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The State-of-the-Art of Wire Arc Directed Energy Deposition (WA-DED) as an Additive Manufacturing Process for Large Metallic Component Manufacture

Authors: Sam C.A. Costello^{a*}, Chloe R. Cunningham^a, Fangda Xu^{a,b},
Alborz Shokrani^a, Vimal Dhokia^a, Stephen T. Newman^a

a. Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY

b. The State Key Laboratory of Industrial Control Technology, and Huzhou Institute, Zhejiang University

Corresponding author address: SC2191@bath.ac.uk

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Abstract

Wire Arc Directed Energy Deposition (WA-DED) also known as Wire Arc Additive Manufacture (WAAM) is a niche additive manufacturing technique for metals that is increasingly offering a competitive advantage to traditional forging and casting methods. Characteristics of WA-DED are high deposition rates and feedstock that is inexpensive compared to powder processes, making it highly efficient for manufacture of large components. This paper reviews WA-DED as a technique for large component manufacture by assessing aspects of the process scalability. Arc processes are compared in terms of their production characteristics showing the relative suitability of each power source. Additional in-situ processes have been identified that can alleviate defects and improve mechanical performance. Investigation of process planning for WA-DED has revealed the potential for material savings that can be achieved by preventing accumulation of errors throughout manufacture. The major finding is that additional in-situ processes and process planning combined with a closed loop feed forward control system can significantly improve the process in terms of mechanical performance, geometric repeatability and resolution. Additionally, it was found that although the degree of isotropy of mechanical performance is commonly investigated, research into the heterogeneity of mechanical performance is limited, and does not assess tensile properties at different locations within deposited material.

1 Introduction

Additive manufacture (AM) is now of great interest to many industries and is considered one of the drivers of the of innovation in industry through the reduction of waste material which has both economic and environmental benefits (Assunção et al., 2018; Singh and Khanna, 2020). ISO ASTM 52900 (ISO ASTM 52900:2021, 2021) divides AM into 7 processes as shown in figure 1. This paper is focused on Directed Energy Deposition (DED) for metal AM which has been further classified in figure 1, by the feedstock used and the heat source that is used. The DED process that is often the most suited process to the production of large metal parts is Wire Arc Directed Energy Deposition (WA-DED). This is primarily due to the process having high deposition rates, which have been quoted as high as 9.5 kg/hr (Martina et al., 2019) without the necessity of depositing material in a vacuum.

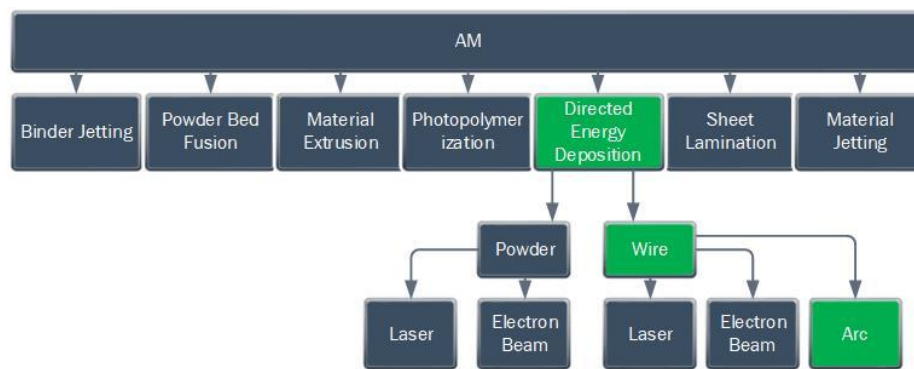


Figure 1 Classification of metal AM processes (ISO ASTM 52900:2021, 2021)

The concept of the WA-DED process is the use of a series of arc welded layers deposited on top of one another to form parts, which can be traced back to Ralph Baker in 1925 with his patent *Method of making decorative articles* that outlined the process of arc welding to form “receptacles or containers” (Baker, 1925). This can be considered extremely prescient as it was not until the 1990s when academics considered arc welding as a means of rapid prototyping (Ribeiro and Norrish, 1996; Spencer et al., 1998). In the early 2000s the process of wire-fed DED began to resemble the modern process in the realisation of slicing strategies and the maturing of CAD/CAM software (Ruan et al., 2006; Zhang et al., 2003). However, the print quality was poor and no mechanical testing occurred, so parts produced could not be considered usable at the time (Zhang et al., 2003). Over the past decade the process has been advanced enabling more complicated geometries, increased deposition rates and improved material and mechanical properties.

This has been achieved with off the shelf equipment and cheap wire feedstock, when compared to powder-based metal AM techniques. This is possible by printing thicker layers allowing for more material to be deposited for a given travel speed compared to Powder Bed Fusion (PBF) processes and other DED processes, by maintaining near net volume production thus leading to low buy to fly ratios (Williams et al., 2016). WA-DED has been shown to be a manufacturing process with excellent material efficiency when compared to other metal AM processes. However, it is well

recognised that on balance other metal AM processes can achieve better surface finishes than the WA-DED process (Leach et al., 2019). In recent years, the mechanical properties of WA-DED printed material has improved drastically and in some cases matches or exceeds mechanical properties of components produced by traditional casting methods (Yili et al., 2018). It has been identified throughout the literature that this can lead to economic and environmental benefits through cost modelling analysis (Cunningham et al., 2017) and Life Cycle Assessment (LCA) (Bekker et al., 2016; Bekker and Verlinden, 2018; Priarone et al., 2020).

It is also recognised there is a wealth of knowledge established in the field of arc welding, despite this WA-DED is still relatively immature in comparison to other metal AM processes. As late as in the last decade review literature on metal AM does not take into account WA-DED under any pseudonym which include: Shaped metal deposition (Baufeld, 2012; Clark et al., 2008), Wire Arc Additive Manufacturing (WAAM), Arc Based Additive Manufacturing (ABAM) (Frazier, 2014; Santangelo et al., 2016; Vayre et al., 2012). Figure 1 shows Scopus search results for PBF, DED and WA-DED. DED processes can be classified as Laser based DED (L-DED), Electron Beam (EB-DED) and arc based DED (A-DED). Furthermore, DED processes can be classified by feedstock in the form of wire or powder. It is worth noting that for this paper both “wire arc additive manufacture” and “WAAM” were searched for as the vast majority of literature appears under this pseudonym. The authors propose using the term WA-DED for this technique in line with ASTM 5290:2021 as it states the subcategory of AM and the power source used to deposit the material. As shown in figure 2, there is a significant uptake in research in not only WA-DED but metal AM as a whole. Although these techniques have noticeably different characteristics and applications it shows interest is broadening across metal AM techniques. Although the as stated immaturity of WA-DED as a process in comparison to PBF or DED as a whole is recognised.

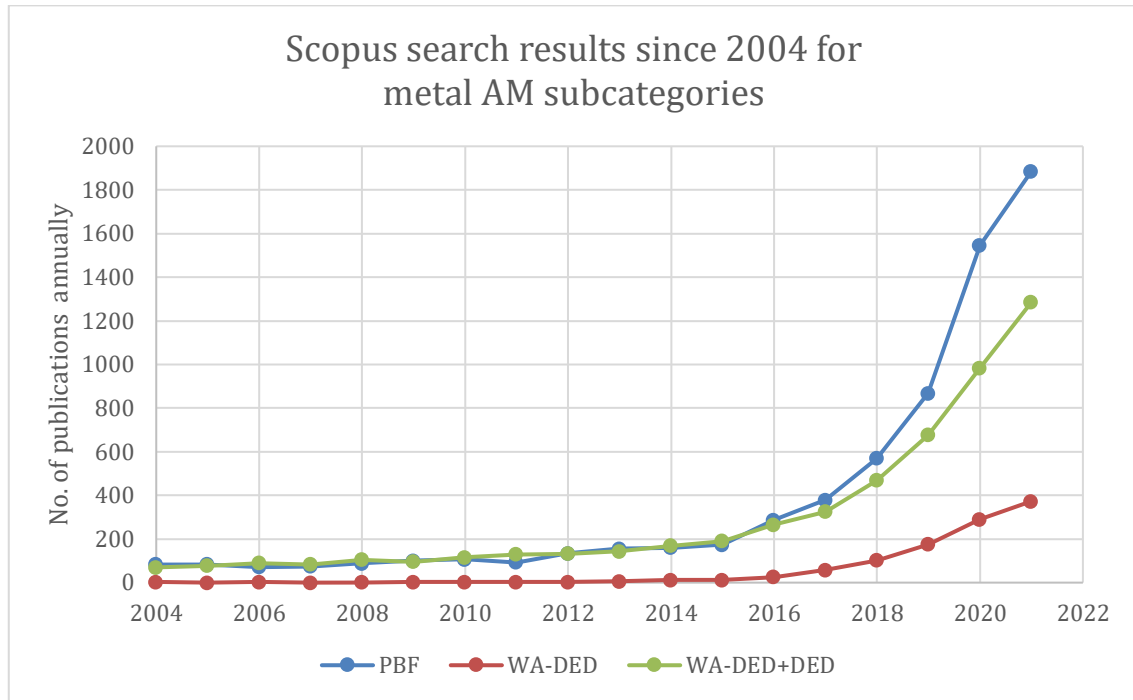


Figure 2 Scopus analysis of recent publications in the field of metal AM

Recent applications in the field of WA-DED include production of large components such as a pedestrian footbridge, a replacement part for a robotic arm and structural nodal connections as shown in figures 3a,3b & 3c (“MX3D Bridge,” 2019; “MX3D ROBOT ARM,” 2019; “TAKENAKA CONNECTOR,” 2019). At TU Darmstadt, a German university, a footbridge has also been designed parametrically and printed in-situ as an example of a large component as shown in figure 4 (Feucht et al., 2020b, 2020a). Cranfield University in the UK, has also created large components which are as large as 2.5m in one direction and another as large as 24kg (Williams et al., 2016). To assess the maturity of WA-DED, for this review paper a part is considered large if the build volume exceeds 0.5m^3 . Moreover, many industries are adopting WA-DED for bespoke components such as maritime components (Queguineur et al., 2018), crane hooks (Plangger et al., 2019), military applications (“AML-3D Defence,” 2021) and space applications (“Relativity Space,” 2022).



Figure 3a,3b & 3c MX3D bridge, MX3D Takenaka connector and MX3D Robot arm (“MX3D Bridge,” 2019; “MX3D ROBOT ARM,” 2019; “TAKENAKA CONNECTOR,” 2019)



Figure 4 TU Darmstadt WA-DED bridge (Feucht et al., 2020a)

1.1 Literature classification and scope definition

Previously, numerous metal AM review papers have been conducted that are industry specific. Readers are referred to the papers in table 1 under the heading “Metal AM” for information on other DED processes such as Laser-DED and Electron Beam-DED as well as information on the other 6 categories of AM including PBF.

Table 1 - Previous review papers and their specialisation

Specific to a Material			
Paper Specification	Metal AM	DED	WA-DED
Aluminium			(Derekar, 2018; Thapliyal, 2019; Vimal et al., 2020)
Nickel Alloys			(Dhinakaran et al., 2020)
Titanium Alloys			(Lin et al., 2021)
Stainless Steels	(Mukherjee and DebRoy, 2019)		(Jin et al., 2020)
Materials Generally	(Mukherjee et al., 2016; Sames et al., 2016)		(Wu et al., 2018)
Specific to an Industry			
Paper Specification	Metal AM	DED	WA-DED
Aviation	(Gisario et al., 2019; Mohd Yusuf et al., 2019; Uriondo et al., 2015)		
Construction	(Buchanan and Gardner, 2019)		(Kühne et al., 2019)
Shipbuilding			(Queguineur et al., 2018; Taşdemir and Nohut, 2020)
Specific to Supporting System Technology			
Paper Specification	Metal AM	DED	WA-DED
Monitoring and metrology	(Everton et al., 2016; Leach et al., 2019)	(Tang et al., 2020)	(Xia et al., 2020a)
Path Planning & Slicing		(J. Xu et al., 2018)	
Process Physics			(Norrish et al., 2021)
Post Processing	(Peng et al., 2021; Shiyas and Ramanujam, 2021)		(Bankong et al., 2022)
General	(Bandyopadhyay et al., 2020; Francois et al., 2017; Frazier, 2014; Vayre et al., 2012; Yakout et al., 2018)	(Dass and Moridi, 2019)	(Cunningham et al., 2018; Dhinakaran et al., 2020; Jafari et al., 2021; J. Z. Li et al., 2019; Rodrigues et al., 2019; Singh and Khanna, 2020; Williams et al., 2016)

2 Wire Arc Directed Energy Deposition

Aspects of WA-DED are described below in line with ASTM 5290:2021 in respect of the heat source, defined as an arc process and the characteristics of the material after deposition. Moreover, the additional in-situ additional processes and process control have been reviewed.

2.1 Arc Processes

The heat sources used in the WA-DED process are off-the-shelf arc welding equipment. As such, the characteristics of the layer geometry that is deposited are directly affected by the process parameters used for deposition.

Three major arc processes used in WA-DED, namely (i) Metal Inert Gas/ Metal Active Gas (MIG/MAG), (ii) Tungsten Inert Gas (TIG) and (iii) Plasma Arc (PA). These can also be adapted by using multiple wires for MIG with two electrodes with independent power sources and for TIG and PA by feeding more than one wire into the arc, known as a tandem wire system. If multiple welding systems were used with multiple motion systems this can be termed as a parallel system. Both tandem wire and parallel systems have the advantage of increasing deposition rates. These terms can be used for classification of WA-DED processes as shown in figure 5. Conventionally the welding current is either constant or pulsed with a regular frequency. Other wave form variants have been identified such as Cold Metal Transfer (CMT), TopTIG and variable polarities variants on conventional welding processes. Table 2 refers to these different arc processes and their respective subcategories such as constant, pulsed, CMT, TopTIG and variable polarity, which employs an alternating current (AC). It is worth noting some literature is listed under multiple subheadings where for instance a tandem wire system is used in conjunction with a variable polarity power source. CMT and TopTIG are popular trademarked variants of MIG and TIG welding respectively which are products of Fronius and Air Liquide Welding (Opderbecke and Guiheux, 2009). CMT uses the digital synchronisation of an oscillated wire with a digitally oscillating current to allow for deposition of precisely one droplet of metal per oscillation discussed further in section 2.1.1. TopTIG pushes the filler wire coaxially with the electrode ensuring that the wire is always inserted into the hottest zone of the arc regardless of the direction of welding. This results in higher deposition rates with a more stable arc and therefore deposition with a more regular deposited geometry (Rodriguez et al., 2018). This is further discussed in section 2.1.2. It is however worth noting that despite these processes being the most popular of their respective types, they are not exhaustive and there are other commercial alternatives. As most of the research reported has focused on these for WA-DED they are the only processes of their types mentioned.

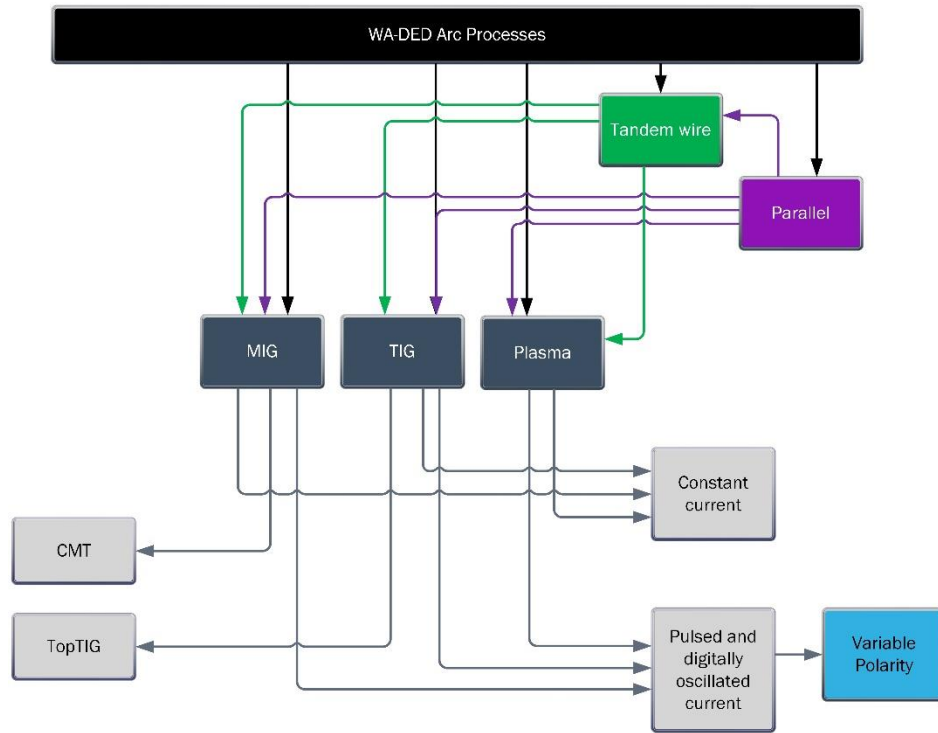


Figure 5 Classification of WA-DED arc processes

Table 2 – WA-DED arc processes and their respective subcategories.

Arc processes	Arc process subcategory	References
MIG	Conventional	(Chen et al., 2017b; Ding and Pan, 2016)
	Pulse and digitally oscillating	(Cunningham et al., 2019; L. Wang et al., 2019)
	CMT	(Feucht et al., 2020b; Laghi et al., 2020a; Li et al., 2020; Radel et al., 2019; Y. Wang et al., 2019; Yili et al., 2018)
	CMT Variable Polarity	(Cong et al., 2017, 2015; Gu et al., 2016; Scotti et al., 2020; Zhang et al., 2019)
TIG	Conventional	(Bai et al., 2016; Wang et al., 2016)
	Pulsed	(Geng et al., 2017; Wu et al., 2017)
	TopTig	(Rodriguez et al., 2018)
	Variable Polarity	(Qi et al., 2018)
Plasma	Conventional	(Lin et al., 2017; Martina et al., 2012; Wu et al., 2014)
	Pulsed	(Lin et al., 2016, 2019; K. Wang et al., 2020)
Tandem wire	MIG based	(Martina et al., 2019; Shi et al., 2019)
	TIG based	(Ke and Xiong, 2020; Liu et al., 2020; Qi et al., 2018)
	Plasma arc based	(Feng et al., 2018; Reisgen et al., 2019)
Parallel system	Plasma arc based	(Autodesk, 2018)

2.1.1 Metal Inert gas (MIG) and Metal Active gas (MAG)

MIG/MAG consists of a fed metal wire that acts as an electrode heated by an arc between itself and the metallic substrate as shown in figure 6 (Haselhuhn et al., 2015). As a result of this heating, the electrode melts and is deposited in the weld pool on the substrate. A shield gas is applied around the electrode and weld pool to protect the hot metal from the atmospheric gases and humidity that can cause oxidation of the part or porosity (Cong et al., 2017). For MIG welding the shield gas is inert, such as Argon and for MAG welding the gas is active such as carbon dioxide.

MIG has found great commercial success in the robotic welding industry due to its cost effectiveness (Anzalone et al., 2013) and its versatility outlined by Kah et al. (2014) due to the potential different types of arc suited for a given application. This has made it the most widely used type of arc process for WA-DED. Furthermore, control of the geometry of the molten pool is limited with an arc power source therefore the control of geometry of deposited layers is also subsequently limited and this is due to the lack of arc stability when a MIG power source is used (Zhang et al., 2018). For large parts, the irregularity of layer geometry creates cumulative geometric inaccuracies throughout the part. Therefore, the adoption of the technique requires an intimate understanding of the technology which is not as yet supported by design standards for metal parts produced with WA-DED (Assunção et al., 2018; Gisario et al., 2019; Kühne et al., 2019; Uriondo et al., 2015).

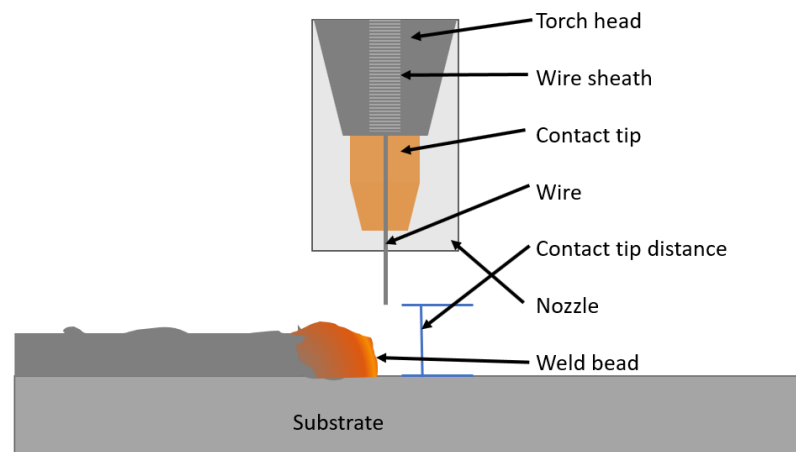


Figure 6 Generic MIG torch schematic

A specific MIG welding process that has been widely researched for WA-DED is cold metal transfer (CMT), a Fronius proprietary product (Fronius, 2021). However there are other manufacturers have products that use complex current waveforms to reduce heat input, spatter and distortion (EWM group, 2021; Milosevic et al., 2016). CMT provides a low energy MIG welding process with an oscillating wire electrode at high frequencies. By synchronising the power signal and wire oscillation, deposition of exactly one droplet of metal with each oscillation is possible (Gerhard et al., 2014; Rodriguez et al., 2018). CMT is capable of high deposition rates with low heat

input (Pan et al., 2018; Y. Wang et al., 2019), lower spatter (Kazanas et al., 2011; Radel et al., 2019), reduced porosity (Cong et al., 2015) and reduced distortion (Elitzer et al., 2022). This lower heat input and precisely controlled deposition rates allows for more complex geometry to be deposited on a larger scale than previously possible such as multi directional pipe joint shown in figure 7.

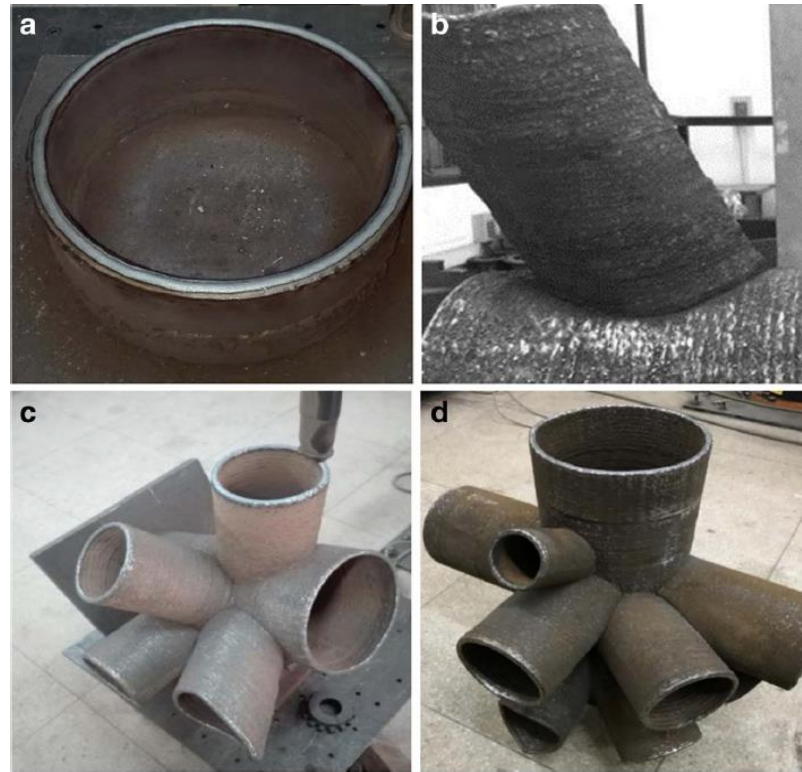


Figure 7 Multi-Directional pipe joint manufactured using CMT (Yili et al., 2018)

The production of truss elements using CMT has been termed as Skeleton Arc Additive Manufacture (SAAM) (Radel et al., 2019; Yu et al., 2019). In principle, an algorithm was proposed that allows for the production of two dimensional or three-dimensional truss elements by depositing droplets on top of one another in a vertical manner. An example of this strut based deposition approach has allowed for the fabrication of a 2 m tall diagrid column as shown in figure 8. It was identified in the literature that, thin wall WA-DED structures could be stiffened using SAAM struts between walls (Radel et al., 2019). This would allow for parts that are significantly lighter for their given volume. Radel et al. (2019) identifies the possible application for energy absorbing structures, such as crumple zones in the automotive industry. Moreover, the development of struts has allowed for the fabrication of lattice structures. The work carried out by Li et al. (2020) followed the process of optimising the current and voltage to minimise the size of each droplet deposited allowing for a more refined lattice strut to be created as shown in figure 9. For large parts, the minimum resolution of such structures is of lesser importance than in smaller parts. However, it will still be vital to ensure that the lattice is sufficiently fine that any point loads on a surrounding thin wall do not punch

through the thin wall. Furthermore, WA-DED as a process is most competitive when the dimensions of a part are large for a relatively small build volume. This enables a reduction of infill for solid parts leading to substantial material savings.

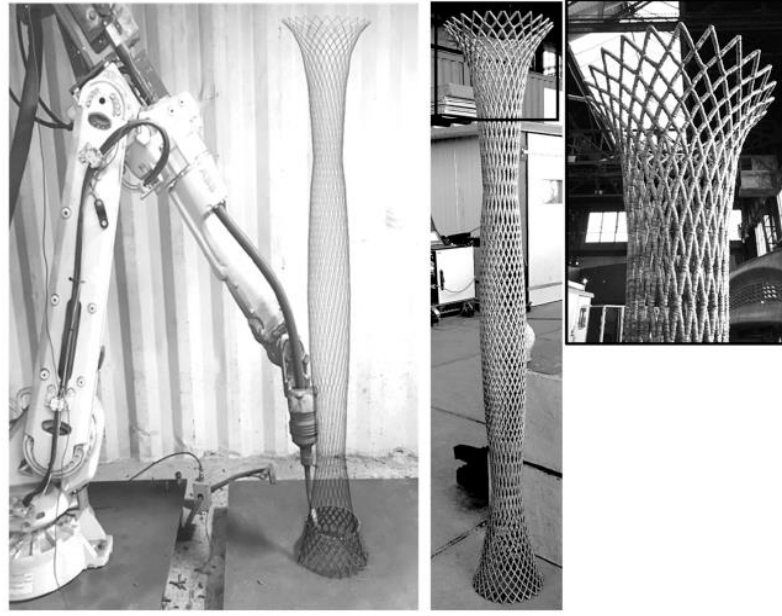


Figure 8 A 2m tall diagrid column made of 316L Si stainless steel (Laghi et al., 2020a)

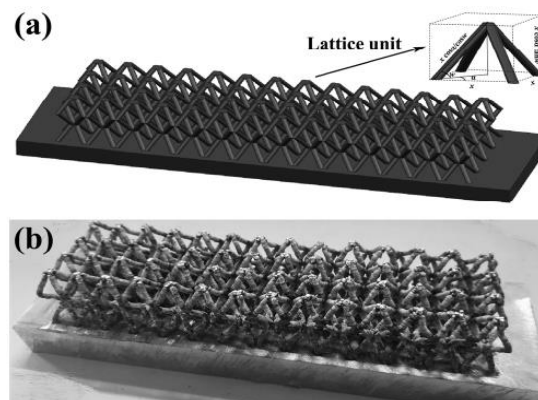


Figure 9 A lattice structure fabricated of aluminium using CMT (Li et al., 2020)

2.1.2 Tungsten Inert Gas

Tungsten Inert Gas (TIG) consists of a non-consumable tungsten electrode and an additional fed wire feedstock with an arc drawn across it which allows deposition of the feedstock onto a substrate shown in figure 10. Due to the high operating temperatures, a shield gas is also used much in the same manner as in MIG. The process offers good versatility for part manufacture as the angle for which the wire is fed in relation to the torch affects deposition characteristics (Geng et al., 2017). For application of TIG welding for large components it has been identified by (Rodriguez et al., 2018) that TOPTig, a specific TIG process that feeds the wire coaxially into the hottest part of the arc can lead to significantly higher deposition rates with regular layer geometry caused by a stable arc.

Recent novel work was conducted using a TIG weld head for the deposition of lattice structures made of stainless steel (H. Zhang et al., 2020). Allowing for light weighting through eliminating the excess material. The work also optimised process parameters, namely arc current and voltage therefore heat input, and reported tensile and ductile properties that exceeded those set by ASTM standards for wrought material by 24.3% (H. Zhang et al., 2020). In addition due to the high heat input but low frequency of deposition cycles, a fine microstructure was observed.

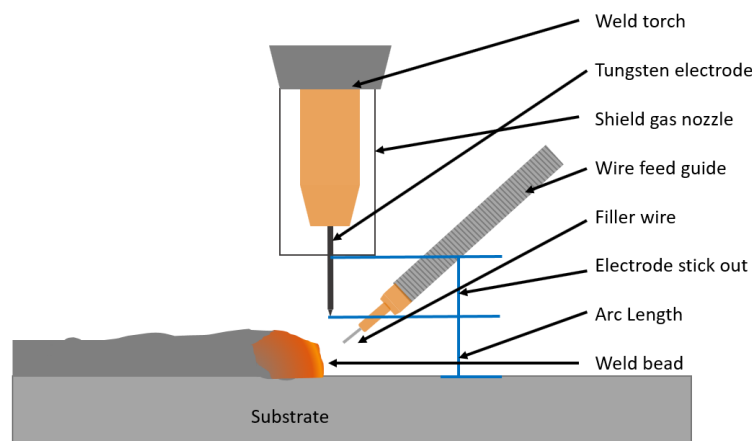


Figure 10 Generic TIG schematic

2.1.3 Plasma Arc

Plasma arc consists of a constricted plasma arc between a tungsten electrode and the previous layer or the substrate. This is similar to TIG welding in the sense that a non-consumable tungsten electrode is used in conjunction with an argon shield gas as shown in figure 11 (Wu et al., 2014). However, in plasma arc a secondary copper electrode is used within the nozzle to ionise an inter gas which is forced between the two electrodes creating a focused beam of plasma (Martina et al., 2012). The extra focusing of the plasma leads to extremely high temperatures that can be in the order of 11000 °C. In addition, this power source has a higher energy density, better arc stability and minimal contamination compared to TIG welding systems, all of which leads to more precisely deposited material (Lin et al., 2017). This allows plasma arc to offer a middle ground between the high deposition rate in MIG processes and other metal AM processes such as Laser PBF. This is because of the relatively precise material deposition offered by plasma arc processes which alleviate some of the concerns raised when depositing with MIG power sources regarding cumulative geometric inaccuracies. However, lower deposition rates compared to MIG arc processes can be a disadvantage for the manufacture of large parts.

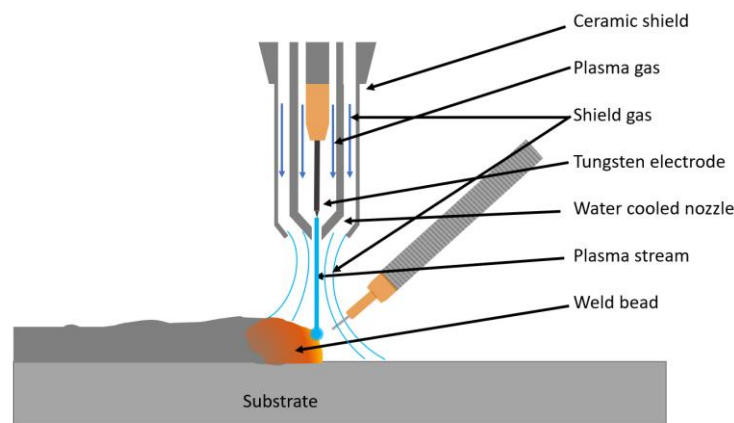


Figure 11 Generic plasma arc schematic reproduced from the work (Aiyiti et al., 2005)

2.1.4 Tandem Wire Arc Welding

Tandem Wire Arc Welding (TWAW) is a method of depositing two fed wires into the same weld pool on the substrate or part leading to far greater deposition rates into a singular weld pool (Martina et al., 2019). This has been achieved in several different ways in the literature using the conventional arc processes as outlined in table 2.

A method identified in the literature especially suitable for large parts is to use two MIG welding torches in tandem with independent power sources. This allows for greater efficiency, deposition rates and the ability to alter the composition of deposited material in different locations in a part manufactured as shown in figure 13b. The benefit of this method is that it allows for a streamlined singular torch head instead of two wires being fed separately towards the torch head in a TIG dual wire system (Abe and Sasahara, 2016; Martina et al., 2019; Shi et al., 2019) as shown in figure 13a. The benefit of this for the production of large components is obvious in the sense that the faster material is deposited, the shorter the time it takes to produce a component. Martina et al. (2019) used this technique to deposit stainless steel. Firstly, the wire feed speed and travel speed were optimized to allow for the 9.5 kg/hr to be achieved. It was found due to the relatively high heat inputs that an epitaxial grain structure was present as shown in figure 12, which was caused by increased thermal energy accumulation during the deposition process. Importantly, there was no discernible change in hardness properties with increased deposition rates. As a result, it was stated that for thicker sectioned parts, there is likely to be a need for an additional cooling process to ensure satisfactory microstructure thus mechanical performance (Martina et al., 2019).

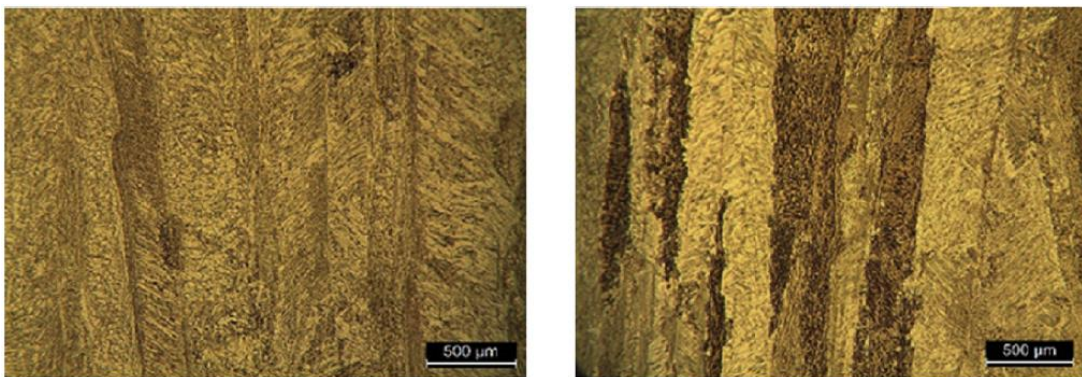


Figure 12 epitaxial grain structure present in tandem wire MIG deposition (Martina et al., 2019)

The research presented by Abe and Sasahara (2016) focused on the interface between two metals deposited and the path planning procedure necessary to ensure a satisfactory bond. They found that there was a negligible difference between the tensile properties of the test specimens formed with a dissimilar metal interface and the tensile properties of each material on their own. This allowed for components to be constructed with an infill material and an external layer around it to allow for different surface and internal properties. Their work also experimented with a path planning solution which allowed for non-solid infill allowing for parts to be made lighter for their given

geometry. This is of particular interest again for large components as it allows for them to be manufactured with potentially a lighter metal infill as well as using less material due to a lattice structure. Furthermore, functionally graded parts could allow for a greater level of optimisation within component design.

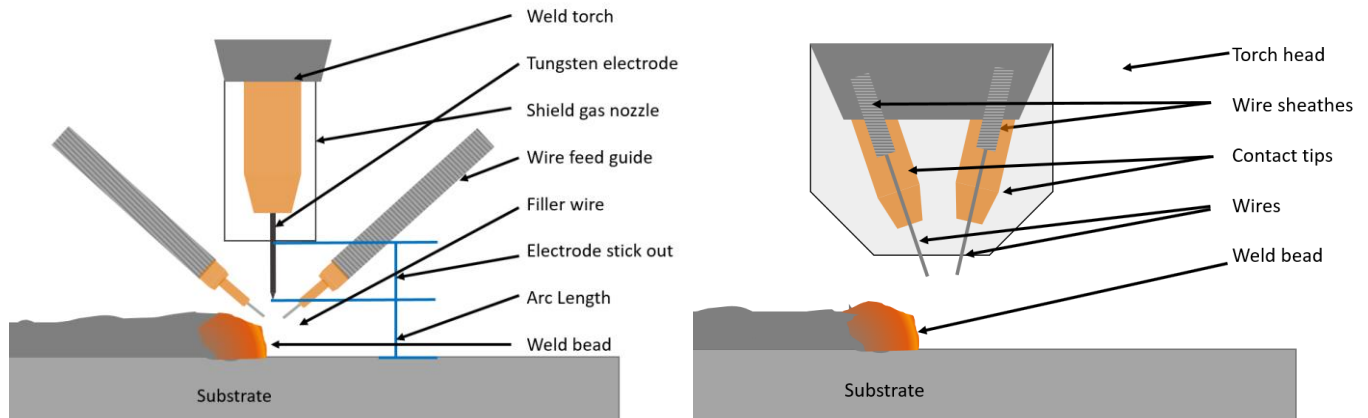


Figure 13a schematic for a TIG tandem wire system, figure 13b a schematic for a MIG tandem wire system reproduced from the work of Somashekara et al. (2017)

2.1.5 Parallel arc processes

The WA-DED process has high deposition rates which makes it suitable for large component manufacture. However, for each arc process used, there is a maximum deposition rate possible as the heat input can only be so high for stable deposition and wire can only be fed through the torch so quickly. Therefore, to improve deposition rates, the use of multiple torches working in parallel is an obvious option.

Autodesk have developed a system that uses two six axis robotic motion systems and two torch heads to double the deposition rates an equivalent system would have previously achieved as shown in figure 14 (Autodesk, 2018). The Autodesk system also has a rotating axis to the working table allowing for the deposition of parts with dimensions 3 m long with a 1 m diameter cross section. Furthermore, they installed the robotic arms onto rails to allow for extending the build dimensions.

Theoretically, this shows how even larger components can be manufactured as the size of the parts is now dictated by how long the rails are and the reach of the motion system. This will have a massive impact on the construction industry where structural components can be many metres in length. Though PBF offers much more design flexibility allowing for structurally optimized components (Galjaard et al., 2015), WA-DED could be utilized for larger structurally optimised components than PBF due to the higher deposition rates and use of larger motion systems as shown in figure 14. Parallel systems in particular would be most suited to large components as higher deposition rates can significantly cut lead times.

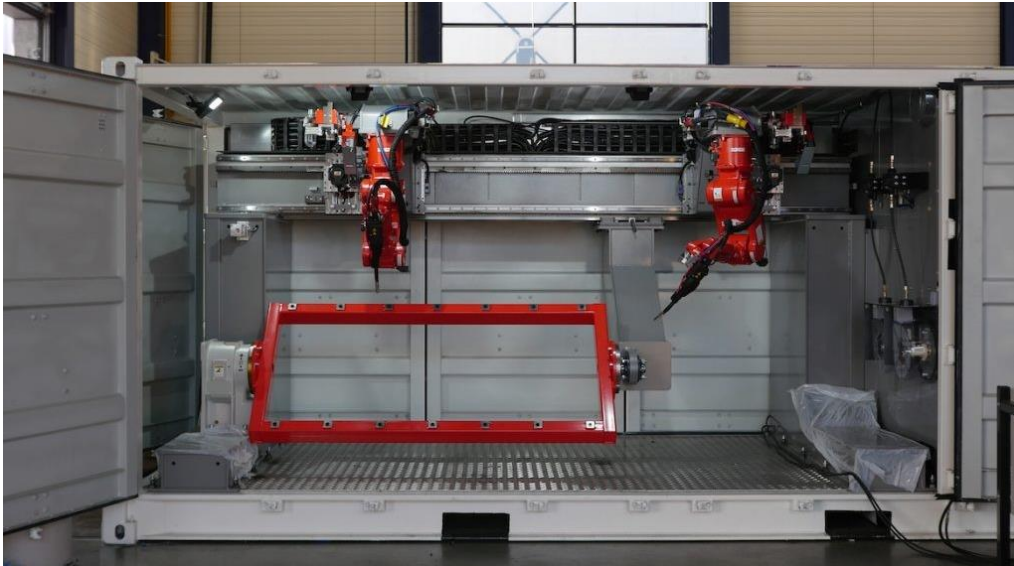


Figure 14 A parallel power source WA-DED system from Autodesk (Autodesk, 2018)

2.2 Mechanical Properties

A wide range of different metal alloys have been deposited using WA-DED. The materials chosen have been broadly researched with numerous arc processes making them ideal for comparison. As material properties vary with each metal, there are a number of challenges associated in general when using AM technology which vary in severity for different metals (Jin et al., 2020; Thapliyal, 2019; Xu et al., 2016). For the design and application purposes, it is vital to characterise the physical and mechanical properties of the WA-DED materials. It is common practice in both industry and academia to compare these properties with that of the wrought material. However, they can be used as a reference on their own. Table 3 shows the most common mechanical tests performed by researchers for WA-DED materials with associated testing standard used for performing the tests. Analysis of the literature indicates that a significant portion of literature is concentrated on tensile and hardness tests at room temperature. Readers are referred to the individual standards as outlined in table 3 for comprehensive testing procedures for tensile, fatigue, toughness and hardness.

Table 4 shows the alloys that have the ability to be deposited using WA-DED without any additional in-situ processes, the material properties, and the arc process that has been used to deposit it. The reason for as deposited properties have been considered is that it allows for comparison between arc processes. As outlined in section 2.4, additional in-situ or post processes could be used to improve the mechanical properties, improve layer geometry or alleviate defects. However, post processes incur a significant increase in lead times thus cost which may prove undesirable for the production of large-scale parts. Literature for additional in-situ processes has been categorised in section 2.4 and comparisons between additional in-situ processes and material purely deposited with an arc power source can be found in the referenced literature in table 4. The materials chosen in table 4 are used in a wide range of industries and have been chosen for this reason along with the breadth to which they've been researched.

Furthermore, the horizontal direction has been defined as the direction in which the power source moves when depositing material, transverse as the perpendicular of this in the same non-vertical plane but parallel to the direction of motion and, finally vertical has been defined as the build direction. It is noted that the vast majority of literature and mechanical testing has been conducted with samples taken out of thin wall structures. Where a thin wall can be defined as a wall generated from just a single pass if the welding torch. More recent literature has had the advantage that blocks of relatively similar 3D dimensions have been accomplished so the further “transverse” direction can be evaluated (C. Wang et al., 2020).

Table 3 Material testing standards for mechanical properties from widely accepted

Tested Property	Standard(s)	References
Tensile	(room temperature) ISO 6892-1:2019	(Aldalur et al., 2020; Kyvelou et al., 2020; Laghi et al., 2020b; Moore et al., 2019; Plangger et al., 2019; Seow et al., 2019; Suárez et al., 2021; B. Wang et al., 2020; H. Zhang et al., 2020)
	ASTM E8/E8M-16	(Biswal et al., 2019; Cunningham et al., 2021, 2019; Dirisu et al., 2020; Lin et al., 2017, 2016; K. Wang et al., 2020)
	ASTM A370-13	(Haden et al., 2017)
	EN10002-2009	(Brandl et al., 2010)
	GB/T228.1–2010	(Li et al., 2020; Wu et al., 2019)
	(at 650°C) EN ISO 6892-2	(Seow et al., 2019)
Hardness	ISO 6507-1:2018	(Cunningham et al., 2019; Lin et al., 2017; Plangger et al., 2019; Seow et al., 2019)
Fatigue life	ASTM E466-15	(Biswal et al., 2019; Dirisu et al., 2020; Zhang et al., 2016)
	ASTM E647-15	(Gordon et al., 2018; Syed et al., 2021)
	EN 1993-1-9	(Bartsch et al., 2021)
Toughness	Charpy NF EN ISO 148-1	(Aldalur et al., 2020; Moore et al., 2019; Plangger et al., 2019; Queguineur et al., 2018)
	ASTM E1820-11	(Plangger et al., 2019)
	ASTM E399-09	(Zhang et al., 2016)

Table 4 - Mechanical properties as deposited of different materials with WA-DED and traditional processes tested at room temperature.

Material	Material Subcategory	Process/ WA-DED Power Source	Tensile mechanical Properties				Reference
			Direction	0.2%YS MPa	UTS MPa	Elong %	
Mild Steel	ER70S-6	MIG Pulse	Horizontal	368+-12	498+-9	36+-4	(Aldalur et al., 2020)
			Vertical	368+-4	501+-3	32+-1	
		CMT	Horizontal	300+-1.5	402+-3	28+-1	(Dirisu et al., 2020)
		As welded	-	>420	500-640	28	(Aldalur et al., 2020)
Aluminium	Al-Cu6.3% (2219-Al)	TIG	Isotropic	112	237	10.7	(Bai et al., 2016)
		TIG	Horizontal	255+-12	350+-13	5.2+-1.4	(Fu et al., 2021)
			Vertical	234+-12	320+-15	3.8+-1.3	
		CMT-Pulsed advanced	Horizontal	128+-2	262+-4	15.8+-0.3	(Gu et al., 2016)
			Vertical	133+-5	264+-2	18.6+-1.5	
		Tandem Wire-MIG	Horizontal	-	255.9	14.9	(Liu et al., 2020)
			Vertical	-	246.7	16.4	
		Wrought	-	267	390	>4	(ASTM B211 / B211M - 19, 2019)
Titanium alloy	Ti-6Al-4V	Pulsed plasma arc	Horizontal	909+-13.6	988+-19.2	7+-0.5	(Lin et al., 2016)
		Continuous plasma arc	Horizontal	877+-18.5	968+-12.6	11.5+-0.5	(Lin et al., 2017)
		Plasma arc	Horizontal	924+-22	992+-38	11+-1	(Suárez et al., 2021)
			Vertical	870+-19	931+-15	16+-2	
		TIG	Horizontal	892+-31	963+-22	16.5+-2.7	(Brandl et al., 2010)
			Vertical	861+-14	937+-21	7.8+-2	
		Wrought	-	828	895	10	(ASTM B381-13, 2019)
		Cast	-	825	895	6	(ASTM B367 - 13(2017), 2017)
Inconel	Inconel 718	TIG	Horizontal	473+-6	828+-8	28+-2	(Baufeld, 2012)
		Plasma arc	Horizontal	525+-7	818+-13	33.3+-2.5	(X. Xu et al., 2018)
			Vertical	506+-2	756+-7	27.9+-1.3	
		Pulsed plasma arc	Horizontal	563+-14	872+-31	34+-3	(K. Wang et al., 2020)
		MIG	Horizontal	549+-10	850+-7	20+-1	(Suárez et al., 2021)
			Vertical	472+-4	790+-7	19+-1	
		Cast	-	758	862	5	(K. Wang et al., 2020)
		Forged	-	1034	1276	12	
Stainless Steel	316L	MIG	Vertical	236+-6	533+-23	48+-2	(Chen et al., 2017a)
		CMT-Continuous	Horizontal	364.5	577.3	43.4	(Rodríguez et al., 2018)
			Vertical	336.9	547	42	
		CMT-Pulsed	Horizontal	374	588	51.1	
			Vertical	331.7	536	45.6	
		TIG TopTig	Horizontal	365.5	590.3	42.3	
			Vertical	322.2	539.9	43.1	
		CMT	Horizontal	369	551	41	(Queguineur et al., 2018)
			Vertical	313	537		
		MIG Speed pulse	Horizontal	418	550+-6	-	(L. Wang et al., 2019)
		MIG Speed arc	Horizontal	417.90	553+-2	-	
		Plasma arc	Horizontal	384+-19	586+-9	40+-4	(Suárez et al., 2021)
			Vertical	342+-9	539+-9	56+-6	
		MIG *1= 10s inter pass dwell time, *2= 15s inter pass dwell time	Horizontal*1	334.3	557.7	-	(Wu et al., 2019)
			Vertical	357.6	603.1	-	
			Horizontal*2	340.7	605.4	-	
			Vertical	361.4	614.4	-	
		CMT	Horizontal	388.5	566.3	39.6	(C. Wang et al., 2020)
			Vertical	353.9	536.1	38.7	
			Transverse	392.7	575	28.4	
		Wrought Annealed	-	170	480	40	(Cunningham et al., 2019)
		Wrought Cast	-	262	552	55	

2.3 Material characteristics associated with WA-DED deposited material affecting mechanical performance

The WA-DED process is novel as a manufacturing process when compared to conventional manufacturing methods such as casting or forging. As such, material characteristics of deposited material are less uniform, with defects that affect both longevity and mechanical performance. These characteristics in the material have been classified by the authors into geometric issues and material issues as shown in figure 15. Geometric issues are largely caused by limited control of the weld pool thus layer geometry as discussed in section 2.1.1. Furthermore, distortion is a direct result of thermally induced residual stresses and as such literature has been reviewed from the perspective of material issues that affect mechanical performance. Distortion and residual stress have been considered separately as they affect geometric accuracy and mechanical performance respectively. The material issues can be further categorised by the scale at which they occur, global structural resilience is defined by characteristics that occur across the entirety of the part such as thermally induced residual stress and fatigue resistance. Defects occur on a macrostructural level such as cracking and porosity, which the remaining issues can be attributed to the non-conformance in microstructure and composition causing anisotropy and heterogeneity in mechanical performance. For literature that is material specific please refer back to table 1. For detailed analysis of particular characteristics and what causes them readers are referred to tables 5 and 6.

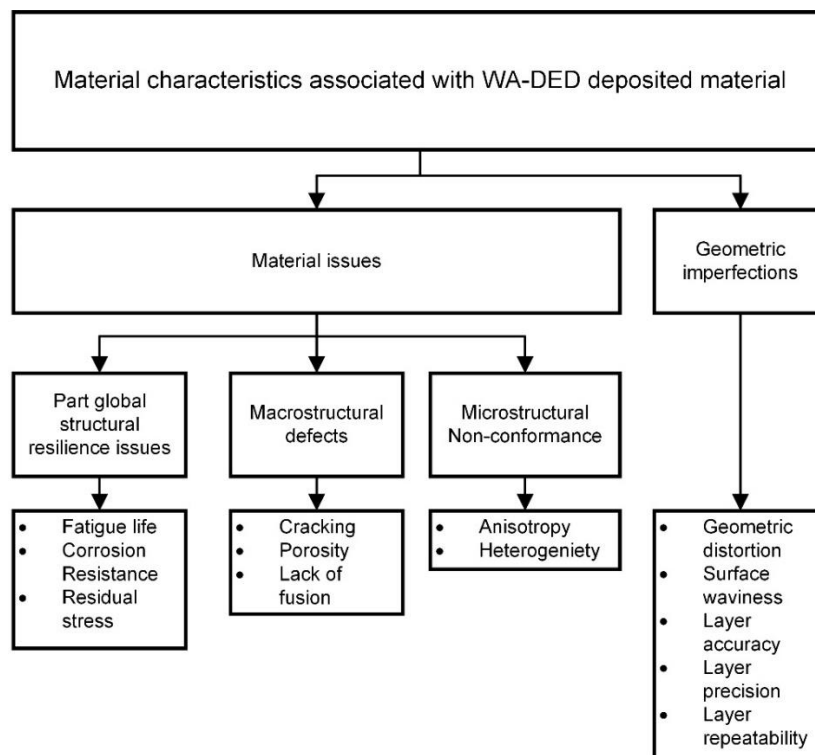


Figure 15 Classification of material defects in WA-DED deposited material

Table 5- referred literature for analysis and causation of part global resilience issues

Part global structural issue	Main Causes
Fatigue life	Large surface roughness (Bartsch et al., 2021; Kühne et al., 2019) Porosity (Biswal et al., 2019) Fine microstructure (Gordon et al., 2018)
Corrosion resistance	Contamination
Residual stress	Large thermal gradients caused by a high heat input (Dai et al., 2020)

Table 6- referred literature for analysis and causation of macrostructural defects

Macrostructural defects	Main cause
Porosity	Contamination of substrate & feedstock (Biswal et al., 2019; Thapliyal, 2019)
Lack of fusion	Insufficient overlap of melt pool and previous layers (Mukherjee and DebRoy, 2019)
Cracking	Residual stresses (Xu et al., 2016)

2.3.1 Material issues

2.3.1.1 Part global structural resilience issues

In the case of metal AM, residual stresses are caused by the contraction of deposited metal as it cools at a different rate compared to its adjacent layers as shown in figure 16 (Bai et al., 2015). As the deposition is layer-by-layer, zones are rapidly reheated and cooled locally causing thermal gradients and differential cooling rates (Dai et al., 2020). As a result, the deposited metal is subject to local tensile and compressive forces where the contraction of a zone is restrained by the metal around it causing tensile stresses. If not alleviated, these stresses can lead to cracking, geometrical distortion and reduced mechanical performance of a given manufactured component (Xu et al., 2016).

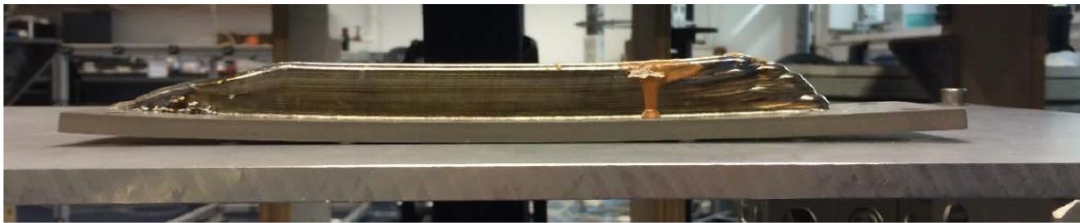


Figure 16 Residual stress induced deformation in a WA-DED deposited wall (Xu et al., 2016)

There is a wealth of literature that focuses on modelling the flow of heat globally for a moving heat source over the whole deposition using thermo-mechanical finite element (FE) analysis (Ding et al., 2011; Mehnen et al., 2014; Mughal et al., 2006; Zhao, 2020). The aim of this is to predict the location and severity of the stresses. This is then used for optimising the process parameters and process planning to minimise the residual stresses. This has been an area of research that has advanced hugely in the last decade with the advent of more powerful computing capabilities allowing for more rigorous analysis. In larger parts this issue is more relevant as thermal gradients will be greater causing more variance in cooling rates. However, due to the data intensive nature of accurate thermodynamic models, it has been thought unthinkable to produce a model for the build-up of an entire part (Cadiou et al., 2020).

In austenitic stainless steels deposited with WA-DED, fatigue cracking resistance has been found to be favourably compared to wrought material (Gordon et al., 2018). Coarse columnar grains cause crack paths to be more torturous for test samples that were taken perpendicular to the build, as more energy is dissipated due to plastic deformation. This means that the direction in which a component is built should be taken into consideration as there is a direction that is preferential to resist cyclic loading. However in both the build direction and that perpendicular wrought standards are exceeded for fatigue life. Conversely, the steel deposited did not meet wrought standards for

ultimate tensile stress which means any components designed would have to remain solely in the region below the yield stress, which does meet ASTM wrought standards (Gordon et al., 2018).

Bartsch et al. (2021) have investigated the effect on fatigue life when multiple low carbon steel wires are incorporated into the weld pool using a MIG torch with two additional wires. They found that multiple wires lead to a poorer fatigue life as surface waviness was greater as shown in figure 17. For large parts that are not machined in their final state, this is an important consideration as the trade-off between fatigue life, deposition rates and the necessity for machining will all have to be considered from both performance and economic perspectives.

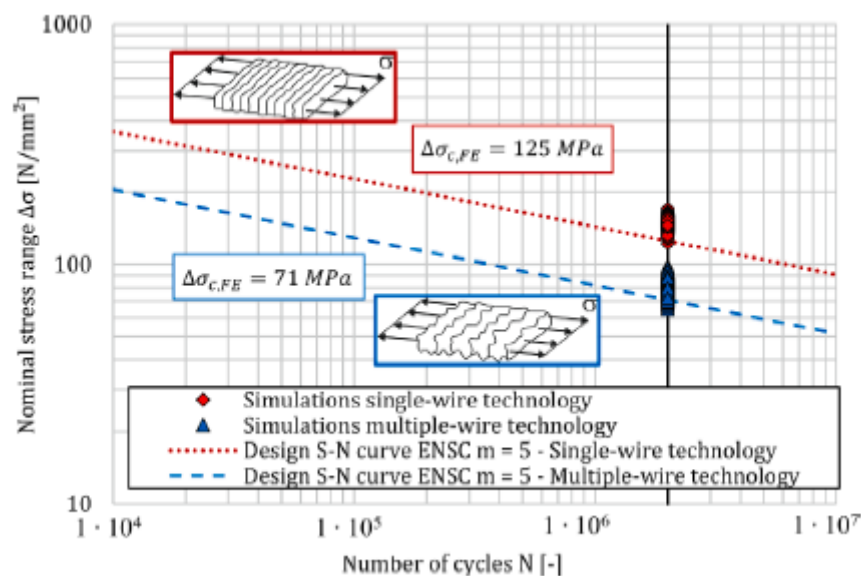


Figure 17 Comparison of fatigue strength of single and multi-wire deposited low carbon steel (Bartsch et al., 2021)

2.3.1.2 Macrostructural defects

Porosity is a major issue in the deposition of metals as the presence of voids within the deposition, reduces the mechanical strength of the deposited metal. In deposition of aluminium alloys this is particularly prevalent (Horgar et al., 2018). This has been extensively reviewed by Thapliyal (2019), who states that the main cause for porosity is contamination of both the substrate and feedstock that leads to gases, principally hydrogen becoming entrapped during the welding process which can range from micropores to pores visible to the naked eye (Thapliyal, 2019). Thapliyal then states that causes can be further broken down into the following categories: process parameters, alloy composition and welding parameters. Porosity has also been found to have a significant detrimental impact on fatigue life of Ti-6Al-4V specimens as well as a significant reduction in ductility. In titanium alloys, this can be attributed to contamination in the feedstock (Biswal et al., 2019).

Porosity can be reduced in a number of ways. (Cong et al., 2017) found the use of CMT with variable polarity could decrease porosity and highlighted the arc mode as a significant factor in

controlling porosity, as shown in figure 18. This can be explained as lower heat input has been found to reduce gas solubility in the welding process which decreases the volume of the voids thus porosity (Cong et al., 2017, 2015). Y. Wang et al. (2019) expanded on this work to assess the effects of arc mode for components that were not just thin wall components. They highlighted that when depositing a multi pass wall, porosity is significantly lower than that of a thin wall section. This can largely be accredited to a higher nucleation rate of grains which is caused by a higher temperature gradient thus cooling rate due to the thermal conductivity of neighbouring deposited material within the block being higher than the air surrounding the deposited block (Cong et al., 2017). This compared to a thin wall deposit, is due to the surface to volume ratio being lower for a multi pass wall.

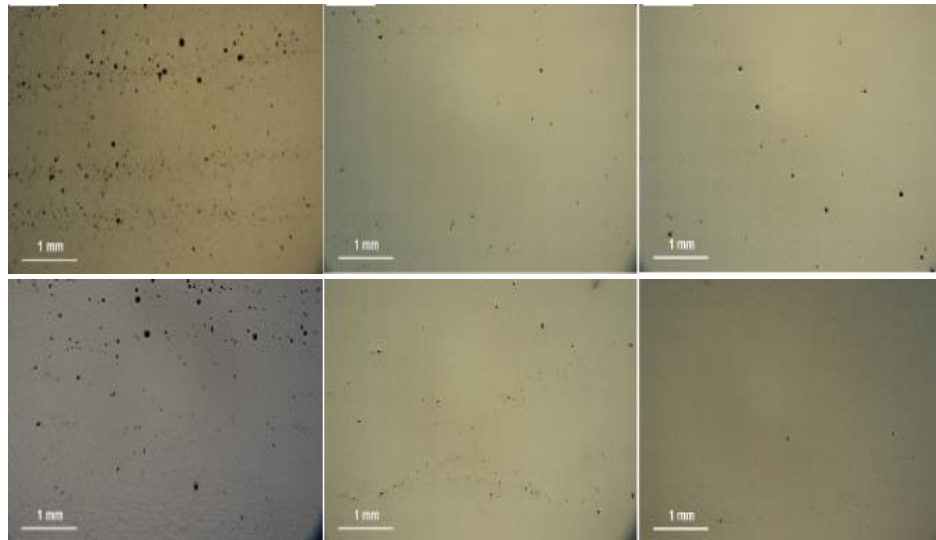


Figure 18 examples of porosity in deposited aluminium (Cong et al., 2017)

2.3.1.3 Microstructural non-conformance

The high heat input used in the WA-DED process results in large thermal gradients in the build direction causing a widely reported epitaxial columnar dendritic grain structure shown in figure 19 (Baufeld, 2012; Seow et al., 2019; Wang et al., 2016; K. Wang et al., 2020; X. Xu et al., 2018). The degree of this anisotropy varies depending on the arc process used as shown in table 4. The main issue identified related to WA-DED of nickel super alloys is anisotropy of mechanical properties (Wang et al., 2016; X. Xu et al., 2018). This microstructural anisotropy has also been found in titanium alloys. This has been attributed to the widely detected large columnar β prior grains growing epitaxially from the substrate in the build direction shows in figure 20 (Hönnige et al., 2020, 2017; Lin et al., 2017, 2016; Martina et al., 2012; Suárez et al., 2021; Wang et al., 2011). As seen in table 4, a significant portion of the literature only published mechanical behaviour in the horizontal direction perpendicular to the build direction.

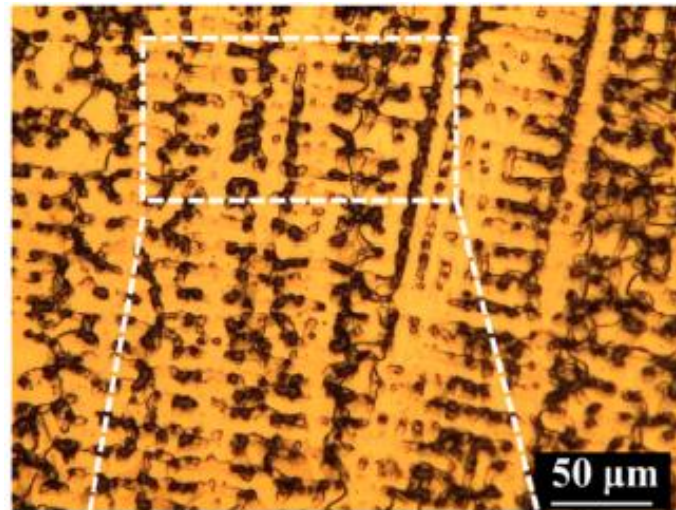


Figure 19 Columnar dendritic grain structure in deposited Inconel 718 (Zhang et al., 2021)

The epitaxial grain growth present in deposited nickel alloys leads to a heterogeneity of microstructure, and subsequent mechanical performance. It has been widely reported in the literature that Laves phases are present in deposited Inconel which causes a reduction in mechanical performance (Seow et al., 2019; Wang et al., 2016; K. Wang et al., 2020; X. Xu et al., 2018). Wang et al. (2016) states that this is because they are recognized as a brittle phase and will act as an initial source of crack propagation. K. Wang et al. (2020) also found the Laves phases are coarser in the middle regions forming chains which leads to a reduced microhardness, this is in agreement with the observations of Wang et al. (2016), as shown in figure 21. This has led to a reported heterogeneous nature to mechanical performance due to a variation in performance in the build direction of the deposited material (Wang et al., 2016). Wang et al. (2016) also notes that a segregation of different elements occurs and increases in severity in the build direction which causes a gradual decrease in microhardness with height. Although K. Wang et al. (2020) found that tensile strength and ductility surpassed the properties of cast and wrought Inconel 718, however, the observations of Seow et al. (2019) who state that mechanical performance is poorer at higher operating temperatures when compared to wrought material. As a key driver for the use of nickel based super alloys is the mechanical performance at high temperatures (Seow et al., 2019), the authors recommend that this should be further researched and tested. Similarly, samples in Ti-6Al-4V also display a heterogeneity in microhardness due to the epitaxial growth of the columnar grains (Lin et al., 2018). Again, for large components it is important to ensure that material is as homogenous as possible, with the extent of the degree of heterogeneity being a major barrier for industrial application. The authors suggest further researched to gain the knowledge of whether the material is capable of meeting conventional standards for mechanical performance compared to forgings and castings. Recent literature depositing Ti-6Al-4V using CMT has shown a more equiaxed grain structure although the microstructure is still heterogenous leading to cyclically heterogenous hardness values (Elitzer et al., 2022).



Figure 20 epitaxial grain growth of sample Ti-6Al-4V (Wang et al., 2011)

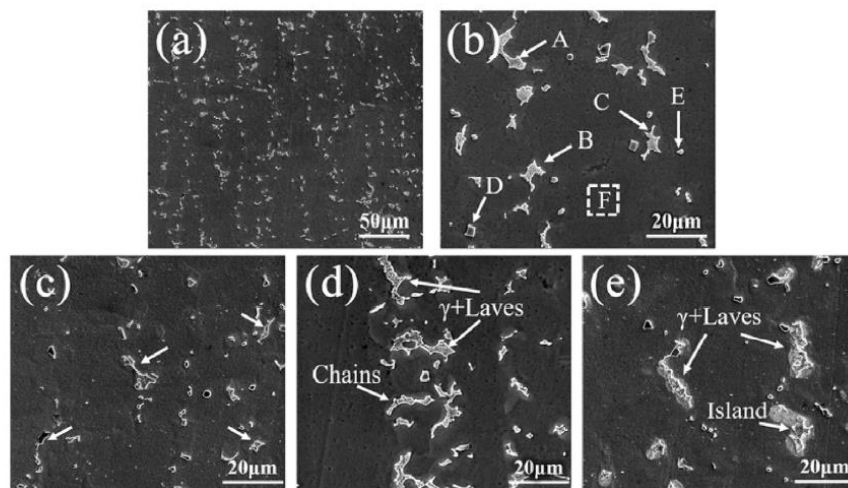


Figure 21 SEM images of the microstructure of Inconel 718 produced with a pulsed plasma arc power source showing (a) low magnified structure; (b) high magnified structure; (c) the bottom section; (d) the middle section; and (e) the top section (K. Wang et al., 2020)

2.4 Wire Arc Directed Energy Deposition Additional Processes

The authors recognize that additional processes have been reported WA-DED processes to improve mechanical performance. Further post processes are recognized, such as heat treatment, cold working, inspection, and machining which represent a significant part of the process chain. For literature on these post processes readers are referred to Bankong et al. (2022), Peng et al. (2021) and Shiyas and Ramanujam (2021) as post processing is outside the boundary of this review. Due to the various problems associated with the WA-DED process mechanical performance can be unsatisfactory compared to material standards for industrial application. As a result, additional processes can be incorporated in-situ to alleviate residual stresses, improve mechanical performance and or allow for more precise deposition.

2.4.1 Additional In-situ Processes

Additional In-situ processes have been shown to improve mechanical properties, improve geometry resolution and to improve geometric repeatability. Processes have been defined arbitrarily into the following categories: Heating, cooling, cold working and vibration based. In table 7 these processes have then been further classified as localised to the or near to the weld pool, applied to the substrate, the top layer or the entire build volume. As such it is worth noting that in the case of heat based processes and cold working that processes applied to the entire volume have been identified as post processes.

Table 7 – Classification of Additional in-situ processes

	Local to weld pool	Substrate based	Top layer (Interlayer)	Total volume
Heating	Inductive (Bai et al., 2015) Laser based (Näsström et al., 2019) Hot wire (Fu et al., 2021; Z. Li et al., 2019)	Preheating (Alberti et al., 2016)		(post process)
Cooling	Gas cooling (Cunningham et al., 2021; Ding et al., 2020; Henckell et al., 2017; Montevicchi et al., 2018) Inductive (Shi et al., 2019)			Immersive (da Silva et al., 2020)
Vibration based	Wire feed (Santangelo et al., 2016)	Ultrasonic (Chen et al., 2020)		
Cold working			Rolling (Gu et al., 2016; Martina et al., 2015; Qiu, 2013) Peening (Hönnige et al., 2020, 2017; Neto et al., 2020)	(post process)

2.4.1.1 Heating

In-situ heat treatments have been localised to the weld pool to allow for a more uniform heat distribution throughout the previously deposited material which helps to reduce residual stresses.

Bai et al. (2015) used induction heaters localised to the weld pool. The position of these heaters was varied locally to the weld pool and they devised a finite element model that could simulate the effects of induction heating which was in good agreement with the experimental data (Bai et al., 2015). Another advantage of heating localised to the weld pool was that a greater precision of geometry is possible. Näsström et al. (2019) used a laser as a secondary heat source to produce a more consistent and calmer weld pool, which in turn led to a significantly smaller standard deviation of layer geometry along the length of the wall as well as a more predictable and manageable geometry as shown in figure 22. Localised in-situ heating is of interest to large components as standardising the shape of the weld pool will enable for more repeatable geometry thus cumulative geometric inaccuracy will be reduced. Furthermore, as it is localised to the weld pool there are no issues with scalability of effectiveness when manufacturing large parts.

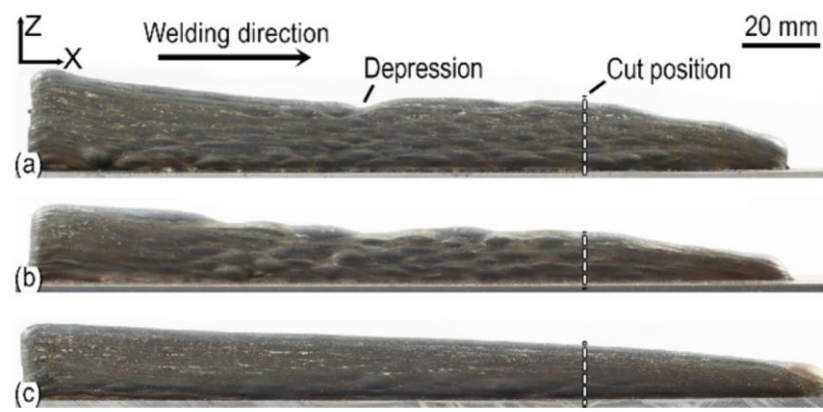


Figure 22 showing the effects on macrostructural geometry a) without b) with a leading laser c) with a trailing laser (Näsström et al., 2019)

Z. Li et al. (2019) focused on refining the microstructure of titanium alloys by using resistive heating of the wire with a TIG power source to lower the heat input required from the arc process. By increasing the current in the wire, it was found that the size of the columnar grains was refined and equiaxed grains were now present as shown in figure 23. Furthermore, due to this lower heat input, the weld pool was more viscous which resulted in thinner taller walls being produced as shown in figure 24. The mechanical performance of the material was not improved in terms of ultimate tensile strength in the vertical direction; it was improved in the horizontal leading to a greater isotropy in mechanical performance which is often not present in titanium material deposited using WA-DED (Z. Li et al., 2019). Later work conducted by Fu et al. (2021) used a hot wire system to deposit the aluminium alloy Al2219 and found that as the resistive current increases a higher deposition rate can be achieved with a reduced porosity exhibiting a less anisotropic mechanical performance.

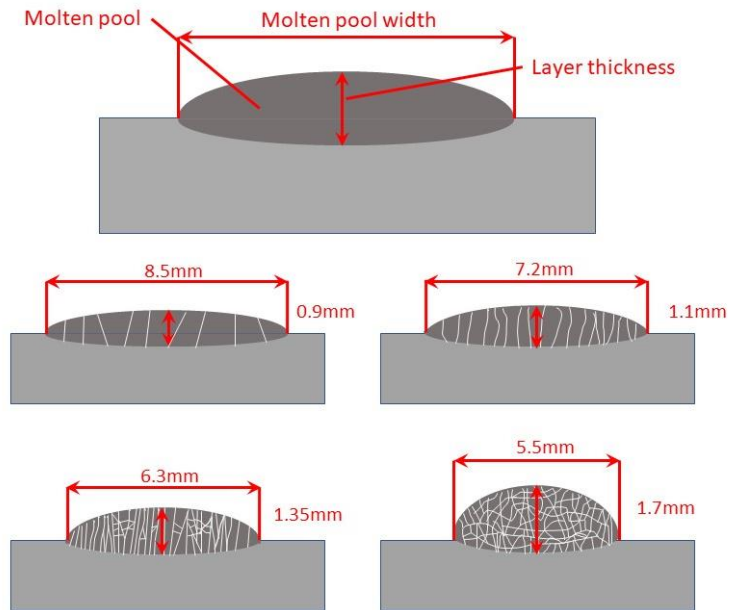


Figure 23 illustrative grain microstructure refinement with increasing resistive current through b-e reproduced from the work (Z. Li et al., 2019)

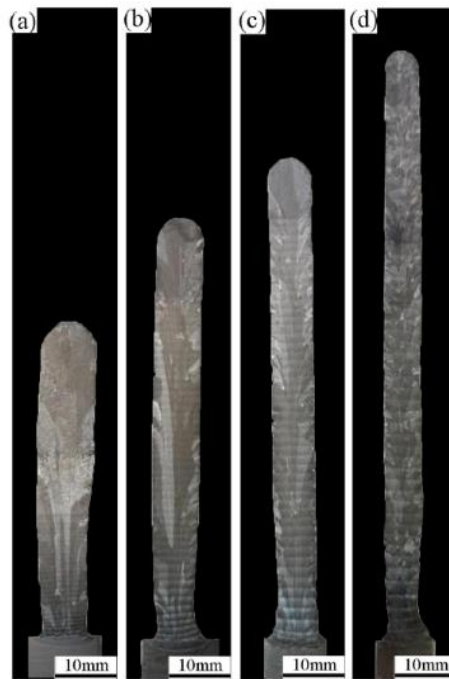


Figure 24 Macrostructural cross sections of deposited walls with gradually increasing resistive current a-d (Z. Li et al., 2019)

2.4.1.2 Cooling

It has been well documented in the literature that high cooling rates leads to a more refined microstructure. This leads to materials with superior mechanical performance. As previously identified by Cunningham et al. (2018), these can be classified as cooling localised to the weld pool and cooling of the entire build volume. The common procedure is to allow a dwell time between deposition of each layer (Montevecchi et al., 2018). This allows for the regulation of excessive heat accumulation during the deposition process. However, this dwell time vastly increases the production time as the net deposition rate is reduced.

Cunningham et al. (2019) explored how the heat input and interpass temperature affected the microstructure, subsequent mechanical performance, and geometric distortion of the deposited material. It was found that higher heat input caused a greater cooling rate thus a superior tensile strength, and that a higher interpass temperature produced a greater ductility as well as a reduction in residual stress and subsequent distortion. However, when both a low heat input and low interpass temperature were used to deposit material, it was identified that a reduced weld pool temperature led to a more equiaxed grain structure. This was due to a strong thermal gradient with a less prevalent direction (Cunningham et al., 2019). Later work from Cunningham et al. (2021) used liquid nitrogen to cool the deposited material localised to the weld pool just after deposition. The gas outlet was approximately 15 mm behind the weld power source which was far enough away as not to disrupt the arc as shown in figure 25. This cooling system was found to produce a much finer microstructure that was feathered, which is much more characteristic of a powder based L-DED process. The cooling method increased the nucleation rate due to a change in direction of the maximum thermal gradient, thus interrupting the standard vertical prevalent thermal gradient which is the cause of columnar grains in the WA-DED process, the main cause of anisotropic mechanical behaviour. This resulted in an increase in the yield stress and Young's modulus when compared to the process when temperature was controlled by an idle time in between deposition of each layer with no loss of ductility (Cunningham et al., 2021).

Research conducted by Ding et al., (2020) also found the use of compressed gas to improve mechanical performance of Ti-6Al-4V using CO₂. An improvement in microhardness and ultimate tensile strength were observed and attributed to large acicular alpha and refined lamellar alpha grains with a greater number of dislocations and grain boundaries as shown in figure 26.

Montevecchi et al. (2018) increased the rate of convective cooling using an air jet impingement technique to prevent heat accumulation. This involved attaching an air nozzle behind the welding power source to provide localised cooling immediately after the metal is deposited. It was found the process could be used to regulate the average temperature throughout the process for each thermal cycle and the size of the weld pool. This data was evaluated with a thermodynamic finite element model which was in accordance with the experimental results (Montevecchi et al., 2018). Later work by Hackenhaar et al. (2020) built a numerical model that could predict the effect of altering the angle of the air nozzle to prevent interference with the arc in the arc process.

Furthermore, they found that the cooling method could prevent heat accumulation in the substrate completely for large idle times between deposition of each layer. They also found that for shorter idle times the cooling method would lower the increase of temperature in the substrate that was measured as more layers were deposited. It was shown from this that although this process was cheap to implement it could aid productivity. However, it was likely that this process has limitations for different arc processes, reactive materials and larger scale depositions (Hackenhaar et al., 2020). Although this method is limited to less reactive metals, it presents a low-cost approach as compressed air is used where previous gas driven active cooling methods used inert gases which are more expensive. Furthermore it was also discovered that the angle of the nozzle had to be such that the compressed air did not interfere with the shield gas around the arc as this caused oxidation of the deposited material and arc instabilities (Hackenhaar et al., 2020; Montevecchi et al., 2021).

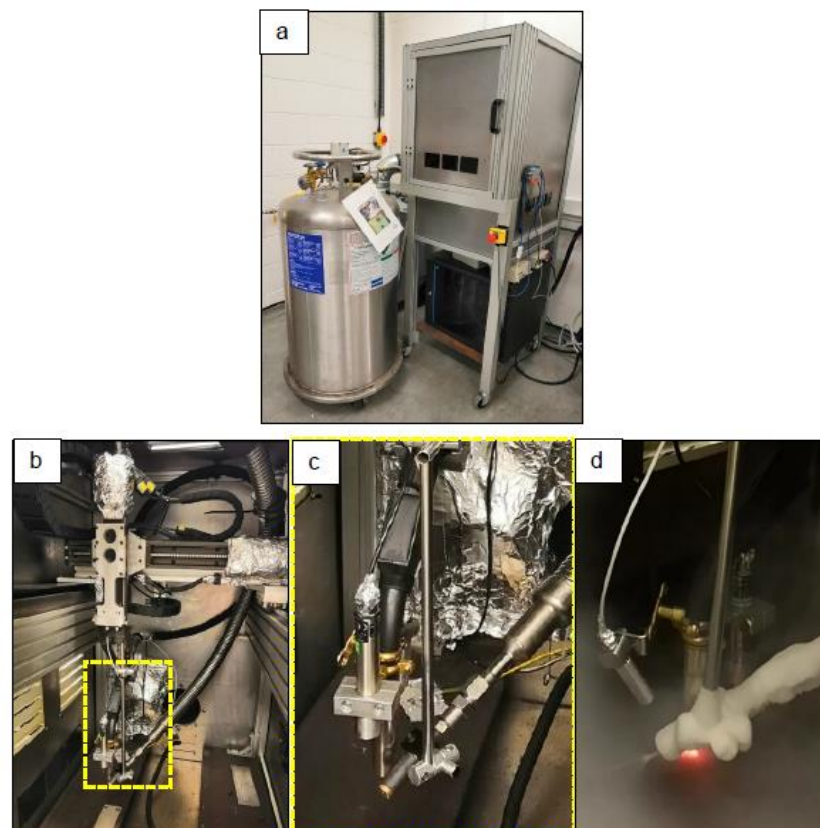


Figure 25 WA-DED set up with cryogenic active cooling a) overall setup, b) cryogenic mounted to z-axis, c) Magnified view of the location of the cryo nozzle mounted to z-axis, d) In-process cryogenic cooling showing the liquid nitrogen jet (Cunningham, 2020)

Shi et al. (2019) used thermoelectric cooling to improve deposition rates. The main benefits of this method compared to other cooling processes were no leakage of coolant, flexible geometry of implementation, long working life, and a highly controllable cooling rate. This was because the cooling rate can be accurately controlled by altering the DC voltage used in the cooler. Shi et al. (2019) found that for a given wall width deposited, a higher deposition rate with lower idle dwell

times could be achieved. This was achieved due to a high heat dissipation rate which also allowed for a finer microstructure to be achieved for a given wall geometry (Shi et al., 2019). Improved deposition rates allow for lower lead times on parts however, this technique was limited to thin wall parts as the coolers have to be placed either side of the wall being deposited.

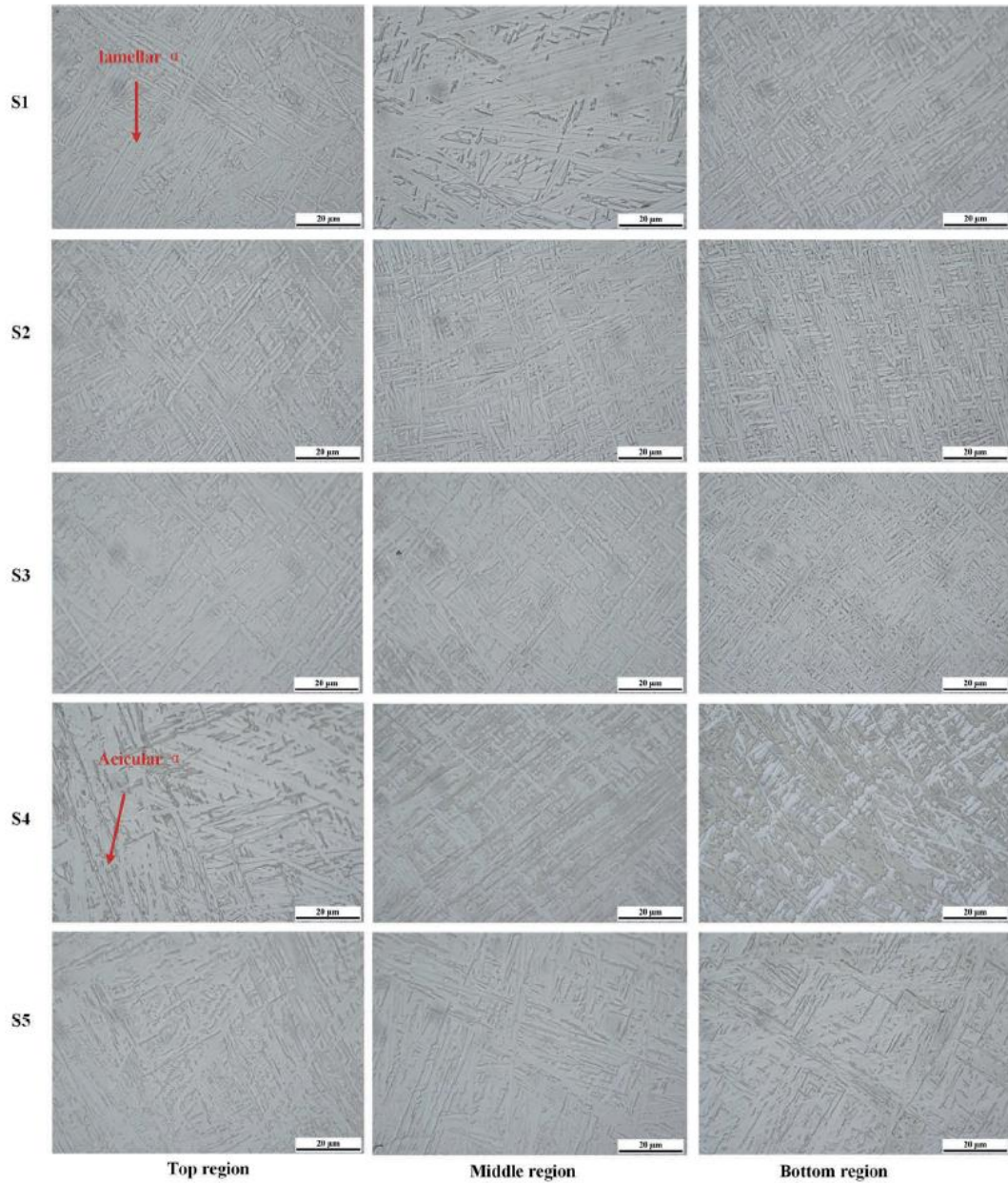


Figure 26 Lamellar and acicular grain structures in Ti-6Al-4V deposited with CO₂ interpass cooling (Ding et al., 2020)

Cooling of deposited material by immersing it in water was proposed by da Silva et al. (2020) as shown in figure 27. This allowed for faster cooling rates allowing for shorter idle times between depositing layers to improve productivity. Compared to natural and passive cooling methods the

material had improved isotropy in mechanical performance particularly in terms of ductility. This method also was found to produce lower surface waviness and larger layer heights with reduced porosity. The material also went through fewer thermal cycles as the immersed material was not reheated during deposition of higher layers. The main drawbacks to this method of cooling are that depositions need to have a primary plane of symmetry as degrees of freedom cannot be incorporated to the substrate as it is submerged in the tank. Furthermore, the maximum size of the deposited component is limited to the size of the tank (da Silva et al., 2020). One of the key advantages to WA-DED over other DED and metal AM methods is the theoretically limitless build volume which is negated by such a cooling method making it unsuitable for manufacture of large components.

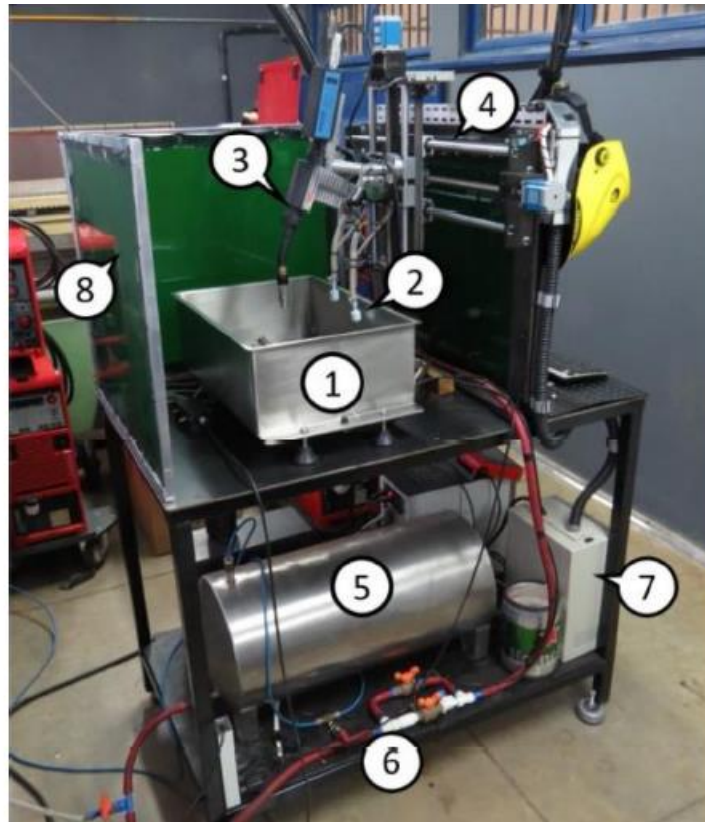


Figure 27 A setup for near immersion active cooling comprised of: water tank(1), float switch(2), CMT torch(3), linear motion system(4), pressurised water tank(5), hydraulic/pneumatic valves (6),CNC controller (7) (Scotti et al., 2020)

2.4.1.3 Cold work based processes

As previously identified, some of the main defects found in the deposited material produced by the WA-DED process are anisotropic mechanical performance, residual stress, porosity, and cracking. Cold working of the deposited material during each interpass of material deposition has been found to alleviate these problems across a number of materials including: Aluminium alloys (Gu et al., 2018, 2016), Titanium alloys (Hönnige et al., 2020, 2017; Martina et al., 2015; Qiu, 2013) and Inconel (X. Xu et al., 2018). A WA-DED system with the capability of in-situ interpass rolling is shown in figure 28.

The in-situ rolling of titanium alloys as shown in figure 29, has been found to refine the microstructure from columnar grains to smaller equiaxed grains leading to more isotropic mechanical performance (Martina et al., 2015; Qiu, 2013). Although the improvements to the tensile properties are only minor (Qiu, 2013), rolling has a significant impact on the fatigue life of the material and the fatigue crack growth rate is much more even in the vertical and longitudinal directions when compared to unrolled material. Qiu (2013) outlined the necessity for more rigorous future work to obtain greater confidence in the isotropy of the material by testing the fatigue life in more directions with thicker samples. In addition, Qiu (2013) identified that the relationship between the fatigue life and the residual stresses in the deposited material would be of interest. Martina et al. (2015) noted that productivity of the WA-DED process would be reduced as the material needed to cool down to a certain temperature before rolling could commence. This would reduce the overall deposition rate which is especially disadvantageous for production of larger parts. Martina et al. (2015) compared two different roller profiles one with a slot and one flat roller. They found that the slotted roller had only a slightly greater effect in terms of refining the microstructure and the flat roller presented a more practical solution for industrial adoption (Martina et al., 2015).

Aluminium alloys have also been subject to in-situ rolling during the WA-DED process. Gu et al. (2016) Noted that for Al-6.3Cu alloy the reduction in grain size was increased by increasing the vertical load the roller applies to the deposited material. This led to the geometry of the layer heights becoming shorter and wider by 44.2%, which was also prevalent as the equiaxed grains became small but elongated in the horizontal direction. There was an increase in mechanical performance especially when a larger force was applied by the roller and the isotropy of the mechanical performance was broadly observed. One of the most interesting findings was that rolling produced a more consistent and finer microstructure than the heat treatment methods (Gu et al., 2016). The authors recognise this is of interest to the production of large parts as it allows for post process heat treatment to be abandoned. Furthermore, the relatively low heat input CMT process used allows for shorter idle times waiting for material to cool after a layer is deposited compared to higher heat input processes, this could lead to greater productivity. Similar results have been found for the cold working of Inconel 718 that show that material can exceed wrought standards even at elevated temperatures (Zhang et al., 2021).

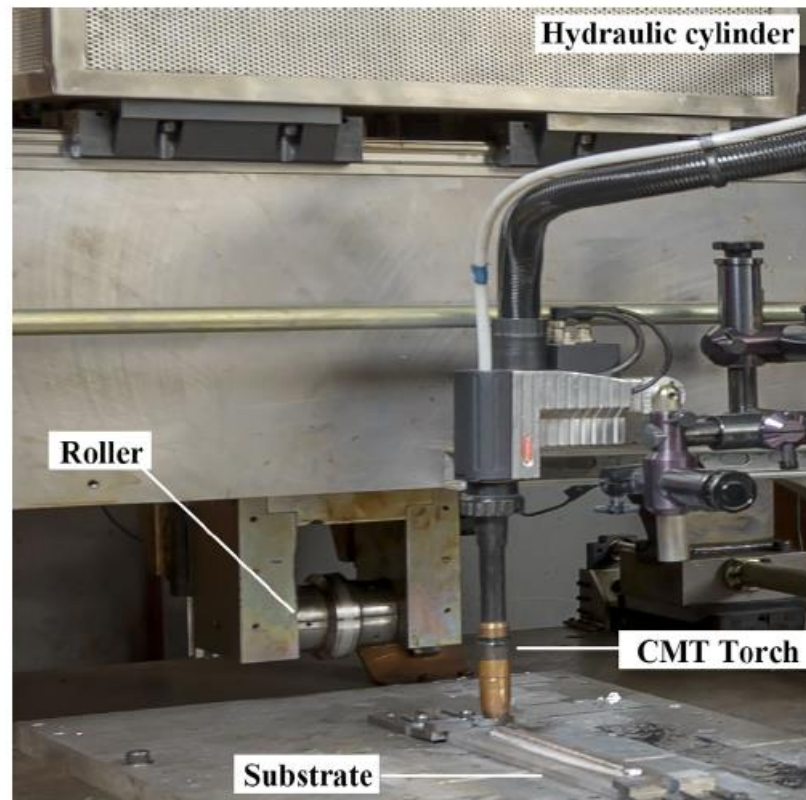


Figure 28 An example setup of a WA-DED system with an in situ cold rolling process (Gu et al., 2016)

Machine hammer peening has been identified as a technique to improve surface microhardness and refine the grain structure of material deposited with a plasma arc WA-DED process and Ti-6Al-4V. Hönnige et al. (2020) identified that it is easier to implement than in-situ rolling for parts of greater complexity. The research experimented with applying peening methods both to the top surface of the deposited material as well as the side surface. Hönnige et al. (2017) measured the topography of the deposited material post peening and showed the previously mentioned improvement of surface hardness as a result of a finer grain structure. Later research then highlighted that peening had a greater penetration depth of the material than was to be expected, this allowed for the effects of in-situ peening to be deeper than that of the remelted zone meaning the effects of peening survived. This allowed for a prevalent growth direction downwards which acted as a grain barrier preventing the growth of large columnar grains which is a common feature of deposited Ti-6Al-4V using high energy density WA-DED processes which allowed for a more equiaxed grain structure to be prevalent, as shown in figure 29 (Hönnige et al., 2020). Both papers highlight that even for the larger wall widths present in plasma arc WA-DED processes the peening penetrated the entire width of the wall, however, peening was not as effective at grain refinement in comparison to interpass rolling methods. Furthermore, research by Neto et al. (2020) explored the effectiveness of peening for thick walls with multiple passes and discovered that a greater penetration depth of work hardening was present in thick wall parts. This was caused by the peening pattern on the top of the each layer causing a plastic strain within the walls complementing

the work hardening. Neto et al. (2020) also discovered that peening can be shown to increase microhardness, as well as improve tensile properties in both the horizontal and vertical directions. The trade off was a reduction of ductility of approximately 9%, however this is not significant as this still exceeds ASTM wrought standards.

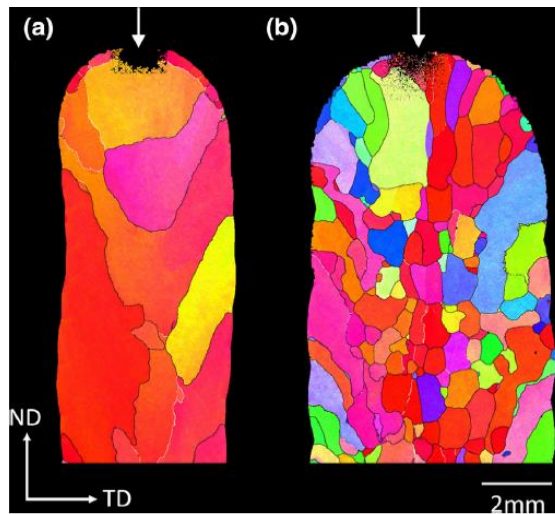


Figure 29 Beta grain refinement due to machine hammer peening of Ti-6Al-4V
(Hönnige et al., 2020)

2.4.1.4 Vibration based processes

Santangelo et al. (2016) experimented with the introduction of vibrations to the wire feed unit with a hot wire TIG system. It was that the vibrations caused the geometry of layers to have a decreased wall width resulting in a greater layer height for a given set of welding parameters. Santangelo et al. (2016) also stated that this was ideal for the manufacture of large parts due to the increased deposition rate of the process due to lower manufacturing times. However it was also stated that at this stage no mechanical testing has been conducted and the WA-DED process has far lower resolution than other metal AM processes (Santangelo et al., 2016). Hence, the need for higher deposition rates to produce larger parts where the minimum deposited spot size is less critical.

Similarly, by applying ultrasonic vibrations to the substrate it has been found that an improvement to mechanical properties is possible while also improving the geometric consistency of deposition (Chen et al., 2020). Due to the vibration of the substrate a greater wetting of the weld pool was observed in the top layer leading to a better spreading of the liquid metal causing an increase in effective area of the wall. It was also observed that a greater grain refinement was present, especially in the samples where an interpass temperature of 100°C was used. This led to more consistent nanohardness in the different regions of the deposited wall and improved tensile properties which were also more isotropic (Chen et al., 2020). Moreover, Zhang et al. (2019) found that when applying ultrasonic vibrations to the workpiece that a finer grain structure with lower porosity was observed when deposition of high strength aluminium alloy using CMT. This led to a

greater ultimate tensile stress when compared to control samples however ductility is reduced and a greater anisotropy observed in the deposited material (Zhang et al., 2019).

2.5 WA-DED Process Planning

2.5.1 Slicing and Build Orientation

Slicing algorithms for AM can be traced back to the advent of layer-by-layer manufacture in the 1980s (Ruan et al., 2006). The initial CAD model is converted into a standard tessellation language (STL) file and sliced into layers for printing. If all of the slices are parallel to one another this is termed 2.5D slicing as the layers have 2-dimensional geometry with a standard prescribed thickness that is defined by process parameters. In WA-DED this is perfectly acceptable for parts of low complexity where support structures are minimised. For more complicated geometries, it is necessary to slice parts in multiple directions. The addition of axes to the working table and dividing the CAD model into multiple sub volumes makes this possible. Previously, this would often require significant user intervention and an understanding of the deposition process to ensure a good quality deposition. This was a major barrier for industrial applications and recent literature has focused on further automating this process. The literature identifies various existing slicing algorithms for AM in general and assesses the strengths and limitations of each algorithm (Ding et al., 2016b; Nguyen et al., 2018). Moreover, a detailed review of the various slicing methods for directed energy deposition in general has been compiled by J. Xu et al. (2018) as well as by Jafari et al. (2021).

Lockett et al. (2017) produced a detailed study that critically assessed the optimal building orientation with a few case study parts and identified the main assessment criteria for the different strategies. These included but not exhaustively: deposited material, number of build operations and build complexity. They were quantified in such a way that a scoring matrix was used that enabled assessment of the different approaches by factoring all the different variables and finding an index score for each option (Lockett et al., 2017). The benefit of this is that should this all be programmed, it would be possible that this decision could be made automatically by manufacturing software minimising user input. Although, it was stated user input would still be necessary to some degree as engineering judgement should be used to ensure a practical solution. Lockett et al. (2017) acknowledged with a multiple attribute decision matrix that with a weighting system one poor attribute could be overlooked if balanced out by a stronger one, meaning that the best ranked solution can be poor in one attribute. Future work was to be carried out to assess more parts to make the weighting more sensitive and assess the suitability for users with less knowledge.

2.5.2 Path Planning

In AM, path planning is categorized as a data pre-processing step. In this step, the WA-DED deposition path for a mechanical part is defined. This path plan is represented in different formats

for different platforms, e.g. for multi-axis gantry systems, path planning is normally represented in G-Code (Ščetinec et al., 2021). Whereas for robotic systems, path planning is represented in its specific code defined by robot manufacturers. It is notable that WA-DED path planning is largely affected by many factors such as geometric complexity of the part, and the intrinsic characteristics of AM process material properties. Numerous studies have been carried out to explore suitable path plans to alleviate specific geometry defects (Venturini et al., 2018, 2016).

Ding et al. (2015) made an early investigation for path planning with the WA-DED process. The authors summarised that path plans in WA-DED include raster path, zigzag path, contour bath, spiral path, continuous path, and hybrid path. They also proposed a new path plan algorithm namely, Medial Axis Transformation (MAT) algorithm, which can solve the filling gap issue that occurs in contour-based path planning strategy (Ding et al., 2015).

Venturini et al. (2018) proposed feature-based path plan strategy aiming to generate optimized path plans for joints on single bead wall parts. A key point in this research is that the authors extracted the middle planes in the thin wall part model as its skeleton. This skeleton was then easily divided into wall segments and different types of joints. For these wall segment and joint features, they discussed the influence of travelling direction, bead overlapping, start-stop points of different types on them (Venturini et al., 2018).

Diourté et al. (2021) also identified that start/stops of the arc will induce a transient phenomenon and will affect the deposition accuracy. To tackle this problem, the authors proposed a continuous three-dimensional path planning (CTPP) strategy, which is basically a helical based path planning strategy. As shown in the Figure 30, using this strategy, a steel part was generated continuously with no arc stop during the process, and the generated parts showed relatively uniform layer appearance (Diourté et al., 2021).

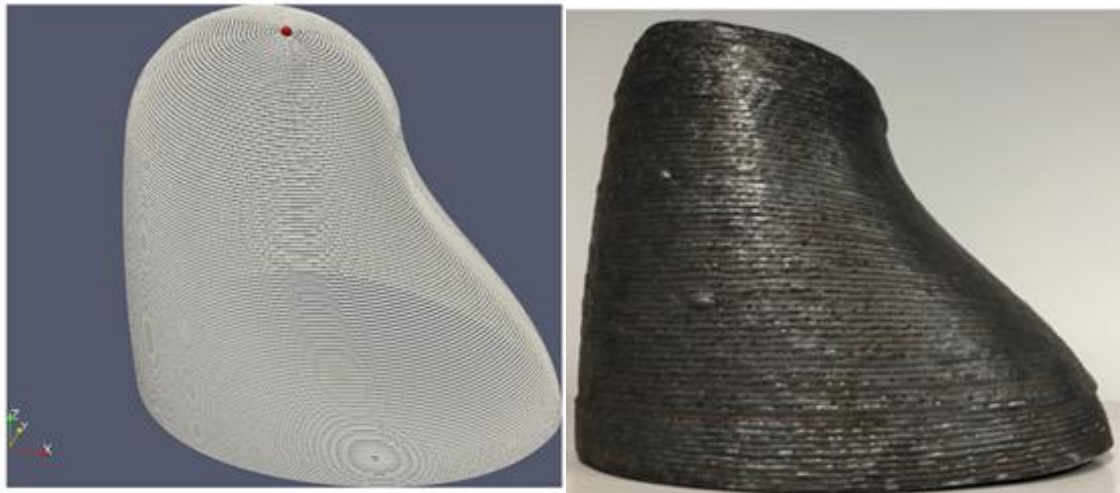


Figure 30 Continuous three-dimensional path planning strategy and its printed part (Diourté et al., 2021) a. 3D Path plan model view b. WA-DED deposited steel parts.

Similar to the aforementioned research, many other researchers proposed geometric-oriented optimization path planning strategies. For example, Yu et al. (2021) proposed a path planning strategy for strut structures. Ding et al. (2021) discussed path plans to solve the sharp corner over-deposition issue. J. Zhang et al. (2020) proposed a path planning strategy on non-planar hot die surfaces.

Apart from this geometric-oriented research, some researchers also investigated WA-DED process-oriented path plans. Yuan et al. (2020) investigated multi-directional path plans for overhang structure deposition on a robotic platform. It is noted that these authors applied part decomposition as a pre-processing step for path planning, and they carried out horizontal deposition on a part. Part decomposition is to decompose complex part models into simpler geometries. As shown in Figure 31, each decomposed geometry could apply different building directions and path plans, moreover, supporting structures could be removed. The decomposition step sometimes is carried out in slicing (Ding et al., 2016b), but it also can be applied in 2D path plan (Ding et al., 2014).

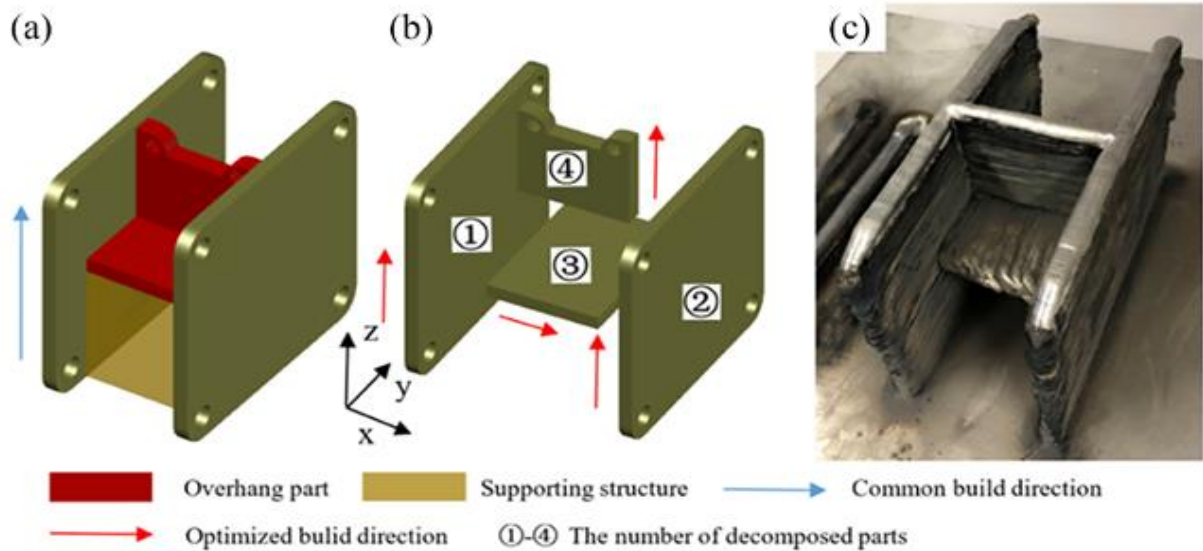


Figure 31 3D model decomposition for WA-DED parts (Yuan et al., 2020) (a) schematic model for building strategy without decomposition step, (b) schematic model for building strategy with decomposition step, (c) Final WA-DED part built with multi-directional decomposition deposition strategy

Michel et al. (2019) proposed a synthetic path planning strategy for WA-DED thin wall parts, in this paper, the authors divided path planning into 3 steps, segmentation, path planning and zoning. The segmentation step is mainly used to decompose the sliced complex 2D layer plan into a combination of simple wall segments. Consequently, the path planning step defines the path plan for each simple wall with consideration of the joint connection strength. Zoning divides each simple wall into different parameters zones to improve part deposition quality. This research incorporated process parameter plans in its path plan, to avoid deposition defects and improve deposition quality, with parameters determined based on prior knowledge of the process. Ščetinec et al. (2021) developed this idea further to a dynamic path planning level. They recognised that due to the instability of the WA-DED process, the deposited layer height may differ from the designated path plan. In this approach the authors automatically measure the layer height variation in the process and apply re-slicing when the average layer height exceeds a limit. This research has arrived to an area that combines process control and path planning.

2.5.3 Process Control

The WA-DED process is a non-linear multi-physical process. Due to the interference from the time varying environment (such as heat accumulation, ambient temperature, oxygen level etc.), a process parameter control method should be applied to achieve targeted macro and micro features. Under the condition that the general WA-DED surface roughness is 0.5mm (Xia et al., 2021), improving forming quality is a major requirement. A growing body of literature has investigated closed-loop feedback control as well as feedforward for the WA-DED process. These methods for WA-DED process control have been summarised and categorised in Table 8.

Table 8 WA-DED Control Methods

Geometry Control	Control Method	References	Arc Process/Material
Single-Layer Single Bead Width Control	Iterative Control	(Xia et al., 2020c)	Fronius CMT/ER70s-6(Steel)
	Model Predictive Control (MPC)	(Xia et al., 2020d)	Fronius CMT/ Mild Steel
Multi-Layer Single Bead Width Control	Proportional Summation Differential (PSD) Controller	(Xiong et al., 2013b)	MIG/ H08Mn2Si(Steel)
	Single Neuron + PID Controller	(Xiong et al., 2016)	MIG/ H08Mn2Si(Steel)
Multi-Layer Single Bead Height Control	Linear Control	(Xu et al., 2019)	MIG/ER70s-6 (Steel)
	PID Controller	(Xiong et al., 2020)	TIG/ER50-6 (Steel)
Multi-Layer Multi Bead Height & Width Control	Fuzzy Logic Controller	(Li et al., 2021)	MIG/H08Mn2Si (Steel)
	Neural Network	(Xiong et al., 2013a)	Fronius CMT/Steel
	Reinforcement Learning	(Dharmawan et al., 2020)	Fronius CMT/316L (Steel)
	Single Neuron PI Controller + Rule-based Controller	(Han et al., 2017)	MIG/Not reported

In an early study, Xiong et al. (2013b) established a method of using computer vision to measure layer width. Here, by using a proportional summation differential (PSD) method and welding speed as a controlled variable, the authors achieved an accuracy of 0.2mm when depositing a 7.5mm with layer, compared with 1.5mm accuracy for open-loop control. Subsequently, Xiong et al. (2016) applied a second-order Hammerstein model between layer width and travel speed to describe the WA-DED dynamic process. Based on this model, the authors achieved varied width deposition ranging from 6mm to 9mm between different layers.

In 2020, Xia et al. (2020c) developed a Model Free Adaptive Iterative Learning Control (MFAILC) method for controlling the width within a layer. These authors established a data-driven inference model to predict layer width, and based on this model, the MFAILC method was trained. Through experimental validation, the algorithm achieved 0.2mm accuracy layer width control (Xia et al., 2020c). In another article, Xia et al. (2020d), used a different process control method, namely

model predictive control, which achieved a width-varying layer from 5.5mm to 8.5mm (Xia et al., 2020d).

The aforementioned literature is focusing on width control for the WA-DED process; a few researchers also explored using advanced control methods to control the layer height for WA-DED parts. Xu et al. (2019) thought layer height should be dynamically associated with deposition rate. Based on this idea, they conducted system identification for layer height and deposition rate and established a system model. Based on this model, the authors achieved height-varying deposition on a pre-defined uneven substrate as shown in Figure 32. Similarly, (Xiong et al., 2020) applied a proportional integral derivative (PID) controller to regulate and improve layer height consistency, and effectively decreased layer height fluctuation within about 0.25mm.



Figure 32 Height varying deposition experiment (Xu et al., 2019) a. schematic diagram for pre-define uneven substrate with height-varying deposition b. deposition result.

Moreover, a few researchers proposed synthetic methods to control the width and height at the same time. In 2013, Xiong et al. (2013a) proposed a neural network method to predict WA-DED layer height and width using process parameters as input. Based on this prediction model, the authors developed a reverse model to train a closed-loop iterative controller (Xiong et al., 2013a). With this controller, the authors achieved 1.535% mean error in width, 1.524% mean error for height. Han et al. (2017) made a trial for combining a single neuron PI controller for width control and a rule-based controller for height control to generate a synthetic controller. This controller minimized the width deviation from 9.5% (open-loop control) to 4% (closed-loop control), and also claimed to have minimized height accumulation error.

In the WA-DED process, due to the time-varying printing process, it is easy to obtain an uneven height within a layer, as the build height increases, the error accumulation may cause significant geometric defects such as humping at the beginning of a layer and slope at the end of a layer. Dharmawan et al. (2020) proposed an in-situ reinforcement learning method to tackle the height accumulation problem. With this method, the height standard deviation of a layer was largely suppressed within 1mm for a 360 mm hexagonal pillar, whereas the reference part without control broke through the 1mm height standard deviation at the position of 50mm, and this error continued to accumulate. In 2021, Li et al. (2021) developed a fuzzy logic control method to push the height error down to only 0.2mm. It is noted that the geometry control for WA-DED is highly correlated to

arc process and material. In the aforementioned literature, it is noted that most researchers selected GMAW and Fronius CMT as an arc process, and various types of steel as feedstock. This combination frees researchers from worrying about the tedious aluminium or titanium oxidization problem. It also brings convenience for us to compare the performance between different process control strategy.

3 Discussion & Scope for future research areas

3.1 Wire Arc Directed Energy Deposition arc processes

The most widely used power source for WA-DED of large parts is MIG due to its lower argon consumption cost in comparison to TIG and plasma arc systems (Cunningham et al., 2017) and higher deposition rates (Tabernero et al., 2018). However, the authors recognise a key consideration of which arc process is most beneficial to the most important performance measure of the deposited material is dictated by what metal is to be deposited. It has also been recognised that as discussed in section 2.1 and section 2.3 design standards specifically for WA-DED are non-existent. At present, industrial bodies are beginning to offer guidance for the production of AM but no specific performance measures.

For large parts the introduction of lattices to the internal build volume will lead to significant material savings and subsequent shorter lead times. It is readily understood higher deposition rates cause shorter lead times. This effect will be compounded if mechanical performance improves therefore greater optimisation of part geometry is achieved. The introduction of the CMT arc process has allowed for the more complex geometry involved in SAAM (Radel et al., 2019) such as the fabrication of lattices (Abe and Sasahara, 2019). Components have also been fabricated with a non-solid infill (Abe and Sasahara, 2016). This provides evidence that components can be fabricated with a lattice in the internal volume. Further research should be conducted assessing to what extent mechanical performance is affected by a lattice infill. Li et al. (2020) states that the compressive performance of the deposited lattice is heavily reliant on the diameter and geometry of the struts deposited. It is recognised that topological optimization should also be applied for SAAM (Yu et al., 2019) moreover, there is also a need for software that is capable of slicing 3D volumes and converting the internal volume into a lattice structure (Yu et al., 2019).

For TIG and Plasma arc processes, one of the main barriers for industrial applications of large part manufacture is lower deposition rates in comparison to MIG (Cunningham et al., 2017). As a result, it is of great importance that the overall process chain is carefully considered to maximise productivity. As identified in section 2.3, the stable nature of the arc allows more consistent deposition geometry minimising the amount of material to be machined post deposition. This has the advantage in terms of material savings and time saved spent in post processing. TIG arc processes offer a better degree of isotropy than plasma arc for deposition of Ti64 (Brandl et al., 2010; Suárez et al., 2021). Furthermore, when a TopTIG power source is used the degree of

isotropy is comparable to that of CMT for deposition of 316L stainless steel (Queguineur et al., 2018; Rodriguez et al., 2018; C. Wang et al., 2020). This shows that for large components TopTIG should be further researched due to its excellent mechanical performance, increased deposition rates and regular layer geometry. Despite TOPTig being well known as a welding process there is limited literature exploring it as an arc process for WA-DED despite the advantages it holds as a welding process making it well suited for additive manufacture.

Tandem wire systems have been found to greatly improve deposition rates over single wire WA-DED arc processes. This has the advantage especially for large parts as MIG compared to tandem MIG sees an increase of 3-4kg/hr to 9.5kg/hr (Martina et al., 2019). However due to the high heat input present in these processes the need for in-situ cooling is a must to prevent excess heat accumulation which leads to defects and undesirable mechanical performance (Martina et al., 2019). Shi et al. (2019) explore the effects of in situ cooling on tandem wire systems but did not mechanically test the deposited material. Future research should focus on a greater variety of cooling methods such as those outlined in section 2.4.1.2 and conduct mechanical testing to ensure the quality of the material deposited at higher deposition rates is of an acceptable quality and exploring the effects on deposition rates with the introduction of in-situ processes. Furthermore, the introduction of these in-situ processes may create additional tool path planning issues with relation to the cooling system and the wire feeding units in tandem TIG and plasma arc systems. An intimate understanding of the hardware setup will be necessary in programming any software necessary to generate toolpaths for such a setup. This means the standardisation of software for tandem wire deposition will be completely reliant on the standardisation of hardware configurations. This could potentially remain as a barrier for industrial adoption. However, an optimal hardware setup can be configured, software could be standardised.

Parallel deposition with multiple welding systems offers the possibility to massively reduce component lead times. Due to the scarcity of these systems it is hard to ascertain the extent of any advantages and disadvantages that may be present. It stands to reason that a major advantage is the improved deposition rate, however the degree of complication to tool path planning has not been assessed.

Another key advancement that will be necessary for better performance will be the creation of purpose built power sources. At present, power sources are conventional arc welding power sources which leads to them operating outside their recommended parameters during the WA-DED process. This leads to downtime when consumables need to be replaced or other performance related issues. This means that for all the stated advantage of the WA-DED process over other metal AM processes due to the higher deposition rates are thus brought into jeopardy. Purpose built power supplies would likely be more expensive so an assessment of the comparative rates of consumable usage should be researched.

3.2 Material characteristics associated with WA-DED deposited material affecting mechanical performance

Residual stresses can be modelled using thermomechanical FE software (Ding et al., 2011; Mehnen et al., 2014). However, these simplify the aspects of the process physics to make the modelling less computational demanding. The deposition process can be accurately modelled but due to their extremely computationally intensive nature, simulation times can reach days for simulating a few seconds of a weld bead (Cadiou et al., 2020). As stated by (Cadiou et al., 2020), this means it is unfeasible at present to model the residual stress throughout deposition of an entire part to this level of precision. As central processing units in computers become more powerful this will become more attainable, however currently for large parts especially this is a more distant reality. Residual stresses can be alleviated at present with post process heat treatment (Chi et al., 2020) and cold working (Colegrove et al., 2013). The introduction of a secondary induction heat source behind the weld pool has been found to be beneficial to decrease the maximum residual stresses present in the deposited metal (Bai et al., 2015). However, the geometry of the process limits the application to thin wall parts as the induction heaters need to be placed either side of the deposited wall which is limiting in terms of practical implementation.

Fatigue life has been shown to be markedly improved by post deposition machining. This is due to the removal of surface waviness which promotes sites for preferential crack propagation (Bartsch et al., 2021). Furthermore it has been found that single wire deposition produces better fatigue life due to lower surface waviness (Gordon et al., 2018). This means that the fatigue life standards for each industrial use will have to be carefully assessed to see if components can be used unmachined. For the construction industry this will be of critical interest as it would represent shorter lead times, monetary savings as well as a lower embodied energy for components if machining does not need to be undertaken. An example of a large component that has been produced and installed unmachined is the MX3D bridge in Amsterdam, this shows that this is a possibility ("MX3D Bridge," 2019).

Porosity has been shown to reduce mechanical performance. However, for most feedstocks this can be almost completely nullified by decontamination of the substrate and feedstock when a sufficient flow rate of shield gas is used (Biswal et al., 2019). For large parts it should be assessed if this reduced porosity remains prevalent throughout a part, as heat accumulates in previous layers. Many industries such as the aerospace industry use large aluminium parts due to the lightweight nature of the material (Sun et al., 2018). As such the reduction of porosity in aluminium is a key driver for industrial application and further research should be conducted. It has also been found that lower heat input arc processes or processes with variable polarity reduce porosity in aluminium alloys which are particularly susceptible to porosity in deposited material (Cong et al., 2017, 2015). The authors recognise that for plasma arc welding with variable polarity is a necessity for deposition of aluminium. Literature on variable polarity plasma arc welding has shown a significant reduction in porosity in welds (Chen, 2018; Yan, 2020). However, such systems may not be compatible with

existing machines and require additional health and safety consideration which may hinder industrial adoption. The authors recommend research be undertaken to assess if there is any advantage in depositing WA-DED material with this arc process.

Anisotropy in the microstructure has been identified as a major issue due to the subsequent anisotropic mechanical performance. This has been shown extensively in particular in nickel based (Seow et al., 2019; X. Xu et al., 2018) and titanium based alloys (Suárez et al., 2021). To reduce the degree of anisotropy it has been shown that this can be achieved by lowering the heat input through the use of CMT (Queguineur et al., 2018; C. Wang et al., 2020). It is also recognised that high heat input arc processes such as plasma arc can still produce components with isotropic mechanical properties through the application of substrate cooling (Lin et al., 2019). For large parts it is more appropriate to control anisotropy by using homogenising deposition conditions. If the substrate is cooled to produce greater cooling rates the effectiveness will diminish with an increase in build heights due to a less steep thermal gradient (B. Wang et al., 2020).

Research on how a heterogenous microstructure causes a variation in microhardness has been widely researched (Chi et al., 2020; Dirisu et al., 2020; Lin et al., 2019). However, the extent of heterogeneity of tensile properties is yet to be researched to the knowledge of the authors. Moreover, Elitzer et al. (2022) shows a variation in compressive strength at the top and the bottom of a deposited specimen. For large components this is crucial to allow for industrial adoption of the WA-DED process and the creation of design standards for deposited parts. The authors recommend including tensile and compressive tests in multiple directions at various heights throughout the wall as well as microstructural characterisation in these locations. This is to ensure that mechanical performance throughout a component is suitably reliable.

3.3 Wire Arc Directed Energy Deposition additional in-situ processes

A laser has been used as a secondary heat source and has been found to greatly improve the consistency of layer geometry deposited (Näsström et al., 2019). However, due to the increased heat input, further investigation should be undertaken to ensure that the subsequent larger thermal gradients do not cause coarsening of the grain structure, as this leads to a deterioration of mechanical performance or deposition rates caused by longer idle interpass cooling periods. Preheating the substrate has also been identified to allow for a more stable arc thus deposition geometry has been found to be improved. However, the process is likely not applicable for the application of large component manufacture as post process heat treatment is still necessary (Alberti et al., 2016).

Resistively heating the wire has found to be a very versatile in-situ process that has been found to allow for greater deposition rates of metals which only require a relatively low heat input (Fu et al., 2021). Metals that require higher heat input are deposited with more refined geometry and microstructure than with a conventional cold wire system (Z. Li et al., 2019). Fu et al. (2021) shows that as porosity is reduced that mechanical performance improves as the reduction of porosity is of

greater effect to mechanical performance than a coarser grain structure. If this were to be assessed further, an optimum value for the resistive current could be found for a given material and process. This allows for mechanical performance to be of the highest possible quality which is vital for the technique to be used to produce parts for industrial application. For large parts this could lead to significant material savings as better mechanical performance would allow for greater optimisation.

Researching the sensitivity of mechanical performance in respect to interlayer dwell times for passive cooling has been investigated (Cunningham et al., 2019). It has been shown that it can be manipulated along with the heat input to allow for mechanical performance to be improved. However, these dwell times can significantly reduce the net deposition rate which especially for large parts makes passive cooling impractical (Montevecchi et al., 2018). This is a particularly important issue for thicker walled parts requiring multiple deposition passes, as passive cooling may not be effective enough by itself or for materials where a high minimum build temperature is necessary. One of the main advantages of WA-DED compared to rival metal AM technology such as PBF and other DED processes, is higher deposition rates allow for larger part sizes to be deposited with shorter lead times (Martina et al., 2019). For large WA-DED components the authors propose a necessity for additional active cooling to prevent excessive accumulation of heat in the deposited material (Montevecchi et al., 2021). Similarly to passive cooling, although effective, the immersion based cooling method proposed by da Silva et al. (2020) has a similar drawback for large parts as the size of the part deposited will always be limited by the size of the immersion tank. Furthermore, parts cannot be printed in multiple directions leading to the possible complexity of potential parts to be compromised (da Silva et al., 2020).

Therefore for the deposition of large parts the authors recommend research focusing on active cooling systems localised to the weld pool in particular the gas based approaches such as those proposed by Cunningham et al. (2021), Montevecchi et al. (2018) and Ding et al. (2020). Through using additional cooling methods this allows for more isotropic thermal gradients with lower idle dwell times. This helps prevent growth of large columnar grains which lead to anisotropic mechanical strength and heterogeneous microstructure which are issues exacerbated in depositing large components. To this date no literature has been found assessing the possibility of combining a secondary heat source and in-situ active cooling localised to the weld pool. The authors hypothesise that this could produce parts of greater geometrical precision and consistency with excellent mechanical performance. Cunningham et al. (2021) and Ding et al. (2020) both show an increase in tensile strength when active gas cooling is used. Therefore, there may be the possibility for a WA-DED process with improved deposition rates, finer geometry and improved mechanical performance.

The air jet impingement cooling method outlined by Montevecchi et al. (2018) and Hackenhaar et al. (2020) in particular, holds promise due to the economic advantage compared to other in-situ methods (Hackenhaar et al., 2020). As it uses compressed air the running costs are relatively low compared to other gas based cooling methods. As the costs involved with in-situ

cooling processes will increase with the amount of material it is important for large parts that costs of additional processes are minimised. Hackenhaar et al. (2020) outlined that for very low idle times (i.e. 10 seconds), this method could not prevent heat accumulation in the substrate. Thus, the process is limited to only being compatible with lower heat input processes. This could potentially limit the compatibility of the process with deposition of materials that require a high heat input. However, this should be explored to understand the limitations of the process in terms of application to existing WA-DED systems. Furthermore, an investigation should be undertaken into the materials that can use the technique together with a quantitative assessment of the economic advantage of the process in comparison to other in-situ cooling systems. Also, if the compressed air is applied too close to the melt pool the shield gas could be disrupted leading to unwanted oxidation of deposited material (Hackenhaar et al., 2020; Montevecchi et al., 2021). In addition, mechanical testing should be conducted to ensure that there isn't a reduction in mechanical performance. A lot of the research that uses active cooling methods does not assess the mechanical performance in multiple directions and only considers samples horizontally as in the case of (Ding et al., 2020). As much as the mechanical performance can be seen to be improved, and that it can be inferred that those properties are more isotropic due to the more isotropic microstructure, this should be confirmed with more rigour in future work. The authors found no literature for the application of in-situ cooling specifically to large components. The literature is limited to the fabrication of linear walls for testing which do not take into account the more complex thermal history involved with more complex parts and the subsequently more complex tool paths.

Rolling as a cold work process has been identified to be able to reduce surface waviness of deposited material with a more equiaxed grain structure and lower porosity (Gu et al., 2018; Martina et al., 2015; Qiu, 2013). However, as Qiu (2013) outlines, the necessity for more rigorous testing to confirm the material isotropy by testing thicker walls should be conducted. This would be similar to the work that has been conducted into the research of machine hammer peening where it has been stated that the process has significant penetration depth to fully affect a single pass thick wall (Hönnige et al., 2020, 2017). Neto et al. (2020) noted that the penetration depth for peening of thick walled sections was greater. This was caused by an induced plastic strain within the walls beneficial to hardness testing although they also stated the mechanisms behind this should be researched further. It should also be noted that peening has been shown to refine the grain structure of deposited material, although it has been proven to be less effective than cold rolling (Hönnige et al., 2020, 2017; Neto et al., 2020). Additionally, it should be implemented with a greater range of materials and arc processes. If it is effective enough to allow for parts to not undertake post process heat treatment it could be key for the manufacture of large parts in a similar way as stated by Martina et al. (2015) for cold rolling processes. However, peening would allow for more complex geometry to be cold worked compared to rolling. This is a key driver for large components as prismatic geometry compatible with cold rolling would likely be produced using traditional manufacturing methods.

3.4 Wire Arc Directed Energy Deposition Process Control

WA-DED parts typically generate accumulated geometry errors and defects during the building process, which is especially important for large components where these errors could become very large. To overcome these geometric inaccuracies, researchers have tried numerous methods to control the process (Xia et al., 2021; Xiong et al., 2020). The authors believe these methods can be categorised into two types, namely, feed-forward and feedback. Feed-forward methods, use process planning techniques to compensate for the accumulation error on the consecutive layers (Diourté et al., 2021; Michel et al., 2019). With feedback methods, it uses closed-loop control to improve the building accuracy (Li et al., 2021; Xu et al., 2019). In 2021, Ščetinec et al. (2021) applied both methods in series to compensate and control the building of WA-DED parts. Future work identified that for improved slicing algorithms should focus on the need to rectify a more complete model to account for the feasibility of physical implementation in regards to torch collisions with deposited material (Ding et al., 2016a; Yuan et al., 2020).

Feed-forward methods are still in their infancy in respect of WA-DED with only a few authors (Ding et al., 2021; J. Zhang et al., 2020) implementing such systems. These systems have been predominantly based on knowledge and experience for manufacturing the same part or similar part features. These methods in the future can be used for the control of various WA-DED processes, such as micro-structure control, strain-stress control, cooling rate control etc. However, for successful implementation further research is required.

There are a large majority of the implementations are in closed-loop control, where various researchers have focused on traditional control methods and also new artificial intelligence (AI) methods. The key difference between these two methods is that traditional control methods try to build up a system model for WA-DED and to stabilize and control the process upon this model (Xia et al., 2020b). In the case of AI methods, these aim to discover the relationship between inputs and outputs using historical process data, and then optimize the process from the AI model (Xiong et al., 2013a).

Both traditional control and AI methods have their drawbacks. Traditional closed-loop control methods rely on sensors, which have difficulties to promptly sense the reaction due to the harsh environment of the WA-DED molten pool. Therefore, this may induce latency in the control loop, making the process unstable. For AI methods, researchers tend to set up a model-free framework to predict (Xiong et al., 2013a) and optimize the process (Dharmawan et al., 2020). These rely highly on labelled historical data, and at present as WA-DED is a process which is continuously evolving with improved deposition rates. There is little verified structure data, which can be used in the applied AI methods. Though researchers have generated their own data in these developments, due to the difference of the system specification, the data lacks the generality to be migrated across different WA-DED platforms. The authors believe to facilitate the development of AI methods, a generic digital twin model needs to be researched and tested across a range of different cartesian and non-cartesian WA-DED platforms using a range of standardized welding systems.

4 Conclusions

Based on the literature it is clear that the WA-DED process is highly suitable for the manufacture of large components with a multitude of different components having been manufactured at this scale. However, it is also clear that the process can be improved with the incorporation of additional processes to improve key drivers such as deposition rates, geometric resolution, and mechanical strength. These drivers need to be monitored and the process closely controlled to allow for less human input into the process, which is of paramount importance for mainstream industrial application.

Below are the key areas that require further research to improve the processes suitability for large component manufacture:

- I. Further research into the application of in-situ cooling with tandem wire arc processes and in particular the effects on deposited geometry and mechanical performance.
- II. Explore the heterogeneity in the microstructure of the deposited metal with greater build sizes as well multiple pass wall structures, and the extent of how the degree of anisotropy changes with build height caused by epitaxial grain growth.
- III. Further mechanical testing for material at higher temperatures that they are likely to operate at in aerospace applications.
- IV. Develop cost analysis and life cycle assessments for software tools for the full process chain including additional in-situ processes.
- V. Provide widespread confirmation that more isotropic microstructure does indeed lead to more isotropic mechanical performance for material deposited employing additional in-situ processes.
- VI. Undertake research to enable greater insight into feed-forward process control methods.
- VII. Development of bespoke welding equipment purpose built for the process parameters used in the WA-DED process.
- VIII. Undertake further research in the form of an assessment of how the heterogenous distribution of defects such as porosity are throughout a WA-DED deposited part.

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