A Review on Wire and Arc Additive Manufacturing (WAAM)

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Abstract - *Modern industry always develops and continuously looking for new investigations and findings in new technologies. Great example for that is aerospace industry, which will need about twenty million tonnes of raw material in next two decades. That is mostly because it uses materials like titanium, which has high BTF (buy-to-fly) ratio. That means it has low material utilisation because it is necessary to buy greater amounts of forgings or ingots to produce a low amount of finished parts, due to its poor machinability. One of the possible solutions are additive manufacturing (AM) technologies. The bases of AM system are motion system, feedstock and energy (heat) source. Their combination enables moving, heating and deposition of material. Mostly, AM technologies use polymer materials, while the use of metals is possible only in its powder form, so products are often porous and not fully functional. WAAM (Wire and Arc Additive Manufacturing) is technology which can offer a solution for these problems. It has been investigated in investigated in last 30 years, although the first patent dates from 1925. WAAM uses metal welding wire as the feedstock and electric arc as the heat source, which makes it a combination of welding and AM technology. It uses ordinary welding equipment (power source, welding torch, wire and protective gas feeding systems), combining it with robotic systems or CNC machines which provide moving of the torch, and that is its first advantage – it can be considerably cheaper than conventional AM technologies, which use specific equipment and materials. Also, it can produce fully functional, near-net-shape products, almost unlimited by size*

Key Words: AM, WAAM, BTF ratio

1. INTRODUCTION

Additive manufacturing (AM) is a technology that promises to reduce part cost by reducing material wastage and time to market.(1) Furthermore, AM can also enable an increase in design freedom, which potentially results in weight saving as well as facilitating the manufacture of complex assemblies formerly made of many subcomponents.(2) A basic AM system consists of a combination of a motion system, heat source and feedstock. Owing to its intrinsic characteristics, each process is naturally suitable for certain applications. For instance, selective laser melting delivers net shape components with high resolution; however, similarly to electron beam melting, deposition rates are relatively low, and part size is limited by the enclosed working envelope. (3) Consequently, this class of processes is best suited to small components with high complexity. The main business drivers for their adoption are freedom of design, customisation and possibly reduced time to market. (1) The benefit associated with the reduction in material waste is limited; the mass of the components is already low to begin with. While the possibility of topologically optimising certain components is important, there is a growing requirement for larger reductions in material waste, for the following reasons. First, with the increasing usage of carbon fibre reinforced polymers, aircraft designers are forced to shift from aluminium to titanium, the former being electrochemically incompatible with carbon.(4) Second, with the current and forecast aircraft market expansion rate, the demand for titanium parts is increasing accordingly.(5) Third, titanium is an expensive material to source and machine.6 Therefore, in the aerospace industry, there is a pressing need for the development of a process that could replace the current method of manufacturing large structures such as cruciform, stiffened panels, wing ribs, etc., which are machined from billets or large forgings, with unsustainable buy/fly (BTF) ratios. This metric is the ratio of the mass of the initial workpiece to the one of the finished product; in the aerospace sector, values of 10 or even 20 are not unusual. (7)

There are a variety of non-conventional methods of manufacturing such as:

1.1 Selective laser sintering (SLS)

Laser-Sintering, which means, methods that helps in the manufacturing of solid parts by solidifying powder like materials layer-by-layer, exposing the surface of a powder bed with a laser or other high energy beam. The laser sintering process is characterized by extreme rapid sintering and solidification. The area of interest in this paper is all about SLS. The SLS technique has a great future potential for the rapid manufacturing of metal components that could be utilized in a variety of applications. SLS machines, such as, Direct Metal Laser Sintering (DMLS) uses single component metal powders. Powders are usually produced by ball milling technique and by other methods such as fluidized beds, blades, brushes, etc. The SLS process was originally developed at the University of Texas at Austin and then commercialized by the DTM Corporation (U.S.) [8]. The schematic diagram of SLS system is as shown in the Fig.1. The SLS uses a laser beam as an energy source to selectively fuse powdered materials into a solid object.

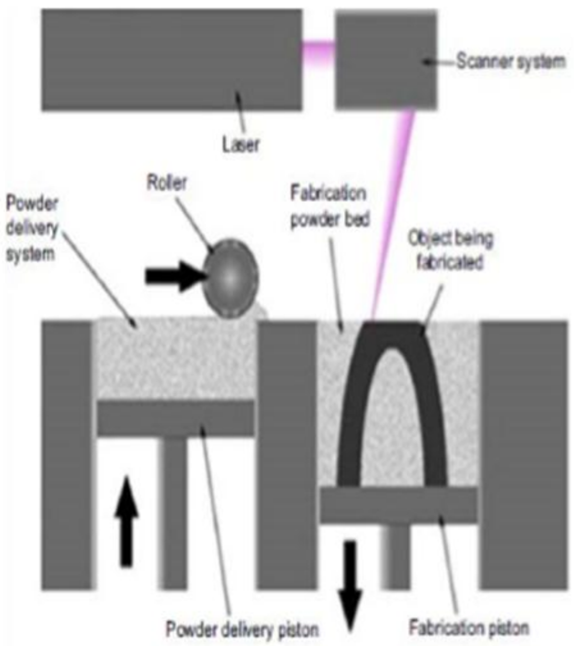

Figure 1. Schematic of the laser sintering process [9]

The process that is carried out in laser sintering techniques is that, the designer designs a part, next the part is sliced on the horizontal plane by using the required software. A chamber in the production machine is filled with powder. A laser runs over the powder, solidifying it and building up a thin layer of material. Layer after layer is built up from bottom to top, until the part is finished. The leftover powder is re-usable, leaving no waste. The term SLS is used often to describe a number of laser-forming processes. SLS is sometime distinguished from SLM because of the difference between the two solidification methods in terms of bonding mechanisms, laser melting related to fully melting the powdered material to its liquid phase, which results in a fully-dense part, whereas laser-sintering relates to liquefying only the surface of the powder particles for bonding the particles to each other. In terms of terminology, laser-sintering and laser-melting are often used somewhat mutually [10].

1.2 Stereolithography

SLA, also known as vat photopolymerization, is a method of creating 3D objects using a light-emitting device (laser or digital light processing) that illuminates and cures a liquid photopolymer resin (thermosetting plastic) layer by layer [11]. SLA has the ability to produce fine features and provide good surface finish with minimum stair stepping effect [12]. Several photopolymer resins can be utilized with SLA: standard (rigid, opaque), castable, and clear, as well as flexible, high temperature, and dental, among others [13]. High-fidelity rapid prototypes for testing, verification, and design of aeroelastic airfoils have been produced with low-stiffness resins, where model similarity between prototypes was highly desired [14]. Cabin accessories such as console control parts with functional knobs as well as full size

1.3. LIGA

The LIGA technique [15,16,17], a German acronym consisting of the letters LI (Ro ̈ntgen LIthographie meaning X-ray lithography), G (Galvanik meaning electroplating) and A (Abformung meaning molding), which is being developed at Forschungszentrum Karlsruhe, offers the possibility to manufacture microstructures with high aspect ratio from a variety of materials (metals, plastics and ceramics). In the first step (X-ray lithography), the absorber structure of an X-ray mask is copied into resist layers by using synchrotron radiation. Usually, polymethylmethacrylate (PMMA) is used as resist material. Through exposure, the molecular weight of the PMMA decreases and therefore becomes soluble in a developer. The spaces generated by the removal of the irradiated plastic material can be filled with metal by electroplating processes. In this way, the negative pattern of the plastics structure is generated as a secondary structure out of metals, such as nickel, copper and gold, or alloys, such as nickel-cobalt and nickel-iron. This technique is used to produce microstructures for direct use, but also tools are made of nickel and nickel alloys for plastics molding. Plastics molding is the key to lowcost mass production by the LIGA process. The metal microstructures produced by deep X-ray lithography and electroforming are used as molding tools for the production of faithful replicas of the primary structure in large quantities and at low cost.

2. Wire and Arc Additive Manufacturing (WAAM)

The combination of an electric arc as heat source and wire as feedstock is referred to as WAAM and has been investigated for AM purposes since the 1990s,[18] although the first patent was filed in 1925.[19] WAAM hardware currently uses standard, off the shelf welding equipment: welding power source, torches and wire feeding systems. Motion can be provided either by robotic systems (Fig. 2) or computer numerical controlled gantries.

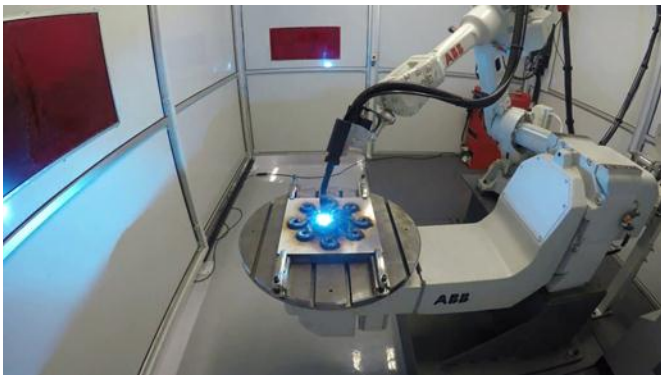
Figure 2. waam system[25]

2.1 Processes

Whenever possible, MIG[20] is the process of choice: the wire is the consumable electrode, and its coaxiality with the welding torch results in easier tool path. In particular,

Process	Condition	Microstructure	YS [MPa]	UTS s [MPa]	EL [%]
Cast	/	/	758 (min)	860 (min)	> 8
Wrought	/	/	860 (min)	930 (min)	> 10
GTAW	AF	Columnar prior β grains + Widmanstätten α/β	/	929 ± 41^a 965 ± 39^b	9 ± 1.2^a 9 ± 1^b
	AF	α phase lamella basket weave structures	/	939 ± 24^a 1033 ± 32^b	16 ± 3^a 7.8 ± 2.3^b
	HT (600 °C/4 h/ FC)	lamellar structure	/	972 ± 41^a 977 ± 14^b	12.5 ± 2.5^a 6 ± 3^b
	HT (834 °C/2 h/ FC)	lamellar structure	/	931 ± 19^a 971 ± 28^b	21 ± 2^a 14 ± 2^b
	AF	Widmanstätten α + banded coarsened lamella α	803 ± 15^a 950 ± 21^b	918 ± 17^a 1033 ± 19^b	14.8^a 11.7^b
	AF	/	861 ± 14^a 892 ± 31^b	937 ± 21^a 963 ± 22^b	16.5 ± 2.7^a 7.8 ± 2^b
	HT (600 °C/2 h/ FC)	/	891 ± 16^a 915 ± 14^b	976 ± 35^a 981 ± 8^b	11.6 ± 2.4^a 6.6 ± 2.6^b
	AN(834 °C/2 h/ FC)	/	856 ± 21^a 893 ± 24^b	931 ± 17^a 962 ± 29^b	20.4 ± 1.8^a 13.5 ± 2^b
Plasma	AF 600 °C/840 °C	Widmanstätten α/β + Columnar β grains	/	/	/
Pulsed-PAM	AF	Prior columnar β + Martensite α'	909 ± 13.6^b	988 ± 19.2^b	7 ± 0.5^b
PAM	AF	Prior columnar β + martensite α'+ fine basket-weave structure	877 ± 18.5^b	968 ± 12.6^b	11.5 ± 0.5^b

Table 1. Mechanical properties of Ti6Al4V fabricated from various WAAM processes.[44]

Fronius cold metal transfer (CMT) is a modified MIG variant,

which relies on controlled dip transfer mode mechanism; this is supposed to deliver beads with excellent quality, lower thermal heat input and nearly without spatter.[21] While meeting these expectations when depositing materials such as aluminum and steel, unfortunately, with titanium, this process is affected by arc wandering[22] which results in increased surface roughness. Consequently, tungsten inert gas,[23] or plasma arc welding,[24] is currently used for titanium deposition. These processes, however, rely on external wire feeding; for deposition consistency, the wire must be fed always from the same direction, which requires rotation of the torch, thus complicating robot programming.[24]

2.2 processes steps

Figure 2. shows simple WAAM system with its main features (wire feeder and power source, robot, welding torch and WAAM part). [26] WAAM starts like any other AM technology – with designing of 3D CAD model using special software or reverse engineering processes, like 3D scanning. That model is then saved in some standard format (usually. stl), which

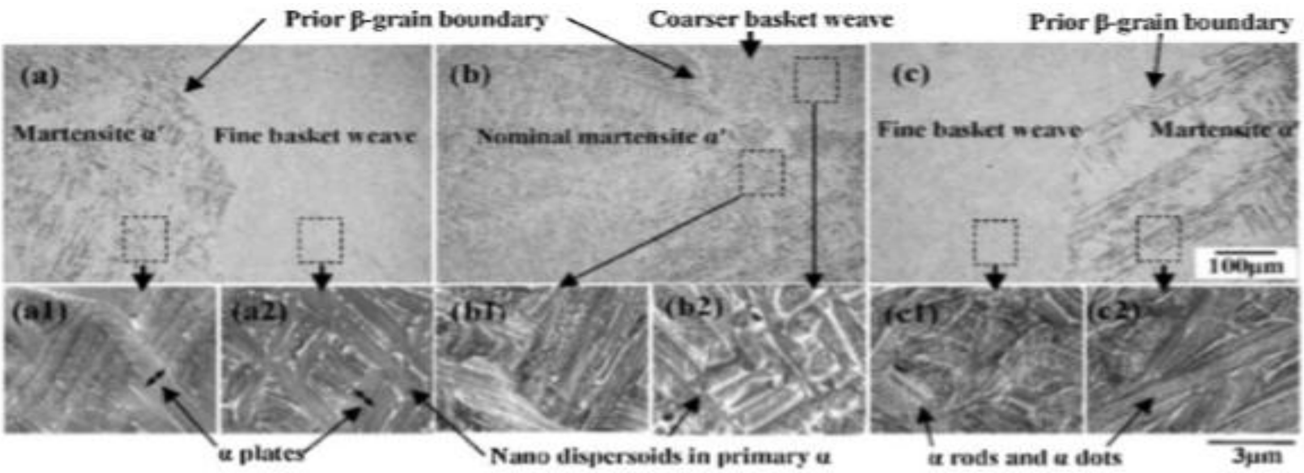

Figure 3.. Optical microstructure of the deposited wall (from Lin, et al. [49]): (a) the bottom region; (b) the middle region; (c) the top region.

represents model's geometry. It is the basis for slicing part per its height into 2D layers, whose contour is then used for generating tool (torch) path. This step is followed by choosing suitable welding parameters (travel speed, current, voltage, etc.) and bead modelling. With generated tool path and chosen welding parameters, the product then can be made by additive manufacturing – the first layer is deposited on the base plate, torch goes up for the specified layer's height and deposits second layer onto it, and the process continues until whole part is made). Some postprocess machining can be done simultaneously [27], but usually, post-processing is done independently, often with heat treatment if it is needed.

Materials	Process	Condition	Microstructure	YS[MPa]	UTS [MPa]	EL [%]
Al6.3Cu	Wrought(2219)	T851	/	267	390	> 4
	CMT	AF	Fine dendrites + equiaxed grains	128 ± 2^a 133 ± 5^b	262 ± 4^a 264 ± 2^b	15.8 ± 0.3^a 18.6 ± 1.5^b
		HT(T6)	Homogeneous dispersed θ precipitates	305 ± 6^a 333 ± 6^b	458 ± 3^a 466 ± 3^b	13.6 ± 0.9^a 14^b

Table 2. Tensile properties of WAAM-fabricated aluminum alloy (2xxx)[44].

This maybe seems simple and easy, but all of this main step contains numerous smaller sub-steps which have to be calculated and implemented carefully in order to produce the high-quality part. Slicing algorithms have been developed to provide layers of better quality [28], as well as different bead modelling methods [29]– [31] and various kinds of path patterns [32]– [34]. Also, there has been a lot of researches regarding optimization of welding parameters [35]– [37] and other welding-related problems like changes in microstructure [38]–40] and problems with heat input [41], [42]. It should be clear this is a complex process where every mistake in some of the steps can cause major defects, affecting the part surface finish, microstructure, mechanical properties and overall quality of the part. Mostly, MIG is welding process used in WAAM. The wire is coaxial with the welding torch, which provides easily generated path. While it is suitable for steel and aluminum, there are problems with arc wandering when it comes to titanium, and part's surface is often rough. For producing titanium parts, TIG is a better choice, but it needs external wire feeding, and to obtain a product of good quality, the wire has to be fed from the same side. It means torch has to be rotated and it makes robot programming and tool path generation much more complicated. [43]

2.3 Metals used in WAAM process

WAAM processes use commercially available wires which are produced for the welding industry and available in spooled form and in a wide range of alloys as feedstock materials. Manufacture of a structurally sound, defect free, reliable part requires an understanding of the available process options, their underlying physical processes, feedstock materials, process control methods and an appreciation of the causes of the various common defects and their remedies. This section reviews the metals that are commonly used in WAAM, with a particular emphasis on the microstructure and mechanical properties of the additively manufactured alloys [44].

i. Titanium alloys

Titanium alloys have been widely studied for application of additive manufacturing in aerospace components due to their high strength-to weight ratio and inherently high material cost. There are increasing demands for more efficient and lower cost alternatives to the conventional subtractive manufacturing methods, which suffer very low fly-tobuy ratios for many component designs. There exists many business opportunities for the WAAM process, particularly for large-sized titanium components with complex structures [45]. It is well accepted that the microstructure of the product depends on its thermal history during the fabrication process. The distinctive WAAM thermal cycle, which involves repeated heating and cooling [46,47], produces meta-stable microstructures and inhomogeneous compositions in the fabricated part [48]. For example, Baufeld et al [47] investigated the microstructures of Ti6Al4V fabricated using

Materials	Process	Condition	Microstructure	YS [MPa]	UTS [MPa]	EL [%]
IN 718	GMAW	AF	Nb precipitates + dendritic structure	473 ± 6	828 ± 8	28 ± 2
IN 625	Cast	/	/	350	710	48
	Wrought	/	/	490	855	50
	PPAM	AF	Laves phase + columnar dendrite structure	438 ± 38[a] 423 ± 22[b]	721 ± 32[a] 718 ± 19[b]	48.6 [a] 49.2 [b]
	PPAW	AF	Laves phase + MC carbides + δ-Ni_3Nb	449	726	43
	PPAW	IC	Laves phase + NbC carbides	480	771	50
	GTAW	HT(980 °C /STA)	Coarser Laves particles + Nb precipitates	469	802	42
	CMT	AF	Nb,Mo precipitates + dendrite structure	/	684 ± 23 [a] 722 ± 17 [b]	40.13 ± 3.7 [a] 42.27 ± 2.4 [b]

Table 3: Mechanical properties of various Ni-based superalloys using different WAAM processes [44].

a GTAW-based WAAM system, and found two distinctive regions on the as-built wall. In the bottom region, where alternating bands are perpendicular to the build direction, a basketwave Widmanstätten structure withαphase lamellae is present, while in the top region, where no such bands appear, needle-like precipitate is the main structure. Similar microstructural evolution has also been observed in the PAW-based process. Lin et al [49,50] reported a graded microstructure along the build direction and identified the martensite α' structure, Widmanstätten structure and basket-wave structure from the bottom to the top region of the fabricated component, as shown in Fig.3. An epitaxial growth of β grains with discrete direction is also observed along the build direction owing to thermal gradient [66], commonly seen in additively manufactured titanium alloy components.

Table 3 summarizes the microstructure and mechanical property data (tensile strength, yield strength and elongation) of Ti6Al4V samples fabricated using various WAAM technologies [47,49,51–57]. The as-forged and as-cast minimum specifications from ASTM standards are also listed for comparison. As shown in Fig.4, the tensile property of as fabricated Ti6Al4V samples is close to that of wrought Ti6Al4V and exceeds that of cast Ti6Al4V as specified by ASTM standards. In addition, WAAM fabricated Ti6Al4V samples show anisotropic properties with lower strength and higher elongation values in the build direction (Z) compared to deposition direction (X), which is mainly attributed to the grain size ofαlamellae and the orientation of the elongated prior β grains.

ii. Aluminum alloys and steel

Although fabrication trials for many different series of aluminum alloys, including Al-Cu (2xxx) [58], Al-Si (4xxx) [59] and Al-Mg (5xxx) [60] have been successfully carried out, the commercial value of WAAM is mainly justifiable for large and complex thin-walled structures, since cost of manufacturing small and simple aluminum alloy components using conventional machining processes is low [61]. Using WAAM to fabricate steel is unpopular for the same reason although it is the most commonly used engineering material [62]. Another reason for the poor commercial application of WAAM in aluminum is that some series of aluminum alloys, such as Al 7xxx and 6xxx, are challenging to weld due to turbulent melt pool and weld defects, which frequently occur during the deposition process. In general, as-deposited additively manufactured aluminum alloy parts have inferior mechanical properties compared to those machined from billet material. In order to achieve higher tensile strength, most of the as-deposited aluminum parts undergo post-process heat treatment to refine the microstructure. Table 2 lists the yield strength (YS), ultimate tensile strength (UTS), and elongation of WAAM-fabricated 2219aluminium alloy samples. Due to the uniform distribution of large diamond particles within the microstructure, the sample exhibits lower UTS and YS than that of the wrought part specified by ASTM standard. However, after heat treatment, significant improvement beyond ASTM standard can be observed in both strength and elongation as a consequence of the grain refinement [63].

iii. Nickel-based superalloys

Nickel-based superalloys are the second most popular material studied by the additive manufacturing research

Table 4: Mechanical properties of other metallic materials fabricated using WAAM process [44].

Materials	Process	Condition	Microstructure	YS[MPa]	UTS[MPa]	EL[%]
Ti/Al	GTAW	AF	Interdendritic γ structures + fully lamellar colonies	424 ± 30[a] 474 ± 17[b]	488 ± 50[a] 549 ± 23[b]	0.35[a] 0.5[b]
		HT(1200 °C/24 h)	Full γ microstructure	425 ± 15[a] 471 ± 14[b]	412 ± 11[a] 472 ± 11[b]	1.1[a] 1.1[b]
		HT(1060 °C/24 h)	Fully lamellar structure	487 ± 14[a] 486 ± 12[a]	569 ± 12[a] 590 ± 4[b]	0.30[a] 0.45[b]
Cu/Al	GTAW	AF	copper twinning	63 ± 2.1[a]	231 ± 2.5[a]	63 ± 4.0[a]
Fe/Al	GTAW	AF	Columnar Fe_3Al grains	847 ± 2[b]	944 ± 19 [b]	3.2 ± 0.1 [b]
Fe/Ni	GMAW	AF	austenite, δ-ferrite in low part; dendritic in up part	/	565 ± 15 [a]	/
Fe/Cu	GMAW	AF	the mixture of α-Fe and ε-Cu	/	305[a]	48.5

community after titanium alloys, mainly due to their high strengths at elevated temperatures and high fabrication cost using traditional methods. Nickel-based superalloys are widely applied in aerospace, aeronautical, petrochemical, chemical and marine industries due to their outstanding strength and oxidation resistance at temperatures above 550°C. To date, various Nickel-based superalloys, including Inconel 718 and Inconel 625 alloy have been studied after WAAM processing [44].

The microstructure of WAAM fabricated Inconel 718 parts generally consists of large columnar grains with interdendritic boundaries delineated by small Laves phase precipitates and MC carbides [64]. Xu et al. [65] reported that columnar dendrite structures decorated with a large amount of Laves phase, MC carbides andNi3Nbare also present in WAAM-fabricated Inconel 625 parts. It is worth noting that the microstructure can be refined to smaller dendritic arm spacing, less niobium segregation and discontinuous Laves phase in the interdendritic regions using post-process heat treatments, which are beneficial to the mechanical properties. Table 3 lists the mechanical properties of several Nickel-based superalloys fabricated using the WAAM process. For GMAW-based WAAM-fabricated Inconel 718 alloy, the yield and ultimate tensile strength is 473 ± 6MPa and 828 ± 8MPa respectively. These values lie between the minimum values specified by ASTM for wrought and cast materials, whereas the elongation is much lower than the standards for both wrought and cast conditions. As for WAAM-fabricated Inconel 625 alloy, the YS, UTS and elongation all meet the requirement set by ASTM for cast materials, and are slightly lower than those for wrought material.

iv. Other metals

Other metals have also been investigated for potential fabrication using WAAM, such as magnesium alloy AZ31 for automotive applications [66], Fe/Al intermetallic compounds [67,68] and Al/Ti [69,70] compounds, as well as bimetallic steel/nickel [71] and steel/bronze [72] parts for the aeronautic industry. The detailed mechanical properties of these materials fabricated using WAAM are listed in Table 4. Most of this research has focused on determining the microstructural and mechanical properties of samples taken from simple straight-walled structures, rather than developing a process to fabricate functional parts. Manufacturing intermetallic parts with accurate pre-designed composition still poses major challenges for the WAAM process.

3. Conclusions

WAAM is interdisciplinary technology with plenty of space and different areas for improving and introducing new ideas. Some investigations suggest interpass rolling as a solution for issues with anisotropic properties [39], other researchers propose including non-destructive testing in process, which can find porosities early [43], while some papers presented the use of new materials. [74] Further investigations should include work on these ideas, alongside improvement of parameters optimization, monitoring, process control, part design and heat treatment, which will all together lead to better understanding and implementation of WAAM technology. With improvements in these areas, WAAM could become a replacement for conventional production methods, like casting and forging, in particular applications. Present issues still limit the industrial use and market's approval of WAAM, but different researches are already suggested to reduce and remove them, so WAAM can become equal to traditional methods.

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