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Development, principles, process physics, implementation and current status

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A Review of Wire Arc Additive manufacturing: Development, Principles, Process Physics, Implementation and Current Status.

Prof. John Norrish¹, Dr Joseph Polden¹, Dr Ian Richardson²

Abstract

Additive manufacturing is now recognised as a viable alternative to processes such as casting, forging, and subtractive technologies such as machining. Wire arc additive manufacturing (WAAM) has emerged as a cost-effective additive manufacturing approach for component fabrication and a considerable body of literature on the subject has become available over the last 30 years. This review references the published work in a critical manner. It traces the development of WAAM, the principles of operation, materials considerations, process options, process physics, numerical simulation, process control, the current status and future research needs.

1. Introduction

The use of arc welding to deposit material, for repair and restoration of worn components, has been practiced in industry for many years, as has the manual creation of ‘art works’ by welders (Fronius, 2018). A patent on making decorative articles by manual deposition of metal by arc welding, was granted in 1925 (USA Patent No. 1,533,300, 1925) and the original production of complete industrial parts by welding, which was known as ‘Shape Welding’, was developed in Germany to produce large nuclear pressure vessel parts in the early 1980’s, (Grosse-Woerdemann 1980). Variants of shape welding were later reported in the USA (Kusmaul 1983). These early systems used simple but innovative mechanisation, and pre-programmed weld bead placement. This approach limited the applications to simple, usually symmetrical shapes. By utilising developments in robotic welding and improvements in arc welding technology, shape welding evolved into a process originally known as ‘Rapid Prototyping’ or ‘Shaped Metal Deposition’ (SMD) in the 1990s (Ribiero 1994). The range of processes which have developed are now commonly referred to as ‘wire arc additive manufacturing’ or more commonly by the acronym WAAM³. There are now many alternative additive manufacturing processes, but the term ‘direct energy deposition’ (DED) has been used to categorise the process in an overall additive manufacturing classification (ISO/ASTM 2015). WAAM specifically refers to the process in which a 3-dimensional metallic object is built up in successive layers using an electric arc as heat source and filler material in the form of a wire to provide the deposit material. The initial weld beads are normally deposited on a substrate, which may be removed after the component is completed. Details of this technique, the principles, features and characteristics, are discussed in the following sections.

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³ A term originally introduced by Cranfield University in the UK.

2. Basic Concepts

All additive manufacturing systems rely on the translation of a 3-dimensional (3D) model of a solid object into a series of layers. The thickness of the layers is dictated by the deposition process being used. The 'model' is usually a 3D computer aided design (CAD) file and the first stage in the process, in which the 3D solid model is divided into layers, is known as 'slicing'. The slicing software was originally developed for stereolithography and produces an STL file defining the geometric coordinates of the layers (Zhang 2003). The next step is the generation of a path which the heat source or deposition system needs to follow in each layer to generate the component profile as illustrated in figure 1. In wire arc additive manufacturing the material is deposited in the form of a weld bead and the control system needs to calculate the expected size of the deposit to establish the layer height and the path width. The welding head is usually carried by a robotic arm or a computer numerically controlled manipulation system, and this is programmed to follow the desired path.

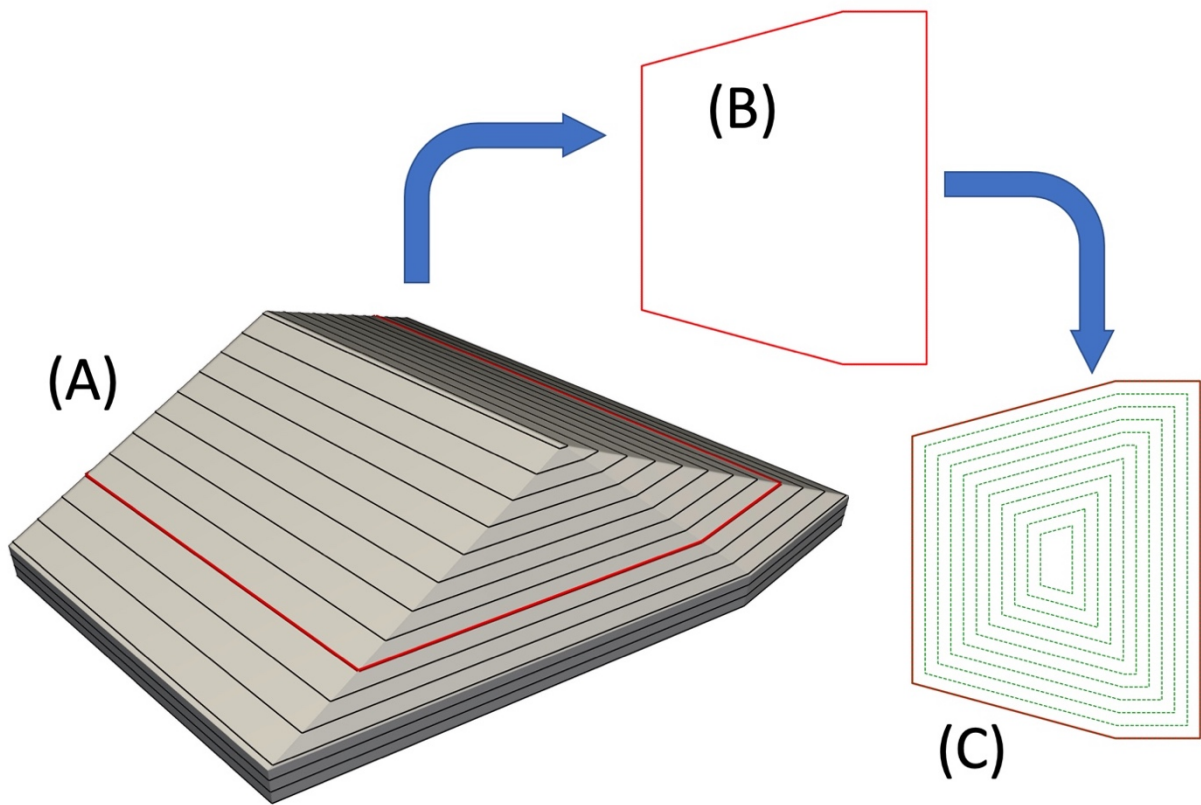


Figure 1. (A)CAD drawing, (B) slicing to produce layer, (C) path generation for weld runs in a layer.

Once the system is programmed with the path geometry and appropriate welding parameters, it may be run to produce the required part. In-situ and post-process monitoring may be employed to ensure the required quality is achieved. These steps have been described in more detail by (Ding 2015) and Pan *et al.* (Pan 2018). A simplified schematic illustration of the principles of WAAM is shown in figure 2.

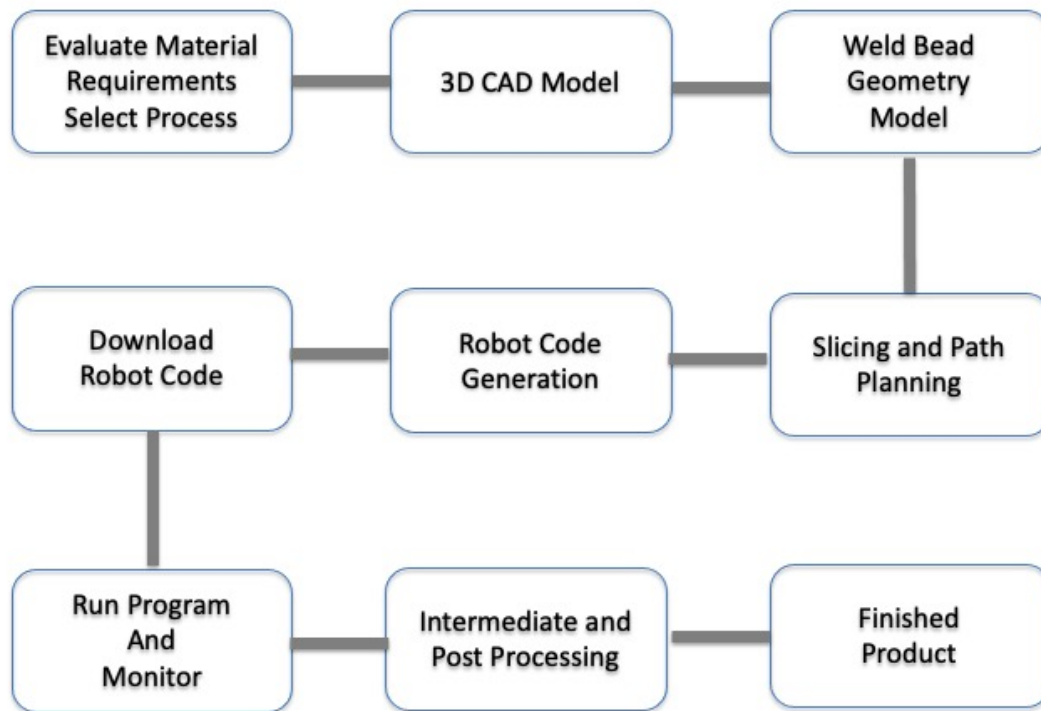


Figure 2. Schematic diagram of WAAM principles.

Slicing the 3D image (Figure 1) is usually carried out with a proprietary software program. For example, Ribiero (Ribiero 1995) used an AutoCad™ DXF file and the Autolisp™ slicing routine to produce horizontal layers. This approach is suitable for components which can be manipulated under the deposition system to build up the deposits vertically. The slicing routine produces a 2D layer but the inter-layer distance or the vertical (Z) direction is dictated by the expected bead height of the deposited material. This in turn depends on the process chosen and the welding parameters, although layer heights of 1.5 to 3.0 mm are typical. The determination of deposited layer dimensions is however a critical element of the process, the manipulation of the welding head cannot be programmed without this information. Numerical simulation may be used to predict bead dimensions and is discussed further in a later section of this review. Alternative slicing routines are required for more complex, multi-directional deposition (Ding 2016) and many alternative solutions have been developed. There are also many alternative path planning routines. As Pan (Pan 2018) points out, these may be simple geometric raster and zig-zag patterns or more complex paths to cater for specific part geometries. Many of the published papers on WAAM which are referenced below are based on the production of simple single wall test samples, but it is important to note that the real justification for the process is the production of relatively complex three-dimensional components such as that shown in figure 3.

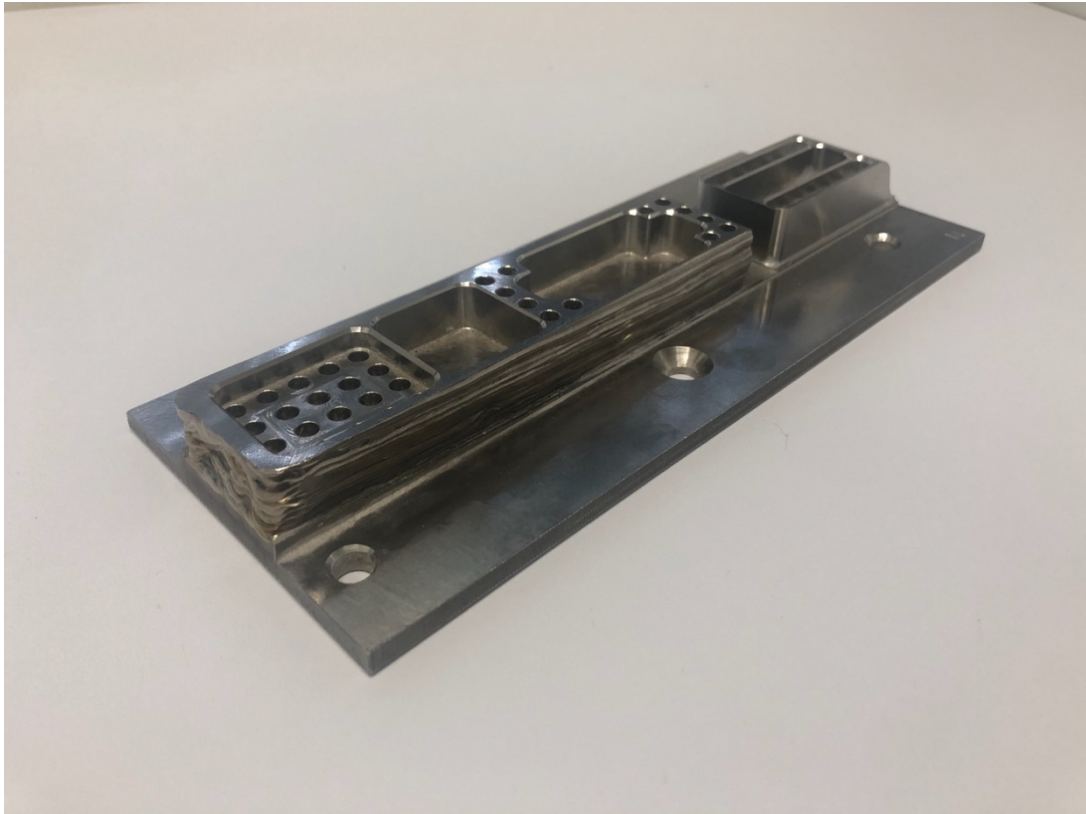


Figure 3. Typical three-dimensional titanium alloy component deposited with WAAM and part machined. (Courtesy of DMTC Ltd. Australia).

3. Process Options

Submerged arc welding (SAW) was one of the earliest processes used for ‘shape welding’ by WAAM, but its restricted positional capabilities and high heat input make it unsuitable for three-dimensional fabrication. It does however remain an appropriate choice for heavy build-up of rotatable components such as large mill rolls, track rollers and mineral processing parts. The most common processes now used for WAAM are gas tungsten arc welding (GTAW), plasma arc welding (PAW), and gas metal arc welding (GMAW).

The basic principles of these three processes are shown in figure 4. These have been described in detail elsewhere (Norrish 2006), but a brief description is given below in relation to their use for WAAM. In addition, some of the process enhancements specifically designed for WAAM are discussed.

Gas tungsten arc welding is probably the simplest process used for WAAM. Although there are several variants, the basic process uses an arc to generate a melt pool, and filler metal is introduced to the melt pool as a solid wire. The filler material is usually fed at a small angle to the workpiece surface and transferred to the front of the pool by contact and surface tension. Some recent variants of the process allow the filler wire to be added more obliquely, this is more conducive to multi-directional operation and the creation of 3D geometries.

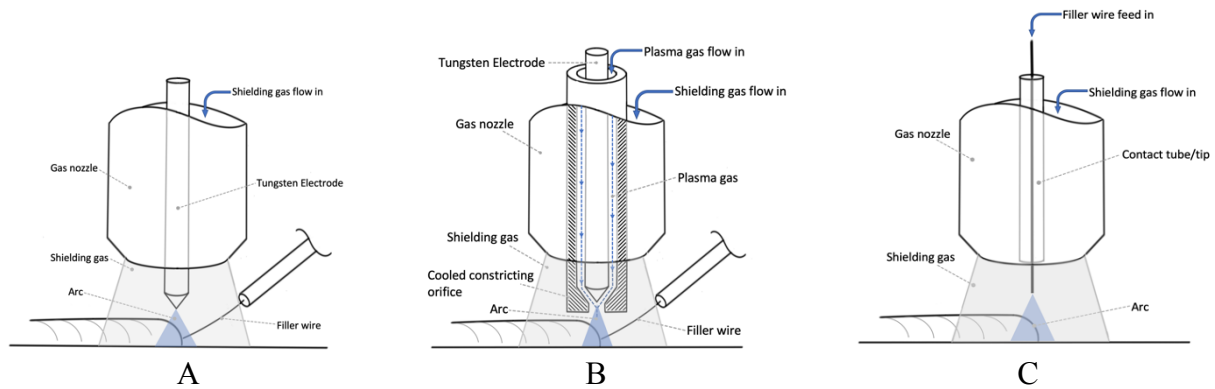


Figure 4. basic WAAM welding processes, (A) GTAW, (B) PAW, (C) GMAW.

The normal mode of operation for GTAW is direct current electrode negative for most materials whilst for aluminium alloys, AC operation is used. The shielding gas is normally inert (argon or helium). The arc generates a downward force on the weld pool due to the interaction of the magnetic field generated around the arc by the flow of charge carriers in the ionised arc atmosphere. This arc force is nominally proportional to the square of the current and since this may cause displacement of the molten weld bead, it is normally desirable to operate at relatively low currents to retain bead shape. One advantage of GTAW is that it operates in an inert atmosphere, this is ideal for materials such as titanium alloys which are susceptible to atmospheric contamination. GTAW arcs are generally very stable and less liable to process instabilities than consumable electrode processes. The disadvantages are that the process is relatively slow and under normal circumstances the wire orientation limits its directional ability.

Process enhancements have been developed for conventional GTAW welding (*e.g.*, keyhole and multi-cathode GTAW), but these are mainly designed to increase productivity and are not appropriate for WAAM. Some possible variants have been investigated and these are discussed below; the most suitable are variable polarity AC, hot wire GTAW, and oscillating wire feed. Variable polarity AC (VP-GTAW) was developed for welding of aluminium alloys, it is designed to improve control of cathodic oxide removal during the workpiece negative half cycle and heating during the electrode negative period. Wang *et al.* (Wang 2002) and (Wang 2004) reported the successful rapid prototyping of cylinders in AA4043 and the general influence of deposition parameters. Ayarkwa *et al.* (Ayarkwa 2017) made a more detailed study of the optimum balance of the cycle times during VP-GTAW additive manufacturing of aluminium AA 5556, and found that 20% electrode positive gave acceptable cleaning, lowest wall width and good deposit appearance for a single wall structure. In normal GTAW the filler wire is unheated but hot wire GTAW uses resistive heating from a separate power supply to heat the wire before it is introduced into the weld pool. Spaniol *et al.* (Spaniol 2020) developed a GTAW hot-wire system specifically for WAAM. This allowed higher deposition rates to be achieved with lower energy input, whilst providing improved dimensional accuracy. Unlike conventional GTAW, in hot-wire operation the wire is introduced at an angle of around 75 degrees to the plate surface and is melted prior to contact with the weld pool by resistive heating. The wire is fed continuously, and the steep angle of wire delivery means that a compact torch head can be used, and this allows multi-directional operation. The system developed by Spaniol (Spaniol 2020) (figure 5) also utilises ‘cathode-focussed’ GTA or CT-TIG (Lohse 2013); a modification of GTAW which utilises improved cooling of the cathode to increase constriction of the arc, increase arc pressure and current density.

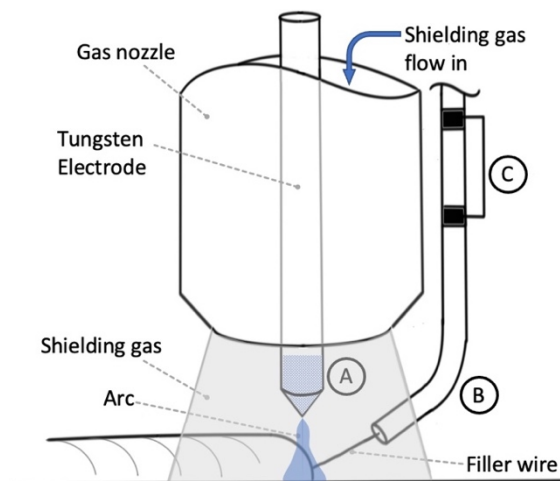


Figure 5. GTAW variant used by Spaniol for WAAM. (A) cathode focussed arc, (B) filler delivery tube, (C) indirect resistance preheating of the filler wire. After (Spaniol 2020).

Another much earlier variant of GTAW was known as ‘Dabber’ gas tungsten arc welding or ‘dabber TIG’ (Rudy 1982). This employs an oscillating wire feed to allow the instantaneous heat input to be reduced and has been used for additive repair of aircraft turbine parts. Recent developments have extended this technology (Silva 2018). By combining wire oscillation with near vertical hot wire addition (known by the proprietary names ‘TOP-TIG’ and ‘TIP-TIG’) a technique which is suitable for WAAM has been developed, as demonstrated by Zhang *et al.* (Zhang 2019). These options potentially increase the productivity of GTAW WAAM whilst allowing increased control of bead profile and energy input by decoupling the arc heating and material transfer.

Plasma arc welding (PAW) is really an extension of GTAW (figure 4a). The different torch arrangement, as shown in figure 4b, involves the use of a water-cooled constricting orifice between the tungsten electrode and the workpiece. A plasma gas is supplied through the orifice and the normal shielding gas is supplied separately. The electrode is normally the cathode, the workpiece is the anode, and the constricting orifice is initially supplied with a positive bias from a low current pilot arc source. The constricting orifice has the effect of preventing ionisation close to its inner wall due to its low temperature. This increased thermal constriction increases the current density in the arc column and also increases the Lorentz force and pressure of the arc on the workpiece. The increased pressure is inversely proportional to the orifice diameter and nominally proportional to the square of the arc current. Under normal circumstances the increased pressure may be a problem in WAAM due to the possibility of weld bead displacement or a phenomenon known as ‘humping’. It may be controlled by careful selection of the operating parameters; particularly current, orifice diameter and travel speed. As in GTAW WAAM, the wire is normally fed into the front edge of the weld pool and is transferred by surface tension. Like GTAW, the process is most suitable for reactive metals such as titanium. For example, (Martina 2012). Lin *et al.* (Lin 2016) used low frequency pulsed PAW to deposit Ti-6Al-4V walls. The reduced heat input compared with continuous PAW was claimed to give improved deposit surface quality and properties suitable for aerospace applications. An innovative variant of PAW for WAAM was introduced by Jia *et al.* (Jia 2020); in this case the filler wire is fed into the arc just below the constricting plasma orifice and transferred to the weld pool as small molten droplets. The authors claim excellent surface finish and a wide operating tolerance range. Unlike conventional GTAW and PAW, the metal is fed into the centre of the pool and theoretically the torch travel may be omnidirectional, offering greater flexibility for deposition path control.

Gas metal arc welding (figure 4c) was one of the first processes used for robotic WAAM and probably offers the best productivity and ease of integration with 3D component generation. GMAW WAAM is suitable for most materials, with the possible exception of those which suffer adverse reactions with the active gas components of some shielding gas mixtures. The filler wire is fed through the central axis of the torch and the arc, making it truly omnidirectional. The features of the process are largely controlled by the mode of metal transfer from the filler wire to the workpiece. The physics of transfer modes and their characteristics have been described elsewhere (Lancaster 1986). These are summarised in table 1.

Table 1 Summary of GMAW transfer modes relevant to wire arc manufacturing

Main Group	Conventional sub-group	Waveform Controlled Mode
Free Flight	Globular Drop Spray Conventional Spray Streaming Spray	Pulsed Transfer Modified Spray
Short Circuit Mixed mode	Short arc, Dip Transfer	Controlled short Circuit Short Circuit-Pulsed Variable polarity

After: (Norrish.J, 2017).

Originally, conventional short circuit transfer was used to manufacture prototype components (Ribeiro 1995). More recently many researchers have used one of the waveform control modes. Unfortunately, most of the publications on WAAM refer to the processes used by their proprietary names (CMT, Cold Arc, STT, RMD etc.) but they all belong to the waveform controlled short circuit mode. (Norrish 2014). This type of transfer provides a controlled weld bead profile and is very suitable for single wall deposits.

While waveform controlled short circuit transfer is the most suitable GMAW mode for single wall deposits due to the relatively low heat input; for filling larger components spray or pulsed transfer may be used. The two modes may be combined to form a thin ‘shell’ followed by filling with the higher heat input variants. Several examples of the application of the various operating modes are also referenced in the ‘materials’ section of this paper.

4. Process Physics

4.1 Introduction

The underlying process physics governs the suitability of any WAAM process for a given application, and also determines the control and modelling strategies required. By definition, the processes covered here are based on the use of an electric arc to form the melt-pool. The type of arcs considered are sustained electrical discharges in ionised gases. Energy is transferred to the workpiece by dissociation, ionisation and recombination of gas and metal vapour, electron and ion transport, conduction, convection and radiation. The key features of this type of heat source for additive manufacture are the control of arc energy, melting efficiency, and the influence on melt pool size, shape and stability. The processes of interest derive from conventional welding processes, the physics of which has been considered by a number of authors. Although there is still a great deal that is not yet fully understood, even though the subject has been examined in some detail. Essentially, the processes can be described in terms of continuity equations of mass, charge, momentum and energy, together with Maxwell’s equations and a generalised Ohm’s law (Lancaster 1984), viz:

Conservation of mass requires

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad \dots [1]$$

where ρ is the mass density and $\mathbf{u}$ the velocity. Conservation of charge is given by

$$\frac{\partial q}{\partial t} + \nabla \cdot \mathbf{J} = 0, \quad \dots [2]$$

where q is the charge per unit volume and $\mathbf{J}$ the current density. Momentum conservation is described by the Navier-Stokes equation

$$\left(\frac{\partial \rho \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \rho \mathbf{u} \right) = -\nabla P + \mu \nabla^2 \mathbf{u} + \mathbf{J} \times \mathbf{B} + (\rho - \rho_\infty) \mathbf{g}_z, \quad \dots [3]$$

where P is the pressure, μ the dynamic viscosity, ρ_∞ the gas density outside the discharge, $\mathbf{B}$ the magnetic flux density and $\mathbf{g}_z$ the acceleration due to gravity. Here inertial terms are balanced by a pressure gradient, viscous stress, electromagnetic forces and a buoyancy force. The assumption of incompressibility, which is often made in the literature, requires the divergence of the flow to be zero and is acceptable provided changes in velocity do not have a significant influence on the internal energy (temperature). Energy conservation requires that the energy generated by the flow of electric current is balanced by enthalpy, radiative and conductive terms

$$\mathbf{u} \cdot \nabla \left(\rho h + \frac{\rho \mathbf{u}^2}{2} \right) - \nabla \cdot (-\kappa \nabla T) + U = \mathbf{J} \cdot \mathbf{E}, \quad \dots [4]$$

where κ is the thermal conductivity, h the enthalpy, U the radiation source strength (energy per unit volume) and $\mathbf{E}$ the electrical field strength.

The generalised Ohm's law takes the form

$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}), \quad \dots [5]$$

where σ is the electrical conductivity and Maxwell's equations may be expressed as

$$\begin{aligned} \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \end{aligned} \quad \dots [6]$$

where μ_0 is the magnetic permeability of free space and ε_0 the permittivity of free space. . The time derivatives in equations 6 are often neglected ($\rightarrow 0$) because the characteristic response of the electromagnetic fields is much faster than that of the thermal and fluid flow fields.

In the above magnetohydrodynamic description, the thermodynamic quantities density, viscosity, thermal conductivity, enthalpy and radiation source strength are functions of temperature and pressure only for any given material. The momentum and energy conservation equations are often cast in different forms, with additional source and/or sink terms (*e.g.*, (Tanaka 2006), (Hertel 2013)); depending on the details of the phenomena being described (*e.g.*, arc, metal transfer, weld pool, flow compressibility *etc.*) however, the overall structure

of the description does not change substantially. The magnetohydrodynamic description implicitly assumes equilibrium through the Navier-Stokes equation and is not valid in the electrode regions of the arc discharge, where collision frequencies are insufficient to result in thermal equilibrium. An analysis of the physics affecting the electrode regions lies outside the scope of this review; interested readers may refer to (Shirvan 2016, Nemchinsky 1994) for further information.

Due to the similarities between the wire arc additive manufacturing processes and conventional welding processes, the same basic physical description applies. Differences arise in consideration of the boundary conditions, in particular with regard to the melt-pool. In conventional welding, the pool is generally in contact with a substantial area of the substrate or already deposited weld metal. Generally during additive manufacturing, a smaller fraction, and in the case of thin-walled structures, a much smaller fraction of the melt-pool surface is in contact with the substrate. This alters the fluid flow within the melt-pool and the subsequent energy transport to the substrate. The different substrate shapes also affect heat flow and cooling rates, which in turn influence the residual stresses, distortion microstructure and mechanical properties of the manufactured component.

4.2 Forces acting on the melt-pool

A number of physical factors influence the shape and properties of a deposited weld bead, these include electromagnetic forces, melt-pool convection, surface tension, gravity, buoyancy as well as arc generated forces and metal transfer characteristics. Some of these factors are considered in more detail below. in the Ou *et al.* (Ou 2021) have examined the shape of a weld deposit during wire arc additive manufacturing using an enthalpy-porosity, volume of fluid approach, together with a surface energy minimisation method, taking account of arc pressure and droplet impact on the melt-pool. They express the conservation of momentum equation as

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \nabla \cdot (\mu \nabla \cdot \mathbf{u}) + S. \quad \dots [7]$$

The source term S (Ou 2021) is given by

$$S = -\nabla P + \rho \beta \mathbf{g}_z (T - T_L) + f_l \frac{d\gamma}{dT} (G_t) \frac{\Delta x_i}{A_s} - C \left[\frac{(1-f_l)^2}{f_l^3 + \varepsilon_z} \right] u_j \quad \dots [8]$$

where β is the volumetric coefficient of thermal expansion, T_L the liquidus temperature, γ the surface tension, G_t the spatial temperature gradient vector, Δx_i the length of the control volume in dimension i and A_s the surface area of the control volume. It should be noted that details included in the source terms differ dependent upon the application and conditions under consideration; factors such as arc pressure, electromagnetic forces, drag forces, metal droplet impingement etc. may be included where relevant. The second term on the right-hand side of equation 8 represents a buoyancy force and the third term the Marangoni force. The fourth term is a frictional dissipation term, which becomes increasingly dominant moving from the edge of the mushy zone toward the solid region when the liquid fraction f_l is less than one. The liquid fraction is assumed to vary linearly with temperature between the solidus T_S and liquidus T_L temperatures, *i.e.*,

$$f_l = \begin{cases} 0 & (T \leq T_s) \\ \frac{T-T_s}{T_L-T_s} & (T_L < T < T_s) \\ 1 & (T \geq T_L) \end{cases} \dots [9]$$

The parameter C is generally chosen arbitrarily; it must be high enough to ensure that the flow comes to a standstill in the solid region but not so high that it causes numerical instabilities, and ε_z is included to avoid division by zero. The selection of the mushy zone constant C can have a significant influence on the computed melt-pool shape. Ebrahimi *et al.* (Ebrahimi 2019) have shown that sensitivity to the constant C increases when the Péclet number Pe^* , which represents the ratio of the rate of heat advection to the rate of heat diffusion close to the melt-pool boundary, is much greater than one. Here

$$Pe^* = \frac{|u| m_t}{\alpha}, \dots [10]$$

where m_t is the thickness of the mushy zone and α the thermal diffusivity.

For a gas metal arc deposit, Ou *et al.* (Ou 2021) noted that peak temperatures are over estimated when fluid flow in the melt-pool is neglected and that depending on the material properties, melt-pool flow can have a significant influence on the calculated deposit height and width. Péclet numbers $\mathcal{O}(10^2)$ indicate that convective flow is a dominant heat transfer mechanism inside the molten pool.

Arc pressure P_a , which depresses the front of the melt-pool pushing molten metal to the rear, is reported to have the greatest influence on deposit height in comparison to other factors such as droplet impact and the Marangoni force. Bai *et al.* (Bai 2018) approximate arc pressure as

$$P_a = \frac{F_{arc}}{2\pi\sigma_p^2} \exp\left(-\frac{x_b^2 + y_b^2}{2\sigma_p^2}\right), \dots [11]$$

where F_{arc} is the time dependent force exerted by the arc plasma, σ_p the standard deviation of the arc current distribution and x_b and y_b are cartesian distances to the arc centre. Corradi *et al.* (Corradi 2020) quote the arc force as

$$F_{arc} = \frac{\mu_o I^2}{8\pi} \left(2 \ln\left(\frac{R_o}{R}\right) + 1\right), \dots [12]$$

where μ_o is the permeability of free space, $I(t)$ is the arc current, R_o the radius at the arc root and R the radius on the melt-pool.

Equation 11 implicitly addresses the electromagnetic force generated by the current flow through the arc. Bai *et al.* (Bai 2018), describe the electromagnetic force per unit area in the melt-pool by the following (simplified) expressions:

$$\begin{aligned} F_x &= -\frac{\mu_m I^2}{4\pi^2 \sigma_j} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right] \left(1 - \frac{z}{L_o}\right)^2 \left(\frac{x-x_o-vt}{r}\right) \\ F_y &= -\frac{\mu_m I^2}{4\pi^2 \sigma_j} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right] \left(1 - \frac{z}{L_o}\right)^2 \left(\frac{y-y_o}{r}\right) \end{aligned} \dots [13]$$

$$F_z = -\frac{\mu_m I^2}{4\pi^2 \sigma_j} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \left(1 - \frac{z-z_o}{L_o}\right)$$

Where μ_m is the permeability, which is the product of μ_o , the permeability of free space and μ_r , the relative permeability, σ_j is the distribution of current density L_o the plate thickness and the radius r is given by $r = ((x - x_o - vt)^2 + (y - y_o)^2)^{0.5}$. In common with all evaluations of electromagnetic force in molten metal melt-pools, the formulation here implicitly assumes a symmetrical current dispersion, which is unlikely to be the case in practice, due to fluid flow, temperature variations and associated differences in electrical conductivity in the melt-pool as well as the asymmetric placement of the current return cable. Unfortunately, there are as yet no generally accepted methods for determining the asymmetry of the current flow in the melt-pool in a physically realistic manner.

The electromagnetic force arises from the volume integral of the vector cross product of current density and magnetic flux density (3rd term on the right-hand side of equation 3). For a symmetric conductor, this typically produces an expression of the form $(\mu I^2/4\pi)$ multiplied by a geometric distribution factor. A radial (pinch) pressure is generated due to the current-magnetic field interaction and in the case of a uniformly diverging current flow, an axial force $F_{em,z}$ is generated such that

$$F_{em,z} = \frac{\mu I^2}{4\pi} \ln\left(\frac{r(z)}{r(z=0)}\right), \quad \dots [14]$$

which contributes to the arc pressure, to droplet detachment and transport through the arc during gas metal arc welding and to convection in the molten metal melt-pool.

The surface tension force F_γ may be written (Ebrahimi 2021)

$$F_\gamma = \gamma \kappa \hat{\mathbf{n}} + \frac{d\gamma}{dt} [\nabla T - \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \nabla T)], \quad \dots [15]$$

where κ is the surface curvature and $\hat{\mathbf{n}}$ the surface unit normal vector. The variation of surface tension γ is generally represented by the formulation of Sahoo *et al.* (Sahoo 1988), which takes account of the influence of temperature and surfactants

$$\gamma = \gamma_m^o + \left(\frac{\partial \gamma}{\partial T}\right)^o (T - T_m) - RT\Gamma_s \ln \left[1 + k_l a_s \exp\left(-\frac{\Delta H^o}{RT}\right)\right] \quad \dots [16]$$

where γ_m^o is the surface tension of pure molten-metal at the melting temperature T_m , R the gas constant, Γ_s the surface excess at saturation, k_l a factor related to the entropy of segregation, a_s the activity of the solute, ΔH^o the standard heat of adsorption, and $(\partial \gamma / \partial T)^o$ the temperature coefficient of the surface tension of the pure molten-metal. For the iron-oxygen and iron sulphur binary systems, the entropy factors k_l are 1.38×10^{-2} and 2.13×10^{-2} respectively and the standard heats of adsorption are 1.463×10^8 J kg⁻¹ mol⁻¹ and 1.662×10^8 J kg⁻¹ mol⁻¹ respectively.

The contribution to convective flow in the weld pool due to the surface tension gradient can be significant. In the case of iron systems with low levels of surfactants, the surface tension gradient is negative, and an outward flow is generated, driven from the high temperature to low temperature regions, (Lancaster 1986). With high levels of surfactants, the surface tension gradient is positive, and an inward flow is formed, driven from low temperature to high

temperature regions. The former results in a wide, shallow melt-pool, the latter in a deeper, narrower pool. The surface tension γ and surface tension temperature gradient $\partial\gamma/\partial T$ are illustrated for the iron-oxygen system in figure 6. At intermediate surfactant levels, more complex flows can be formed, with outward driven flow occurring in the higher temperature region and inward flow in the lower temperature regions, dependent on surfactant concentration and the temperature at which the surface tension temperature gradient changes sign.

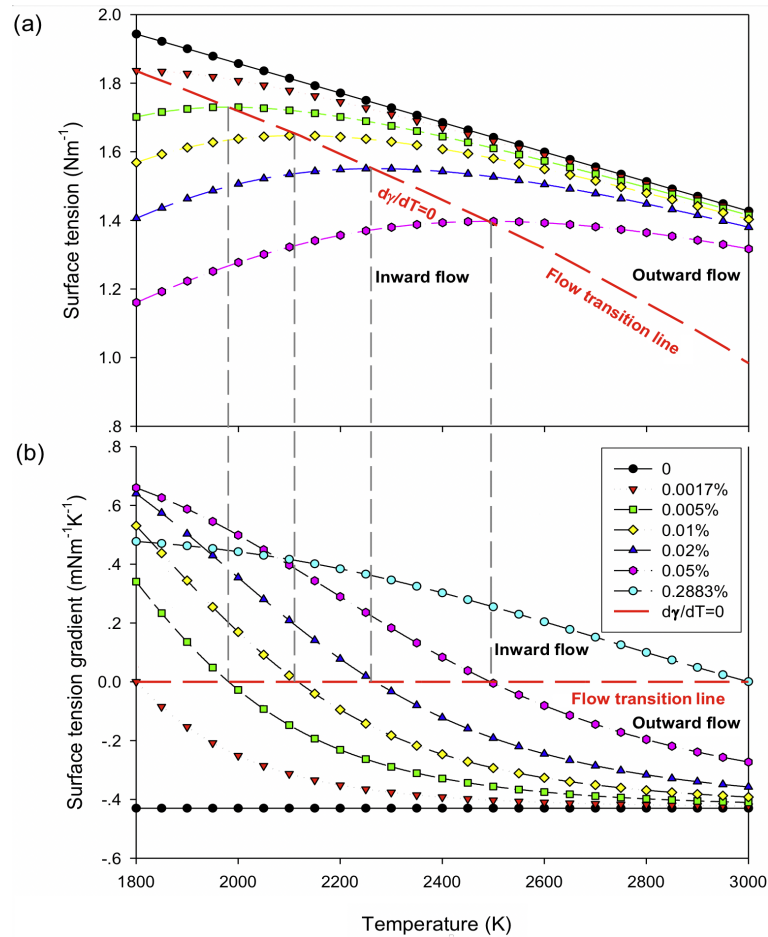


Figure 6 (a) Surface tension and (b) temperature coefficient of surface tension as a function of temperature and oxygen concentration in the Fe–O binary system (after Zhao 2010).

In the presence of (some) inward driven flow, Zhao *et al.* (Zhao 2009) have also shown that the vortex patterns formed in the rear of a moving weld pool oscillate due to minor imbalance in spatial distribution of surface tension forces acting from either side of the pool. Surface tension driven fluid flow cannot therefore be treated as axi-symmetric and the associated energy transport to the substrate cannot strictly be regarded as time invariant.

Aucott and co-workers (Aucott 2018) have directly visualised the flow in gas tungsten arc generated steel melt pools with different surfactant concentrations. They show vortex behaviour, with flow velocities in the range 0.13 to 0.54 ms^{-1} , which agrees reasonably well with the results from numerical predictions (see for example Kidess *et al.* (Kidess 2016)). Surface tension is often found to be significant when accounting for the forces acting on the weld pool (Aucott *et al.* (Aucott 2018), Tanaka and Lowke (Tanaka 2006) and may be the

dominant force driving metal flow and corresponding energy transport in liquid metal melt pools (see for example (Ou 2021), (Bai 2018), (Rios 2018)). Corradi *et al.* (Corradi 2020) examined the effect of longitudinal and circular magnetic oscillation of a gas tungsten arc on the integrity of a thin wall titanium alloy deposit and conclude that surface tension may increase as a result of the applied oscillation. They also noted that the peak temperature in the melt pool is reduced during arc oscillation. Changes in the surface tension driven flow are presumably related to the temperature redistribution, although no explicit reasoning is provided. Ríos *et al.* (Rios 2018) explain the shape of the weld bead in a similar thin-walled titanium alloy deposit based on the dominance of the surface tension force over the hydrostatic force.

The shear stress τ_a acting on the weld pool surface due to radial outward flow of plasma across the surface after impingement of the arc jet may be estimated from an expression of the form

$$\tau_a = \mu_p \frac{du_p}{dz}, \quad \dots [17]$$

where μ_p is the dynamic viscosity of the plasma, u_p the plasma velocity and z the coordinate perpendicular to the melt-pool surface (Wang 2017, Lee 1995). However, it is more appropriately incorporated into the Navier-Stokes equation (2nd term on the right-hand side of equation 3). Tanaka and Lowke (Tanaka 2006) predict a shear stress of around 40 Pa for a stationary 150A argon TIG arc, comparable to the predicted magnitude of the surface tension induced stress. The true shear stress will depend upon the contour of the weld pool and boundary layer effects, which may be expected to occur when the Reynolds number exceeds about 10^2 ; these factors are not generally included in the published process models.

The buoyancy force is often computed from a Boussinesq approximation, which ignores inertial differences (as shown in equation 8, 2nd term on the right-hand side) *viz*:

$$F_b = \rho \beta g_z (T - T_L), \quad \dots [18]$$

The buoyancy force is generally small compared to the electromagnetic, plasma drag, and surface tension driven forces, particularly when operating in the down-hand orientation, where the higher melt-pool temperatures occur on the upper melt pool surface (Bai 2018, Ou 2021, Kim 1997).

4.3 Wire Melting and Metal transfer

The wire addition during wire arc additive manufacturing may be broadly split into two classes, none-axial wire additions, typical of WAAM with the TIG and Plasma welding processes and axial wire additions typical of WAAM with the GMAW process. For TIG and Plasma processes, the literature on metal transfer is rather sparse and dominated by reports on experimental studies. Taguchi *et al.* (Taguchi 1979a,b) describe different stages of metal transfer from the wire to the melt-pool in terms of the droplet growth duration t_g and the contact duration between the wire and melt-pool t_c . Four transfer modes are characterised as follows:

Mode 1,	$t_c \gg t_g$	the wire is virtually in constant contact with the melt-pool
Mode 2,	$t_c \approx t_g$	contact time is approximately equal to the droplet growth period
Mode 3,	$t_c \ll t_g$	large droplets grow, transfer is rapid
Mode 4,	$t_c \rightarrow 0$	droplets transfer without bridging between the wire and pool

In the absence of contact with the melt-pool (mode 4), melting occurs due to heat transfer from the arc plasma, resulting in local plasma cooling. Droplets form and are held in place on the wire tip due to surface tension, while gravity and drag from the flowing arc plasma act as detachment forces. In cases of high plasma velocities, such as plasma welding with high currents and high plasma gas flow rates, or when the wire tip is close to the arc axis at moderate to high currents, relatively small metal droplets can be detached from the wire tip and transferred to the melt-pool. In the absence of such conditions, the metal droplet continues to grow until gravity and plasma drag overcome the surface tension and metal drips into the melt pool in relatively large globular droplets. The force due to gravity is simply determined by the product of the droplet mass and the acceleration due to gravity. The drag force F_d may be estimated from an expression of the form

$$F_d = \frac{1}{2} C_d A \rho_p u_p^2 \quad \dots [19]$$

where C_d is the drag coefficient, A the cross-sectional area perpendicular to the flow, ρ_p the plasma density and u_p the plasma velocity (Lancaster 1986), The drag coefficient is estimated from the Reynolds number Re

$$C_d = \frac{K_1}{Re} - \frac{K_2}{Re^2} + K_3 \quad \dots [20]$$

The equation is formulated as a curve fit to the experimentally derived drag coefficient - Reynolds number relationship (Morsi 1972). Li *et al.* (Li 2015) quote values for the constants K_1 to K_3 of 46.5, 116.67 and 0.6167 respectively, yielding drag coefficients of 2.1 to 1.4 for Reynolds numbers between 10 and 100. These differ slightly from the tabulated values presented by Morsi and Alexander for spherical particles in air, which lie between 4.1 and 1.07 for the same range of Reynolds number.

For cold wire addition to GTAW and Plasma processes, mode 1 is generally favoured as it offers a smooth and continuous transfer of material into the melt pool, particularly when the wire is fed at a relatively shallow angle to the workpiece surface. Ríos *et al.* (Rios 2019) report that mode 1 has the widest parameter operating envelope, however, by its nature, it does not lend itself to droplet detection, which could be advantageous for control purposes. Mode 1 is typically achieved when the wire is fed close to or in contact with the substrate at the edge of the melt-pool. Mode 2 generally occurs when the wire tip is located further away from the substrate surface. In this case, metal is transferred in droplets and the droplet detachment can be detected as a dip in the arc voltage. Both modes 1 and 2 offer stable metal transfer conditions. Transfer of relatively large droplets (mode 3) is more likely to occur when the angle of consumable addition (relative to the substrate surface) is high. Transfer in mode 3 is generally less stable than modes 1 & 2 and associated with spatter formation.

Wire melting and metal transfer in WAAM with the gas metal arc process is governed by the same physics as that for gas metal arc welding. Wire melting rate may be determined from the Halmøy equation

$$W_m = \alpha I + \beta \ell I^2 \quad \dots [21]$$

where α is a constant related to arc heating and β is a constant related to resistance heating. A derivation of this expression, which is instantaneously valid, is presented by Halmøy (Halmøy 1979). The relationship is appropriate for currents above a few tens of amperes. Under stable

welding conditions, the wire feed rate W_R is adjusted to match the melting rate. The typical response rate of a wire feed system is much lower than that of the welding current, hence during pulsed welding, the wire feed rate must match the mean melting rate $\bar{W}_m$ which is given by

$$\bar{W}_m = \int_{\text{one pulse cycle}} W_m(I(t)) dt. \quad \dots [22]$$

For a pulse with a purely square waveform

$$\bar{W}_m = \alpha \bar{I} + \beta \ell \left(\bar{I}^2 + \frac{(I_p - I_b)^2 t_p t_b}{(t_p + t_b)^2} \right), \quad \dots [23]$$

where t is time, subscripts p and b refer to the peak and base pulse segments respectively and $\bar{I}$ is the mean current. Allum (Allum 1983) showed that for resistive wires and large differences between peak and base current, the excess melting term $\beta \ell (I_p - I_b)^2 t_p t_b / (t_p + t_b)^2$ can account for up to 40% of the total wire melted. As welding power increases linearly with current and burn-off has a current squared component, high deposition rates can run the risk of reduced fusion in the substrate and hence, lack of fusion defects. For more complex waveforms, such as those associated with controlled transfer processes, equation 22 remains valid; the form of the expression for $\bar{W}_m$ (equation 23) will change, but the basic structure; *i.e.*, a resistive heating component with elements of current squared dependencies, should remain.

In waveform-controlled transfer the current varies considerably at a relatively high frequency (around 100 to 200 Hz) and the transient current must be considered. This is particularly important in the case of the calculation of arc energy and heat input. As Norrish (Norrish 2017) has pointed out and as required in ISO/TR 18491 (ISO/TR 18491, 2015), arc energy should not be based on average current and voltage but should be calculated on the basis of instantaneous energy (IE) formed from the sum of all instantaneous elements (divisions) in the waveform such that

$$IE = \sum_{n=1}^n (I_i U_i t_i) \quad \dots [24]$$

where I_i is an element of instantaneous current, U_i the corresponding instantaneous voltage and t_i the time interval between successive instantaneous measurements. The true energy E (heat input) is then given by the instantaneous energy divided by the weld length. Measured errors between average and true arc energy may vary between 5 to 20%, and this may have a significant effect on the modelling and procedure control in GMAW-WAAM (Norrish 2017).

Whilst conventional short circuit transfer is commonly used in positional welding and has been found to be applicable to WAAM, the transfer of material from the wire tip is somewhat statistically variable. This is mainly due to the potentially high short circuit currents which can result in explosive rupture of the thin bridge connecting the wire to the weld pool. Optimised operating parameters are a function of the static and dynamic characteristics of the power supply, set voltage, secondary circuit inductance and wire feed speed, with limited scope for adjustment. The waveform controlled short circuit systems allow the transient current to be controlled with respect to time, in response to the various phases of the short circuiting and arcing cycles. This enables preheating of the wire tip prior to short circuiting, reduction of the short circuit current, and transfer of material from the wire to the weld pool predominantly under the influence of surface tension. To extend the control range of the process, the wire feed

may be reversed momentarily during the short circuit, this aids the clearance of the short circuit and allows higher wire feed speeds to be used without the risk of ‘stubbing’. Wire retraction allows some slight decoupling of the dependency of arc power on wire feed and improves overall process stability. Although the proprietary names often incorporate the term ‘cold’ in fact the arc energy is still governed by the current and is very similar to that of conventional short circuit transfer. The welding systems used for WAAM are usually factory pre-programmed with the key waveform parameters and while some minor output adjustment is available, the main relationship between wire feed speed and current is predetermined for given consumable types by the manufacturer, giving a synergic control response.

Metal transfer during gas metal arc welding has been examined by a number of researchers. Broadly speaking, transfer at low frequencies of relatively large droplets can be approximated by consideration of the static forces acting on the droplet. These comprise, gravity, surface tension, electromagnetic forces, a drag force due to flow of the surrounding gas and a reaction force due to vaporisation from the surface, see for example Lancaster, (Lancaster 1986), Choi *et al.* (Choi 2001). At high droplet transfer frequencies and with droplets smaller than the wire diameter, the transfer behaviour is dominated by dynamic forces (Choi *et al.* (Choi 2001), and Allum, (Allum 1985); *i.e.*, by the inertia of the moving liquid metal on the wire tip. According to Lowke (Lowke 2009), the transition from globular to spray transfer occurs when the pressure at the centre of the base of the molten drop from the electromagnetic pinch force exceeds the surface tension pressure, which occurs when

$$I = 2\pi \left(\frac{\gamma D}{\mu_0} \right)^{0.5} \dots [25]$$

where D is the wire diameter and the other symbols have their usual meaning. More recently, several authors have reported on integrated models describing the dynamic development of molten droplets (see for example Zhao 2018, Hertel 2013, Ogino 2016) a detailed review of these however lies outside the scope of the present work.

5. Numerical Simulations

Proponents of wire arc additive manufacturing are primarily interested in building 3D structures with appropriate control over the dimensions and properties. Numerical simulations based on an understanding of the process physics can be employed to predict important aspects of the geometry and properties of the deposited component, including deposit shape and size, melt pool stability, residual stresses, distortion microstructure and mechanical properties.

5.1 Bead geometry prediction

As explained above, bead geometry prediction is an essential prerequisite of layer height and width control for path planning and this subject has been addressed by a number of authors. Using techniques ranging from the fitting of geometric profiles to experimental results to assessment of fluid flow and solidification of the melt-pool. Ogunbiyi (Ogunbiyi 1997) and Ribiero (Ribeiro 1997) used analysis of variance and regression models based on experimental trials. These techniques provide satisfactory results but are limited to the process envelope defined in the experimental trials. Karmuhilan (Karmuhilan 2018) used a similar experimental approach and ANOVA analysis of variance to identify significant variables. This was followed

by the use of an artificial neural network (ANN) to produce feed-forward analysis and predictive modelling of bead geometry based on the significant process variables. Good correlation with experimental results was found, but again the applicability of the model remains limited to the specific training data.

The three-dimensional curved surface profile of a bead deposit can be calculated from the magneto-hydrodynamic equations governing the melt-pool together with appropriate boundary conditions. A surface energy minimisation approach based on the method of Lagrange multipliers has been explored by Kim *et al.* (Kim 2003), Zhang *et al.* (Zhang 2004) and Hejripour *et al.* (Hejripour 2018). The total surface energy includes the surface tension energy, the potential energy due to gravity, the work performed by the arc force displacing the weld pool surface and the energy contribution due to droplet impingement. The governing equation for the free surface profile (Ou 2021) is given by

$$\rho g_z \phi = \lambda + P_a + P_d - 2\gamma\kappa + \gamma \left[\frac{(1+\phi_y^2)\phi_{xx} - 2\phi_x\phi_y\phi_{xy} + (1+\phi_x^2)\phi_{yy}}{(1+\phi_x^2+\phi_y^2)^{3/2}} \right], \quad \dots [26]$$

where ϕ is the height function, subscripts x and y indicate derivatives of the height function, γ is the surface tension, κ the surface curvature, λ the Lagrange parameter, g_z the acceleration due to gravity and ρ the liquid density. In common with equation 11, the arc pressure P_a is

$$P_a = \frac{\mu_m \eta I^2}{8\pi \sigma_p^2} \exp\left(-\frac{x_b^2 + y_b^2}{2\sigma_p^2}\right), \quad \dots [27]$$

where η is the arc efficiency, I the current and σ_p the standard deviation of the arc current distribution. The droplet pressure distribution is

$$P_d = \frac{\rho v_d f_d}{\pi r_d^2} \exp\left(-\frac{2(x_b^2 + y_b^2)}{r_d^2}\right), \quad \dots [28]$$

where v_d is the droplet velocity, r_d the droplet radius and f_d the averaged volumetric transfer frequency (units of $\text{m}^3 \text{s}^{-1}$). The 4th term on the right-hand side of equation 26 represents the Laplace pressure which arises due to surface tension and curvature of the surface and the fifth term represents the pressure required to change the curvature (see Lopez 2009).

Although fluid flow in the weld pool has been addressed by a number of researchers, few have extended their work to consider elemental mixing in the melt-pool. (Hejripour 2018) track the elemental concentration through an expression of the form

$$(\mathbf{u} + \mathbf{v}_w) \cdot (\nabla C_i) = \nabla \cdot (D_i \nabla C_i), \quad \dots [29]$$

where $\mathbf{u}$ is the fluid velocity, $\mathbf{v}_w$ the welding speed, C_i the concentration gradient of element i and D_i the diffusion coefficient of element i in the melt pool. For an Inconel 718 deposit on a stainless steel substrate, the authors found relatively uniform mixing in the body of the melt-pool, but an unmixed region close to the fusion boundary with the substrate, which decreased in extent as the (GTAW) wire addition rate increased. In this study, the authors neglected evaporation, which may be expected to be of importance for alloys containing volatile elements and deposition conditions involving low fluid flow velocities, such as those encountered for example with zinc containing (7000 series) aluminium alloys.

Ou *et al.* (Ou 2021) employed an iterative root-finding algorithm to determine the correct value of the Lagrange parameter. The calculated bead widths and heights for single bead thickness Ti-6AL-4V deposits shows good agreement with experimental values, as shown in figure 7.

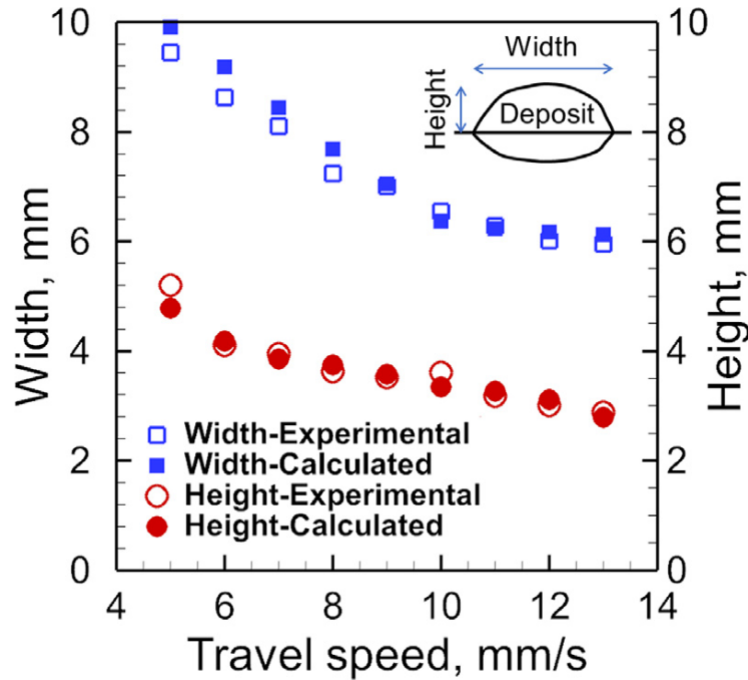


Figure 7. Comparisons of the calculated deposit height and width with experimental results from Ayed *et al.* (Ayed 2020) for Ti-6Al-4V single bead width deposits at travel speeds varying from 5 mm/s to 13 mm/s (from Ou 2021).

A less computationally intensive approach to assessment of the bead dimensions is described by Ding *et al.* (Ding 2015) and Hu *et al.* (Hu 2020), involving a combined geometric and experimental based approximation of the bead profile during multi-pass deposition. The initial (GMAW) bead profile is fitted with a parabolic function

$$y = -\frac{4h}{w^2}x^2 + h, \quad \dots [30]$$

where h is the bead height and w the bead width. In the work of (Hu 2020) subsequent beads of equal cross-sectional area are approximated with either a circular function if the distance between bead centre lines is below a critical value or a rotated parabolic function, if the distance between bead centres exceeds the critical limit. The limiting case occurs when a chord drawn between the toes of the second bead forms a tangent at the point of contact with the first (figure 8).

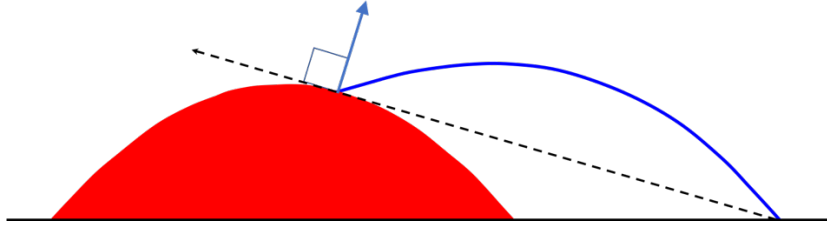


Figure 8. Illustration of the critical overlap condition for the switch from a circular to a parabolic fit function for bead profile (see Hu 2020).

The optimal overlap ratio required to maintain as flat a surface as possible is reported to lie in the range ~ 0.63 to 0.77 (Hu 2020) depending upon operating parameters, with the ratio moving to the lower end of the range with increasing bead width to height ratio. Conversely, Ding *et al.* (Ding 2015) report stable overlapping at overlap ratios greater than ~ 0.74 . The difference in findings most likely arising from different operating conditions and/or material properties.

In addition to the geometric models, several statistically based (artificial neural network) studies have been published relating bead geometry to operating parameters (see for example (Karmuhilan 2018), Li *et al.* (Li 2018), Dinovitzer *et al.* (Dinovitzer 2019)). Both the geometric and statistically based approaches offer fast and efficient estimations of bead profiles; however, details are material and experimental condition specific (especially for the statistically based approaches); *i.e.*, these approaches do not contain all the relevant process physics. Considerable care should therefore be taken to ensure that models are appropriately tuned to cases or conditions of interest that differ from those reported in the published works.

A more fundamental modeling approach was taken by Cadiou *et al.* (Cadiou 2020) who used a comprehensive multiphysics model, based on the conservation of mass, momentum, and energy together with Maxwell's equations to model the controlled short circuit WAAM process. Experimental data from a five-layer WAAM deposit in stainless steel was used to obtain video images of the weld pool and layer height, and macro sections of the deposited material were also obtained. The results allowed fairly accurate prediction of weld pool length and are claimed to give a good indication of layer height, but the weld width is significantly over estimated. The authors claim that this error may be due to lack of consideration of wettability and Marangoni surface tension driven fluid flow in the weld pool.

Whilst coupled arc and melt-pool models have been developed for welding applications (*e.g.*, Jian 2015, Tanaka 2006, Murphy 2017), these generally place a heavy demand on computational capacity. The time taken for the layer-by-layer simulation of large-scale components with multiple deposit (weld) passes, may become prohibitive. Hybrid three dimensional computational models have previously been developed for bead shape prediction and simulation in welding applications (Murphy 2017) (Chen 2020) and although these are related to conventional weld bead shapes, they offer a practical approach which could be applied to reduce computational overheads. Generally, in order to simplify the models and reduce calculation time, the arc is often de-coupled from the melt-pool and the detailed physics of the plasma-material interaction is replaced by a simplified equivalent heat source. The power density distribution has been represented in a number of forms for the simulation of additive manufacturing (Srivastava 2020); although, for wire arc process simulations, the distribution is usually based upon a Gaussian function. Some authors apply a simple Gaussian distribution

(Abe 2020 and Bonifaz 2019); however, the most widely applied heat source representation is the double-ellipsoidal distribution (Goldak 1984). The heat distribution at the front and at the rear of a moving heat source q_n , is represented by two semi-ellipsoids having different eccentricity

$$q_n(x, y, z, t) = \frac{6\sqrt{3} f_n Q}{a.b.c.\pi^{1.5}} \exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3[z+v(\tau-t)]^2}{c_n^2}\right), \quad \dots [31]$$

where the subscript n refers to the front (f) or rear (r) semi-ellipsoid, a is the half width and b the depth of the semi-ellipsoid, c_n the lengths of the melt pool to the front and rear, f_n the fractions of heat in the front and rear ellipsoids, such that $f_f + f_r = 2$, τ a lag factor that defines the position of the source at time $t = 0$ and v the welding velocity. In general, the constants a , b and c_n may be determined from the dimensions of the weld pool. The energy input rate Q is given by

$$Q = \eta I V, \quad \dots [32]$$

where η is the process efficiency, I the current and V the arc voltage. Process efficiency is often used in numerical simulations as a fitting parameter to obtain results that agree with experimental observations. Alternatively, generic efficiencies can be derived from values quoted in standards such as EN 1011-1:2009 or ISO/TR 17671-1 or derived from calorimetric measurements (see for example Dupont and Marder 1995, Joseph 2003, Nasri 2014), the latter potentially providing values that most closely match the operating conditions under consideration.

5.2 Distortion and residual stress simulation

The double ellipsoid model has been used by many authors to predict thermal, mechanical and material properties of WAAM components (see for example Michaleris 2014, Lundbäck 2011, and Graf 2018). Chen *et al.* (Chen 2018) employed a rotated double ellipsoid distribution to simulate the heat source during electron beam based WAAM involving a thin walled Ti-6AL-4V deposit. Ding (Ding 2011) employed the double ellipsoid heat distribution to calculate the residual stress state in a thin walled (single bead width) deposit and compared results to experimental measurements. Finite element models were constructed with both Eulerian (fixed) and Lagrangian (moving) frames of reference. The mesh was pre-defined and material added using the element birth technique. Material properties were taken from Zhang and Michaleris (Zhang 2004), with enhanced thermal conductivity at temperatures above 1773 K to account for convective heat transfer in the melt-pool. Radiation and convection coefficients were assumed to be temperature independent and set to 0.2 and 5.7 W m⁻² K⁻¹ respectively. Results from the thermal model show good overall agreement with measured temperatures for 500 mm long 4 and 8 layer mild steel walls. The simulated stress profiles show a strong influence of clamping on the maximum stress in the deposited wall (figure 9). After clamp release, the 500 x 60 x 12 mm³ base plate was observed to distort substantially, Contraction of the deposited material resulted in bending in the build direction, with either end of the plate lifting 3.5 mm with respect to the centre location.

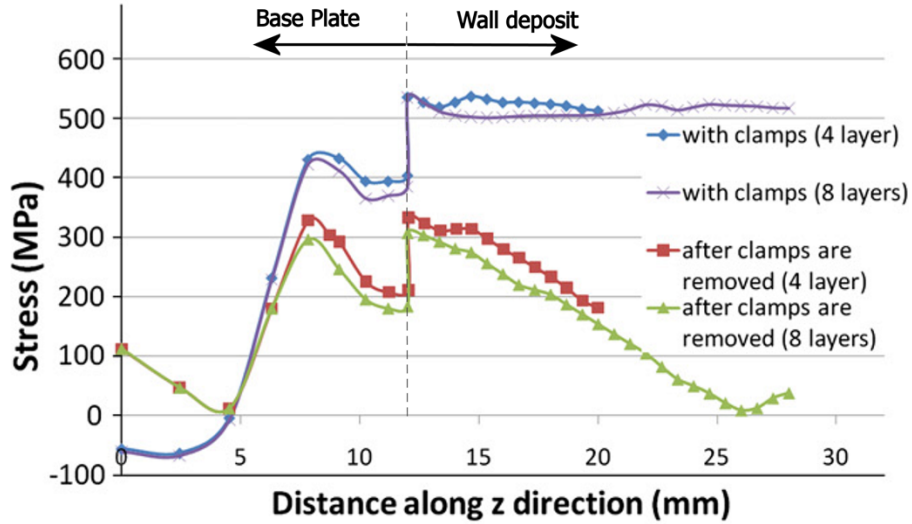


Figure 9. Simulated and measured longitudinal stress profiles taken along a line perpendicular to the base plate surface in the build direction and halfway along the 500 mm plate length (from Ding 2011).

Results from the mechanical model were also compared with measured residual stresses. Whilst it is not possible to measure the stress directly, the stress state can be derived from strain diffraction measurements using Hook's law, which may be written

$$\sigma_{ij} = \frac{E}{(1-\nu)} \varepsilon_{ij} + \delta_{ij} \frac{\nu E}{(1+\nu)(1-2\nu)} (\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}) \quad \dots [33]$$

where E is the Young's modulus, ν is Poisson's ratio, δ_{ij} is the Kronecker delta, ε the strain and the subscripts refer to components of the strain tensor with $i = j$ being normal strains and $i \neq j$ shear strain components. The derived strain is an average over the measured gauge volume, which in this case was $2 \times 2 \times 2 \text{ mm}^3$ for measurement of the longitudinal stress and $2 \times 20 \times 2 \text{ mm}^3$ for measurement in the transverse and normal directions (figure 10).

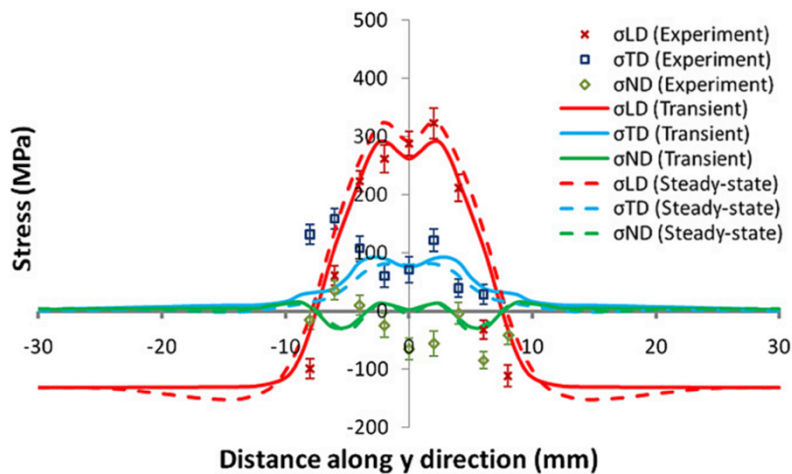


Figure 10. Comparison of measured and simulated residual stresses in a 3 layer single bead width mild steel wall (Ding 2011) .

The agreement is remarkable considering that solid phase transformations were neglected and material properties and in particular changes in the material strength (hardening), induced by successive thermal cycles were not taken into account.

(Ding 2011) report that up to 80% reduction in computation time can be obtained by adopting a steady state computational approach based on the Eulerian frame of reference, compared to the transient Lagrangian reference frame. This observation agrees with the earlier work of Zhang and Michaleris (Zhang 2004), who also report an improvement by up to 2 orders of magnitude, but note that angular deformation is overpredicted with the Eulerian approach which implicitly ignores end effects at the start and stop locations. The Eulerian approach is therefore only valid for deposits where a steady state condition prevails over the majority of the specimen length.

For the analysis of residual stress and distortion, the governing equation for the thermomechanical analysis requires that

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} + \nabla \cdot \boldsymbol{\sigma} + \mathbf{F} = 0, \quad \dots [34]$$

where ρ is the density, $\mathbf{u}$ the displacement vector, $\boldsymbol{\sigma}$ is the stress tensor and $\mathbf{F}$ the body force per unit volume. For a purely static analysis, the first term becomes zero. The total strain may be written in terms of the spatial gradient of the displacement vector $\mathbf{u}$ (Zhang 2004)

$$\boldsymbol{\varepsilon}(\mathbf{r}, t) = \frac{1}{2} [\nabla \mathbf{u}(\mathbf{r}, t) + (\nabla \mathbf{u}(\mathbf{r}, t))^T]. \quad \dots [35]$$

Assuming small deformation, the additive decomposition of total strain

$$\boldsymbol{\varepsilon}_{tot} = \boldsymbol{\varepsilon}_{el} + \boldsymbol{\varepsilon}_{pl} + \boldsymbol{\varepsilon}_{th}, \quad \dots [36]$$

where the subscripts refer to elastic, plastic and thermal contributions and

$$\boldsymbol{\varepsilon}_{th} = \alpha \Delta T, \quad \dots [37]$$

where α is the temperature dependent thermal diffusivity. Many authors neglect the contribution due to solid phase transformations; however, in those cases where they are included, the strain decomposition becomes

$$\boldsymbol{\varepsilon}_{tot} = \boldsymbol{\varepsilon}_{el} + \boldsymbol{\varepsilon}_{pl} + \boldsymbol{\varepsilon}_{th} + \boldsymbol{\varepsilon}_{vol} + \boldsymbol{\varepsilon}_{tr}, \quad \dots [38]$$

the extra terms representing the volumetric expansion and trip induced plastic strain (Jimenez *et al.* (Jimenez 2020). For martensitic transformations, the volumetric strain component can be derived from the well-known Koistinen-Marburger equation, relating the martensite fraction to the temperature, hence

$$\boldsymbol{\varepsilon}_{vol} = \boldsymbol{\varepsilon}_T f_{eq} [1 - \exp(-b(M_s - T))], \quad T \leq M_s \quad \dots [39]$$

where f_{eq} is the austenite phase fraction at the start of the transformation, b the growth constant, typically taken 0.011 K^{-1} for low carbon steels (Pan 1992), M_s the martensite start temperature and $\boldsymbol{\varepsilon}_T$ the total strain-increment due to volume change when all austenite transforms to

martensite. Jimenez *et al.* (Jimenez 2020) report that displacive solid phase transformations have a significant influence on the computed stress distribution.

Any volume element within a WAAM deposited structure can undergo several thermal cycles, the number, peak temperature and profile of which depend upon material properties, component geometry, WAAM process and associated boundary conditions. The combined thermal treatment can change the metallurgical structure and hence the mechanical properties of the material. Unfortunately, many authors neglect work hardening in their mechanical models; however, some include isotropic hardening (see for example Lundback 2011, Zhang 2004, Huang 2020) and a few (*e.g.*, Cambon 2020, Mirkoochi 2020) consider a mixed mode isotropic – kinematic model. Although the latter is physically more realistic, it requires additional computational time and often, an isotropic model can be used with little loss of accuracy.

Important factors that have a direct influence on the results of numerical simulations include the treatments of convective and radiative heat losses and material properties. Radiative heat losses Q_R are generally represented by

$$Q_R = \varepsilon \sigma_{SB} (T^4 - T_a^4), \quad \dots [40]$$

where σ_{SB} is the Stefan -Boltzmann constant, T_a the ambient temperature and ε an emissivity coefficient. Convective heat loss Q_{cv} is represented by

$$Q_{cv} = h_c (T - T_a), \quad \dots [41]$$

where h_c is the convective heat transfer coefficient. Values of h_c and ε are generally not reported and of those that are (table 2), there is little consistency. It appears common practice to select coefficients to obtain a best fit between simulations and experiments. The treatment of material properties falls broadly into three categories; temperature independent properties; temperature dependence of only some of the properties or temperature dependence of all relevant properties; table 3 summarises the different approaches. (Dai 2010) for example note that accurate prediction of residual stresses and component distortion are dependent upon appropriate material property data. However, it is not always possible to determine the details of the material properties employed from the information supplied in the published literature and there is rarely any consideration of the influence of these properties on the results of the simulations reported.

Production of three-dimensional components using wire arc additive manufacturing can involve several hours of arc on time (see for example reference to the production of a ship propeller in Lin *et al.* (Lin 2019). High deposition rates and high welding speeds are therefore of interest to minimise production time. High welding speeds can however lead to defects including bead humping, whereby the deposited bead profile in the length direction shows systematic peaks and troughs. The phenomenon is associated with liquid metal displacement due to the balance of forces acting on the arc, with insufficient time for the melt-pool to flow and the shape to stabilise prior to solidification.

Table 2 Summary of reported emissivity and convection coefficients.

h_c [W m ⁻² K ⁻¹]	ε	Material(s)	Author
8 (liquid-gas interface) 80 (forced convection from shielding gas) 8.4 (elsewhere)	Not specified.	Ti-6AL-4V & Tool Steel	Ou <i>et al.</i> (2021)
242 (forced convection from shielding gas) 10 (elsewhere)	0.7	Inconel 738 & Steel	Bonifaz, (2019)
2000 (steel to table) 100 (magnesium to table) 35 (metal to air)	Not specified.	Mg alloy & Steel	Graf <i>et al.</i> (2018)
8.5 (substrate top surface) 4.0 (substrate bottom surface) 12.0 (wall surface)	0.2	Steel	Montevecchi <i>et al.</i> (2017)
15 (all surfaces)	$0.428-1.28 \times 10^{-5} T$ $1788 \text{ K} < T < 2600 \text{ K}$ $0.425-1.05 \times 10^{-5} T$ $T_m < T < 2920 \text{ K}$	Ti-6AL-4V	Bai <i>et al.</i> (2018)
100 (all surfaces)	Not specified	Stainless Steel	Jayanath and Achuthan (2018)
5.7 (metal to air) 300 (metal to base plate)	0.2	Steel	Ding <i>et al.</i> (2011)

Table 3 Summary of approaches to (solid phase) material properties.

Condition	Property	Authors
Temperature independent	-	Abe <i>et al.</i> (2020), Bonifaz, (2019), Hejripour <i>et al.</i> (2018), Kim <i>et al.</i> (2003), Michaleris <i>et al.</i> (2014), Zhou (2016)
Selected temperature dependency	C_p, κ	Bai <i>et al.</i> (2018), Cadiou <i>et al.</i> (2020), Li <i>et al.</i> (2019), Ogino <i>et al.</i> (2018), Ou <i>et al.</i> (2021), Xiong (2017)
	C_p, κ, η	Jian and Wu (2015)
	$C_p, \kappa, E, \sigma_y, \nu$	Zhang and Michaleris (2004), Ding <i>et al.</i> (2011)
	E, σ_y	Chen <i>et al.</i> (2018)
Most or all properties temperature dependent	-	Graf <i>et al.</i> (2018), Jayanath and Achuthan (2018), Park (2020)

5.3 Humping phenomena

The humping phenomenon in welding has been addressed by a number of authors, *e.g.*, (Savage 1979). Kumar and DebRoy (Kumar 2006) provide a brief review of the various approaches. Bradstreet (Bradstreet 1968) considered the melt-pool in the form of a liquid cylinder with an applied Rayleigh instability and derived an expression for a critical pool length L_c in terms of the cylinder radius R

$$L_c = 2\pi R. \quad \dots [42]$$

Humping occurs when the pool length exceeds this critical value. Gratzke *et al.* (Gratzke 1992) extended the analysis to consider a partially bound liquid cylinder, predicting a critical length of

$$L_c = 2\pi R \left(1 - \left(\frac{\pi}{2(\pi-\theta)} \right)^2 \right)^{-0.5}, \quad \dots [43]$$

where θ is the half angle between the axis of the cylinder and the contact location with the surface of the workpiece. In these models, gravitational and shear forces acting on the pool are ignored. Kumar and DebRoy, (Kumar 2006) describe humping in terms of a Kelvin-Helmholtz hydrodynamic instability. The instability is driven by surface waves travelling in the opposite direction to the weld and the analysis considers the effects of surface tension, shear force, pressure gradient, and gravity.

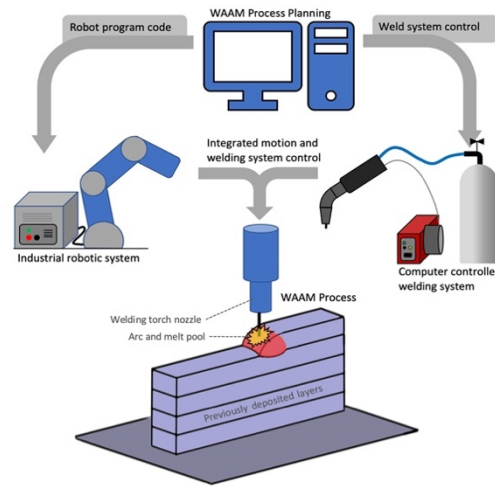
The authors derive an expression for the surface waves and conclude that humping occurs at high welding speeds, the critical speed varying with welding conditions and decreasing with increasing current. The onset of humping is delayed when the forces acting on the melt pool surface driving the liquid to the rear of the pool are reduced; *i.e.*, when a low density shielding gas or low ambient pressure is employed or when a leading torch angle (push position) is employed. Chen and Wu, (Chen 2010) modelled humping during high speed gas metal arc welding using a magnetohydrodynamic approach with surface energy minimisation. They also present an expression for the velocity of the rearward moving molten metal in terms of process dependent coefficients. More recently, Yuan *et al.* (Yuan 2020) have experimentally addressed humping behaviour with the GMAW CMT process during positional wire arc additive manufacturing. They describe a qualitative behavioural model and ascribe the occurrence of humping to the effect of backward metal flow and gravity. Humping is found to be more prevalent when welding in the vertical up direction and least prevalent when welding in the vertical down direction.

6. Equipment Requirements

The common WAAM systems are based on an industrial robot, and a welding package. It is however clear that the most productive practical methodology for WAAM reflects the known approach from welding experience; that the optimum welding position is the ‘downhand’ or flat position where the weld is deposited vertically on a horizontal workpiece. For three dimensional components this suggests that the work piece should be positioned horizontally under the robot head, which requires a workpiece positioner integrated with the robot. These basic requirements are illustrated in figure 11 A and B.



A



B

Figure 11. (A) schematic illustration of WAAM system, (B) typical basic WAAM system arrangement.

There are a wide variety of common robot systems, integrated positioners and welding packages available; these offer the end user flexibility and can offer a very large operating envelope. Many early WAAM studies used independent robotic hardware, and these continue to be used in the research activities cited in this review. The use of this approach requires some understanding of robot programming, slicing path optimisation and the process control. Several CAD slicing software and offline robot programming packages are commercially available but the WAAM system user needs to integrate these with parameter prediction and welding controls in order to implement the complete system.

In most cases the workpiece can easily be manipulated as suggested above, but some researchers have attempted to deposit material at varying angles to the ideal vertical orientation (Yuan 2020). As expected, this approach introduced several difficulties in control of deposit geometry, which the authors attempted to solve by optimisation of the welding parameters.

7. Material Considerations

Many research papers have focussed on the feasibility of using WAAM for specific materials. In fact, since WAAM is essentially a welding process; it therefore follows that if the material can be deposited as weld metal it is likely to be suitable for WAAM. It is also evident that many of the metallurgical issues related to material weldability will be experienced in WAAM deposits.

The range of materials which have been investigated over the last 20 years include aluminium alloys, ferritic and austenitic steels, nickel alloys, copper alloys, titanium alloys, intermetallic, multi-material metallic composites and functionally graded materials.

Several early investigations were conducted with plain carbon ferritic steels and stainless steels. Consumable filler wires for a range of steels are widely available, particularly for the GMAW process which is well suited to WAAM applications in these materials. As expected, the properties of the deposits are very similar to those of as welded ‘all weld metal’ samples produced from the same filler materials. The heat input and cooling rate influence tensile

strength, toughness and hardness but these characteristics are well understood from welding practice. For thin wall structures, relatively low heat input and rapid cooling rates are used to control deposit profiles. In ferritic steels, some dilution and epitaxial grain growth may occur in the first layers deposited on the substrate, but these features are lost after a few layers and a relatively fine equiaxed grain-size is usually achieved in the bulk of the deposit. The absence of large columnar grain growth leads to fairly isotropic properties with respect to the build direction as opposed to the weld direction, although there may be a variation in properties across the deposit height as the thermal conditions stabilise. The deposits are dense and under normal operating conditions, should be free from defects. General porosity or low density is not a problem with these materials, unlike materials formed by powder-based additive manufacturing processes. Random porosity only occurs if gas shielding is inadequate. With ferritic steels the source of any porosity is usually nitrogen absorption in solution and ejection during solidification and phase transformation (Norris 2006). Solidification cracking and hydrogen assisted cold cracking are unlikely in GMAW, GTAW and PAW if low hydrogen conditions are maintained. A range of higher strength low alloy (HSLA) steels (Dai 2019) and heat resistant 2.25Cr 0.25 Mo steels have been successfully fabricated using WAAM. The properties of higher alloy steels are usually similar to the cast or 'annealed' condition and must be heat treated in a similar manner to cast or wrought product to achieve the required strength levels. There have been some attempts to control WAAM material properties in HSLA steels, by in-situ control of the thermal cycle (Tiago 2019), but this approach is limited by the constraints of deposit profile. Normally the filler wire for additive manufacture of steel is selected from the wide range of commercial solid wires developed for welding; however, Lin *et al.* (Lin 2019) used a metal cored wire to form a component from a 0.45% carbon steel equivalent to XC45. The resulting deposit had equivalent mechanical properties to AISI 1045 material, although there was significant anisotropy between the build and welding directions. The use of metal cored wire in GMAW WAAM however increases the possible range of materials which can be deposited in this way. Lin *et al.* (Lin 2019) also used a metal cored wire in a study of the microstructure and mechanical properties of WAAM deposits in medium carbon steel.

The wire arc additive manufacture of austenitic stainless steels is relatively straightforward and has been comprehensively reviewed by Jin *et al.* (Jin 2020). A wide range of stainless steels were investigated; from the fully austenitic to precipitation hardening and martensitic grades. There is a possibility of solidification cracking and random porosity, although these phenomena are well understood from the welding literature on stainless steel weldability and may be controlled by selections of suitable filler wire composition and heat input and efficient cleaning and shielding (Lancaster 1999). Similarly, the optimum control of microstructure and the austenite-ferrite phase balance has been elucidated by Lancaster and is largely achieved by choice of consumable. A more common issue affecting the WAAM deposition of stainless steels is the increased residual stress and distortion compared with other production processes such as casting. These effects result from the low thermal conductivity, the high coefficient of expansion and the non-uniform thermal field experienced during deposition. The residual stresses can be reduced by post weld heat treatment, but several in-process thermal control methods have also been used in an attempt to reduce the distortion and residual stress.

WAAM is an appropriate method for fabricating nickel alloys as a cost effective alternative to casting and forging. Many of these alloys are used in high value aerospace applications where high temperature corrosion resistance is often required. The use of arc welding to join these materials has resulted in a wide range of consumable wires being available. Random porosity and solidification are sometimes found in nickel alloy welds due to nitrogen, carbon monoxide

and hydrogen solution, but these are normally controlled by adding nitride forming or deoxidising elements to the filler wire. Solidification cracking is controlled in a similar way. The common welding wire compositions are likely to be suitable for WAAM. The WAAM process has been used for Inconel™ and Nimonic™ superalloys as well as nickel-copper alloys such as cupro-nickel and nickel aluminium bronze. Ribiero (Ribiero 1996) successfully fabricated a relatively complex prototype bearing ring shown in figure 13, from both low carbon steel and Inconel 718, using robotic WAAM and GMAW, with conventional short circuiting metal transfer. More recently Mookara (Mookara 2020) investigated the microstructure development of Inconel 625 deposited by WAAM using waveform controlled GMAW. The research demonstrated the control of metal droplet transfer mode as a means of improving deposit quality. Hassel *et al.* (Hassel 2020) also used waveform controlled GMAW to deposit Inconel 617 walls for metallurgical studies. It was suggested that the successive layer melting, and thermal gradients were responsible for continuous vertical grain growth and this was responsible for some anisotropy in the mechanical properties. The prospect of producing favourable monocrystalline structures for high temperature service was suggested by this work. Dhinakaran *et al.* (Dhinakaran 2020) recently reviewed the use of WAAM for production of nickel superalloys and concluded that WAAM is a viable alternative to other manufacturing processes for these materials.

Nickel aluminium bronze (NAB) is used in marine environments for pump bodies, impellers and propulsion devices. Good mechanical properties and excellent corrosion resistance are key requirements for operation in these environments. WAAM offers a viable alternative to casting of components due to the shorter lead time and greater design flexibility. Several researchers have examined the properties of WAAM deposits in NAB (Ding 2016), (Shen 2018) (Kim 2020), (Baby 2020), (Queguineur 2020). Kim *et al.* compared the mechanical properties of WAAM GMAW deposits with those of castings and found that in spite of anisotropy and differences related to the weld path, overall, the properties exceeded those of the cast sample. In addition, porosity levels were very low in the WAAM deposits in comparison with cast material. Shen *et al.* found similar results in relation to anisotropy and mechanical properties. They conducted a series of post deposition heat treatments and a detailed study of the resultant microstructural changes. Post deposition quenching and tempering at 650°C increased the tensile strength and reduced the anisotropy, compared with as-deposited structures.

The weldability of aluminium alloys has been researched extensively and practical procedures have been developed to ensure sound welds can be produced. These same measures can be applied to additive manufacturing. Porosity is again a problem for aluminium alloys, as is solidification cracking. In this case, porosity is usually the result of hydrogen in solution in the liquid phase and rejected during solidification. This can be avoided by careful cleaning of the substrate and welding consumables, and efficient inert gas shielding. Solidification cracking of aluminium alloys is a well understood phenomena in arc welding, cracking susceptibility is associated with high heat input, large weld pools and specific ranges of the common alloying elements Si, Mg, Mn and Cu. For example, the susceptibility to cracking in aluminium silicon alloys peaks at around 1% silicon. In welding it can be avoided by careful choice of filler metal composition (Lancaster 1999), this may be more difficult in additive manufacture and reduced heat input techniques may be necessary. The high thermal conductivity, low melting point, high fluidity and low surface tension of the molten aluminium also require careful control of welding parameters and processes to prevent progressive thermal accumulation which can produce unacceptable profiles in WAAM deposits. Pramod (Pramod 2020) made aluminium-5% silicon alloy (4043) cylinders using waveform controlled GMAW. The researchers appeared to have some difficulty in controlling bead profile, in spite of claimed process

optimisation. The need to machine 3 mm from the surface to remove excess surface roughness is evidence of this. Gierth *et al.* (Gierth 2020), used a variety of waveform controlled GMAW process modes to reduce the arc energy input, whilst producing sound deposits, low porosity levels and satisfactory profile and surface quality.

One of the first groups of materials to receive significant commercial attention for WAAM were the titanium alloys. The interest in titanium was prompted by the high cost of manufacturing titanium components for aerospace applications. Components are typically machined from a solid titanium billet and very high material wastage results in what is known as a high ‘buy to fly’ ratio. Near net or additive manufacture significantly reduces this wastage. Titanium alloys can readily be fabricated by welding, but the main constraint is the reaction of the material with the atmosphere, which can cause interstitial embrittlement by contamination with oxygen and nitrogen. In WAAM, as in welding of these materials, it is essential to practice excellent cleaning and maintain an inert atmosphere in the weld zone and during cooling. Welding experiences suggest that inert gas shielding must be maintained until the weld bead temperature has dropped below 400 °C to avoid adverse effects. Hoye (Hoye 2015) made a detailed investigation of the potential for atmospheric contamination of the common Ti-6Al-4V alloy using GTAW and showed that, with adequate shielding, the depth of the affected layer was normally so small that it would be removed by light finish machining. In the common Ti-6Al-4V alloy, pronounced columnar growth is found in the build direction during WAAM. Bermingham *et al.* (Bermingham 2019) examined the mechanism of equiaxed grain nucleation in titanium Ti-6Al-4V and noted the beneficial effect of La₂O₃ additions on grain refinement, as well as the need for control of the temperature gradient during deposition to allow for constitutional supercooling.

Intermetallic, multi-material and functionally graded materials may be produced by WAAM processes. Shen *et al.* (Shen 2017) investigated the production of iron-aluminides whilst Ma *et al.* (Ma 2015) produced titanium aluminide samples. Both used a twin wire GTAW WAAM system to produce single wall deposits. Shen produced iron-aluminide deposits with up to 30% aluminium content. The deposits had a pronounced columnar grain structure but were porosity free and had reasonable mechanical properties. Shen (Shen 2016) produced functionally graded steel-aluminium deposits by progressively adjusting the feed speed ratio of the two filler wires. The deposit composition changed along the bead deposition axis from 100% steel to 50% aluminium. The deposits were structurally sound and had acceptable mechanical properties. Liu *et al.* (Liu 2013) fabricated a functionally graded steel-silicon bronze structure using shaped metal deposition (SMD). The deposited material was sound, free from defects throughout, and the composition varied from 100% steel to 100% silicon bronze. A tensile test across the material interface failed at 305 MPa in the bronze section of the deposit, indicating adequate strength and structural integrity of the functionally graded structure. The initial study of titanium aluminide by Ma indicated that a sound full density γ -TiAl-based alloy could be produced by this method, although there was evidence of micro-segregation in different regions. Later work by Ma (Ma 2016) using careful control of the thermal cycle during deposition and produced improved microstructures and acceptable mechanical properties. It was however necessary to use continuous heating of the substrate to maintain inter-pass temperatures of around 400°C to produce a favourable phase balance and low residual stress. A recent study by Leicher *et al.* (Leicher 2020) produced a multi-material composite structure designed to emulate the properties of dual phase steels. The deposit was built up using layers of 75% austenitic steel and 25% high strength ferritic-martensitic steel. The resultant structure enabled mechanical properties to be tailored to meet loading requirements; with the ductile austenitic matrix supporting the high strength layers.

8. Materials considerations Summary

It should be noted that whilst the studies above indicate the overall feasibility of fabricating structures in most metallic engineering materials, the majority of this work has been carried out on simple single wall, multilayer deposits. The results indicate that sound defect free deposits can be made with appropriate control of deposition parameters and post weld treatment. In general, the properties of the ‘as deposited’ material are at least equivalent (and in some cases superior) to those of cast material, and often approach those of the wrought product. Whilst it may be expected that the properties may be similar to those of a multi-layer joint weld, as Wittig *et al.* (Wittig 2021) point out, the thermal conditions for single wall deposits are very different from those experienced in a welded joint and may result in slower cooling. To achieve the equivalent properties in the case of duplex stainless steel, studied in the work by Wittig the filler composition was modified. The physics of heat transfer obviously needs to be considered in relation to material and part configuration in WAAM. Figure 12 gives an indication of the range of tensile properties collected from some of the reported studies.

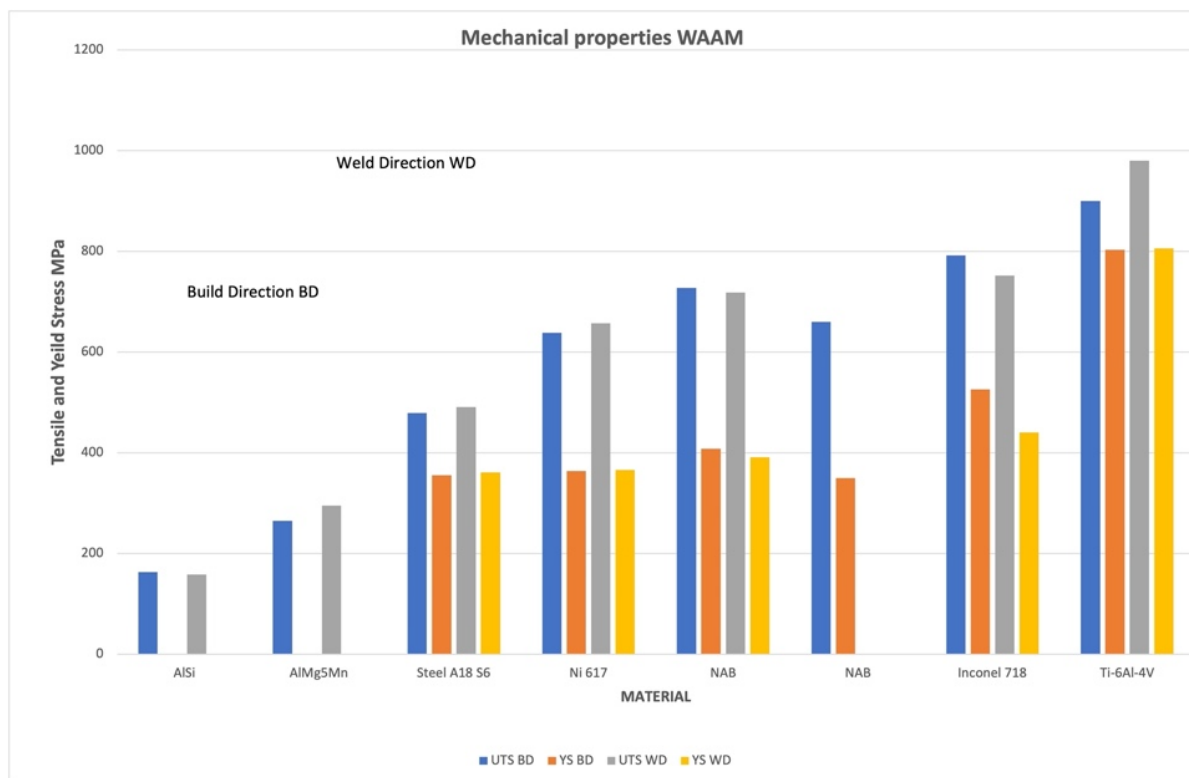


Figure 12. Range of mechanical properties for various materials, BD-build direction, WD-weld direction. From references quoted above.

The single wall approach is convenient for metallurgical analysis and mechanical testing; however, it may not simulate the properties of complex 3D structural components. The published work suggests that the deposition often results in mechanical property anisotropy, this may be controlled by compositional modifications and in-situ control of welding parameters. In many cases this anisotropy is no worse than that produced by mechanical deformation of wrought products. Porosity has also been reported in some WAAM deposits,

for example in aluminium alloys; however, this is usually attributable to entrained gases and the same well-established methods of control used in fusion welding can prevent this problem. Unlike powder based additive manufacturing processes, reduced density and porosity from incomplete bonding is not an issue in WAAM. Whilst residual stress and distortion can be an issue these can often be dealt with ‘in-situ’ by controlling the welding parameters, and deposition sequence or by post processing of the deposit.

9. Process Control

Online monitoring of the weld process for quality assessment and feedback-based control, which can adjust process parameters in real time, can provide a means to improve the quality and reliability of WAAM. This is of particular importance for the manufacture of more complex componentry. Compared to other areas of research, online sensing and control of the WAAM process is at a relatively early stage of development. Research into process monitoring and control for traditional welding practices is well established, but less of this work has been adapted specifically for additive manufacturing. As in other areas of WAAM research, most of the work conducted is targeted at thin-wall applications. Xia *et al.* (Xia 2020) do however discuss some of the perceived issues regarding the control of quality in WAAM deposited materials. They identify two groups of ‘defects’ which are common to arc welding and WAAM. These are re-classified here and shown in table 4 below. Additional issues identified in the other ‘material considerations’ above have been added in italics.

Table 4 Issues identified by Xia *et al.*, (Xia 2020) and other authors above.

Group A: Common to welding	Group B: More pronounced for WAAM
Porosity	Distortion (deformation)
Cracking (HACC and solidification)	Geometric accuracy and repeatability
Poor bead profile (undercut, burn through)	Surface finish, surface defects
Oxidation	<i>Residual stress</i>
<i>Metallurgical quality</i>	<i>Epitaxial columnar grain growth</i>
<i>Mechanical properties</i>	<i>Anisotropy</i>

The issues identified in group A of table 4 have been investigated thoroughly for welding and are avoided by optimisation of consumable selection, adequate shielding gas cover, equipment design, welding parameters and most importantly by the application of welding procedure control as discussed below. Features such as porosity, surface oxidation and bead profile may be detected by post weld Non-Destructive Examination, but weld procedure control is essential for minimisation of crack susceptibility and to ensure the desired metallurgical quality, and mechanical properties are met. These later issues can only be detected by destructive testing. To avoid destructive batch testing, the essential welding parameters (voltage, current, travel speed, heat input) are monitored to ensure they fall within specified limits determined by an initial welding procedure test. These parameters may be continuously monitored during welding or WAAM using computer-based data logging systems (Norrish 2002) (Ogunbiyi 1997). In fact, most of the advanced welding systems used for WAAM are equipped with on-line data collection and associated software, which allows statistical process control to be implemented. High speed data collection also allows a measure of ‘apparent’ defect detection; indicating deviation from normal process behaviour, such as a change in metal transfer mode or instability in GMAW, which may be caused by shielding failure (Sannazzaro 1998).

The group B issues are more likely to be experienced in WAAM and may be controlled to some extent by procedural control and process optimisation. However, the experimental datasets used in these tasks are typically generated under a set of nominal laboratory conditions. In contrast to this, the WAAM process varies with time, where conditions will deviate unpredictably, especially in larger or more complex parts. As the build process continues, factors such as heat accumulation, slag build up, non-linear weld paths and irregular surface profiles adjacent to the weld pool will all contribute to skew the predictive planning models away from the actual parameter values required at a given time. Complicating this is the fact that overall process stability and repeatability are sensitive to build sequences and welding disturbances, which suggests that in order to achieve high geometric accuracy and process repeatability, online sensing and development of control systems to adjust WAAM process parameters in real time are required. These issues were identified by Xia (Xia 2020), and the lack of sensing and control of the WAAM process is noted as a potential barrier to its uptake into various industries. Xia identified a variety of different sensing systems that have been developed to monitor the WAAM process. Vision based sensing systems are common, as they can directly monitor and analyse the dynamics of the melt pool. Vital information, such as melt pool width and height, can be captured in real-time and used for feedback-based control of the welding process. Abnormal behaviour, such as spatter, can also be observed as a measure of process stability and potentially indicate the presence of defects. Couto *et al.* (Couto 2020), developed passive vision systems capable of robustly monitoring deposited bead widths. Xiong (Xiong 2016) extended these efforts by developing the feedback-based control necessary to correct for deviations from expected behaviour. Haliisch *et al.* (Haliisch 2020) used a two-colour pyrometric camera to determine the temperature profile and size of the melt pool. Tang *et al.* (Tang 2017) developed a vision system which trails behind the molten pool and analyses the newly solidified seam for common welding-based defects such as porosity, humping and undercut. Other researchers have developed vision systems to monitor other aspects of the WAAM process; for example, Zhan (Zhan 2017) developed a vision system to monitor and provide real time positional corrections for non-linear welding wire stick out from the wire delivery tip of a plasma WAAM system. Bonaccorso (Bonaccorso 2011) developed a control scheme based on a combination of direct vision and measured welding arc voltage as a means of maintaining constant arc-length during deposition with the GTAW process.

Post deposition measurement of deposited layer height is also an area of interest, laser structured light systems are commonly used to measure the actual deposited layer height. Deviations from planned values can then be accounted for by replanning subsequent layers with updated welding parameter sets. Kissinger (Kissinger 2019) developed an online method of measuring deposited layer height, which makes use of interferometric analysis of the output from a laser diode to rapidly determine the height of the newly deposited bead from the weld head. This work did not however include feedback control based on the data obtained. Other methods of measuring layer height have made use of measured arc or filler wire resistance and it is suggested that the arc voltage control systems commonly used for GTA welding could be applied to track layer height. Cuiuri (Cuiuri 2000) conducted a detailed investigation of on-line estimation of contact tip to workpiece distance (CTWD) in current controlled short circuit transfer and developed a method of reliably estimating CTWD from dynamic resistance measurement in the short circuit period. This measurement can be combined with robot position feedback as an on-line layer height indicator or control system.

Whilst vision systems are commonly used for monitoring and controlling the WAAM process, a variety of alternative sensing technologies are also being investigated. Process phenomena

such as thermal cycles/build-up, arc current/voltage output and acoustic signal emission, may possibly provide useful information about the quality of a given WAAM process. Li *et al.* have recently submitted a paper (Li 2021) which uses high speed data collection and incremental learning analysis in a similar manner to that previously suggested by Ogunbiyi. The system shows promising results for identification of bead irregularities.

A number of researchers, including (Xu 2018) , (Chabot 2019) and (Xia 2020), are now developing multi-sensor monitoring and control systems using these phenomena. By utilising process data from a variety of sensing systems, they suggest that a more robust WAAM process control system can be realised. These research efforts have developed much of the sensing hardware required, however at present, a full feedback-based control strategy has yet to be implemented.

10. WAAM Process Enhancements and post processing

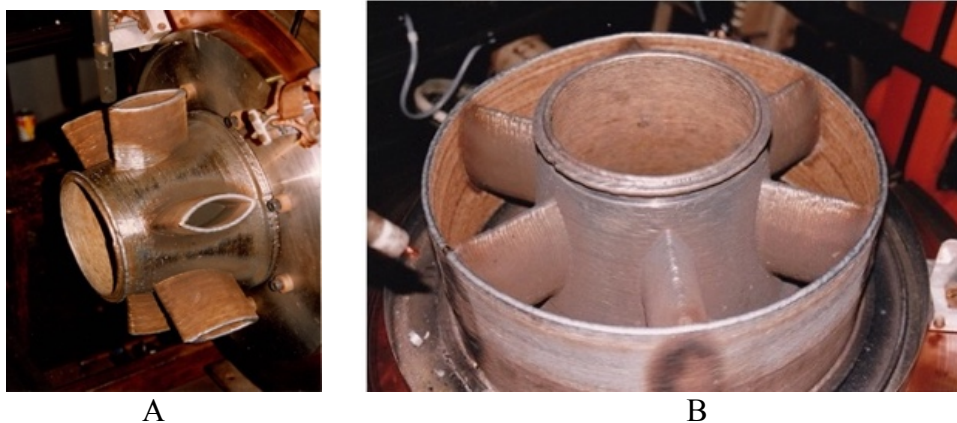


Figure 13. (A) shows the orientation used for depositing the vanes, the vanes were built up incrementally and the hub was indexed after a few runs. (B) shows the finished component with the outer ring deposited, prior to machining. Courtesy of A.F Ribiero (Ribiero 1996).

One limitation of the normal WAAM processes is the delay between successive weld runs, which is often required to control heat input, bead profile, surface finish and deposit metallurgy. This delay restricts productivity and various methods have been proposed to reduce it. Reisgen *et al.* (Reisgen 2020) used several strategies, including immersion of the part in a water bath, high pressure air jet cooling and aerosol jet cooling. The highest cooling rate was achieved with the water bath which reduced the workpiece temperature to 100 °C after 38 seconds. In reality this approach would be difficult to achieve in practical applications. Air jet and aerosol cooling achieved 100 °C after 63 to 75 seconds. These cooling times compared favourably with the time required for the naturally cooled reference sample, which was 700 seconds to 100 °C. The work was conducted on structural steel and the researchers recognised the metallurgy issues which arise with steel and other materials in the presence of water vapour. Others have used a water-cooled worktable to support the substrate, although this protects the worktable it has little effect on subsequent build up layers. Wu *et al.* (Wu 2018) used a CO₂ cooling spray nozzle to cool WAAM GTAW deposits, after completion of each layer, in order to examine the effect on the material properties of Ti-6Al-4V. It was reported that the cooling

improved bead geometry repeatability and reduced surface oxidation with no adverse effect on material properties. Later Wu (Wu.B.P.C, 2019) investigated the use of this approach for distortion control. It was reported that an 80% reduction in build time was achieved and by optimising parameters an 81 % decrease in longitudinal distortion and 69% reduction in transverse distortion was obtained.

The increased probability of distortion and accumulation of residual stresses have been mentioned elsewhere in this review. In an effort to control microstructure and residual stress Colegrove *et al.* (Colegrove 2013) developed a high-pressure post weld rolling technique. Using a grooved roller, it was possible to reduce residual stress and distortion in steel wall structures without lateral deformation of the weld bead. Rolling, causes plastic deformation, introduces stored strain energy that can (at least in the case of the Ti alloys) lead to nucleation upon reheating, resulting in a more or less equi-axed grain structure (*c.f.* the elongated grains through several layers in the absence of rolling).

The group later achieved similar results with titanium alloys using machine hammer peening (Honninge 2017). Although not always necessary, post deposition mechanical deformation has become an accepted means to improve deposit quality. Facilities for this are incorporated in some commercial WAAM systems, as is intermediate and post deposition machining.

Distortion and residual stress may also be controlled by deposition sequence and balanced build up on opposite sides of a common neutral axis. In addition, machining (Zhang 2019) may be used to correct the effects. The component shown in figure 13 indicates the sequential build-up of the aerofoil vanes as the central hub was indexed to achieve a balanced heat input and limit distortion on a complex three dimensional structure.

11. Codes and Standards

The development of appropriate codes and standards is likely to play an important role in ensuring that WAAM is used more widely. There has been some effort to generate additive manufacturing standards over the last 10 years. The American Society for Testing of Materials (ASTM) published ASTM 52900-15 (ASTM 2015) in 2015, this defines various process options and key additive manufacturing terms, including ‘direct energy deposition’, the classification which covers WAAM. Unfortunately, whilst comprehensive, the original standard focusses on powder-based processes. The same approach has until recently been followed by ISO technical committee ISO/TC 261. The American Welding Society has taken a slightly different path in AWS D20.1/D20.1M.2019 (AWS 2019), recognising that WAAM is basically a welding process, it includes sections on the well proven quality system based on procedure qualification which is common in welding technology. The principles of procedure qualification as a means of quality control in welds should apply equally to WAAM. These principles are embodied in many international welding codes such as ASME IX, ISO 15614, AS/NZS 1554. The nomenclature adopted by AWS for WAAM includes GTA-DED for GTAW WAAM, and similarly GMA-DED for GMAW and PA-DED for Plasma arc processes. It is interesting to note that ASME has recently established a ‘joint committee to evaluate the use of additive manufacture for pressure technology (pressure vessels and boilers), ASME has also commenced work ‘to consider in situ monitoring of metal additively manufactured aerospace parts’.

12. Current Status

Over the last decade there has been an exponential growth in papers related to wire-arc additive manufacture, SCOPUS reports around 300 publications in 2020. The subjects covered in these papers are analysed by SCOPUS as 10% Physics, 38% Engineering and 31% Materials. Using this information and the publications cited in this review as a guide the development and current status of wire arc additive manufacturing is illustrated in figure 14.

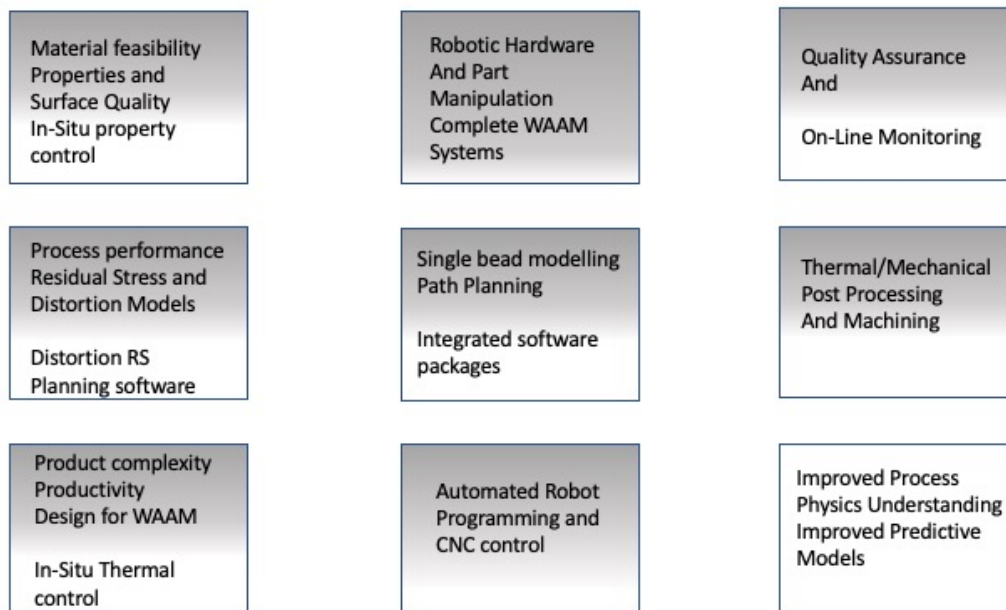
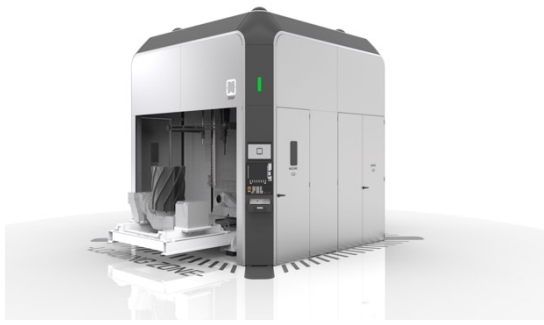


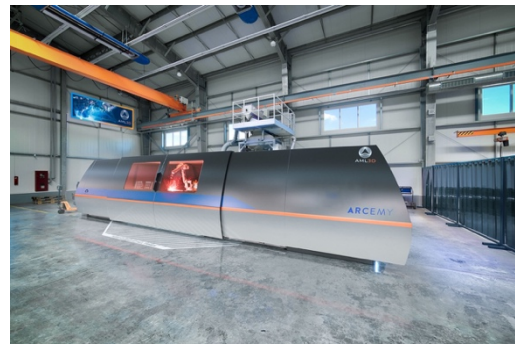
Figure 14. Development of WAAM technology and current status. The stronger shading of the elements in figure 14 indicate a subjective assessment of the degree of completion and the lighter shading indicates the scope for innovation and development.

The overall feasibility of the wire – arc additive manufacturing has been clearly demonstrated over the last 10 years. A very acceptable range of robust process options for GTAW, GMAW and PAW have been established and the enhancements described above are expected to provide continuing performance benefits. The capabilities of WAAM have also been confirmed for a very large range of common engineering materials, as illustrated above, and in addition the technique has also enabled multi-material composite and functionally graded materials to be produced.

The basic hardware requirements for WAAM are readily available, and in common use in industry for welding fabrication. Implementation of WAAM does however require advanced robotic programming skills and access to suitable slicing and path planning capabilities.



A



B

Figure 15. (A) Totally integrated ‘turnkey’ WAAM system (courtesy of GEFERTEC GmbH, Germany). <https://www.gefertec.de/en> and (B) A large purpose designed WAAM system (courtesy of AML3D™ Australia), <https://aml3d.com/technology/>.

Standard CAD packages, independent slicing software, and automatic off-line robot programming software are all available, but path planning strategies and bead geometry prediction require some additional user expertise, as does the need to integrate individual software packages. Some larger companies in the aerospace and maritime industries have been able to implement the technology ‘in-house’ (Queguineur 2020) and there are some commercial integrated software packages available to assist with the in-house implementation of WAAM by fabricators.

The welding system suppliers and research bodies cited above can offer limited feasibility studies and prototyping facilities, whilst independent WAAM service providers can offer software, peripheral hardware and support packages to enable experienced manufacturers to implement WAAM in their existing facilities.

Competitive additive manufacturing systems, for example, those using the powder-based laser technology, are normally offered as fully integrated, turnkey installations which have a similar configuration to CAD machining centres. Whilst this may reduce the overall flexibility and operating envelope compared with robotic WAAM, it enables rapid adoption of technology by end users. A similar approach has recently been developed by at least one international supplier as shown in figure15(A). Other commercial service providers can now offer WAAM prototyping and very large-scale 3D WAAM manufacturing facilities, purpose designed to suit particular applications. Figure 15 (B) shows one of the largest of these systems which was recently supplied by the Australian company AML3D™.

13. Summary and Future Research Requirements

Additive manufacturing (AM) is a viable alternative to other manufacturing processes. When compared with other AM processes, WAAM offers improved productivity and excellent component integrity in many materials. The principal limitation of WAAM is the slightly inferior surface quality and dimensional precision. These issues can be addressed by careful process control and integrated finish machining. It has however taken nearly 20 years since its feasibility was demonstrated for WAAM to reach the commercial levels of exploitation described above. Although there has been an exponential rise in research publications on WAAM, many of these have been devoted to materials studies based on the elementary fabrication of single wall structures. In most cases these studies have confirmed what was expected from well-established materials weldability studies. Study of the papers indicates that

WAAM provides a convenient platform to generate materials research publications, but the underlying process technology may not always be fully appreciated. An example of this is the predominant use of one specific commercial, waveform controlled short circuit transfer mode. It appears that researchers have adopted this particular option on the basis that it is a ‘cold’ material deposition technique. In fact, conventional short circuit transfer which offers a similar heat input was originally used successfully for WAAM. The waveform control techniques can enhance process control and stability but there are a large number of commercially available variants which would offer the same results. An understanding of the underlying waveform control technology and process physics (Norrish 2014) would certainly improve process optimisation for WAAM. It is also clear that many researchers have assumed an arc energy measurement based on mean voltage and current. Since waveform control processes involve rapid transient variations in arc parameters this method of measurement is incorrect, giving significant errors, and the approach recommended by ISO/TR 18491 must be applied (Norrish 2017).

Developments in recent years have been stimulated in part by the availability of sufficient computational power at an affordable price to cope with the calculations required to turn three-dimensional CAD drawings into suitably sliced series of weld head motions, with coupled welding process parameters, suitable for the production of complex solid objects. As is so often the case with developments in the welding sphere, progress has, to a large extent, been experimentally led. Unlocking future potential will require further integration of the process physics to elevate WAAM to the level of an established industrial technology.

Ideally, the end user requires a predictive suite of models that will enable designers to produce complex 3D structures within specified tolerances and with defined (but not necessarily constant), material properties at all locations within the structure. Such an approach will enable designers to optimise materials and engineering designs in a way that is not possible with conventional materials. Examples of the use of WAAM to produce such functionally graded and composite material properties have already been examined (Liu 2013, Srinivasan 2020) and progress in this area would be facilitated by improved predictive models.

Whilst the primary physics of the welding processes is fairly well established, translating the knowledge into a form readily accessible to process engineers remains a challenge. WAAM very often involves very long periods of arc-on time and factors influencing dynamic process stability and/or behaviour are not yet fully documented; these include (but are certainly not limited to) analysis of (i) spatter formation and spatter suppression in consumable welding processes, (ii) electrode wear mechanisms in non-consumable welding processes, (iii) magnetically induced instabilities (arc blow) around complex structures, (iv) analysis of shielding efficiency as a function of welding process, gas selection, position, welding parameter selection, process orientation etc. and the resultant influence that these factors have on melt-pool characteristics and geometry, and (v) fluid flow in the melt-pool and its influence on melt-pool and deposit geometry and local thermal history. Furthermore, effort is also required to improve residual stress and distortion predictions and verification methods, particularly for large numbers of thermal cycles on structures with local variations in the degree of restraint (for example due to variable wall thickness, wall cross-overs *etc*).

It is not sufficient to understand the nature of factors influencing process performance; it is also necessary to develop quantitative prediction capabilities in order to determine when intervention is required. Links must also be established with relevant metallurgy, so that appropriate properties can be developed by ‘in-situ’ control of both composition and cooling

rates at all locations within a structure. If the true potential of WAAM is to be unlocked, it is also necessary to invert many of the existing materials models (in particular the thermal field, stress field and metallurgical predictions) so that appropriate welding parameters may be selected to deliver the desired result.

To enable WAAM to be used confidently for future 3D component fabrication, reliable control of quality must be achieved. Developing additive manufacturing standards will have a role in this, but the emphasis has until recently been focused on powder based additive manufacture rather than wire arc processes and this aspect needs to be addressed. Since WAAM is essentially a welding process it is likely that formal procedural control as required by ISO 9001 and welding fabrication standards will ultimately be necessary. This implies that on-line monitoring and documentation and qualification of initial test components followed by continuous on-line monitoring of production will be required. It may be possible to use single layer deposits to qualify very simple components but the complex thermal behaviour in building complex 3D structures may mean complete components may be required for qualification testing. There is scope for thermal modelling to be developed to determine these testing and procedure qualification requirements, but this implies a better understanding of the process physics discussed above.

If welding procedure control is implemented, relatively simple online quality monitoring can be realised based on statistical analysis of welding parameters compared against established qualification values. In addition, process abnormalities may be reported based on analysis of high-speed welding data, as previously demonstrated for welding. Post process or in-situ temperature monitoring and layer height control may also be required. These techniques may be easily developed from welding systems, but their development is ongoing and will require further research to integrate them into WAAM systems.

The development of robust, feedback-based, control of the WAAM process is however a key requirement in the overall progression of the technology. These control techniques can enhance the accuracy and reliability of the WAAM process and are also critical in the eventual qualification of deposited parts. Reliable control of the WAAM process will involve the monitoring of multiple aspects of the overall process. At the current stage of development, a number of tailored solutions which can monitor and address individual process irregularities have been developed, however these technologies are somewhat disparate in nature (and hardware used) and have not yet been integrated together in a robust system. In addition, integration of these sensing technologies into the control loop also has its challenges. In the last 20 years, the major robot manufacturers have worked closely with welding hardware suppliers to develop robotic welding systems that are well integrated and feature tight synchronisation between robot motions and welding control. Integration of external sensing technologies into the robot/welder control loop is however yet to be achieved to the same degree for WAAM.

The understanding of process operation, bead geometry prediction, material properties, residual stress and distortion has been greatly assisted by the work on process physics and numerical simulation. Further work in this area is however required to refine some of the models, for example to extend the range of materials and include phase transformations and transformation induced plasticity (omitted in some of the publications reviewed here) in numerical models. It would also be beneficial to develop 'hybrid' simulations based on

comprehensive numerical models but feeding into a simple interactive user interface, this is an approach previously used for welding parameter prediction.

Several of the papers reviewed referred to the production of multi-functionally graded materials. This approach has been used successfully in surface engineering and deserves further investigation using WAAM or a combination of additive manufacturing technologies.

14. Conclusion

The wire arc additive manufacturing (WAAM) processes are now established as an alternative to traditional fabrication techniques. The basic hardware systems and software for their implementation are readily available and capabilities are being steadily expanded. The WAAM process has however been the subject of significant research effort in recent years. Much of the research has been dedicated to materials studies on simple structures but many practical applications of the technology are now emerging and complete manufacturing systems are now available. There is however considerable scope in the applied physics field to enhance the performance and exploitation of WAAM. In particular:

- 1) A few of the cited researchers have used a knowledge of process physics in an attempt to improve the process operation and material characteristics. There is scope to apply process physics to tailor the process modes and optimise process parameters specifically for WAAM.
- 2) The understanding of process operation, bead geometry prediction, material properties, residual stress and distortion has been greatly assisted by the work on process physics and numerical simulation. Further work in this area is however required (as explained in section 14 of this paper) to refine some of the models, for example to extend the range of materials and include phase transformations and factors such as transformation induced plasticity.
- 3) The monitoring of WAAM to provide on-line quality assurance is probably key to the wider acceptance of the technology. This will involve multisensor fusion and the development of new mathematical modelling techniques to provide meaningful quality data.

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