can be verified. Depending on the material and part designs, it might be helpful to re-orientate the torch relative to the melt pool position to achieve a different torch angle.

5.2.5 The motion system should be designed to minimize risk to WAAM operators. The risk is best minimized by conducting WAAM within an enclosure. Interlocks, guarding, and emergency stops can also reduce the risks posed as can operating the system in a separate area clearly marked with the possible hazards.

NOTE 1 If WAAM is conducted in the open rather than an enclosed environment, greater risk is posed to WAAM operators.

NOTE 2 See BS EN ISO 10218 for guidelines on industrial robotics.

5.3 Arc technology: torch, power, and wire supply

5.3.1 In principle, any arc welding fusion welding process covered in ISO/TR 25901-3:2016 can be integrated to a WAAM machine. However, due to the need for automated, high quality deposition (i.e. low contamination and high levels of cleanliness), the following arc technologies are commonly applied:

a) metal inert-gas (MIG) or metal active gas;

NOTE This process is also known as gas metal arc (GMA).

b) tungsten inert-gas (TIG) or tungsten active-gas (TAG); and

NOTE This process is also known as gas tungsten arc (GTA).

c) plasma arc (PA).

NOTE This may use a transferred arc or non-transferred arc. More information about these arc technologies is available from TWI [8-10]. Use of a plasma transferred arc is more common with powder based DED.

5.3.2 In MIG/MAG, the wire is fed coaxially through the torch, whereas the wire is separately fed into the melt pool in PA and TIG/TAG and may require re-orientation for consistent deposition allowing for changing tool path directions in WAAM. For each arc technology, the functionality to modulate the arc current using pulse mode is usually available to reduce overall heat input and stabilize metal transfer.

5.3.3 The weldability of materials for each arc technology can differ and should guide the selection of arc technology for WAAM. The weldability may vary depending on the polarity applied. Typically, non-consumable electrode processes (i.e. PA and TIG/TAG) use direct current electrode negative polarity to avoid overheating and deterioration of torch elements. However, for materials that require cathodic cleaning action due to stubborn oxides on the surface, alternating current and variable polarity might be used for non-consumable electrode arc technologies.

5.3.4 Arc blow might occur for certain materials and arc technology combinations, reducing dimensional consistency of the WAAM deposit. Reasons why this might occur include emission of conductive ions around the melt pool, or magnetism in the material being deposited.

NOTE Depending on the cause, arc blow might be alleviated through providing additional grounding connections to the build platform, control of shielding gas composition or additional processes, including but not limited to, heating ahead of the melt pool or oscillation of the torch.

5.3.5 Provided the arc technology can produce the material to satisfactory quality levels, the selection of the arc technology should also be tailored to suit the user application. For example, if a high deposition rate is prioritized, MIG/MAG or PA might be preferred to TIG/TAG. If quality and process stability are prioritized, a non-consumable electrode might be selected. By providing the highest energy density electric arc, PA enables high travel speeds and reduced sensitivity to changes in arc length.

NOTE See [11-12] for comprehensive guidance and information regarding weldability and arc technology advantages, limitations and equipment.

5.3.6 Other factors that should be considered in the selection of an arc technology pertain to tool path planning capability. Non-consumable electrode arc technologies allow the wire feed speed (WFS) to be controlled independently of arc power. This might be useful for deposition of intersecting features and minimizing the geometrical variation caused by start and stops. However, these variations may also cause variation in microstructure.

5.3.7 MIG/MAG power supplies often have pre-programmed synergic lines that adjust the arc current and voltage for a given wire material and wire diameter based on the WFS selected. With such systems it is not possible to adjust the WFS independently of arc power.

5.3.8 For the power supply, torch, and wire feeder to operate consistently without failure or affecting deposition quality throughout the build, these systems should be specified appropriately for the given WAAM duty cycle considering any dwell periods. Often water-cooling of the torch and power supplier is required to achieve this.

5.3.9 Consumables within the power supply, torch, and wire feeder that require replacement at regular intervals should be maintained so that wear-related deterioration does not affect the quality of the WAAM deposit.

5.3.10 The arc power supply generates currents leading to magnetic fields near the welding cable and the workpiece. The risk of damaging electronic WAAM equipment through electro-magnetic interference should be evaluated and equipment should be protected or low-voltage arc-striking and stabilizing strategies used if necessary. High frequency striking voltage is often used with TIG/TAG to avoid electrode pick-up.

NOTE 1 BS EN 60974-10 provides guidance on establishing electro-magnetic compatibility for arc welding equipment.

NOTE 2 A high frequency striking voltage is often used with TIG/TAG power supplies to generate the arc and avoid electrode pick-up associated with contact-based arc striking.

5.3.11 The route and length of the path of the cable-hose assembly from the wire feeder to torch end should not obstruct the wire from feeding freely. The wire spool can be attached to the wire feeder at the power supply, or the torch might be equipped with a small wire reel. Depending on the production rates and size of parts produced, a wire management routine might be adopted, or larger wire spools used to minimize disruption to production.

5.3.12 Multiple wire feeders can be used to enhance the deposition rate, or combining wires of different composition to achieve parts of composition alloyed in-situ or functionally grade material properties. Wire feeders can feed the wire into the melt pool by push or push-pull wire feed drives. Push-pull wire feeders can also retract the wire and are often recommended for consistent wire feeding of softer wires such as aluminum alloys and for long cable-hose assemblies.

5.3.13 This can be useful in WAAM where routines to automatically adjust and maintain the relative position of the wire are implemented to achieve consistent deposition throughout the build (see **6.4**). Often the wire supplied to the melt pool from the wire feeder has a helix or cast angle due to the manufacturing process and supply on a spool. If the length of the helix is too large, or varies throughout the build, problems with arc blow might occur and stability of WAAM might vary for different travel directions.

NOTE See BS EN IEC 60974-1:2018, BS EN 60974-2:2013, BS EN 60974-3:2014, BS EN 60974-4:2016, BS EN 60974-5:2013, BS EN 60974-7:2013, BS EN 60974-11:2010, BS EN 60974-12:2011, BS EN IEC 60974-14:2018 for arc welding equipment guidance.

5.4 Shielding and fume extraction

5.4.1 As in welding and other AM processes, shielding is required to protect the melt pool from atmospheric contaminants. Where shielding gas is used, an adequate flow rate of shielding gas should be provided to flood the melt pool and neighboring hot metal. This stabilizes the arc, excludes atmospheric gases, and provides cooling to the melt pool. The flow rate should be high enough to provide a satisfactory amount of penetration, whilst preventing turbulence which introduce atmospheric gases to the gas column causing porosity and poor arc stability.

5.4.2 In most cases, shielding gas is delivered through the torch, however, for materials that are highly susceptible to atmospheric contamination, additional measures might be required. This includes the use of inert chambers or flexible tents, or localized shielding by trailing shield or through fixtures. Shielding gas coverage might also be extended to protect side walls during re-heat cycles.

5.4.3 WAAM shielding gas selection is dependent on the material being deposited. There can be several options of shielding gas composition any material, and these affect the arc characteristics.

NOTE See BS EN ISO 14175:2008.

5.4.4 As shielding gas and fumes are released during WAAM, to minimize the hazard posed to the WAAM operator the air quality of the working environment should be controlled within safe exposure limits. Depending on the machine configuration, this involves extraction or recirculating gas, or a purifier system.

NOTE Guidance on control and hazards relating to welding fumes can be applied to direct energy deposition systems and can be found on the Health & Safety Executive website [13, 14].

5.5 Fixtures

5.5.1 Fixtures should be used to control residual stress induced distortions during the build to acceptable levels that allow stable deposition in accordance with the part specification.

5.5.2 Fixtures used in WAAM are typically static, although recent research suggests these might also dynamically vary the restraining force imposed onto the substrate to reduce distortion [15]. Although the WAAM build might be stabilized by secure fixturing, on release from the fixture post-processing might be required to avoid non-compliance with the required geometric, physical or material properties.

NOTE Mechanical tensioning of the workpiece through heavy jigs, fixings, clamps and other technologies can restrict the possible distortion, however, it may increase the maximum residual stress in the part [16].

5.5.3 Interpass temperature control, or heat treatment (see **7.2**) might be used post-process to correct distortion in the as-built structure. In some cases, the part should remain restrained by fixtures until the part has been satisfactorily stress relieved.

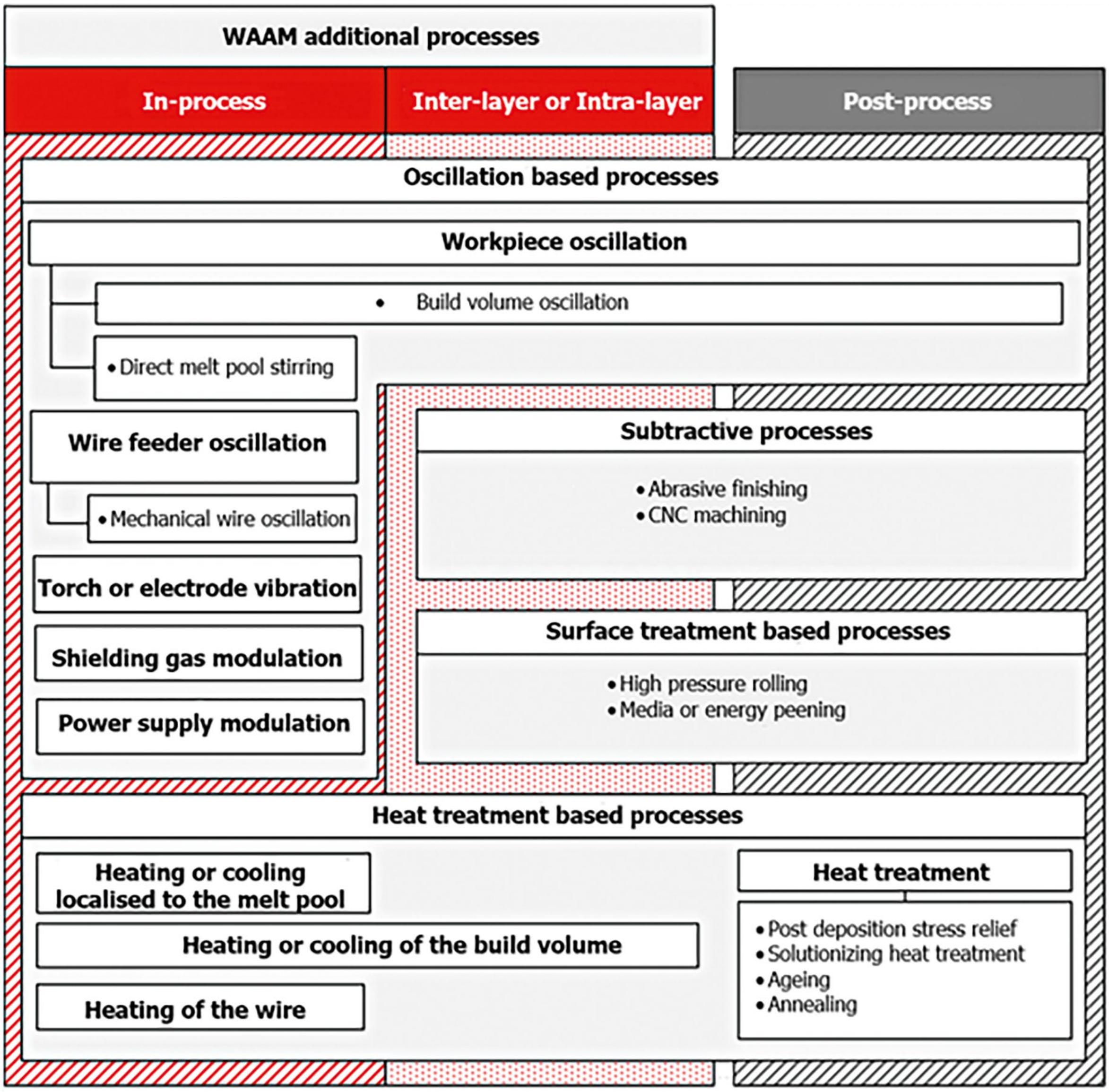
NOTE For production of new parts, the use of thicker substrates can reduce total distortion upon release from fixtures. However, this can increase the fixture restraining force required to prevent distortion during the build.

5.6 Optional additional equipment

5.6.1 General

5.6.1.1 WAAM can apply optional additional processes to enhance part quality or processing efficiency. The additional processes that might be applied in WAAM are outlined in Figure 4, categorized by the timing of which they are applied to achieve resultant effects. The additional processes might be in-situ of WAAM deposition, affecting the dynamics of the melt pool directly, or carried out on an intra-layer or inter-layer basis. In some cases, additional processes might also be employed for post-processing as highlighted by the processes in Figure 4, which also fall into the WAAM post-process category.

Figure 4 – The additional processes that can be applied in-situ of WAAM deposition, or on an intra-layer or inter-layer basis



NOTE 1 This is not intended to be a complete compilation of all possible additional processes that may be applied in WAAM, but an overview of those already applied or are those that may be directly transferable from the welding industry.

NOTE 2 Some processes that are classified as an additional process may also be used in WAAM post-processing.

NOTE 3 This figure is adapted from [17] which provides a comprehensive review of additional process applications.

5.6.1.2 Some processes are commonly applied in WAAM and solutions can be readily obtained from existing supply chains. Examples of these include:

a) power supply modulation through pulse current;

b) heating or cooling of the build volume via the build platform; and

c) synchronized power supply modulation and wire feed oscillation.

5.6.1.3 The application of other additional processes in WAAM are typically limited to specialist applications, where the material weldability or design specification means that in-situ, intra-layer or inter-layer correction is required. In many cases, research and development is currently ongoing to understand the full impact of their application on WAAM build quality.

5.6.1.4 These processes might also increase processing efficiency, indirectly, by eliminating the requirement for extensive, costly post-processing.

5.6.2 Oscillation-based processes

5.6.2.1 The oscillation based additional processes that can be applied in WAAM are classified by the target of the oscillation or modulation as shown in Figure 4, and can involve the workpiece, wire, torch or electrode oscillation and shielding gas or power supply. These processes are applied in welding industry to improve quality of welds for a wide range of applications [18].

5.6.2.2 Build volume oscillation derives from welding, where it can reduce residual stress and influence the microstructure and solute distribution within solidified material to avoid hot cracking when applied in-situ [19]. Build volume oscillation is not a commonly applied additional process in WAAM, however, it should be considered for WAAM materials of challenging weldability [20]. It should be noted that for large WAAM parts, the energy associated might be high.

5.6.2.3 Direct melt pool stirring might be implemented using electro-magnetic arc oscillation [21-22] or insertion of an oscillating probe directly into the melt pool [23] to achieve grain refinement and disrupt columnar grain growth. Torch or electrode vibration also imparts oscillations to the arc and subsequently the melt pool to cause melt pool stirring which can also result in grain refinement [24].

5.6.2.4 Shielding gas modulation can be implemented by pulsing between shielding gases of different compositions and thermal conductivities [25]. This can vary the arc diameter to stir the melt pool, regulate metal transfer mode and can be useful if the shielding gas contains a high costing component.

5.6.2.5 Power supply modulation is often a built-in feature of an off-the-shelf arc power supply that can result in melt pool stirring and regulation of droplet detachment from the wire.

The modulations might include single or double pulse current, or ultrasonic excitation of the current signal [26-27]. Power supply modulation can be applied with direct, alternating or variable polarity current.

5.6.3 Subtractive processes

5.6.3.1 Additional subtractive finishing processes should be applied for surfaces that are difficult to access post-build, where the WAAM as-built surface roughness or dimensional tolerance is unacceptable. Whilst other subtractive processes are possible, CNC machining is most common in WAAM due to the volume of material often required to be removed.

5.6.3.2 The subtractive machining process might be carried out in separate dedicated CNC machining set up or in the same set-up. Subtractive finishing can be applied on an intra-layer basis if the subtractive finishing process is carried out in the same set-up as the WAAM deposition, although this requires parallel working and expansion of the motion system configuration.

5.6.3.3 Although the stability of WAAM deposition depends on the surface finish of the last WAAM bead deposited, stable deposition process usually can be preferentially achieved through management of processing parameters rather than inter-layer or intra-layer CNC machining.

CNC machining should only be used to promote process stability if the process parameters cannot be selected to effectively control deposition stability due to the decrease material utilization and manufacturing efficiency.

5.6.4 Surface treatment

5.6.4.1 Surface treatment processes, including high pressure rolling, energy and media peening applied surface of the WAAM deposit have been shown to induce the following benefits:

d) grain refinement;

a) elimination of porosity;

b) reduction in anisotropy and residual stresses; and

c) improvement of the geometric repeatability of the deposit.

5.6.4.2 Surface treatment processes can be carried out on an intra-layer basis immediately behind the torch. However, the temperature range within which rolling is effective should be considered and the surface treatment delayed if necessary and applied on an inter-layer basis, to allow the build to cool to the required temperature.

5.6.4.3 For high pressure rolling, the profile of the roller should be selected with consideration for the WAAM deposit width and productivity requirements. For example, an inverted profile roller might be more appropriate for achieving microstructural transformation in wider walls than the equivalent process carried out with a flat roller [28]. The profile should be positioned to avoid slipping on the convex WAAM bead surface or bending of the WAAM deposit.

5.6.4.4 The depth below the surface for which surface treatment is effective determines how often the process should be applied during the WAAM build. The surface treatment force should be high enough to induce required microstructural changes and stress relief, however, it should not indent the surface of the WAAM bead.

5.6.4.5 While more usually applied to the top surface of the WAAM deposit between layers, high pressure interpass rolling might also be applied to the side surface of the WAAM bead. Research has indicated this might be significantly more effective than top surface rolling, in terms of residual stress and distortion reduction [29]. Side surface high pressure rolling is suited to thin wall type WAAM parts and path planning of the WAAM deposition and rolling process should be sequenced to provide access to the side walls. Additionally, the opposite surface to which the side rolling is applied should be rigidly supported to avoid plastic deformation of the WAAM deposit. Ease of application is therefore dependent on the geometry of the part, and specialist tooling may also be applied. Significant improvements to material properties can be achieved with peening in WAAM [30].

5.6.5 Heat transfer-based processes

5.6.5.1 Build platforms with integrated cooling channels can be adopted to provide active cooling of the build volume. This allows deposition to proceed more rapidly without interpass cooling and prevent excessive heat accumulation.

5.6.5.2 The cooling capacity of the build platform should be specified to provide effective heat transfer for the entire build volume. As the cooling effect diminishes further away from the build platform, it might not be possible to sustain the cooling rate required for tall builds and an adjustment of process parameters, including interpass time, may be required.

5.6.5.3 For the initial layers, WAAM process parameters should be adjusted in accordance with the enhanced cooling rate as build quality may be negatively affected by lack of fusion, arc blow and spatter.

5.6.5.4 In-situ cooling of WAAM deposition relative to the melt pool might be applied in a variety of ways, including thermo-electric cooling or forced convective cooling. This can be an effective way of maintaining stable heat dissipation characteristics without reducing the heat input and wire feed speed. For equivalent arc technology processing parameters, cooling might stabilize the WAAM bead geometry, providing an improved EWW/TWW ratio (see **6.5**) and enhancement of deposition efficiency. The layer height might also increase, which may benefit productivity of thin wall deposits by reducing the number of deposition passes required to generate the equivalent height, providing the volume of post-processing material removal where required does not increase uneconomically. It can also allow WAAM to become more competitive in terms of processing times compared to conventional processes which tend to have much higher throughput.

5.6.5.5 For cooling localized to the melt pool, the cooling source should not introduce turbulence to the arc that disrupts the deposition process and should not contaminate the WAAM metal. It may also need re-orientation for changing travel direction if applied trailing to the WAAM torch. In welding, application of a steady solid CO_2 stream behind the melt pool significantly reduces residual stress in single butt welds of titanium and austenitic stainless-steel alloy [31] and some effects have been shown to be transferable to WAAM [32].

NOTE The distance from the cooling source to the melt pool is critical to residual stress reduction as the mechanism of stress reduction is dependent on influencing the melt pool shape and thermal field.

5.6.5.6 Devices that heat the wire prior to transfer to the melt pool are widely available in the welding industry for TIG/TAG or GTA. The primary benefit is that the energy from the arc can melt a greater volume of wire compared to unheated wire. This can increase deposition rates and productivity. Heating may also be employed, localized to the melt pool or to the build volume in general, to reduce the cooling rate. As heat can accumulate during WAAM builds, depending on the desired interpass temperature, external heating may not be required. The preheating of material, as in welding, can provide benefits including a reduction in residual stress, improved material properties or crack elimination, depending on the material.

NOTE 1 Recommended pre-heat temperatures for welding a range of metal alloys are outlined in [33].

NOTE 2 Additional heating may not be required if the interpass time can be managed to maintain the build temperature within the desired range throughout the build using the residual heat from the deposition process.

6 WAAM

6.1 Key process parameters

6.1.1 A limited range of process parameter combinations result in a defect-free, stable WAAM deposition. There are many processing parameters that influence WAAM deposition. The major arc technology-based parameters include:

a) Current;

b) Voltage;

c) Wire feed speed (WFS);

d) Travel speed (TS);

e) Interpass temperature;

f) Arc length;

g) Electrode angle;

h) Contact tip distance (CTD) and stickout;

NOTE *Applicable for MIG/MAG or GMA arc technology only.*

i) Stand-off; and

j) Wire diameter.

NOTE *Variations in wire diameter and composition may impact the quality of the WAAM deposit.*

6.1.2 For new parts, where the build platform comprises a substrate, the thickness and profile of the substrate should be selected to control residual stress and distortion to acceptable levels according to the part specification, or to levels that can be corrected by additional processes or stress relief heat treatment post-process. This might involve using thicker substrates or modifying the profile of a substrate cross-section to follow the deposition path more closely. As the build platform cannot be modified for repair or feature addition applications, residual stress and distortion should be controlled within acceptable levels by managing the arc technology-based parameters, additional processes, or stress relief heat treatment post-process.

6.1.3 For a given voltage in MIG/MAG, constant specific heat input from the electric arc is provided for fixed ratios of WFS to TS. Control of this metric can enable rapid generation of process parameters that provide stable deposition.

NOTE *Heat input is often minimized by control of the major arc technology process parameters or pulse arc additional processing (see **5.6**) in WAAM to limit grain growth of the WAAM microstructure to improve material properties. Heat input minimization might also reduce porosity content by reduction in droplet temperature and associated reduction of gas solubility in the melt pool.*

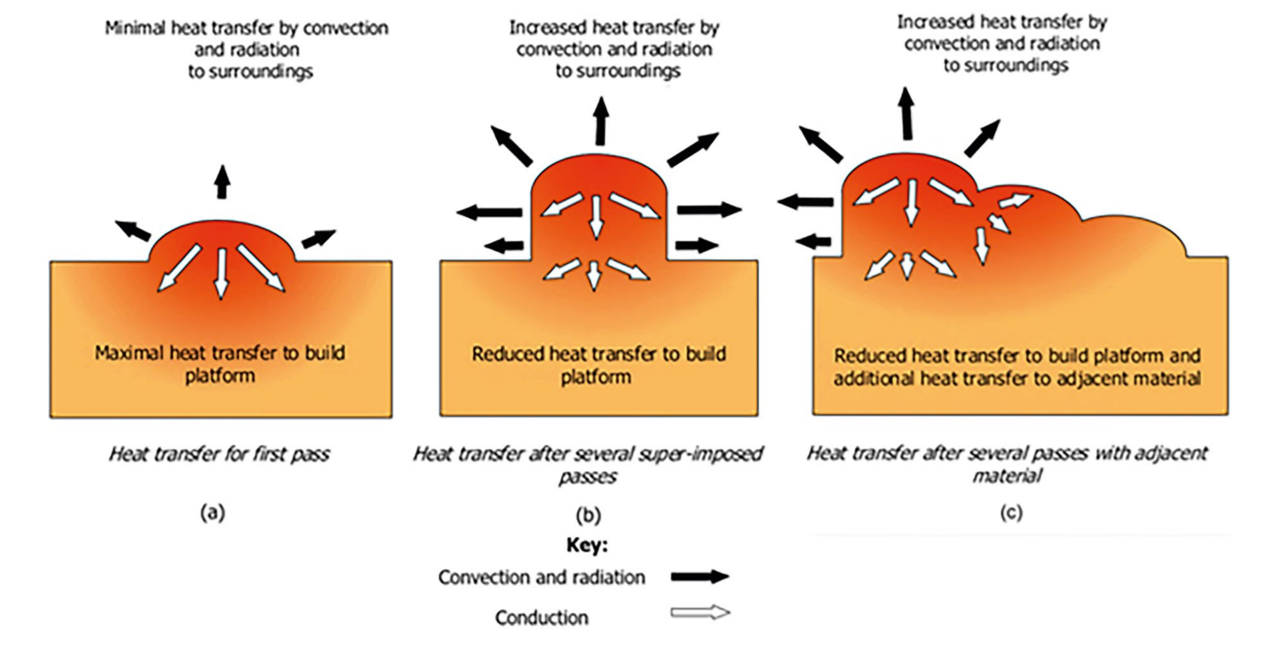
6.1.4 Process parameters might need to be varied depending on the build stage or part design to maintain a stable deposition. For example, at the start of the build, heat is rapidly dissipated by conduction through the build platform as shown in Figure 5a). However, as the build height increases, heat transfer through conduction becomes less effective, and dependent on convection and radiation as shown in Figure 5b).

6.1.5 As heat dissipation is less effective and pre-heat is usually present from previously deposited material, the arc power may be reduced to maintain a constant layer height and width, or dwell periods used to regulate the interpass temperature.

6.1.6 The interpass temperature should be the highest allowable in relation to the geometric, material and physical properties to minimize the effect on manufacturing efficiency. For continuous fixed cross-sections, these methods can allow the build to complete under steady-state thermal characteristics.

6.1.7 The process parameters may also need to vary to maintain stable deposition depending on the part design. Part designs with changing cross-sectional width as shown in Figure 5c) result in an inconsistent thermal profile due to additional heat transfer to adjacent WAAM beads. This can result in transitionary microstructure and phase content within the part and subsequently anisotropic material properties, as well as influence the geometry of the WAAM bead.

Figure 5 – Schematic of various heat transfer modes in WAAM that might occur depending on the stage of the build and part design



NOTE Figure 5 is adapted from [19].

6.1.8 Process modelling and simulation (see **6.3**) might be used to establish the thermal profile during WAAM and to guide process development. Variation of process parameters can also be used to reduce severity of the humping at the start and cratering at end of the WAAM bead. This can improve quality of deposited bead geometry as well as improving arc stability by maintaining a consistent CTD and stickout throughout the build.

6.2 Path planning

6.2.1 As in other AM processes, the workflow for WAAM path planning begins with representation of the part geometry in a CAD model which is then sliced into layers, from which the tool paths can be planned and subsequently a set of instructions sent to the motion system.

NOTE Adaptive slicing algorithms can be employed for 5-axis motion systems in DED, see ASTM F3147.

6.2.2 The path planning strategy affects the quality of the WAAM build in several ways. The WAAM process planner should consider that the use of weaving in the travel direction, rather than using linear motion, increases the heat input. By increasing the heat input, depending on the material and substrate thickness, this might increase residual stress and coarsen the microstructure. However, weaving can be helpful as a filling strategy for parts of changing cross-sectional thickness in the travel direction and lessening the number of starts and stops during the process. The number of starts and stops should be minimized to increase productivity of WAAM.

This might also minimize the incidence of defects at the start and end of deposition to improve overall build quality.

6.2.3 An alternating tool path direction can also be used to manage the humping at the start and cratering at end of the WAAM bead.

NOTE 1 Dimensional inaccuracy can be managed by creating an overbuilding path planning strategy, but this may require a greater volume of material to be deposited. This might have to be removed in post-processing, which can be detrimental for expensive or hard-to-machine materials.

NOTE 2 Tool paths might be planned to minimize non-value adding dwell periods. This can involve balancing deposition between multiple parts.

6.2.4 The stair-step effect in WAAM can be significant due to layer heights of several millimeters. Surfaces where the stair-step effect can be prioritized for avoidance should be aligned so that the resolution of the motion system, rather than the layer height, determines the surface profile.

6.2.5 The build direction is also significant to the development of residual stresses for part designs of high aspect ratios and to minimize distortions it is preferable for the shortest length to be aligned with the build platform. For part designs that contain a symmetry plane, it might be possible to deposit alternating between the top and underside of the substrate to neutralize the residual stress introduced.

6.3 Process modelling and simulation

6.3.1 Thermal, mechanical or thermo-mechanical models may be developed to simulate the WAAM process to optimize the process parameters and set up. The capability to simulate and model the WAAM process reduces the need for experimental trial and error optimization.

6.3.2 Although at this stage a process plan cannot be generated based on modelling results, they provide useful qualitative and, in some cases, quantitative information that can guide the development of the process plan. The range of variables that can be investigated includes residual stress, material properties, phase and microstructural development.

6.3.3 Simulation packages that allow the WAAM process to be modelled are available from several providers and are evolving in capability as the WAAM process matures. Welding simulation programs may also be adapted to investigate WAAM, providing super-position of WAAM beads is possible.

6.4 In-process monitoring and control

6.4.1 In-process monitoring and control should be adopted to ensure consistent and reliable equipment performance and process output in accordance with the part specification. Closed or open-loop feedback may be implemented, including manual intervention if appropriate.

6.4.2 The key process parameters that influence the heat input in WAAM can be monitored and might be corrected in-situ of deposition with a suitable closed loop feedback control algorithm. Variables that should be monitored include layer width and height, CTD, and arc stability, which can be determined from monitoring arc voltage and current. The wire feed speed and interpass temperature might also be monitored.

NOTE For guidance on monitoring and calibration of DED machines, see ASTM F3187.

6.4.3 The control system should automatically shut down upon an error signal and alert the WAAM engineer or operator. Where corrective measures are possible and cost-effective within the machine and software's capability, the process plan should be updated. Depending on the error identified, this might include re-calibration of the machine axes, adjustment of contact tip distance, fixturing, deposition parameters, or tool path.

6.4.4 Alternatively, CNC machining may be used to remove defective material, followed by manual or automatic adjustment of the process plan, to infill this area. Intermittent stress relief heat treatment may be used to reduce distortion to acceptable levels where excessive substrate deflection has been detected.

6.4.5 Interruption of the build cycle affects the thermal profile and hence quality of the build. In materials and parts where this is not acceptable, modification of process plan should be carried out to avoid pauses or breaks during the build, or to neutralize their effects in accordance with the part specification.

6.5 Evaluating the performance of the process parameters and path planning

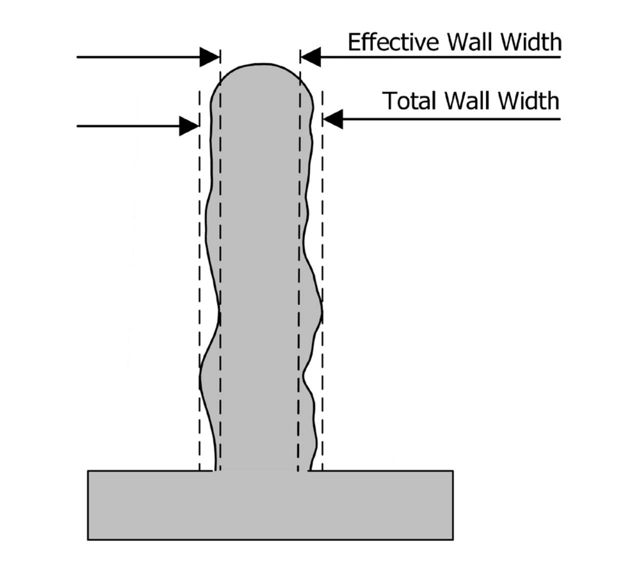
6.5.1 The efficacy of the WAAM process parameter and path planning routine can be evaluated using the performance measures shown in Table 2. Depending on the application, trade-off may be required between quality-related performance measures related to geometrical, physical and material properties, and cost.

Table 2 – Example of performance measures

Geometric properties	Physical properties	Material properties	Cost
• Layer height • Surface roughness • Effective wall thickness • Total wall thickness • Level of fit relative to simulated preform	• Porosity • Cracks • Micro-fissures • Distortion • Spatter • Lack of fusion	• Mechanical properties • Corrosion resistance • Fatigue life • Scatter and heterogeneity of material properties	• WAAM deposition rate • Additional processing total process time • WAAM and additional process consumables • Post-process total process time • Post-process consumables

6.5.2 Effective wall width (EWW) and total wall width (TWW), as shown in Figure 6, are performance measures related to WAAM geometric capability. The ratio of EWW to TWW is indicative of the level of finishing required with additional processes during the build or post-process.

Figure 6 – Schematic of a WAAM thin-wall section showing effective wall width and total wall width



7 Post-processing

7.1 Surface Finishing

Where the application requires a smoother surface finish than that provided by as-built WAAM, or to achieve a geometric or dimensional tolerance, finishing of the preform is usually applied by CNC machining although other material finishing processes might be applied.

7.2 Heat treatment

7.2.1 Heat treatment can be used in WAAM to improve as-built material properties or alleviate residual stress within the preform. Many metal alloys derive their strength from precipitation strengthening. Therefore, unless the thermal profile of the WAAM build can be controlled to provide the desired level of age hardening during the build, a post-process solutionizing and/or aging heat treatment should be used to obtain the desired mechanical properties relative to specification.

7.2.2 While heat treatment can be used to simultaneously achieve desired material properties and relieve residual stresses, the effectiveness of post-deposition stress relief temperature is limited by the size, metallurgy and physical properties of the part. Heat treatment might not be capable of achieving the required specification as a stand-alone process and adjustments or alternative post-processing can also be required.

NOTE 1 *The temperature that may provide ideal stress relieving conditions might affect as-built material properties through grain growth, recrystallization and development of deleterious phases.*

NOTE 2 *See PD CEN ISO/TR 14745:2015 for post-weld heat treatment parameters for steels and BS EN ISO 17663:2009 for quality requirements for heat treatment for welding and allied processes in welding.*

NOTE 3 *Due to the high levels of solute segregation and lack of surface treatment energy in WAAM for some materials, full recrystallization may not be possible through typical heat treatment times and temperatures.*

7.3 Inspection

7.3.1 A tactile or scanning measurement technique should be used to verify the preform geometry compared to the part specification and provide input to a CAM program for post-process finishing, where required, to achieve part specification. The data captured during inspection might also be compared to that predicted by process modelling and simulation.

7.3.2 Post-process inspection might not be required for every build if:

a) the data has already been captured during in-process monitoring and control; or

b) WAAM process capability is established using statistical process control.

7.3.3 Other inspection procedures might be necessary and include destructive and non-destructive testing.

NOTE *See ASTM F3187 and BS PAS 6011 for guidance on non-destructive testing methods.*

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