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# A review of Wire Arc Additive Manufacturing (WAAM) of Aluminium Composite, Process, Classification, Advantages, Challenges, and Application

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**Abstract.** Wire-arc additive manufacturing (WAAM) is a common metal 3D printing technique that offers several benefits, including the high rate of deposition, cheap price, and efficacy for complex parts. Even though (WAAM) has demonstrated its ability to meet the demands of manufacture components on medium-to-large size made of (Al) for the automotive and other related industries, WAAM cannot currently use as a complete production procedure due to practical issues such as mechanical properties that aren't matched and the presence of significant residual stresses. the AM technologies offer promising new benefits with the MMCs as a solution for some challenges. This article reviews the MMCs Mixing technique and their critical issues, AM classification, WAAM process with advantages and challenges. also reviews WAAM of some AMCs with different reinforcements and power sources. The results of the study of the influence of reinforcement particles on the structure showed that they were changed grains structure from the columnar dendrite to equiaxial dendrites after the solidification and improves hardness.

## 1. Introduction

With the advancement of technology in various high-tech fields, the need for high-performance materials is becoming increasingly urgent. Metal matrix composites (MMC) have been people's favourite artefacts in many areas, like aerospace and military, and they are often irreplaceable. Most MMCs' mechanical properties are determined by their reinforcing fillers. Nitride ceramics (TiN, BN) [1, 2], oxide ceramics ( $Al_2O_3$ ,  $SiO_2$ ) [3, 4], carbides (TiC, WC) [5, 6], and various carbon allotropes [7] are the most recent MMC reinforcement materials. The inclusion of raw materials in the manufacturing process, which includes various assembly and rapid prototyping processes, is referred to as additive manufacturing (AM) [8]. The American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) characterized AM as "the process of connecting materials to make objects from 3D model data, typically layer by layer" [9]. **AM have gain its importance not only** due to the many advantages it has such the ability to handle multiple materials (metals, polymers, ceramics, and other materials), but also its ability to produce novel, complex, and close to the final shape of the part with no additional tools and requirement for re-fixing. AM ensures single-piece assembly or custom manufacturing [10]. Because the process has a centralized manufacturing process, it reduces task time and material waste, thereby improving overall

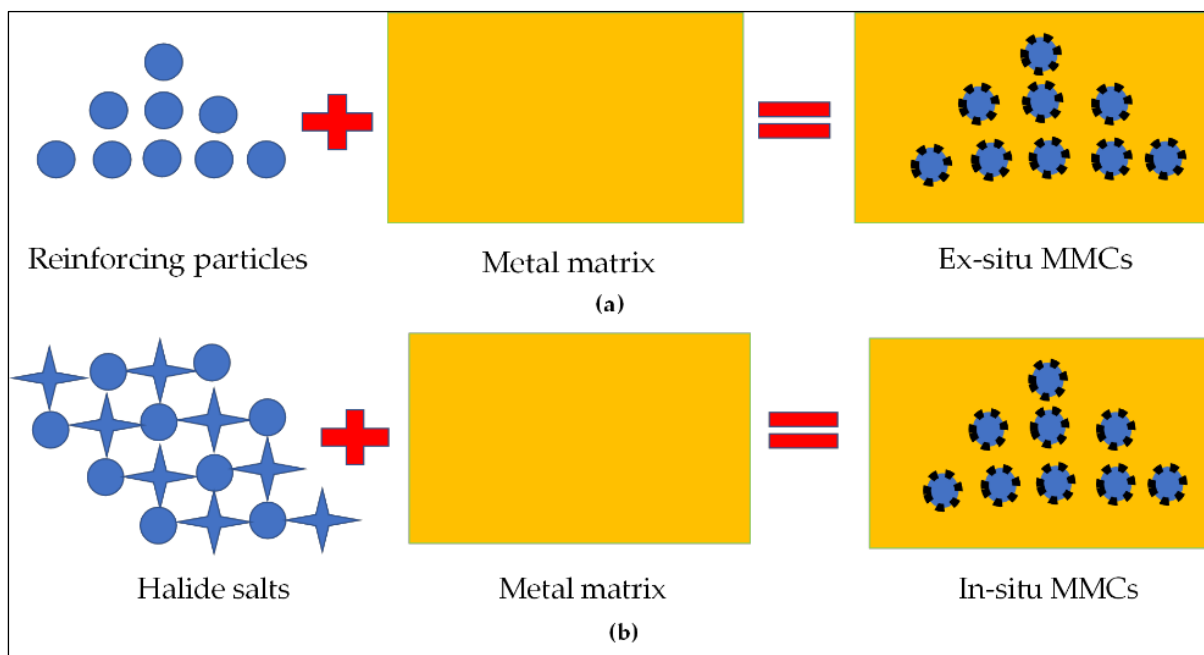


procurement costs, thus improving the buy-to-flight rate (BTF), and together with enhancing the feedback flexibility of turning raw materials into structures [11].

Aluminium and aluminium alloys, among the massive metal materials, are very common in many emerging industries (such as transportation and aerospace) due to their lightweight. At the same time, metal three-dimensional (3D) printing technology [12,13] is the key driving force behind Industry 4.0. In this regard, it is critical to investigate the majority of the effects of metal 3D printing on the production of aluminium MCs. [14].

## 2. Metal Matrix Composites (MMCs)

A metal matrix and a dispersed metal, ceramic, or polymer process are usually used in MMCs [15]. In-situ and ex-situ MMCs are the two types [16]. Figure (1a) shows the ex-situ MMC process, which involves fabricating reinforcement materials (generally particles) and mixing them into a metal matrix externally. In an MMC like this, the reinforcement is regularly broken and cold-welded as particles. As shown in Figure (1b), in-situ MMCs are made by a chemical reaction between halide salts and metal substrates and are thermodynamically more stable than ex-situ MMCs. In-situ, MMC has a compatible, high interface bonding power, as well as better mechanical properties. MMC has many benefits, but the production of completely dense MMC is hindered by potential challenges (such as gas entrapment, particle aggregation, and macro-and micro-cracks) [17].



**Figure 1.** Graphical illustration of MMC (a) ex-situ (b) in-situ [16]

### 2.1 Mixing Techniques of MMCs.

available a variety of MMC mixing techniques. The main goal of these processing methods is to achieve uniform reinforcement material dispersion in the matrix to achieve defect-free microstructures. Table 1 shows a variety of MMC mixing techniques [17].

Table (1) Various MMC mixing techniques

Technique Name	Description	Ref.
Stir Casting	Mechanical stirring and solidification of the mixture are used to incorporate ceramic particles (reinforcing materials) into a liquid metal matrix.	[18]
Rheo-casting	The reinforcing particles are mixed with the substrate, which is usually metal, in this process. The temperature ranges of the extended matrix are solidus and liquidus. Mechanically ambushed strengthening grains in the matrix.	[19]
Squeeze casting	Pressure is used in this method, and it is maintained until the molten alloy solidifies. Pressure-assist technology improves the mechanical properties and qualities of the finished product by refining the grains.	[20]
Powder metallurgy	Fine powder particles are combined and compacted into the desired shape. Mainly, material heating is also involved.	[21,22]
Advanced shear technology	Advanced shear under melting conditions technology is used. Shear stress is appropriate to obtain a combination of exceptional cohesion and ductility. It is used on the liquidus metal's particles.	[23]
Ultrasonic assisted casting	Matrix composite material (NMMC) with excellent reinforcement distribution is a well-known method for producing lightweight nano metals. However, due to liquid metal clustering, NMMC has severe problems with uniform dispersion. The ultrasonic device has a casting process that can be incorporated.	[24,25]
Friction stirring process	A type of plastic deformation process that is possibly changing the mechanical properties and microstructure of a material.	[26]

## 2.2. Critical Issues

The type of reinforcement material, the manufacturing method, and the matrix composition have no bearing on each other. However, because of the various interactions between the reinforcing material and the matrix in the molten state, they are closely related to molten metal production. The initial processing method influences the factors that control the distribution of reinforcement content. Secondary processing methods (such as extrusion and rolling) are needed for the processing of powder metallurgy composite materials because the composite material must be completely consolidated [27]. Other methods, such as molten metal infiltration, spray casting, and molten metal mixing, can create a substantially fully consolidated product, but extrusion, for example, can increase efficiency by adjusting the reinforcement material distribution. Many factors influence the mechanical properties of MMCs, but there are still some areas that need to be explored further. The cost-effectiveness of MMCs in various applications will eventually determine their commercial performance [28]. This necessitates the use of the best possible manufacturing, machining, and recycling techniques. Figure (2) depicts popular metal matrix composite material processing methods and related main issues. While powder metallurgy holds promise in terms of dispersion control, it is restricted in terms of shape complexity. Additionally, the mechanical properties obtained are minimal. In addition to the wettability constraint, the liquid process suffers from a lack of control over the dispersibility of filler particles. The spraying method is reliant on other methods to form the shape, and it also lacks process control capabilities. High development time, scale, and shape constraints restrict diffusion bonding methods. Many of these drawbacks can be overcome using additive manufacturing techniques if unique metal matrix composite materials are successfully used [29].

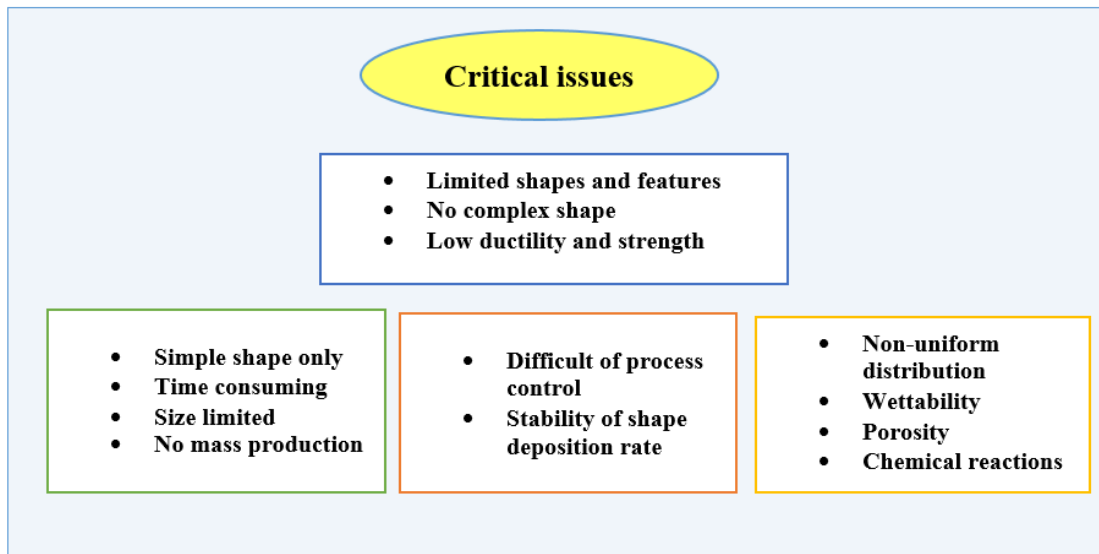


Figure 2. The key issues of the traditional MMC processing route [29]

### 3. Additive Manufacturing

Additive manufacturing is a technique that originated from 3D printing and enables the manufacture of end-use parts directly from CAD data. The use of complex intermediate tools is eliminated due to the layering of materials [30]. This would significantly reduce the manufacturing cycle and allow for greater design freedom and the development of more complex shapes. AM also allows for environmentally friendly product design. Other advantages of additive manufacturing include waste reduction, environmental safety, and optimum design for lean manufacturing. [31]. The American Society for Testing and Materials (ASTM) describes AM and divides AM technology into seven divisions, according to ASTM International Committee F42. Only four of these methods can make metal parts, and only one of them can be combined with the addition of metal fillers to make additively produced moulded parts, as shown in Figure (3) [11].

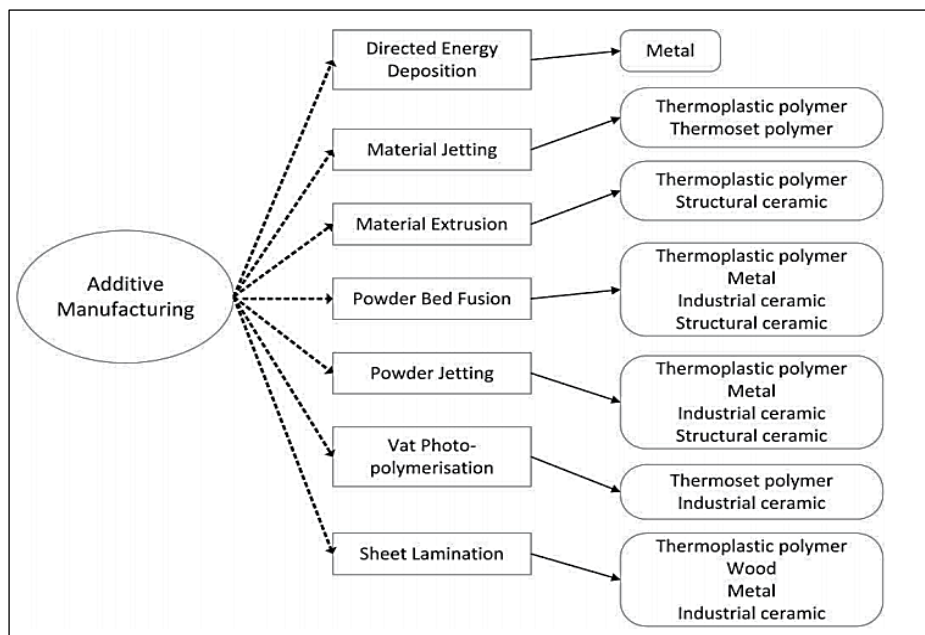


Figure 3. AM process classification with corresponding material handling functions [11]

### 3.1. WAAM Process

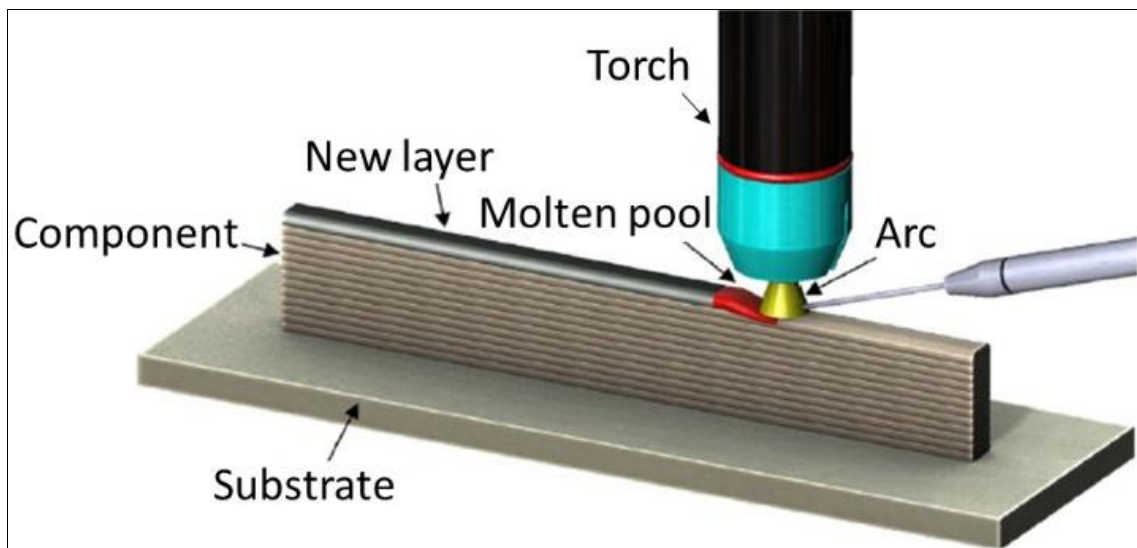
Since 1920, the technology of depositing weld metal to manufacture entire components has been adopted, and this technology is now used as an arc and additive manufacturing (WAAM) technology. This technology has several benefits, including a higher BTF ratio as compared to conventional manufacturing methods, the ability to potentially ignore the size limit of component manufacturing, and cost-effectiveness in comparison to powder-based processes that depend on expensive materials [11]. WAAM is included in to direct energy deposition (DED), according to ASTM F2792-12a [32]. It's also known as a heat source made from an electric arc and a raw material made from metal wire. Figure (4) depicts this mechanism schematically. WAAM is based on the automatic welding process as a concept. Rapid prototyping (RP), shape melting (SM), shape welding (SW), shape Metal deposition (SMD), solid freeform fabrication (SFF), and even 3D welding have all been used to describe WAAM in recent years. [33].

#### 3.1.1 Classification of WAAM

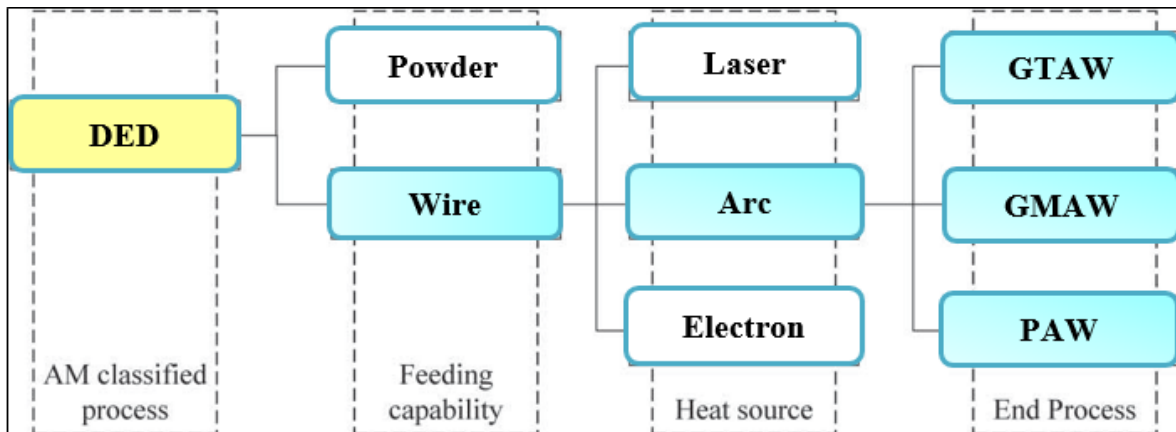
According to the nature of the heat source, there are usually three types of WAAM technology, as shown in Figure (2):

1. GMAW-based (Gas Metal Arc Welding) [35].
2. GTAW-based (Gas Tungsten Arc Welding) [36].
3. PAW-based (Plasma Arc Welding) [37].

GMAW-based WAAM deposition rates are 2-3 times higher than GTAW or PAW-based techniques. GMAW-based WAAM, on the other hand, is less stable, and more spatter and welding fumes are generated because the current is applied directly to the raw material. The processing conditions and productivity of the target component are directly affected by the choice of WAAM technology [38].



**Figure 4.** A schematic diagram of (WAAM) process [34].



**Figure 5.** Typical classification of WAAM [11]

### 3.1.2. WAAM Advantages and Challenges

#### \*Cost-efficient

Because of the significant difference in raw material costs, wire-based technology is 2 to 50 times more cost-effective than powder-based technology. WAAM will save 7–69% on titanium component production compared to traditional methods [39].

#### \*BTF ratio

When manufacturing complex aero-engine parts from inventory, a BTF ratio of 30 is not unusual. When using WAAM to make the same pieces, on the other hand, a significant amount of material can be saved. The BTF ratio for high-cost titanium alloys is 1.2 [40].

#### \*High deposition rate

WAAM can achieve a steel deposition rate of close to 10 kg h<sup>-1</sup> [40,41], which is about 16 times faster than the powder deposition process's maximum rate of 600 h<sup>-1</sup> [42]. The explanation for this is that the shape of a single bead will vary drastically. The powder-based process produces beads with a thickness varying from a few microns to 1 mm [43], while the WAAM process produces beads with a height of 1-2 mm [44,45], which may increase in proportion to the deposition rate.

#### \*Solidification behaviours

The large weld pool solidification in WAAM can be compared to the traditional casting method, though the latter's solidification behaviour in the centre and periphery will differ [11].

#### \*High production rate

To achieve high productivity, the wire feed speed should be optimized, as this allows for uncontrolled weld deposition, raising the process's instability and, as a result, the surface roughness. (Williams et al.) believe that [40], To keep the BTF ratio below 1.5, the deposition rate for steel must be less than 4 kg h<sup>-1</sup> and less than 1 kg h<sup>-1</sup> for aluminium and titanium alloys. The conclusion is that the deposition-prepared WAAM object must be machined. The rate is higher than the above. As a result, WAAM is not the final forming operation for any component where surface roughness is a critical factor [11].

#### \*Thermal cycles effect

The solidified weld metal and the substrate are subjected to thermal cycling as metal is added layer by layer using an electric arc. The exothermic effect induces partial melting and heat treatment of the previously deposited layer, as well as extending the non-isothermal heat treatment effect or three to four layers below the deposited weld bead. The amount of change is determined by the amount of heat

applied and the material's thermophysical properties. Thermal cycling causes the deposited metal to expand and contract, causing a significant amount of residual stress in the base material and formed components [46,47].

#### \*Production of medium- to large-scale

Unlike laser and electronic-based methods, which restrict the total size of objects due to the size of the chamber, WAAM may create objects of any size. WAAM is therefore ideal for the production of medium and large parts due to its high deposition rate and potentially limitless metal deposition capability. However, the greater bead volume and higher surface roughness limit its application to the development of low- and medium-complex parts as compared to the powder-based method (25  $\mu\text{m}$  or less cited by Gu [42]) [11].

#### \*The mechanical properties

WAAM products' mechanical strength falls short of that of forged products with identical chemical properties or filler wires. WAAM sections have highly directional tensile properties that are determined by the deposition pattern used during the object's creation. WAAM pieces are stronger in a particular direction due to their tensile properties [11].

### **4. Aluminium Alloys**

Aluminium alloys welding has always been difficult due to the aluminium oxide layer's formation and solidification nature. WAAM use in aluminium alloys is limited due to the main issue of porosity. Due to this restriction, some research into the effects of heat treatment on WAAM Al parts has been conducted. Heat treatment is not possible for all aluminium alloys. When it occurs During the manufacturing of aluminium parts, it is preferable to use alternating current (AC) [48]. Removal of a higher melting point natural surface oxide film (aluminium oxide). If this is not the case, the molten residue will become trapped inside the molten pool, contributing to holes and internal defects as well as a major reduction in the mechanical properties of the component. Periodic polarity reversals cause turbulent pool dynamics, which causes the extremely difficult WAAM of aluminium alloy, which can result in reduced component accuracy. Fundamental properties of aluminium alloy welding include high thermal expansion coefficient, high solidification shrinkage, high thermal conductivity, a broad solidification temperature range, and high hydrogen solubility [49].

### **5. Review of WAAM of Aluminium Matrix Composites**

Deng Yaqi et al investigated  $\text{TiB}_2$  reinforced Al-7Si-Cu-Mg composites made by arc addition and casting. The mechanical properties of aluminium-based composites are improved by  $\text{TiB}_2$  particles, which are nano- or sub-micron in size and have normal and circular morphology. In terms of microstructure and properties of aluminium matrix composites, two related processes are compared. The distribution of alloying elements in the  $\text{TiB}_2$ -reinforced Al-Si-based composite material of (WAAM) is found to be more distributed by comparing SEM and EDS study.  $\text{TiB}_2$  particles have a smaller size and a more uniform distribution. The hardness of the deposited microstructure increases when compared to the as-cast condition. The silicon phase in the as-cast sample is very large and is constantly distributed around the grain boundary, while the silicon phase in the deposited microstructure is dispersed and smaller. The heat treatment of WAAM Al-Si composite material was carried out, and two heat treatment mechanisms were compared: solution post ageing and ageing. After one ageing, the hardness of the material rises to 127 HV10, and under the condition of ageing after solid solution, it increases to 139 HV10. It is found that the reinforced Al-Si-based composite material can reach the supersaturated solution state through WAAM [ 50].

Yang Qingfeng et al studied ( $\text{TiB}_2$ +Al-Si) composites made by TIG WAAM. The microstructure and mechanical properties were investigated. Large-volume samples were prepared using TIG wire and electric arc AM technology. In-situ  $\text{TiB}_2$ +Al-Si composite material was used as the deposition metal,



and 1.6mm filler wire was heat treated with T6. Bulk samples' microstructure and mechanical properties are examined before and after heat treatment. The texture of the original sample parallel to the direction of the weld seam and perpendicular to the direction of the weld seam is identical, consisting of columnar dendrites and equiaxed crystals, according to the experimental results. The sample's hardness increased after T6 heat treatment, there are more defects in the cracks and the cracks are ductile [51].

Geir Langelandsvik et al studied the effect of wire and arc additive manufacturing of aluminium ceramic composites on the mechanical properties and microstructure, showed great potential for the production of high-strength materials. This study used a novel screw extrusion method to prepare an aluminium alloy containing TiC nanoparticles. By incorporating (TiC) nanoparticles into the commercial aluminium alloy A5183 raw material wire, a fine particle material with lower solidification crack sensitivity and enhanced strength can be obtained. Compared with the commercial AA5183 benchmark, the thin-walled WAAM deposited with TiC modified AA5183 Al-Mg alloy has the performance of grain refinement. By adding TiC, the hardness is also increased by 13%. Due to the formation of a large number of pores in the TiC modified alloy, the tensile properties are very poor [52].

Shuang Lei et al. studied additive manufacturing and casting impact on the structure and mechanical properties of Al-Cu composites. electron beam melting (EBM) and Cold metal transfer (CMT) are used to make the TiB<sub>2</sub> strengthened Al-5Cu composite material additively fabricated. TiB<sub>2</sub> particles are nano, with some sub-micron-sized particle clusters, and have a round or nearly round morphology with no sharp angles. The results show that adding TiB<sub>2</sub> particles to an Al-5Cu alloy will greatly enhance its mechanical properties. additive fabrication methods such as (CMT) and (EBM) can significantly improve the microstructure of composite materials. The grain size of TiB<sub>2</sub> reinforced Al-5Cu composite material is reduced from more than 100µm in the CMT process to 40 µm, whereas it is reduced to 25 µm in the EBM process comparing with conventional casting. After heat treatment, the hardness of additive manufacturing mad with EBM for (TiB<sub>2</sub> + Al-5Cu) composites can exceed 153 HV10. Consequently, the fine grain and high hardness of this technology demonstrate that AM is a viable approach for improving the structure and mechanical properties of Al-Cu composites [53].

Daniel Oropeza studied additive manufacturing and welding tests, Aluminium 7075 wire with Tic nanoparticles was used. Due to its exceptional special strength properties, this alloy Aerospace systems often use (Al 7075-T73 heat treatment). Because of difficulties in producing Al 7075 from the melt, welding, casting, and additive manufacturing were previously restricted. The ability of nanoparticle (Tic) additives to test the solidification behaviour of high-strength aluminium alloys was demonstrated in this study with the first Al 7075 components cast, welded, and additively manufactured. This study looks at the properties of nanoparticle-enhanced aluminium 7075 on welded parts, overlays, and wire-based additive manufacturing. Both as-welded and after T73 heat treatment, the hardness and tensile strength of the deposited materials were calculated, demonstrating that Al 7075 T73 properties can be recovered in welded and layer-deposited components. Al 7075 can now be welded or additively manufactured into crack-free, high-strength parts from a wire, according to the report [54].

Geir et al. studied the growth of (Al+TiC) wire material for AM by used metal screw extrusion. Ceramic grain refiners have a lot of promise as alloy additives for reducing crack sensitivity and increasing strength. As a result, the concept of metal screw extrusion has been used to develop a general solid-state manufacturing route for nanoparticle-reinforced aluminium wires. A wire was made from an Al-Si alloy AA4043 that contained 1% TiC nanoparticles by weight. The material's cumulative strain is calculated during the metal screw extrusion process, and the method is categorized

as a severe plastic deformation (SPD) method. It has been discovered that after the metal screw has been extruded, The grain refinement effect can be limited by a chemical reaction between silicon and TiC particles. Arc bead deposition on the board was done with metal screw extrusion and commercial materials. After arc deposition, the addition of TiC causes the crystal grain form to change from cylindrical to equiaxed, increasing the hardness. The AA4043-TiC material had a large number of pores, which may have been caused by hydrogen contamination on the TiC surface before metal screw extrusion. The results are promising and point in a new direction for the advancement of aluminium alloy additive manufacturing [55].

Peng et al. investigated the impact of integrating TiCnps into WAAM on mechanical properties, grain boundary structural evolution, solute redistribution, crystal orientation evolution, and phase transformation (AA 2319). The addition of 5 m TiCps to the system decreased the nucleation free energy, allowing nuclei to form on the particle's surface. It was discovered that the addition of (TiCnps) eliminates grain boundary segregation and columnar crystal defects. The addition of approximately 80 nm TiCnps decreased the solid-liquid growth rate (R), indicating that TiCnps were more likely to be spread successfully as nucleation particles inside the grains. Micro-pools with several nucleation sites impaired grain boundary segregation and increased the concentration of copper in the Al matrix. Due to the difference in Cu atom concentration, the fine spot-like  $\theta'$ -CuAl<sub>2</sub> phase, as well as the dendritic  $\theta$ -CuAl<sub>2</sub> phase along the grain boundary, were all transformed into semi-coherent alpha-Al+  $\theta$  CuAl<sub>2</sub> phases. Due to the strong interfacial bonding between the fine spot-like phase and TiCnps and the Al matrix, the deposited 3219 aluminum alloy exhibited improved mechanical properties.

Table (2a) Summary of Literature Review study the effect of aluminium-based composite additive manufacturing on microstructure and mechanical properties

Reference	[50]	[51]	[52]	[53]	[54]	[55]	[56,57]	
Aluminum-based composite	Matrix	Al-7Si-Cu-Mg	Al-7Si-1Mg-Cu	AA5183	Al-5Cu	AA7075	AA4043	AA2319
	Reinforced	TiB <sub>2</sub>	TiB <sub>2</sub>	TiC	TiB <sub>2</sub>	TiC	TiC	TiC
	Volume or mass fraction	-----	2.5 wt%	1 vol% TiC	-----	----	1 wt. %	(0.5,1.0, 1.5,2.0) wt. %
	particles size	Nano or submicron-sized	-----	40–60 nm	Nano and some submicron clusters	Nano	40–60 nm	40 nm
	Morphology or crystal structure	regular with round	-----	fcc crystal structure	round and near-round (no sharp angles)	---	---	fcc
Power source	CMT	TIG	CMT	(CMT) ,(EBM)	TIG	GMAW	MIG	
Welding wire diameter (mm)	2.5	1.6	1.2	2.0	3.2	1.1–1.2		
The dimension of the as-deposited sample(mm)	140*20*80	-----	220*8*80	180 *200*80	-----	-----	-----	
Current (A)	170	-----	85	170, 35 mA	180	100	101	
Voltage (V)	19.2	-----	16.6	18.3, 60	-----	19		
Feeding speed	5.8 m/min	-----	5.0 m/min	3.8m/min 500 mm/min	254 mm/min	9 mm/s	2m/min	

Table (2d) Summary of literature review study of the effect of aluminium-based composite additive manufacturing on microstructure and mechanical properties (The composite fabrication method and the result)

	<b>The composite fabrication method</b>	<b>The Result</b>
<b>Yaqi et al, 2018 [50]</b>	The composite material is manufactured by using a mixture salts method.	<ul style="list-style-type: none"> <li>• In comparison to as-cast and as-deposited welding wire, the alloy elements in as-deposited samples are often in solid solubility, and the second phase is dispersed.</li> <li>• The welding wire had the highest hardness due to its internal tension. The deposited state has a higher hardness than the as-cast state. The increase in hardness can be due to a decrease in grain size and an increase in solid solubility.</li> <li>• In the as-cast sample, the silicon phase is wide and uniformly distributed along the grain boundary, while the silicon phase in the deposited microstructure is dispersed and smaller.</li> </ul>
<b>Qingfeng et al, 2019 [51]</b>	prepared using a mixture of salts method	<ul style="list-style-type: none"> <li>• The parallel to the weld structure is identical to the perpendicular to the weld structure. Columnar and equiaxed crystals make the sedimentary sample's composition, with silicon and TiB<sub>2</sub> particles distributed along the grain boundary.</li> <li>• TiB<sub>2</sub> particles aggregate in a variety of ways, resulting in grain and Si refinement.</li> <li>• The grain size of the sample increases significantly after T6 heat treatment, and the shape of silicon varies from the original strip to a lump with a size of 2-5 um.</li> <li>• After T6, the sedimentary sample's hardness increases.</li> </ul>
<b>Geir et al, 2020 [52]</b>	In the screw extrusion process, the TiC modified wire is made by mixing monolithic AA5183 wire with TiC nano-powder.	<ul style="list-style-type: none"> <li>• The deposited WAAM thin wall has compared with the commercial AA5183 benchmark, the (TiC-+AA5183) alloy shows refined grains, the hardness is also increased by 13%.</li> <li>• The tensile properties of the TiC modified alloy is weak due to the formation of a large number of pores.</li> </ul>
<b>Shuang et al, 2020 [53]</b>	Prepare Al composite material by salt-metal reaction method.	<ul style="list-style-type: none"> <li>• WAAM (TiB<sub>2</sub>+ Al-5Cu) will refine the microstructure of composite materials and reduce grain size (more than 100 μm) than the traditional casting using CMT and EBM technology.</li> <li>• AM technology becomes a promising method for optimizing microstructure and mechanical properties The performance of composite materials.</li> </ul>

Daniel et al,2020 [54]	-----	<ul style="list-style-type: none"> <li>• Can weld common spaceship 7075 T73 aluminium the Al 7075 welding wire reinforced with TiC nanoparticles can restore mechanical properties through T73 heat treatment after welding.</li> <li>• Al 7075 T73 is manufactured by a wire-based additive manufacturing process, and its performance is similar to that of wrought materials.</li> <li>• Quantify the preliminary mechanical properties of Al 7075+TiC<sub>nps</sub> during welding and after T73 heat treatment.</li> </ul>
Geir et al,2020 [55]	<p>A wire of AA4043 is cut into 25±10 mm granules, then cleaned and heat to ensure that any organic residues are removed. The granules are mixed with 1% by weight of TiC powder in a cylindrical plastic container. The (AL + TiC) mixture was rolled and mixed in the air at 70 rpm for five days. There is a black dry TiC coating on the particles.</p>	<ul style="list-style-type: none"> <li>• A ternary Intermetallic phase form from a solid-state chemical reaction occurs between (Al +Si + TiC).</li> <li>• The arc deposition of TiC reinforced wire shows that after the solidified columnar dendrites are transformed into equiaxed dendrites, the grain structure has changed and the hardness has increased. In the accumulated deposit material, there were a lot of hydrogen pores, which may be attributed to TiC pollution in the air.</li> </ul>
Peng et al,2020 [56]	<p>The coating speed is used to control the coated TiC<sub>nps</sub> with different mass fractions.</p>	<ul style="list-style-type: none"> <li>• By incorporating TiC<sub>nps</sub> into the WAAM process, uneven microstructural features and columnar crystals were removed, the average grain size was reduced, and grain boundary segregation and increased Cu element concentration in Al-matrix were inhibited.</li> <li>• When TiC<sub>nps</sub> is applied, the solid-liquid interface's growth rate slows down.</li> <li>• Because of the lower solidification rate, secondary dendrites will expand, promoting the transformation of dendrites to equiaxed dendrites.</li> <li>• When subjected to tensile stress, the samples without TiC<sub>nps</sub> cracks begin at the grain boundary in the brittle CuAl<sub>2</sub> phase, propagating along the grain boundary. On the brittle alpha-Al+CuAl<sub>2</sub> step, cracks begin to form within the grain in TiC<sub>nps</sub> samples. To improve strength and plasticity, cracks must bypass the TiC<sub>nps</sub> and '-phase.</li> </ul>

## 6. Applications of WAAM

As a result of its diversified uses, WAAM has wide industrial applications, including aerospace and maritime transportation. Concerning the complexity of the more of the work and the alloy is, the more prominent WAAM will be. Figure (6) depicts the fabrication and thermal testing of liquid rocket engine equipment used at NASA's Marshall Space Flight Center [58]. WAAM made a 2.1-meter-long mechanical excavator that weighs just over a ton, as shown in Figure (7) [60].

The results of this are conventional industrial and artistic, as well as 3D printing allows for versatile and effective work and gives architectural and esthetic designers freedom to apply the use of WAAM. Mass art is sure to emerge because of the popularization of

metal sculpture[58]. The example in Figure (8), of the full-metallic bridge from MX3D and Arup engineers at Imperial College that was constructed and tested in Amsterdam's harbor, is provided as an example of WAAM flexibility and versatility [61].

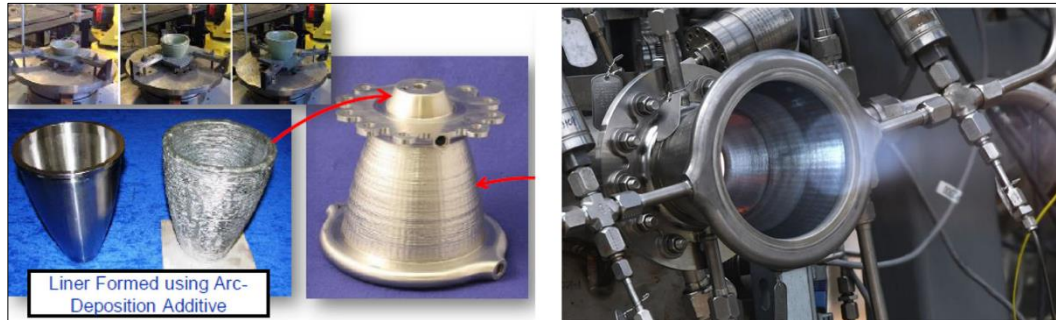


Figure 6: WAAM Liquid rocket engine combustion device [59]

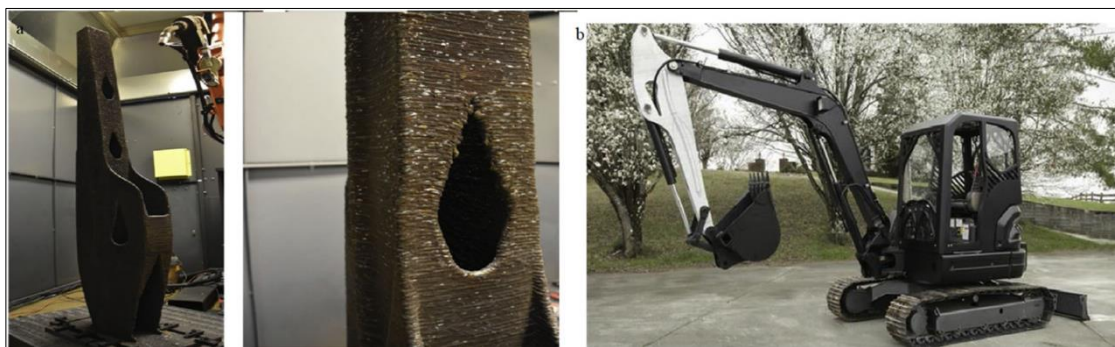


Figure 7: WAAM forming large mechanical arm. a Printed arm. b Installed arm [60]



Figure 8: a Load testing of the MX3D bridge; b the MX3D bridge at Dutch Design Week 2018 [61]

### 7. Conclusions

This article reviewed the manufacture of aluminium metal matrix composites through additive manufacturing (WAAM). Taking into account the key aspects of metal matrix material processing, the WAAM process, the advantages and challenges of this method, it was found that the additive manufacturing method is considered to be a better alternative method for processing metal matrix composite materials. The mixing methods of MMCs

and their critical issues, classification of AM processes, WAAM process with advantages and challenges also were reviewed. The review was also included the discussion of WAAM of some AMCs with different reinforcement materials (TiC, TiB<sub>2</sub>) and different power sources. The results showed that the solidified deposited material with reinforcing particle prepared by wire arc welding had an identical structure in both parallel and perpendicular to the weld direction. Where the columnar dendrite grain's structure changed to equiaxial dendrites shape, leading to improves hardness and other mechanical properties. The deposited material had a large number of pores, which may be attributed to contamination of the reinforcing particles exposed to the air.

#### References

- [1] Ma, J., Kang, J., & Huang, T. (2016). Novel application of ultrasonic cavitation for fabrication of TiN/Al composites. *Journal of Alloys and Compounds*, 661, 176-181.
- [2] Hu, Z., & Tong, G. (2015, October). Laser sintered thin layer graphene and cubic boron nitride reinforced nickel matrix nanocomposites. In *AOPC 2015: Micro/Nano Optical Manufacturing Technologies; and Laser Processing and Rapid Prototyping Techniques* (Vol. 9673, p. 967302). International Society for Optics and Photonics.
- [3] Rajkovic, V., Bozic, D., & Jovanovic, M. T. (2010). Effects of copper and Al<sub>2</sub>O<sub>3</sub> particles on characteristics of Cu–Al<sub>2</sub>O<sub>3</sub> composites. *Materials & Design*, 31(4), 1962-1970.
- [4] Wang, H., Geng, H., & Liu, C. (2012). The influence of SiO<sub>2</sub> on the aluminum borate whisker reinforced aluminum phosphate wave-transparent materials. *Procedia Engineering*, 27, 1222-1227.
- [5] Ma, Z. Y., Mishra, R. S., & Tjong, S. C. (2002). High-temperature creep behavior of TiC particulate reinforced Ti–6Al–4V alloy composite. *Acta materialia*, 50(17), 4293-4302.
- [6] Yuan, J., Zhang, X., Li, B., Wang, X., & Sun, K. (2017). Microstructure and tribological behavior of NiAl/WC composites fabricated by thermal explosion reaction at 800° C. *Journal of Alloys and Compounds*, 693, 70-75.
- [7] Bakshi, S. R., Lahiri, D., & Agarwal, A. (2010). Carbon nanotube reinforced metal matrix composites-a review. *International materials reviews*, 55(1), 41-64.
- [8] WHITE L. *ADDITIVE MANUFACTURING MATERIALS STANDARDS, TESTING AND APPLICABILITY*. Nova Science Publishers, New York; 2015.
- [9] ISO/ASTM52900 - 15 Standard Terminology for Additive Manufacturing - General Principles - Terminology, Standard, American Society for Testing Materials, West Conshohocken, USA, 2015.
- [10] Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., ... & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, 69, 65-89
- [11] Derekar, K. S. (2018). A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium. *Materials science and technology*, 34(8), 895-916.
- [12] Chen, M., Li, X., Ji, G., Wu, Y., Chen, Z., Baekelant, W., ... & Kruth, J. P. (2017). Novel composite powders with uniform TiB<sub>2</sub> nano-particle distribution for 3D printing. *Applied Sciences*, 7(3), 250.
- [13] Chen, T., & Lin, Y. C. (2017). Feasibility evaluation and optimization of a smart manufacturing system based on 3D printing: a review. *International Journal of Intelligent Systems*, 32(4), 394-413.
- [14] Hu, Z., Chen, F., Xu, J., Nian, Q., Lin, D., Chen, C., ... & Zhang, M. (2018). 3D printing graphene-aluminum nanocomposites. *Journal of Alloys and Compounds*, 746, 269-276.
- [15] Hu, Y., & Cong, W. (2018). A review on laser deposition-additive manufacturing of ceramics and ceramic reinforced metal matrix composites. *Ceramics International*, 44(17), 20599-20612.
- [16] Gu, D. (2015). *Laser additive manufacturing of high-performance materials*. Springer.
- [17] Mahmood, M. A., Popescu, A. C., & Mihailescu, I. N. (2020). Metal matrix composites synthesized by laser-melting deposition: a review. *Materials*, 13(11), 2593.
- [18] Gupta, M., Lai, M. O., & Lim, C. Y. H. (2006). Development of a novel hybrid aluminum-

- based composite with enhanced properties. *Journal of Materials Processing Technology*, 176(1-3), 191-199
- [19] Naher, S., Brabazon, D., & Looney, L. (2005). Development and assessment of a new quick quench stir caster design for the production of metal matrix composites. *Journal of Materials Processing Technology*, 166(3), 430-439
- [20] Narasimha, B. G., Krishna, V. M., & Xavier, A. M. (2013). A review on processing of particulate metal matrix composites and its properties. *International Journal of Applied Engineering Research*, 8(6), 647-666.
- [21] Das, S., Behera, R., Datta, A., Majumdar, G., Oraon, B., & Sutradhar, G. (2010). Experimental investigation on the effect of reinforcement particles on the forgeability and the mechanical properties of aluminum metal matrix composites. *Materials Sciences and Applications*, 1(05), 310.
- [22] Manjunathal, H., & Dinesh, P. (2013). Fabrication and properties of dispersed carbon nanotube-Al6061 composites. *International Journal of Innovative Research in Science, Engineering and Technology*, 2(2), 500-507.
- [23] Barekar, N., Tzamtzis, S., Dhindaw, B. K., Patel, J., Babu, N. H., & Fan, Z. (2009). Processing of aluminum-graphite particulate metal matrix composites by advanced shear technology. *Journal of Materials Engineering and Performance*, 18(9), 1230-1240.
- [24] Barekar, N. S., Tzamtzis, S., Babu, N. H., Fan, Z., & Dhindaw, B. K. (2009). Processing of ultrafine-size particulate metal matrix composites by advanced shear technology. *Metallurgical and Materials Transactions A*, 40(3), 691.
- [25] Donthamsetty, S. (2010). Investigation on mechanical properties of A356 nanocomposites fabricated by ultrasonic assisted cavitation. *Journal of Mechanical Engineering*, 41(2), 121-129.
- [26] Chen, C. L., Tatlock, G. J., & Jones, A. R. (2010). Microstructural evolution in friction stir welding of nanostructured ODS alloys. *Journal of Alloys and Compounds*, 504, S460-S466.
- [27] Diehl, W., & Stöver, D. (1990). Injection moulding of superalloys and intermetallic phases. *Metal Powder Report*, 45(5), 333-338.
- [28] Mishra, R. S., Bieler, T. R., & Mukherjee, A. K. (1995). Superplasticity in powder metallurgy aluminum alloys and composites. *Acta metallurgica et materialia*, 43(3), 877-891.
- [29] Behera, M. P., Dougherty, T., & Singamneni, S. (2019). Conventional and additive manufacturing with metal matrix composites: A perspective. *Procedia Manufacturing*, 30, 159-166.
- [30] Gero, J. S., Maher, M. L., & Sudweeks, F. (Eds.). (1995). *Computational models of creative design: third International Round-Table Conference on Computational Models of Creative Design*, Heron Island, Queensland, Australia, 3-7 December 1995. Key Centre of Design Computing at the University of Sydney.
- [31] Wong, K. V., & Hernandez, A. (2012). A review of additive manufacturing, *ISRN Mech. Eng*, 1, 1-10.
- [32] Standard, A. S. T. M. (2012). *Standard terminology for additive manufacturing technologies*. ASTM International F2792-12a.
- [33] Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology*, 81(1), 465-481.
- [34] McAndrew, A. R., Rosales, M. A., Colegrove, P. A., Hönnige, J. R., Ho, A., Fayolle, R., ... & Pinter, Z. (2018). Interpass rolling of Ti-6Al-4V wire+ arc additively manufactured features for microstructural refinement. *Additive Manufacturing*, 21, 340-349.
- [35] Ding, D., Shen, C., Pan, Z., Cuiuri, D., Li, H., Larkin, N., & van Duin, S. (2016). Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part. *Computer-Aided Design*, 73, 66-75.
- [36] Dickens, P. M., Pridham, M. S., Cobb, R. C., Gibson, I., & Dixon, G. (1992). Rapid prototyping

- using 3-D welding. In 1992 International Solid Freeform Fabrication Symposium.
- [37] Spencer, J. D., Dickens, P. M., & Wykes, C. M. (1998). Rapid prototyping of metal parts by three-dimensional welding. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 212(3), 175-182.
- [38] 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. *Journal of Manufacturing Processes*, 35, 127-139.
- [39] Williams, S., & Martina, F. (2015). Wire+ arc additive manufacturing vs. traditional machining from solid: a cost comparison. Technical report. Welding engineering and laser processing Centre, Cranfield University.
- [40] Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire+ arc additive manufacturing. *Materials Science and Technology*, 32(7), 641-647.
- [41] Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire+ arc additive manufacturing. *Materials Science and Technology*, 32(7), 641-647.
- [42] Gu, D. (2015). Laser additive manufacturing (AM): classification, processing philosophy, and metallurgical mechanisms. In *Laser additive manufacturing of high-performance materials* (pp. 15-71). Springer, Berlin, Heidelberg.
- [43] Herzog, D., Seyda, V., Wycisk, E., & Emmelmann, C. (2016). Additive manufacturing of metals. *Acta Materialia*, 117, 371-392.
- [44] Xiong, J., & Zhang, G. (2013). Online measurement of bead geometry in GMAW-based additive manufacturing using passive vision. *Measurement Science and Technology*, 24(11), 115103.
- [45] Geng, H., Li, J., Xiong, J., Lin, X., & Zhang, F. (2017). Optimization of wire feed for GTAW based additive manufacturing. *Journal of Materials Processing Technology*, 243, 40-47.
- [46] Withers, P. J., & Bhadeshia, H. K. D. H. (2001). Residual stress. Part 1—measurement techniques. *Materials science and Technology*, 17(4), 355-365.
- [47] Withers, P. J., & Bhadeshia, H. K. D. H. (2001). Residual stress. Part 2—Nature and origins. *Materials science and technology*, 17(4), 366-375.
- [48] Wang, H., Jiang, W., Ouyang, J., & Kovacevic, R. (2004). Rapid prototyping of 4043 Al-alloy parts by VP-GTAW. *Journal of Materials Processing Technology*, 148(1), 93-102.
- [49] Ding, Y., Muñoz-Lerma, J. A., Trask, M., Chou, S., Walker, A., & Brochu, M. (2016). Microstructure and mechanical property considerations in additive manufacturing of aluminum alloys. *MRS Bulletin*, 41(10), 745-751.
- [50] Deng, Y., Li, X., Wu, L., Yang, Q., & Chen, Y. (2018, July). Microstructure and Performance of WAAM TiB<sub>2</sub>-Reinforced Al-Si-Based Composites. In *Chinese Materials Conference* (pp. 321-328). Springer, Singapore.
- [51] Yang, Q. F., Xia, C. J., & Deng, Y. Q. (2019). Microstructure and Mechanical Properties of TiB<sub>2</sub>/Al-Si Composites Fabricated by TIG Wire and Arc Additive Manufacturing. In *Materials Science Forum* (Vol. 944, pp. 64-72). Trans Tech Publications Ltd
- [52] Hu, Z., Chen, F., Xu, J., Nian, Q., Lin, D., Chen, C., ... & Zhang, M. (2018). 3D printing graphene-aluminum nanocomposites. *Journal of Alloys and Compounds*, 746, 269-276.
- [53] Lei, S., Deng, Y. Q., Li, X. F., Wu, L., & Chen, Y. C. (2020). Effect of Casting and Additive Manufacturing on the Microstructure and Mechanical Property of Al-Cu Composites. In *Materials Science Forum* (Vol. 993, pp. 718-722). Trans Tech Publications Ltd.
- [54] Langelandsvik, G., Grandcolas, M., Skorpen, K. G., Furu, T., Akselsen, O. M., & Roven, H. J. (2020). Development of Al-TiC Wire Feedstock for Additive Manufacturing by Metal Screw Extrusion. *Metals*, 10(11), 1485.
- [55] Langelandsvik, G., Grandcolas, M., Skorpen, K. G., Furu, T., Akselsen, O. M., & Roven, H. J. (2020). Development of Al-TiC Wire Feedstock for Additive Manufacturing by Metal Screw Extrusion. *Metals*, 10(11), 1485.
- [56] Jin, P., Liu, Y., Li, F., Li, J., & Sun, Q. (2021). Realization of structural evolution in grain



- boundary, solute redistribution and improved mechanical properties by adding TiCnps in wire and arc additive manufacturing 2219 aluminium alloy. *Journal of Materials Research and Technology*, 11, 834-848.
- [57] Jin, P., Liu, Y., & Sun, Q. (2021). Evolution of crystallographic orientation, columnar to equiaxed transformation and mechanical properties realized by adding TiCps in wire and arc additive manufacturing 2219 aluminum alloy. *Additive Manufacturing*, 39, 101878
- [58] Gradl, P. R., Greene, S. E., Protz, C., Bullard, B., Buzzell, J., Garcia, C., ... & Cooper, K. G. (2018). Additive manufacturing of liquid rocket engine combustion devices: a summary of process developments and hot-fire testing results. In *2018 Joint Propulsion Conference* (p. 4625).
- [59] 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. *The International Journal of Advanced Manufacturing Technology*, 1-50.
- [60] Greer, C., Nycz, A., Noakes, M., Richardson, B., Post, B., Kurfess, T., & Love, L. (2019). Introduction to the design rules for metal big area additive manufacturing. *Additive manufacturing*, 27, 159-166.
- [61] Buchanan, C., & Gardner, L. (2019). Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges. *Engineering Structures*, 180, 332-348.