The International Journal of Advanced Manufacturing Technology (2023) 127:4995–5011
https://doi.org/10.1007/s00170-023-11623-7

CRITICAL REVIEW

Applications of wire arc additive manufacturing (WAAM) for aerospace component manufacturing

Harshita Pant[1] · Anisha Arora[1] · Ganga Sutha Gopakumar[2] · Utkarsh Chadha[3] · Amir Saeidi[4,5] · Albert E. Patterson[4,6]

Received: 9 January 2023 / Accepted: 20 May 2023 / Published online: 10 July 2023

Abstract

Wire arc additive manufacturing (WAAM) is an emerging technology for metal processing that offers many advantages for aerospace-grade production. It provides significant design complexity and freedom offering very fast material deposition rates and relatively good material properties. It is also based on simple hardware and materials and is easy to apply in the field, making it an ideal tool for the aerospace industry. This article reviewed the major application sectors in the aerospace industry where WAAM has been successfully used with some examples, some of the aerospace-relevant modeling and simulation work for WAAM that has been done, and the current status of the significantly used WAAM materials of interest to the aerospace industry (particularly, aluminum, titanium, and nickel alloys). It was found that the most important benefits offered by WAAM to the aerospace industry were its very fast material deposition rate, its flexibility and simplicity, and its ability to process aluminum alloys much more effectively than most other AM processes. There are still areas to be explored before WAAM could be fully integrated into the aerospace design and manufacturing system, but it is well on its way and promises to be an essential technology in the future.

Keywords Wire arc · Additive manufacturing · Aerospace manufacturing · Aerospace-grade metal alloys

1 Introduction

One of the emerging areas of manufacturing technology that promises great benefits for the aerospace industry is wire arc additive manufacturing (WAAM) [1–7]. Like traditional arc welding but with the intention of building up complex metal parts in layers, this process has become more refined and widely used in recent years. In addition to the significant design freedom and wide variety of materials provided by all additive manufacturing (AM) processes, WAAM offers the ability to deposit a large volume of material very quickly. Over the next couple of decades, the aerospace sector is expected to need about 20 million tons of raw materials, including many materials that have a high buy-to-fly (BTF) ratio such as aluminum, nickel, and titanium alloys where BTF is described as the ratio between the mass of raw material to the mass of the final product, where a low number indicates a large amount of wasted material in the processing [8–16]. Much of this material is wasted during traditional processing, driving the high BTF ratio commonly seen. Processing such a volume of material efficiently and sustainably will come with many challenges, many of which WAAM promises to alleviate due to its low waste and energy requirements, processing automation, and its fast material deposition rates.

From a manufacturing perspective, WAAM (Fig. 1) is a hybrid AM process combining traditional AM concepts

✉ Albert E. Patterson
aepatterson5@tamu.edu

1 Department of Manufacturing Engineering, School of Mechanical Engineering, Vellore Institute of Technology, Vellore 632014, Tamil Nadu, India

2 Department of Space Engineering, University of Surrey, Surrey, Guildford GU2 9GU, UK

3 Department of Materials Science and Engineering, University of Toronto, Toronto, Ontario M5S 2Z9, Canada

4 Department of Engineering Technology and Industrial Distribution, Texas A&M University, College Station, TX 77843, USA

5 Department of Materials Science and Engineering, University of California, Davis, Davis, CA 96516, USA

6 J. Mike Walker ’66 Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA

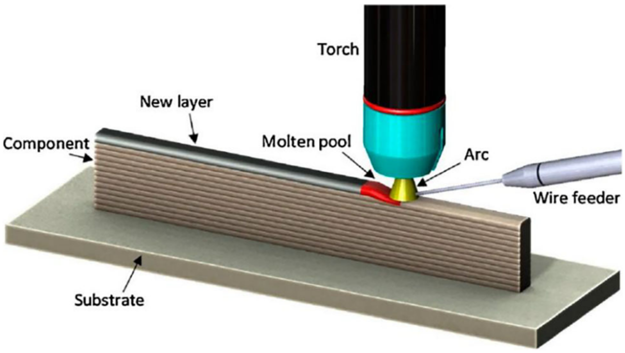


Fig. 1 Process diagram for WAAM [23] reproduced under the terms of a CC-BY license

and robotic control with arc welding, allowing selective deposition of the material at a fast rate and relatively good material properties [4–7, 9, 17–19]. The raw feedstock is a wire or other metal filament, while the fusion between layers is accomplished via an electric arc which melts and fuses the deposited material in a scanning pattern. Therefore, WAAM is considered a scanning-type AM process, producing anisotropic properties within each layer as well as between the layers. Shielding gas (most commonly argon or helium) is used to protect the melt pool and prevent oxidation in a similar way as traditional arc welding processes. Using helium as a shielding gas can significantly affect the cost of WAAM; while it offers benefits such as improved quality and productivity, it is more expensive in some localities than other gases such as argon or carbon dioxide. Therefore, the decision to use helium should be made after a thorough cost-benefit analysis. This assists with fusion between layers and prevents scale or oxides from producing poor fusion and adhesion between the layers [15, 19–22].

A complete WAAM process consists of three stages in total, as demonstrated in Fig. 2. First is software-based planning of target components, followed by WAAM-based deposition of metallic materials, and finally the subsequent post-treatment of the deposited components, including post-heat or post-mechanical treatment, to obtain intended mechanical properties and microstructure and dissipate residual stress [10, 24–26]. Due to different technical requirements and different levels of production, many different WAAM system designs have been developed, each tailored to a specific application domain. The most common variations are those based on gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW), often colloquially known as TIG and MIG welding, respectively. Other variations exist that are based on cold metal transfer (CMT) and tandem gas metal arc welding (TCMAW) (both variations of GMAW) and plasma arc welding (PAW) [3, 11, 12, 27, 28]. Table 1 shows the common types WAAM systems observed in the literature, with details about their heat sources and process characteristics. Figure 3 shows process diagrams for the major WAAM process types.

For WAAM, the cost of materials and investments is lower than other additive manufacturing technologies [30]. The welding wire is used as feedstock in WAAM, which offers a wide choice of materials and allows for speedier manufacturing because of its rapid deposition rate. This method can produce deposition rates of 50–130 g/min, which is far more than any other existing metal AM process [29–31]. It produces near-net-shape products, resulting in less machining

Fig. 2 Flowchart of WAAM process

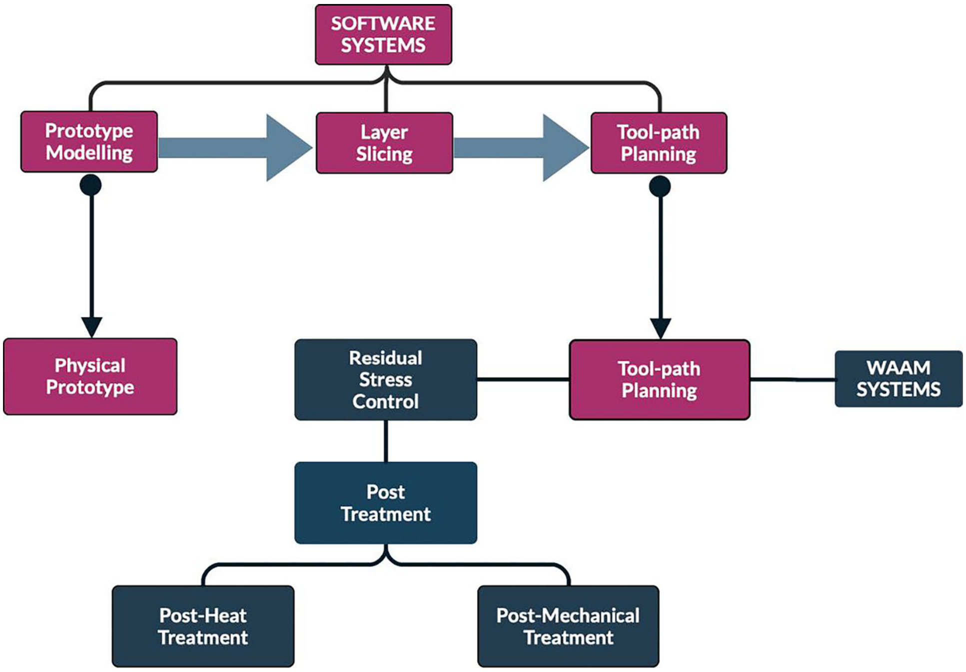
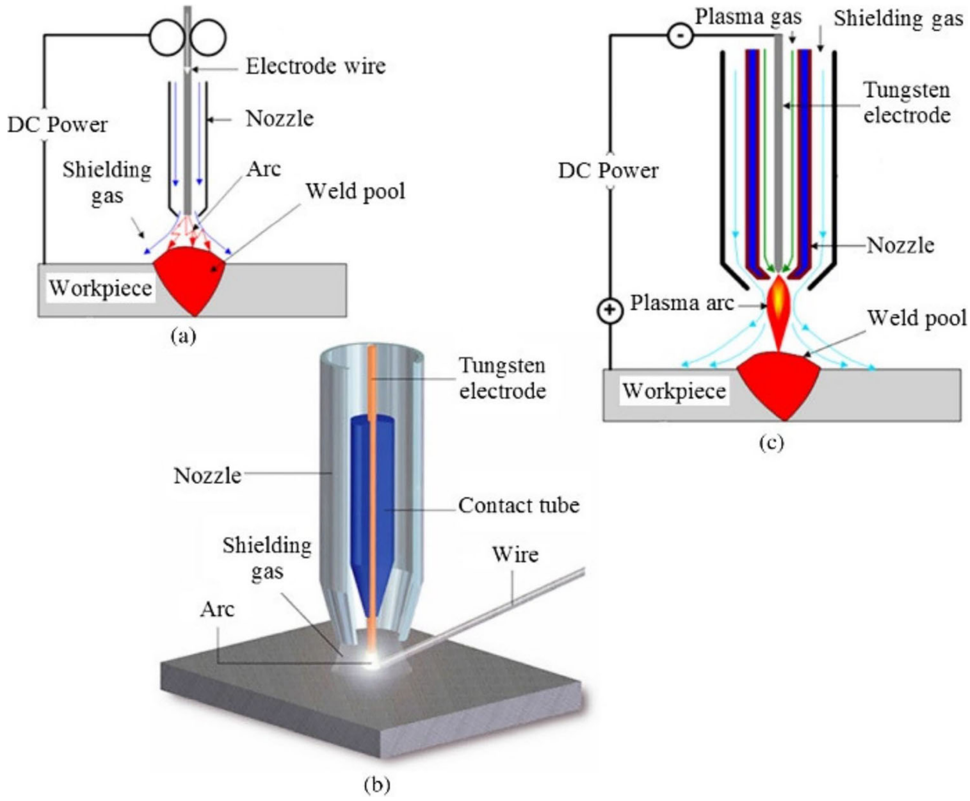


Table 1 Comparison of several types of WAAM processes

Process Type	Energy Source	Process Characteristics
Based on GTAW	GTAW	(1) Electrode: non-consumable, (2) wire feed: distinct, (3) rate of deposition: 1–2 kg/hour, (4) rotation of torch is required
Based on GMAW	GMAW	(1) Electrode: consumable, (2) rate of deposition: 3–4 kg/hour, (3) poor arc stability
	CMT	(1) Electrode: consumable, (2) rate of deposition: 2–3 kg/hour, (3) heat input: low, (4) high dimensional accuracy, (5) little to no splatter
	TCMAW	(1) Electrode: two consumable wires, (2) rate of deposition: 6–8 kg/hour, (3) mixing materials into custom alloys and bimetallics is easy using this process
Based on PAW	Plasma	(1) Electrode: non-consumable, (2) wire feed: distinct, (3) rate of deposition: 2–4 kg/hour, (4) rotation of torch is required

and less waste that would be seen with parts made using casting or other common processes and helping to produce very large components [23, 29, 31]. The resulting material properties are also generally better than those seen with other AM processes such as selective laser melting (SLM), electron beam melting (EBM) and direct metal eposition (DMD) [10, 13, 27, 29].

However, there are some potential issues that must be mitigated or at least accounted for during the use of WAAM. Since it is a scanning-type AM process, it is more likely to have defects, pores, and inclusions. In addition, the use of an electric arc to complete the fusion opens up the possibility of introducing carbon or slag into the welds, as well as the typical welding concerns such as residual stresses and distortion. One of the main techniques for preventing these issues when using WAAM is to use a construction strategy known as symmetrical building. This usually involves depositing material on both sides of the build plate, helping to balance the residual stresses. Once the build is started, the geometry is built from the inside toward the boundaries to prevent



(a)
(b)
(c)

Fig. 3 Basic WAAM process types: **a**GMAW-based WAAM, **b** GTAW-based WAAM, and PAW-based WAAM [29] reproduced under the terms of the CC-BY license material defects and gaps. Once the part is completed, it can be post-processed to reduce the anisotropy and remove any remaining destructive residual stresses [4–7, 14, 15, 29, 32–34].

This article reviews the current state-of-the-art and progress made in applying WAAM to the aerospace industry to solve some of the many manufacturing problems in that sector. Of particular interest during this review were the modeling and simulation approaches, major application areas, WAAM materials, and comparisons with other AM processes employed by the aerospace industry. This material collected during this review is presented in several sections, beginning with Sect. 2 where the research questions and outline of the review is shown. Section 3 explored application sectors and problems that WAAM can help solve, followed by a discussion of modeling and simulation work in Sect. 4. From here, Sect. 5 discusses progress on developing and characterizing materials processed using WAAM. Section 6 presents a discussion on the comparison of WAAM with other AM (both metal and non-metal) processes used in aerospace design. Considering the previous sections, Sects. 7 and 8 provides some discussion and future research directions for WAAM in the aerospace sector.

2 Review approach and major research questions

Once the topic and scope of the review were established, a set of search keywords (approximately 30) was compiled, which were then used by the authors to search for relevant literature in English on Google Scholar, Scopus, EI Compendex, Web of Science, and the major AM-related journals and conference proceedings. A list of the search keywords and journals searched is available upon request from the corresponding author. After this search was done, the reference lists of each paper were analyzed to find additional relevant references that may have been missed during the main search. The full-text versions of each paper were collected and screened for relevance and credibility, with any papers in obviously predatory journals being removed from the set being considered. In addition, all the conference papers, book chapters, and theses for which a journal version was found by the same authors were removed from the set in favor of the journal version. The final check for new papers was completed on December 17, 2022; the authors made every effort to identify and include every relevant paper published and distributed before that date. Copyright permissions were obtained for all figures not unique to this paper, with the exception of figures that were published using a CC-BY license. In all cases, the sources of the figures were cited and acknowledged. The major research questions explored in the course of this review were:

- In brief, what is WAAM and how does the process work? (Sect. 1).
- How can WAAM be used to solve some of the major manufacturing problems encountered in the aerospace industry? (Sects. 1 and 3).
- What specific sectors within the aerospace industry has WAAM been used for and how successful were those applications? (Sect. 3).
- What modelling and simulation work has been done to better understand and control WAAM for applications relevant to the aerospace industry? (Sect. 4).
- What progress has been made on WAAM for common materials used in the aerospace industry? (Sect. 5).
- Within the aerospace sector, how does WAAM compare in terms of usefulness and applicability to other AM (metal and non-metal) processes? (Sect. 6).

3 WAAM in the aerospace industry

The aerospace industry is continuously looking for reliable lightweight aerospace parts with good mechanical properties and high strength-to-weight ratios. These materials will help advance the aerospace industry by improving fuel efficiency, reducing carbon emissions, improve the size and safety of payloads, and to meet industry safety and reliability targets. Designers currently have two major options for accomplishing this, namely (1) reducing the amount of material used or (2) using lighter materials. In both cases, concerns come up about reliability, safety, and cost since old and established materials and design methods are discarded in favor of new and emerging ones. The use of AM in general and WAAM in particular can aid greatly in this when the manufacturing characteristics are taken into account.

From a general engineering perspective, aircraft and spacecraft designers need to be able to maximize performance of the selected materials and design geometry, while using the minimum amount of material. The material must be minimized both to minimize the mass of the aircraft but also to preserve material (since many aerospace-grade materials are rare and expensive) and reduce waste as much as possible. In many cases, this need to minimize the use of material can create design adversity, where performance and reliability requirements struggle to be met using the available materials. In addition, it is also vital that aerospace components be maintainable and replaceable, as these systems often have long lifespans and operate in some very extreme environments. WAAM in particular can aid in solving these problems, as it allows very durable and strong materials to be processed by selective deposition. This not only allows stronger and more durable materials to be used, but also provides the ability to optimize the placement of it [35].

Since a wide range of excellent manufacturing processes (both additive and traditional) exist to produce smaller components without the disadvantages of WAAM (thermal shock, residual stresses, welding inclusions, and others), the main emerging area of application for the aerospace industry is in creating large parts, tanks, trusses/spars, and airframes. STELIA Aerospace (Toulouse, France) designs aluminum airframes and frame sections (Fig. 4a and b) for several different Airbus aircraft. They have successfully used WAAM to create some of the sections, as shown in Fig. 4c [37, 38]. The demonstration part measures $1m^2$ and was manufactured by depositing layers of aluminum wire welded by electric arc.

While the creation of frames and whole spars (Fig. 5a), Cranfield University and Thales Alenia Space) are the most obvious applications of WAAM for these design problems, it has also been used successfully for some other structures as well. The fuel head tank (Fig. 5b) and another unspecified part (Fig. 5c) for a Lockheed Martin aircraft were also successfully manufactured using WAAM. Some other applications that have been explored were the manufacturing of frame stiffening ribs (Fig. 5d) and satellite breadboards (Fig. 5e). In order to explore the feasibility of using WAAM to create an entire aircraft using WAAM, a large section (nose cone) was manufactured by Aircraft Research Association Ltd (ARA), Bedford, and WAAM3D. The dimensions were 190 mm in diameter and 350 mm in length. In order to be tested in ARA's own transonic wind tunnel in the summer of 2022, the component has been successfully integrated into a wind tunnel model [36]. More information about these technologies and case studies can be found on the respective companies' websites [37–40] if the reader is interested.

A major emerging area of concern and study within WAAM, particularly for high-risk or high-precision applications such as those encountered in the aerospace, automotive, and medical industries, is testing and evaluation of the parts. While beyond the main focus of this review, it is an important consideration that could affect how the technology is used and perceived by potential users. The solutions proposed so far fall into three main categories: (1) in-process defect detection [41], (2) non-destructive evaluation of finished parts [42], and (3) application of manufacturability constraints during design to ensure effect post-processing [43, 44]. For process monitoring, a sensor network method was developed by Xu et al. [12] and used to monitor for process errors during WAAM of titanium alloys. Hauser et al. [45] developed a similar but more simple method using cameras and computer vision software to complete the process monitoring during aluminum WAAM. A larger-scale monitoring method for WAAM systems using robotic arms was presented by Dharmawan et al. [46], where reinforcement learning was used to correct errors during the process. Finally, a predictive control model for WAAM based on system mechanics was developed and refined by Xia et al. [47]. While most of the existing studies are not related directly

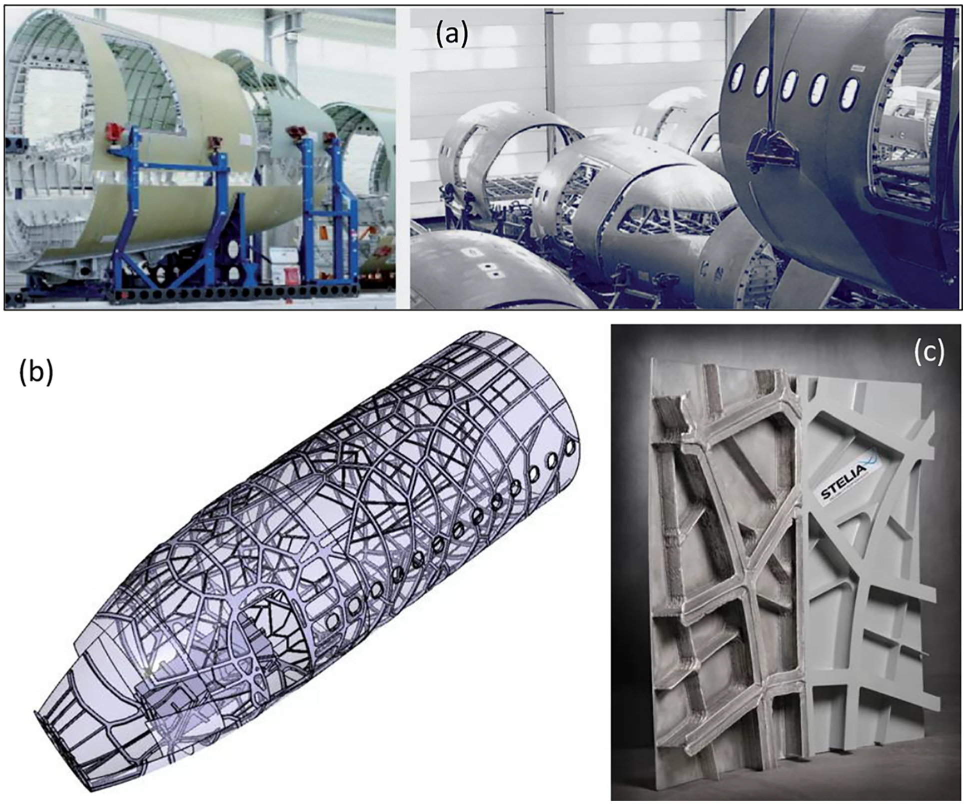


Fig. 4 **a** and **b** Aluminum airframe designs from STELIA Aerospace, with **c** close-up example of a section manufactured using WAAM [36] Figures reproduced under the terms of a CC-BY license. The sections shown in (**a**)-(**b**) are approximately 3.5 m in diameter, while the panel in (**c**) is approximately 1 m square

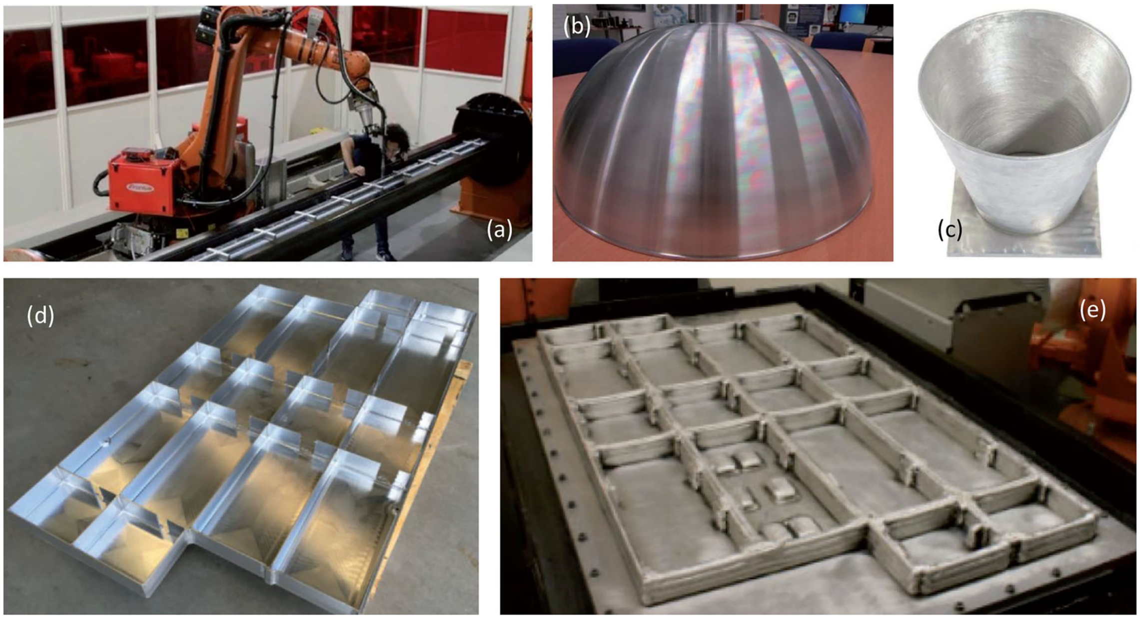


Fig. 5 **a** 6-m aircraft spar, **b**fuel tank, **c**conical part, **d** panel stiffeners, and **e** satellite breadboards manufactured using WAAM [36]. Figures reproduced under the terms of a CC-BY license. The parts shown vary in size from up to 6 m long in (a) to only 200 mm in diameter for (c). The part shown in (b) is approximately 1 m in diameter, while the builds in (d)–(e) are about 2 m×3 m in size

to aerospace applications, the primary non-destructive evaluation methods for finished WAAM parts has been X-ray techniques, as shown by Raguvaran et al. [42], Rodrigues et al. [48, 49], Shen et al. [50], and Morais et al. [51]. In terms of post-processing, the main manufacturability constraints for WAAM parts have been related to machinability of the finished parts. Works by Hoye et al. [52], Ceritbinmez et al. [53], Veiga et al. [54], Feier et al. [55], and Gou et al. [56] have explored this extensively.

4 Modeling and simulation of WAAM

Simulations at different length scales are being performed to improve the quality of the final WAAM products. Given the needed precision and reliability of aerospace applications, it is vital that the mechanics of the process be well-understood and easily controllable. The defects found in WAAM products, pores, cracks, distortion, non-homogeneous chemistry, and large columnar grain structure, all are related to the process variables and composition of the alloys used. Pores can be formed because of gas dissolution in molten metals, i.e., hydrogen in aluminum alloys. Cracks can be associated with shrinkage in solidification and the internal stress that is developed due to contraction during solidification and cooling. One category of simulations is focused on optimizing the process by understanding the effects of thermal cycles, deposition rate, travel speed, molten pool size, etc. Wu et al. [57] and Aldarur et al. [58] used finite element method simulations (Fig. 6) to study the effect of thermal cycle and pool size on the microstructure and properties of Ti-6Al-4V. They showed an increase in the width of the molten pool results in columnar grains. In the same way, Ogino et al. [59] used numerical methods to predict the shape of the molten pool and show managing the torch temperature and speed affects the shape of the pool.

Rolling ultra-high-frequency pulsed (UHFP) arc and ultrasonic vibration are examples of processes that are used along with WAAM to enhance the mechanical properties of printed parts. These hybrid processes are also investigated computationally as some of their effects cannot be measured experimentally. Computational fluid dynamic (CFD) was used to study the effect of ultrasonic vibration on the pool size [60]. The study showed that the flow rate and high-temperature diffusion are improved; hence, a more uniform temperature distribution is formed. It also significantly changes the pressure field in the molten pool which promotes equiaxed grain structure formation. The predictions of the simulations were confirmed by analyzing an AISI 1045 steel WAAM part. The effect of UHFP on NiTi WAAM product was also investigated using CFD [61]. It was shown that the velocity fluctuation frequency of different points in a molten pool is higher when UHFP is used, and it leads to an equiaxed grain structure. It also showed a deeper penetration of the pool is possible when UHFP is used. Figure 7 shows the setup of the simulation.

CALPHAD-based simulations (calculation of phase diagrams) that use thermodynamic databases are used to

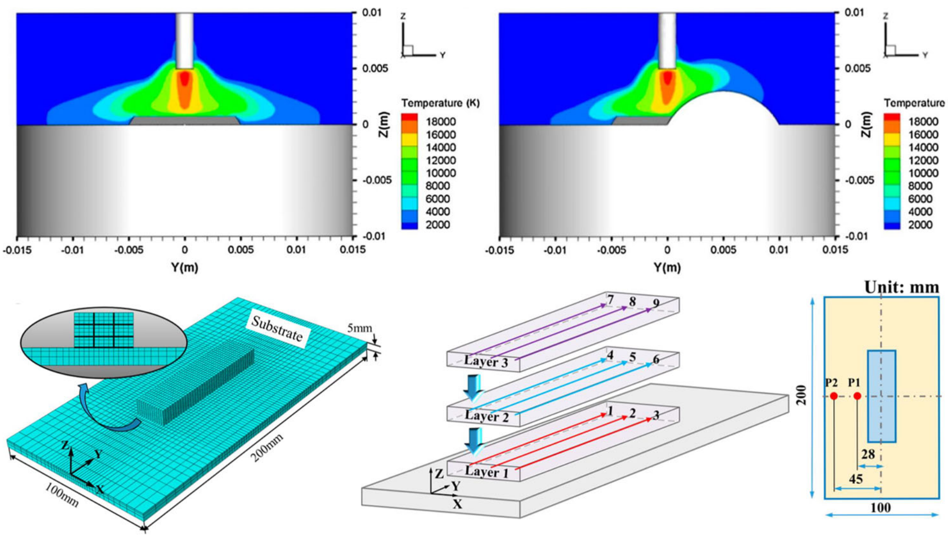


Fig. 6 WAAM simulation model [57] Figure reproduced under the terms of a CC-BY license

calculate equilibrium phase diagrams to predict transition temperatures and phases. It is an especially important method when using multi-element alloys. Information extracted from these diagrams can be used to determine the alloy's behavior during solidification and whether it is susceptible to crack formation or segregation [62–67]. The CALPHAD method predicts the cooling rates at which precipitate phases are formed, based on which an appropriate heat treatment is determined. The Scheil-Gulliver solidification model and diffusion-controlled transformation simulations are used to understand the non-equilibrium solidification in AM. In Al-Zn-Mg-Cu system development [68], the heat treatment process was determined by Scheil-Gulliver solidification simulation and CALPHAD. The presence of phases such as Mg2Si and Al3Zr are predicted by these models. Post-WAAM heat treatment for grade 91 steel was also designed based on the prediction of precipitate formations during non-equilibrium solidification. The heat treatment, 2 h of homogenization at 1200 °C, and 2 h of aging at 760 °C resulted in an ultimate tensile strength 200 MPa higher than wrought products. A two-step heat treatment was developed for Al-Zn-Mg-Cu alloy using CALPHAD simulations [51]. Welk et al. used the CALPHAD method to investigate the effect of different alloying elements on the freezing range of Ti-6Al-4V [69]. By increasing the freezing range of an alloy, a more significant undercooling can be created that leads to the formation of smaller and equiaxed grains.

5 WAAM aerospace-grade materials

Many studies on the WAAM mechanism and performance on various materials, focusing on titanium alloys, aluminum alloys, and nickel-base alloys have been conducted. The deposited material undergoes multiple thermal cycles during the construction of a WAAM workpiece. During these heat cycles, various grain patterns occur in distinct layers along the deposition direction. These grain structures determine the mechanical properties of the workpiece. Many column particles have grown significantly from the substrate and are compact towards the boundary section with a high gradient temperature. Often these metals seem to be appropriate for WAAM forming workpieces, but residual stress, deformation, and precision concerns persist [58, 70–74]. Alloys of other materials may be widely used with WAAM in the future, particularly alloys based on magnesium and copper, for the aerospace industry. During this review, it was found

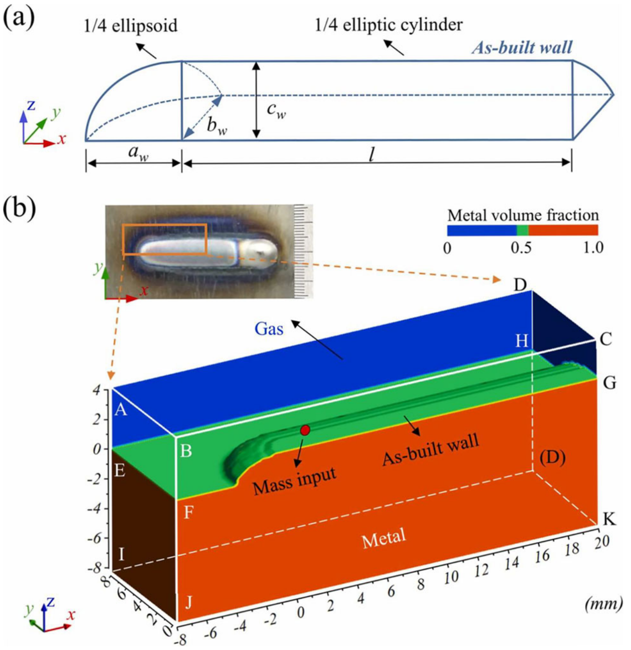


Fig. 7 WAAM simulation model [57]. Figure reproduced under the terms of a CC-BY license

that WAAM has been used successfully for various kinds of steel and some magnesium alloys, but these applications were not related to aerospace problems and therefore were out of the scope of this review. The alloys available for WAAM are limited, so it is necessary to design new ones as new applications and problems arise. Much of the modeling and simulation work for WAAM has focused on the behavior of the alloys and developing new alloys that are not susceptible to the formation of common defects in the WAAM process. For example, aluminum alloys in the 7000 series which have high strength and are important in the aerospace industry are not weldable because of the formation of cracks, hence not appropriate for WAAM. Many groups are trying to design new aluminum alloys for WAAM [36, 62–67, 75, 76].

5.1 WAAM-processed titanium alloys

Titanium alloys generally have excellent natural characteristics such as a high strength-to-weight ratio and good toughness. Its fatigue strength, growth resistance, oxidization rate, and corrosion resistance are high as well. Molding, forging, and casting are the most common methods of processing titanium alloys, but these methods present many problems with aerospace-grade materials [77]. Naturally, titanium and its alloys have low thermal conductivity, very high viscosity (i.e., low fluidity), and an expandable modulus, which can result in the material being difficult to form even when heated [28, 58, 78, 79] and encourages defects in the material structure. Titanium is also subject to surface oxidation during processing (especially during machining), which can insulate the material bulk and prevent the even distribution of heat [80, 81]. In addition to a higher energy requirement to process the material, it also causes accelerated tool and mold wear. Special equipment is generally required to keep these risks at an acceptable level. In contrast, the hardware and processing methods used by WAAM are low-cost and straight-forward. No special equipment or tools/molds are needed with WAAM, as the method is the same as used with other easier alloys (such as aluminum) [57, 82].

There are two common forms of titanium alloys used in the aerospace industry and can be processed easily using WAAM [83, 89]: α phase and β phase depending on the metal's crystal structure. The properties of the β phase are that its ductility is high and tensile strength is moderate. The lattice structure of β phase is body-centered cubic (BCC), whereas that of α-phase is hexagonal close-packed (HCP). The strength of α phase is high but is also quite brittle. Various titanium alloys are divided into 5 types based on their phases, α-Ti alloys, near α-Ti alloys, $\alpha + \beta$ Ti alloys, near β-Ti (metastable β) alloys, and β-Ti alloys. Table 2

Table 2 Comparison of types of titanium alloys processable using WAAM [83–86]

Type	Lattice	Examples	Characteristics	Aerospace Applications
α	HCP	Pure titanium, TI-5Al-2.5Sn	Stabilizers are used to strengthen the solid solution. Not suitable for cold operation as the smoothness of HCP is much lower than BCC metals leading to plastic deformation at low temperatures. Specific thermal processing needed. Not heat-treatable	Airframes, brackets, structural turbine parts
Near α	HCP	IMI 685, IMI 829, TI-1100	Formed by adding 1–2% ions to α-Ti alloys. Adding a β stabilizer helps improve performance. Low-temperature Youngs modulus, strength, and corrosion resistance can all be improved. Better balance of strength, creep resistance, and heat performance than pure α-Ti alloys. Not heat-treatable	Gas turbine engine boxes, structural components, airframe skins, and jet engine compressor blades
$\alpha + \beta$	Mixed	TI-6Al-4V	Microstructure of $\alpha + \beta$ Ti alloys is like that of α-Ti alloys but has more β stored solvents. $\alpha + \beta$ Ti alloys can be heated to varying temperatures to achieve a particular feed area's desired microstructures and mechanical properties. Very durable with best general fatigue strength of all Ti alloys. Heat treatable	Most common form of Ti used in aerospace industry, used for a large variety of applications. Can be used for most applications filled by steels but offering a 40% reduction in mass
Near β	BCC	Ti-10V-2Fe-3Al	Contains 10–15% β concentrates. Very easy to weld and forge compared to other Ti alloys. Extremely high strength and wear resistance. Microstructure can be unstable with lower temperature resistance	Spar structures, flat rolled parts, ducting, clips and brackets, aircraft floors. Has been used to make springs
β	BCC	Ti-22V-4Al	Contains 30% β solvents. β-Ti alloys are stronger and more wear-resistant than α-Ti alloys. Good cooling properties. Most brittle of all Ti alloys, lowest fatigue strength	Very rarely used outside of heat exchangers and small non-structural parts due to brittleness

Lattice types shown for room-temperature cases shows a comparison of the characteristics for each one. The benefits of WAAM are most apparent for the applications requiring large or unusually shaped parts. Due to the special lightweighting requirements, the aerospace industry may cater to most WAAM titanium applications, even over other common materials such as aluminum and stainless steel [31, 82, 83, 87, 88, 90]. Table 3 shows the major studies completed using WAAM and titanium alloys observed in the literature; the WAAM type and mechanical properties after WAAM were collected from each for the table.

5.2 WAAM-processed aluminum alloys

Aluminum alloys are low-cost, have a high strength-to-weight ratio, have good fatigue and fracture properties, and are generally easy to process with existing manufacturing processes. Most alloys also have good weldability. Therefore, it has been widely used for structures from the beginning of aircraft and spacecraft development. With the advent of modern manufacturing techniques, such as CNC machining and friction stir welding, aluminum alloys can be used to make both very small and very large parts easily [13, 91]. Aluminum alloys are also generally very stable and do not present themselves in drastically different chemical structures like titanium alloys (aluminum has a face-centered cubic (FCC) crystal structure), making specific studies with WAAM much easier to complete. Table 4 shows some examples of WAAM-processable aluminum alloys that have been used successfully for aerospace applications.

It has been observed that WAAM-processed aluminum alloys have similar problems and concerns, such as cracking, porosity, cracking, and inconsistent grain structure, seen in cast and welded aluminum [16, 94, 98]. Therefore, it is safe to assume that the same mitigation strategies developed for such processing would also be relevant for WAAM-processed aluminum; however, not much has been explored on this question for WAAM, and therefore, it is an important point for future research projects to consider. As with traditional arc welding, most of the WAAM processing of aluminum alloys is done using a GTAW-based (i.e., TIG) method [91, 92, 99–101]. However, the CMT technique has been shown to work for aluminum alloys under some conditions [93, 102]. The deposition rate for aluminum alloys has been found to be about one kg/hour using WAAM, which is extremely fast compared even to other alloys processed using this method [92, 99, 100].

5.3 WAAM-processed nickel alloys

Because of their structural stability at high temperatures and extreme environments, their toughness, and corrosion resistance, nickel alloys are widely used in the aerospace industry. Due to this and the generally high cost of processing, nickel alloys are an idea choice for WAAM [79, 103, 109], particularly Inconel 718 and Inconel 625 [110, 111]. Table 5 shows the major studies completed using WAAM and nickel alloys observed in the literature during this review; the WAAM type and mechanical properties after WAAM were collected from each for the table.

6 WAAM versus other AM processes in the aerospace industry

The aerospace market for AM components comprises metal and non-metallic materials (especially polymers), which are highly connected to both critical and standard aircraft parts [9, 35, 112–114]. The common metal and non-metal AM technologies are listed in Table 6, with examples of applications in the aerospace industry. In the aircraft industry, premium metals such as titanium alloys, aluminum alloys, nickel-based superalloys, and special steels are in great demand [35, 52, 114–117]. Aerospace components' complexity in structure, functioning, and properties often leads to various manufacturing challenges and higher costs. Traditionally, complicated aerospace components comprise multiple simple parts attached with various welds, screws, and bolts, which further needed a greater inspection, whereas aerospace components manufactured by AM technology enables part consolidation [118–120], resulting in a decrease

Table 3 Example aerospace titanium alloys processed using WAAM. Yield and ultimate stress values shown are averages unless otherwise specified

Alloy	Aerospace Applications	WAAM	Yield σ (MPa)	Ultimate σ (MPa)	Ref
Ti-6Al-4V	Turbine blades, structural parts, exhaust systems, airframes, window frames, aircraft armor, landing gear, hydraulics	PAW	864–1020	925–1094	[10]
		PAW	862	931	[11]
		GTAW	N/A	N/A	[87]
		PAW	N/A	N/A	[12]
		GTAW	765	872	[24]
		GMAW/CMT	N/A	N/A	[82]
		GMAW/CMT	N/A	N/A	[31]
		GMAW/CMT	850–860	900–915	[88]

Table 4 Example aerospace aluminum alloys processed using WAAM

Alloy	Aerospace Applications	WAAM	Yield σ (MPa)	Ultimate σ (MPa)	Ref
AlMg5Mn	Forged aluminum structural parts, low-weight brackets	GMAW	N/A	266–282	[91]
5A06	Sheet metal, structural parts, bent metal frames, brackets	GTAW	124	273	[92]
5356	Aircraft welded joints, wrought aluminum parts, brackets	Hybrid GMAW/GTAW	N/A	270	[93]
		GMAW	120	265	[94]
7A55-Sc	Sheet metal, structural parts, brackets	CMT	293	337	[95]
2219	Sheet metal, structural parts, brackets	CMT	177–322	328–465	[96]
7075	Very large structural components and frames	GTAW	310	435	[97]

Yield and ultimate stress values shown are averages unless otherwise specified

in overall inventory cost. As the number of components in any assembly decreases, it reduces the number of tools and writing, testing, and production costs [114, 121].

One of the main reasons for the high cost of manufacturing aerospace parts is the BTF ratio. BTF is described as the ratio between the mass of raw material to the mass of the final product, where a low number indicates a large amount of wasted material in the processing. According to current scenarios, block-shaped raw material is milled to obtain large structural components for the aerospace industry. This results in a high amount of wastage, leading to a high BTF ratio and hence the high cost of tooling. Metals such as alloys of titanium, aluminum, nickel-based superalloys, and special metals are highly demanded in the aerospace industry. In 1970, 15 tons of titanium alloy were used in the Boeing 737, but in 2009, 100 tons were used in the Boeing 787. The demand for these metals is growing all the time. However, over 90% of the metal is machined away during fabrication, resulting in significant waste. Titanium made up 93

A process that combines additive manufacturing with machining is a positive approach to overcoming these traditional manufacturing method issues. Table 7 compares various types of AM used in the aerospace industry [52, 112, 113] based on some major relevant process parameters. Aerospace metals are very expensive, often fragile, and sometimes unsuitable for manufacturing with one of the powder-based metal AM processes [116], restricting the types of AM processes that can be used to produce aerospace components. AM processes in general have the potential to reduce the BTF ratio from about 20:1 (for traditional machining) to around 5:1, with WAAM being the most flexible and rapid process [12, 83, 104, 122]. In addition to being far more efficient and sustainable and making better use of exotic or rare materials, this will greatly reduce the cost and difficulty

Table 5 Example properties of aerospace nickel alloys examined after WAAM processing

Alloy	Aerospace Applications	WAAM	Yield σ (MPa)	Ultimate σ (MPa)	Ref
Inconel 718	Extreme environment parts, cryogenic tanks, rings, casings	GMAW PAW GTAW	473 438–485 423–438	828 690–754 718–721	[103] [104] [105]
Inconel 625	Piping and fuel lines, pumps, valves, exhaust system, nozzles, turbine blades	PAW GTAW CMT	480 469 N/A	771 802 684–722	[106] [107] [108]
Invar 36	Heat exchangers, heat-sensitive parts, pendulums, instrumentation, sensor brackets	PAW GMAW	N/A N/A	N/A N/A	[58] [58]

Yield and ultimate stress values shown are averages unless otherwise specified

Table 6 Metal and non-metal AM technologies relevant to aerospace manufacturing

	Metal AM Technology	Non-Metal AM Technology
Technology	Cold spray (CS)	Vat photopolymerization (VPM)
	Binder jetting (BJ)	Material jetting (PolyJet)
	Powder bed fusion (PBF)	Fused filament fabrication (FFF)
	Directed energy deposition (DED)	Polymer selective laser sintering (PSLS)
Uses	Rapid tooling	Rapid tooling
	Rapid metal prototyping	Rapid non-metal prototyping
	Direct metal part fabrication	Direct non-metal part fabrication
	Part repair	part repair
Aerospace field examples	Blisk repair (DED)	UAV wing design (PolyJet/FFF)
	Satellite antenna bracket (PBF)	Boeing 777–300ER door handle (FFF)
	Helicopter engine combustion chamber fabrication (DED)	Ratchet wrench printed by NASA on the International Space Station (PSLS)
	Lap joint reinforcement (DED)	Camera case prototyping (FFF)

Adapted from a table discussed in [112] Reused with permission. WAAM falls under the directed energy deposition technology family

of making aerospace-grade parts [30, 52]. WAAM is promising because, in addition to offering the design freedom and material customization offered by all AM processes, it has a very rapid material deposition rates, is safer to use than many other AM processes, and can make very large and awkwardly shaped parts easily [83, 122–124]. A good example was presented by Norsk titanium, who developed the first titanium WAAM component for an aircraft, specifically the 787 Dreamliner. After WAAM was integrated into the design and fabrication process, the overall cost of the part was reduced by 30% and the processing time was reduced by 75% [122–125].

7 Discussion

This review explored the current uses, modeling and simulation methods, and materials for the wire arc additive manufacturing process relevant to the aerospace industry. For the major problems encountered in this sector, the major differences between WAAM and other AM processes were also briefly examined. While WAAM is useful in a wide variety of production and design sectors (for example, as discussed by Li et al. [2], Vimal et al. [13], Rosli et al. [17], Jin et al. [23], Chen et al. [34], Najmon et al. [35], Langelandsvik et al. [70], Treutler et al. [71], Raut et al. [72], Liu et al. [79], Meiners et al. [90], Dhinakaran et al. [9, 109], Wu et al. [111], Uriondo et al. [114], and Cunningham et al. [123]), it offers some specific benefits to the aerospace industry that no other major process currently existing can offer in such a combination. For example,

- WAAM can provide the excellent design freedom of AM, while also offering a very fast material deposition rate. This dramatically improves the buy-to-fly ratio for the exotic aluminum alloys and titanium and nickel alloys commonly used for aircraft and spacecraft due to the low amount of waste.
- WAAM can produce a very wide range of part scales (from small parts to potentially entire aircraft). While the

Table 7 Comparison of different types of AM technologies used in the aerospace industry

Technology	Energy (W)	Efficiency (%)	Surface Roughness (μm)	Build (mm^3)	Layer Thickness (μm)	Ref
Laser powder bed fusion	100–3000	2–5	4–11	500 × 350 × 300	20–100	[113]
Electron beam powder bed fusion	3500	15–20	23–35	200 × 200 × 180	100	[113]
Laser metal deposition	500–3000	2–5	20–50	900 × 1500 × 900	1000–2000	[112]
WAAM	2000–4000	70	500	Potentially unlimited	1000–2000	[112]

precision is less than can be gained from other AM and traditional processes, WAAM parts are relatively easy to post-process to bring them to the required precision.
- WAAM does not require any special tooling during or after the process, making it suitable for the custom one-off parts often needed in the aerospace industry.
- WAAM also does not require any special enclosed environment or vacuum to operate successfully, making it extremely flexible and easy to apply in most cases. Similarly to traditional GMAW and GTAW welding, the shielding gas (argon, helium, CO_2) can be applied directly through the torch or wire feed.
- While WAAM does have some issues with incomplete fusion, residual stresses, cracking, and similar, it is generally far less than what is encountered with other AM processes and many traditional processes such as casting.
- Essentially any weldable metal can be processed using WAAM.
- The hardware for WAAM and the raw materials (filler wire and shielding gas) can be obtained easily for a relatively low cost.
- WAAM has the potential to be a good open-source AM process as all of the components needed can be obtained at any good hardware store. Unlike most AM processes, this allows it to be used in much less-than-ideal conditions and places.
- The process is conceptually simple (unlike many other AM processes) and is relatively easy to control.
- WAAM can be easily combined with other processes (such as milling or turning) to create synergistic hybrid processes.

Despite the benefits and potential applications of WAAM, there are some challenges and limitations associated with this process that can limit its use for some applications.

- The primary challenges is related to the process parameters, which can affect the mechanical properties of the final product significantly. These parameters include the wire feed rate, arc voltage, welding speed, and the distance between the electrode and the work piece. While these parameters are not dificult to understand, controlling them in real-time during processing can be a major challenge.
- Another challenge is the limited range of materials that can be used in WAAM. The process is typically restricted to materials that can be wire-fed easily, which limits the range of metals that can be deposited. Unlike other DED processes (such as laser engineered net shaping (LENS), WAAM cannot easily process brittle metals or metal/ceramic composite materials.
- The hardware needed for processing is relatively inexpensive and simple, but can become expensive very quickly for any increase in control and precision needed.
- The material properties are generally good for WAAM (assuming the process parameters are set correctly), the natural surface quality it typically quite bad without post-processing.

WAAM is an extremely versatile AM process, being able to use several different approaches to welding the material (GTAW, GMAW, CMT, PAW) to expand the variety of materials that it can process and reduce the cost and material investment to use it. As demonstrated during this review, WAAM in several different forms has been well-validated by both the aerospace industry and academic researchers. While not able to produce small detailed parts with the precision of powder bed fusion or metal injection molding and being subject to the typical AM issues (anisotropy, cracks, residual stresses, voids), it is emerging as one of the go-to metal AM processes. For the time being, it appears to be best suited for large parts with low tolerances (or which will be machined to spec later) but as shown in several sections of this review, it is steadily improving and expanding the boundaries of its usefulness. While not much aerospace-related modeling and simulation work has yet been done, the studies reviewed show that much is being learned about how to manage and control the process, which in turn is making the process more useful and precise.

The great majority of the studies reviewed were concerned with the materials that WAAM can process. Within the papers that were concerned with aerospace applications or that studied materials commonly used in the aerospace industry, the three major types of materials were aluminum alloys, titanium alloys (mostly limited to Ti-6Al-4V), and nickel alloys (primarily Inconel 718 and Inconel 625). At the current time, the titanium and nickel alloys studied for WAAM are largely the same as those used in other AM processes (particularly MPBF). While WAAM was successful in processing these (and showing promise to process other similar alloys), it is a stand-out among metal AM processes for its ability to work well with aluminum alloys [36]. Aluminum is often a difficult material to process additively, but WAAM appears to do it very well. It also shows great potential for the processing of titanium alloys; while all of the studies found used Ti-6Al-4V (the most common titanium alloy processed by all AM processes), WAAM offers the potential to work equally well with other titanium alloys which may provide great benefits for use in extreme environments.

In addition to its ability to provide good factory parts for aircraft and spacecraft, WAAM offers two more major benefits for the aerospace sector: (1) on-demand low-cost spare parts and (2) field repair. These will be particularly useful in the future for military applications and space missions, where aircraft and spacecraft can be repaired and maintained in the field without the need to carry and store spare parts. In terms of repair, WAAM offers a safer and less complex alternative to the powder-based directed energy deposition (DED) process normally used for additive repair. While a more "quick and dirty" option than DED, it definitely has great potential in applications where a significant volume of material needs to be deposited or the conditions do not work well for DED. For both WAAM and DED, post-processing and inspection would need to be done to bring the parts into spec and ensure they are ready to be used again.

8 Conclusions and future work

In conclusion, the WAAM process is a very promising tool for the design, production, and maintenance of aircraft and spacecraft in the future. It is a very simple and low-cost alternative to many other metal AM processes, while offering most of the same benefits. It can provide good results with a wide variety of materials (beyond the aerospace materials discussed in this review), showing particular promise with aluminum and titanium alloys. Its very high deposition rate and low waste provide a good tool to dramatically reduce the potential buy-to-fly ratio for aerospace applications, while providing good properties and relatively reliable products. Future work on WAAM in the aerospace domain should focus on more detailed modeling and simulation of the process, more experimental characterization of the materials produced with WAAM, mixing of materials to make functionally-graded materials and alloys, and on developing design rules for applying WAAM to the aerospace industry. Academic researchers should also focus on completing replicable and scholarly studies of the process beyond what has been done and demonstrated by the various companies discussed in this review.

Author Contributions HP: Study design, literature collection and analysis, first draft section writing. AA: Study design, literature collection and analysis, first draft section writing. GSG: Study design, literature collection and analysis, first draft section writing. UC: Study design, review coordination, literature collation, first draft preparation, figures. AS: Study design, supervision, literature collection and analysis, figures, final draft preparation and polishing. AEP: Supervision, study design, literature collection, figures, final draft preparation and polishing, journal submission and correspondence. All opinions and conclusions are solely those of the authors.

Availability of data and materials The raw data is available upon reasonable request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Williams SW, Martina F, Addison AC, Ding J, Pardal G, Colegrove P (2016) Wire + arc additive manufacturing. Mater Sci Mater Med 32(7):641–647
2. Li JZ, Alkahari MR, Rosli NAB, Hasan R, Sudin MN, Ramli FR (2019) Review of wire arc additive manufacturing for 3d metal printing. Int J Autom Technol 13(3):346–353
3. Baier D, Bachmann A, Zaeh MF (2020) Towards wire and arc additive manufacturing of high-quality parts. Procedia CIRP 95:54–59
4. Ding D, Pan Z, van Duin S, Li H, Shen C (2016) Fabricating superior NiAl bronze components through wire arc additive manufacturing. Materials 9(8):652
5. Ding DH, Pan ZX, Dominic C, Li HJ (2015) Process planning strategy for wire and arc additive manufacturing. In: Advances in Intelligent Systems and Computing. Springer International Publishing, pp 437–450
6. Ding D, Pan Z, Cuiuri D, Li H, van Duin S, Larkin N (2016) Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing. Robot Comput-Integr Manuf 39:32–42
7. Ding D, Pan Z, Cuiuri D, Li H (2014) A tool-path generation strategy for wire and arc additive manufacturing. Int J Adv Manuf Technol 73(1–4):173–183
8. Chen J (2012) Hybrid design based on wire and arc additive manufacturing in the aircraft industry. Master's thesis, Cranfield University, UK
9. Dhinakaran V, Stalin B, Ravichandran M, Balasubramanian M, Chairman CA, Pritima D (2020) Wire arc additive manufacturing perspectives and recent developments. IOP Conf Ser Mater Sci Eng 988(1):012102
10. Alonso U, Veiga F, Suárez A, Artaza T (2019) Experimental investigation of the influence of wire arc additive manufacturing on the machinability of titanium parts. Metals 10(1):24
11. Veiga F, Val AGD, Suárez A, Alonso U (2020) Analysis of the machining process of titanium ti6al-4v parts manufactured by wire arc additive manufacturing (WAAM). Materials 13(3):766
12. Xu F, Dhokia V, Colegrove P, McAndrew A, Williams S, Henstridge A, Newman ST (2018) Realisation of a multi-sensor framework for process monitoring of the wire arc additive manufacturing in producing ti-6al-4v parts. Int J Comput Integr Manuf 31(8):785–798
13. Vimal K, Srinivas MN, Rajak S (2021) Wire arc additive manufacturing of aluminium alloys: a review. Mater Today Proc 41:1139–1145
14. Rodrigues TA, Duarte V, Miranda R, Santos TG, Oliveira J (2019) Current status and perspectives on wire and arc additive manufacturing (WAAM). Materials 12(7):1121
15. Ding D, Pan Z, Cuiuri D, Li H (2015) Wire-feed additive manufacturing of metal components: technologies, developments and future interests. The Int J Adv Manuf Technol 81(1–4):465-481
16. Tripathi U, Saini N, Mulik RS, Mahapatra MM (2022) Effect of build direction on the microstructure evolution and their mechani-

cal properties using GTAW based wire arc additive manufacturing. CIRP J Manuf Sci Technol 37:103–109

17. Rosli NA, Alkahari MR, bin Abdollah MF, Maidin S, Ramli FR, Herawan SG (2021) Review on effect of heat input for wire arc additive manufacturing process. J Mater Res Technol 11:2127–2145
18. Ding D, Pan Z, Cuiuri D, Li H (2015a) Process planning for robotic wire and arc additive manufacturing. In: 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA). IEEE
19. Ding D, Pan Z, Cuiuri D, Li H (2015) A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM). Robot Comput-Integr Manuf 31:101–110
20. Lockett H, Ding J, Williams S, Martina F (2017) Design for wire + arc additive manufacture: design rules and build orientation selection. J Eng Des 28(7–9):568–598
21. Reisch R, Hauser T, Kamps T, Knoll A (2020) Robot based wire arc additive manufacturing system with context-sensitive multivariate monitoring framework. Procedia Manufacturing 51:732–739
22. Wu B, Pan Z, van Duin S, Li H (2019) Thermal behavior in wire arc additive manufacturing: characteristics, effects and control. In: Transactions on Intelligent Welding Manufacturing. Springer Singapore, pp 3–18
23. Jin W, Zhang C, Jin S, Tian Y, Wellmann D, Liu W (2020) Wire arc additive manufacturing of stainless steels: a review. Appl Sci 10(5):1563
24. Bermingham M, Nicastro L, Kent D, Chen Y, Dargusch M (2018) Optimising the mechanical properties of ti-6al-4v components produced by wire + arc additive manufacturing with post-process heat treatments. J Alloys Compd 753:247–255
25. Martina F, Roy MJ, Szost BA, Terzi S, Colegrove PA, Williams SW, Withers PJ, Meyer J, Hofmann M (2016) Residual stress of as-deposited and rolled wire + arc additive manufacturing ti-6al-4v components. Mater Sci Technol 32(14):1439–break1448
26. Henckell P, Günther K, Ali Y, Bergmann JP, Scholz J, Forêt P (2017) The influence of gas cooling in context of wire arc additive manufacturing—a novel strategy of affecting grain structure and size. In: The Minerals, Metals & Materials Series. Springer International Publishing, pp 147–156
27. Lin Z, Goulas C, Ya W, Hermans MJ (2019) Microstructure and mechanical properties of medium carbon steel deposits obtained via wire and arc additive manufacturing using metal-cored wire. Metals 9(6):673
28. Veiga F, Suárez A, Artaza T, Aldalur E (2022) Effect of the heat input on wire-arc additive manufacturing of invar 36 alloy: microstructure and mechanical properties. Weld World 66(6):1081–1091
29. Li F, Chen S, Shi J, Tian H, Zhao Y (2017) Evaluation and optimization of a hybrid manufacturing process combining wire arc additive manufacturing with milling for the fabrication of stiffened panels. Appl Sci 7(12):1233
30. Cunningham C, Wikshåland S, Xu F, Kemakolam N, Shokrani A, Dhokia V, Newman S (2017) Cost modelling and sensitivity analysis of wire and arc additive manufacturing. Procedia Manuf 11:650–657
31. Mishurova T, Sydow B, Thiede T, Sizova I, Ulbricht A, Bambach M, Bruno G (2020) Residual stress and microstructure of a ti-6al-4v wire arc additive manufacturing hybrid demonstrator. Metals 10(6):701
32. Knezović N, Topić A (2018) Wire and arc additive manufacturing (WAAM) – a new advance in manufacturing. In: Lecture Notes in Networks and Systems. Springer International Publishing, pp 65–71
33. Ding D, He F, Yuan L, Pan Z, Wang L, Ros M (2021) The first step towards intelligent wire arc additive manufacturing: an automatic bead modelling system using machine learning through industrial information integration. J Ind Inf Integr 23:100218
34. Chen X, Kong F, Fu Y, Zhao X, Li R, Wang G, Zhang H (2021) A review on wire-arc additive manufacturing: typical defects, detection approaches, and multisensor data fusion-based model. Int J Adv Manuf Technol 117(3–4):707–727
35. Najmon JC, Raeisi S, Tovar A (2019) Review of additive manufacturing technologies and applications in the aerospace industry. In: Additive Manufacturing for the Aerospace Industry. Elsevier, pp 7–31
36. Botila L (2019) Considerations regarding aluminum alloys used in the aeronautic/aerospace industry and use of wire arc additive manufacturing waam for applications. Weld Mater Test 4:9–24
37. www.stelia-aerospace.com/en/p14-aerostructures/, (2023a). Accessed 15 Mar 2023
38. www.3dprint.com/79389/3d-printed-fuselage/, (2023b). Accessed 15 Mar 2023
39. www.waammat.com/about/demo-parts, (2023c). Accessed 15 Mar 2023
40. www.waam3d.com/parts#print-with-us, (2023d). Accessed 15 Mar 2023
41. Li Y, Polden J, Pan Z, Cui J, Xia C, He F, Mu H, Li H, Wang L (2022) A defect detection system for wire arc additive manufacturing using incremental learning. J Ind Inf Integr 27:100291
42. Raguvarun K, Balasubramaniam K, Rajagopal P, Palanisamy S, Nagarajah R, Hoye N, Curiri D, Kapoor A (2015) A study of internal structure in components made by additive manufacturing process using 3 d x-ray tomography. In: AIP Conference Proceedings. AIP Publishing LLC
43. Val AGD, Cearsolo X, Suarez A, Veiga F, Altuna I, Ortiz M (2023) Machinability characterization in end milling of invar 36 fabricated by wire arc additive manufacturing. J Mater Res Technol 23:300–315
44. Patterson AE, Lee YH, Allison JT (2021) Generation and enforcement of process-driven manufacturability constraints: a survey of methods and perspectives for product design. J Mech Des 143(11):110801
45. Hauser T, Reisch RT, Breese PP, Lutz BS, Pantano M, Nalam Y, Bela K, Kamps T, Volpp J, Kaplan AF (2021) Porosity in wire arc additive manufacturing of aluminium alloys. Additive Manuf 41:101993
46. Dharmawan AG, Xiong Y, Foong S, Soh GS (2020) A model-based reinforcement learning and correction framework for process control of robotic wire arc additive manufacturing. In: 2020 IEEE International Conference on Robotics and Automation (ICRA). IEEE
47. Xia C, Pan Z, Zhang S, Polden J, Wang L, Li H, Xu Y, Chen S (2020) Model predictive control of layer width in wire arc additive manufacturing. J Manuf Process 58:179–186
48. Rodrigues TA, Escobar J, Shen J, Duarte VR, Ribamar G, Avila JA, Maawad E, Schell N, Santos TG, Oliveira J (2021) Effect of heat treatments on 316 stainless steel parts fabricated by wire and arc additive manufacturing?: microstructure and synchrotron x-ray diffraction analysis. Additive Manuf 48:102428
49. Rodrigues TA, Farias FWC, Avila JA, Maawad E, Schell N, Santos TG, Oliveira JP (2023) Effect of heat treatments on inconel 625 fabricated by wire and arc additive manufacturing: an in situ synchrotron x-ray diffraction analysis. Sci Technol Weld Join 1–6
50. Shen C, Pan Z, Ma Y, Cuiuri D, Li H (2015) Fabrication of iron-rich fe-al intermetallics using the wire-arc additive manufacturing process. Additive Manuf 7:20–26
51. Morais PJ, Gomes B, Santos P, Gomes M, Gradinger R, Schnall M, Bozorgi S, Klein T, Fleischhacker D, Warczok P, Falahati A, Kozeschnik E (2020) Characterisation of a high-performance al-zn-mg-cu alloy designed for wire arc additive manufacturing. Materials 13(7):1610

52. Hoye N, Cuiuri D, Rashid RAR, Palanisamy S (2018) Machining of GTAW additively manufactured ti-6al-4v structures. Int J Adv Manuf Technol 99(1–4):313–326
53. Ceritbinmez F, Günen A, Gürol U, Çam G (2023) A comparative study on drillability of inconel 625 alloy fabricated by wire arc additive manufacturing. J Manuf Process 89:150–169
54. Veiga F, Suárez A, Aldalur E, Goenaga I, Amondarain J (2023) Wire arc additive manufacturing process for topologically optimized aeronautical fixtures. 3D Print Additive Manuf 10(1):23-33
55. Feier A, Buta I, Florica C, Blaga L (2022) Optimization of wire arc additive manufacturing (WAAM) process for the production of mechanical components using a CNC machine. Materials 16(1):17
56. Gou J, Wang Z, Hu S, Shen J, Liu Z, Yang C, Bai Y, Lu WF (2022) Effect of cold metal transfer mode on the microstructure and machinability of ti-6al-4v alloy fabricated by wire and arc additive manufacturing in ultra-precision machining. J Mater Res Technol 21:1581–1594
57. Wu Q, Lu J, Liu C, Fan H, Shi X, Fu J, Ma S (2017) Effect of molten pool size on microstructure and tensile properties of wire arc additive manufacturing of ti-6al-4v alloy. Materials 10(7): 749
58. Aldalur E, Suárez A, Veiga F (2022) Thermal expansion behaviour of invar 36 alloy parts fabricated by wire-arc additive manufacturing. J Mater Res Technol 19:3634–3645
59. Ogino Y, Asai S, Hirata Y (2018) Numerical simulation of WAAM process by a GMAW weld pool model. Weld World 62(2):393–401
60. Ji F, Qin X, Hu Z, Xiong X, Ni M, Wu M (2022) Influence of ultrasonic vibration on molten pool behavior and deposition layer forming morphology for wire and arc additive manufacturing. Int Commun Heat Mass Transf 130:105789
61. Ke W, Oliveira J, Cong B, Ao S, Qi Z, Peng B, Zeng Z (2022) Multi-layer deposition mechanism in ultra high-frequency pulsed wire arc additive manufacturing (WAAM) of NiTi shape memory alloys. Additive Manuf 50:102513
62. Nomoto S, Kusano M, Kitano H, Watanabe M (2022) Multi-phase field method for solidification microstructure evolution for a ni-based alloy in wire arc additive manufacturing. Metals 12(10):1720
63. Sridar S, Klecka MA, Xiong W (2022) Interfacial characteristics of p91 steel - inconel 740h bimetallic structure fabricated using wire-arc additive manufacturing. J Mater Process Technol 300:117396
64. Zhang D, Qiu D, Gibson MA, Zheng Y, Fraser HL, StJohn DH, Easton MA (2019) Additive manufacturing of ultrafine-grained high-strength titanium alloys. Nature 576(7785):91–95
65. Alipour S, Moridi A, Liou F, Emdadi A (2022) The trajectory of additively manufactured titanium alloys with superior mechanical properties and engineered microstructures. Additive Manuf 60:103245
66. Ho A, Zhao H, Fellowes JW, Martina F, Davis AE, Prangnell PB (2019) On the origin of microstructural banding in ti-6al4v wire-arc based high deposition rate additive manufacturing. Acta Mater 166:306–323
67. Donoghue J, Davis A, Daniel C, Garner A, Martina F, da Fonseca JQ, Prangnell P (2020) On the observation of annealing twins during simulating β-grain refinement in ti-6al-4v high deposition rate AM with in-process deformation. Acta Mater 186:229-241
68. Klein T, Schnall M, Gomes B, Warczok P, Fleischhacker D, Morais PJ (2021) Wire-arc additive manufacturing of a novel high-performance al-zn-mg-cu alloy: processing, characterization and feasibility demonstration. Additive Manuf 37:101663
69. Welk BA, Taylor N, Kloenne Z, Chaput KJ, Fox S, Fraser HL (2021) Use of alloying to effect an equiaxed microstructure in additive manufacturing and subsequent heat treatment of high-strength titanium alloys. Metall and Mater Trans A 52(12):5367–5380
70. Langelandsvik G, Akselsen OM, Furu T, Roven HJ (2021) Review of aluminum alloy development for wire arc additive manufacturing. Materials 14(18):5370
71. Treutler K, Wesling V (2021) The current state of research of wire arc additive manufacturing (WAAM): a review. Appl Sci 11(18):8619
72. Raut LP, Taiwade RV (2021) Wire arc additive manufacturing: a comprehensive review and research directions. J Mater Eng Perform 30(7):4768–4791
73. Priarone PC, Pagone E, Martina F, Catalano AR, Settineri L (2020) Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing. CIRP Annals 69(1):37–40
74. Klein T, Arnoldt A, Lahnsteiner R, Schnall M (2022) Microstructure and mechanical properties of a structurally refined al-mg-si alloy for wire-arc additive manufacturing. Mater Sci Eng A 830:142318
75. Zhang H, Wang Y, Vecchis RRD, Xiong W (2022) Evolution of carbide precipitates in haynes® 282 superalloy processed by wire arc additive manufacturing. J Mater Process Technol 305:117597
76. Sargent N, Jones M, Otis R, Shapiro AA, Delplanque JP, Xiong W (2021) Integration of processing and microstructure models for non-equilibrium solidification in additive manufacturing. Metals 11(4):570
77. Martina F, Roy M, Colegrove P, Williams SW (2014) Residual stress reduction in high pressure interpass rolled wire + arc additive manufacturing ti-6al-4v components. In: 2014 International Solid Freeform Fabrication Symposium. University of Texas at Austin
78. Shi X, Ma S, Liu C, Wu Q, Lu J, Liu Y, Shi W (2017) Selective laser melting-wire arc additive manufacturing hybrid fabrication of ti-6al-4v alloy: microstructure and mechanical properties. Mater Sci Eng A 684:196–204
79. Liu J, Xu Y, Ge Y, Hou Z, Chen S (2020) Wire and arc additive manufacturing of metal components: a review of recent research developments. Int J Adv Manuf Technol 111(1–2):149–198
80. Bermingham M, Thomson-Larkins J, John DS, Dargusch M (2018) Sensitivity of ti-6al-4v components to oxidation during out of chamber wire + arc additive manufacturing. J Mater Process Technol 258:29–37
81. Bambach M, Sizova I, Sydow B, Hemes S, Meiners F (2020) Hybrid manufacturing of components from ti-6al-4v by metal forming and wire-arc additive manufacturing. J Mater Process Technol 282:116689
82. Sizova I, Hirtler M, Günther M, Bambach M (2019) Wire-arc additive manufacturing of pre-forms for forging of a ti–6al–4v turbine blade. In: AIP Conference Proceedings. AIP Publishing
83. Lin Z, Song K, Yu X (2021) A review on wire and arc additive manufacturing of titanium alloy. J Manuf Process 70:24–45
84. Weiss I, Semiatin S (1999) Thermomechanical processing of alpha titanium alloys–an overview. Mater Sci Eng A 263(2):243–256
85. Yamada M (1996) An overview on the development of titanium alloys for non-aerospace application in japan. Mater Sci Eng A 213(1–2):8–15
86. Boyer R, Briggs R (2005) The use of β titanium alloys in the aerospace industry. J Mater Eng Perform 14(6):681–685
87. Wu B, Ding D, Pan Z, Cuiuri D, Li H, Han J, Fei Z (2017) Effects of heat accumulation on the arc characteristics and metal transfer behavior in wire arc additive manufacturing of ti6al4v. J Mater Process Technol 250:304–312

88. Halisch C, Milcke B, Radel T, Rentsch R, Seefeld T (2022) Influence of oxygen content in the shielding gas chamber on mechanical properties and macroscopic structure of ti-6al-4v during wire arc additive manufacturing. Int J Adv Manuf Technol 124(3–4):1065–1076
89. Kennedy J, Davis A, Caballero A, Byres N, Williams S, Pickering E, Prangnell P (2022) β grain refinement by yttrium addition in ti-6al-4v wire-arc additive manufacturing. J Alloys Compd 895:162735
90. Meiners F, Ihne J, Jürgens P, Hemes S, Mathes M, Sizova I, Bambach M, Hama-Saleh R, Weisheit A (2020) New hybrid manufacturing routes combining forging and additive manufacturing to efficiently produce high performance components from ti-6al-4v. Procedia Manuf 47:261–267
91. Gierth M, Henckell P, Ali Y, Scholl J, Bergmann JP (2020) Wire arc additive manufacturing (WAAM) of aluminum alloy AlMg5mn with energy-reduced gas metal arc welding (GMAW). Materials 13(12):2671
92. Geng H, Li J, Xiong J, Lin X, Zhang F (2017) Optimization of wire feed for GTAW based additive manufacturing. J Mater Process Technol 243:40–47
93. Zuo W, Ma L, Lu Y, yong Li S, Ji Z, Ding M (2018) Effects of solution treatment temperatures on microstructure and mechanical properties of TIG-MIG hybrid arc additive manufactured 5356 aluminum alloy. Metals Mater Int 24(6):1346–1358
94. Derekar K, Lawrence J, Melton G, Addison A, Zhang X, Xu L (2019) Influence of interpass temperature on wire arc additive manufacturing (WAAM) of aluminium alloy components. MATEC Web Conf 269:05001
95. Guo X, Li H, Pan Z, Zhou S (2022) Microstructure and mechanical properties of ultra-high strength al-zn-mg-cu-sc aluminum alloy fabricated by wire + arc additive manufacturing. J Manuf Process 79:576–586
96. Yang J, Ni Y, Li H, Fang X, Lu B (2023) Heat treatment optimization of 2219 aluminum alloy fabricated by wire-arc additive manufacturing. Coatings 13(3):610
97. Fu R, Guo Y, Cui Y, Wang J, Lei H, Liu C (2023) Large-size ultra-high strength-plasticity aluminum alloys fabricated by wire arc additive manufacturing via added nanoparticles. Mater Sci Eng A 864:144582
98. Thapliyal S (2019) Challenges associated with the wire arc additive manufacturing (WAAM) of aluminum alloys. Mater Res Express 6(11):112006
99. Geng H, Li J, Xiong J, Lin X, Huang D, Zhang F (2018) Formation and improvement of surface waviness for additive manufacturing 5a06 aluminium alloy component with GTAW system. Rapid Prototyp J 24(2):342–350
100. Geng H, Li J, Xiong J, Lin X, Zhang F (2016) Geometric limitation and tensile properties of wire and arc additive manufacturing 5a06 aluminum alloy parts. J Mater Eng Perform 26(2):621–629
101. Bai JY, Yang CL, Lin SB, Dong BL, Fan CL (2015) Mechanical properties of 2219-al components produced by additive manufacturing with TIG. Int J Adv Manuf Technol 86(1–4):479–485
102. Silva CMA, Bragança IMF, Cabrita A, Quintino L, Martins PAF (2017) Formability of a wire arc deposited aluminium alloy. J Braz Soc Mech Sci Eng 39(10):4059–4068
103. Alonso U, Veiga F, Suárez A, Val AGD (2021) Characterization of inconel 718® superalloy fabricated by wire arc additive manufacturing: effect on mechanical properties and machinability. J Mater Res Technol 14:2665–2676
104. Xu F, Lv Y, Xu B, Liu Y, Shu F, He P (2013) Effect of deposition strategy on the microstructure and mechanical properties of inconel 625 superalloy fabricated by pulsed plasma arc deposition. Mater Des 45:446–455
105. Baufeld B (2011) Mechanical properties of INCONEL 718 parts manufactured by shaped metal deposition (SMD). J Mater Eng Perform 21(7):1416–1421
106. Bauccio M (1993) ASM metals reference book. ASM International
107. Xu F, Lv Y, Liu Y, Shu F, He P, Xu B (2013) Microstructural evolution and mechanical properties of inconel 625 alloy during pulsed plasma arc deposition process. J Mater Sci Technol 29(5):480–488
108. Wang J, Sun Q, Wang H, Liu J, Feng J (2016) Effect of location on microstructure and mechanical properties of additive layer manufactured inconel 625 using gas tungsten arc welding. Mater Sci Eng A 676:395–405
109. Dhinakaran V, Ajith J, Fahmidha AFY, Jagadeesha T, Sathish T, Stalin B (2020) Wire arc additive manufacturing (WAAM) process of nickel based superalloys - a review. Mater Today Proc 21:920–925
110. Benakis M, Costanzo D, Patran A (2020) Current mode effects on weld bead geometry and heat affected zone in pulsed wire arc additive manufacturing of ti-6-4 and inconel 718. J Manuf Process 60:61–74
111. Wu B, Pan Z, Ding D, Cuiuri D, Li H, Xu J, Norrish J (2018) A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. J Manuf Process 35:127–139
112. Chadha U, Abrol A, Vora NP, Tiwari A, Shanker SK, Selvaraj SK (2022) Performance evaluation of 3d printing technologies: a review, recent advances, current challenges, and future directions. Prog Addit Manuf 7(5):853–886
113. Chadha U, Selvaraj SK, Lamsal AS, Maddini Y, Ravinuthala AK, Choudhary B, Mishra A, Padala D, Lahoti SMV, Adefris A, Dhanalakshmi S (2022) Directed energy deposition via artificial intelligence-enabled approaches. Complexity 2022:1–32
114. Uriondo A, Esperon-Miguez M, Perinpanayagam S (2015) The present and future of additive manufacturing in the aerospace sector: a review of important aspects. Proc Inst Mech Eng G J Aerosp Eng 229(11):2132–2147
115. Hoye N, Li HJ, Cuiuri D, Paradowska AM (2014) Measurement of residual stresses in titanium aerospace components formed via additive manufacturing. Mater Sci Forum 777:124–129
116. Colomo AG, Wood D, Martina F, Williams SW (2020) A comparison framework to support the selection of the best additive manufacturing process for specific aerospace applications. Int J Rapid Manuf 9(2/3):194
117. Cottam R, Palanisamy S, Avdeev M, Jarvis T, Henry C, Cuiuri D, Balogh L, Rashid RAR (2019) Diffraction line profile analysis of 3d wedge samples of ti-6al-4v fabricated using four different additive manufacturing processes. Metals 9(1):60
118. Chadha C, Crowe K, Carmen C, Patterson A (2018) Exploring an AM-enabled combination-of-functions approach for modular product design. Designs 2(4):37
119. Nie Z, Jung S, Kara LB, Whitefoot KS (2019) Optimization of part consolidation for minimum production costs and time using additive manufacturing. J Mech Des 142(7):1–16
120. Schmelzle J, Kline EV, Dickman CJ, Reutzel EW, Jones G, Simpson TW (2015) (re)designing for part consolidation: understanding the challenges of metal additive manufacturing. J Mech Des 137(11):111711
121. Ghimire T, Joshi A, Sen S, Kapruan C, Chadha U, Selvaraj SK (2022) Blockchain in additive manufacturing processes: recent trends & its future possibilities. Mater Today Proc 50:2170–2180
122. Cai X, Dong B, Yin X, Lin S, Fan C, Yang C (2020) Wire arc additive manufacturing of titanium aluminide alloys using two-wire TOP-TIG welding: processing, microstructures, and mechanical properties. Additive Manuf 35:101344

123. Cunningham C, Flynn J, Shokrani A, Dhokia V, Newman S (2018) Invited review article: strategies and processes for high quality wire arc additive manufacturing. Additive Manuf 22:672–686
124. Xu T, Tang S, Liu C, Li Z, Fan H, Ma S (2020) Obtaining large-size pyramidal lattice cell structures by pulse wire arc additive manufacturing. Mater Des 187:108401
125. Titanium N (2017) Norsk titanium to deliver the world’s first faa-approved, 3d-printed, structural titanium components to boeing. https://www.businesswire.com/news/home/20170410005330/en/Norsk-Titanium-to-Deliver-the-World%E2%80%99s-First-FAA-Approved-3D-Printed-Structural-Titanium-Components-to-Boeing. Accessed 15 Mar 2023