Composites and Advanced Materials

Composites and Advanced Materials
Volume 32: 1–23
© The Author(s) 2023
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/26349833231210572
journals.sagepub.com/home/acm
Sage

Welding-based additive manufacturing processes for fabrication of metallic parts

C Rathinasuriyan[1], PV Elumalai[2], J Bharani Chandar[1], K Karthik[1], Sreenivasa Reddy Medapati[2], Ahmad Aziz Alahmadi[3], Mamdooh Alwetaishi[4], Ali Nasser Alzaed[5], MA Kalam[6] and Kiran Shahapurkar[7]

Abstract

Additive Manufacturing (AM) is modernizing the manufacturing industry by enabling the layer-by-layer deposition process to manufacture objects in nearly any form with minimum material waste. However, components developed utilizing the AM process have dimensional constraints. To address this issue, AM-produced metal materials can be coupled with various welding processes. This article focuses on the foundations, highlighting the distinguishing features, capabilities, and challenges of welding-based AM processes by categorizing them into two major groups; arc welding-based AM like Cold Metal Transfer (CMT), Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), and high-energy density welding based AM like Laser Beam Welding (LBW) and Electron Beam Welding (EBW). The prior study findings of welding-based AM metal components on mechanical characteristics and microstructural characterization have been addressed. This work will aid researchers, academicians, and professional welders since it gathers vital information on welding-based AM processes. Furthermore, current research in the arena of welding-based AM and its future opportunities has been discussed.

Keywords

additive manufacturing, metal additive manufacturing, wire arc additive manufacturing, welding, welding-based additive manufacturing

Introduction

Additive Manufacturing (AM) is a revolutionary manufacturing method that emerged in the 1980s[1] AM is the manufacturing process that can be recognized as a 3D printer or rapid prototyping, where the components are developed layer-by-layer and digitally controlled.[2–4] AM is a near-net-shape fabrication technology that can significantly increase design freedom and shorten the lead time of production, completely different from traditional fabrication techniques like casting, forging, and machining. As a result, AM offers excellent prospects for intelligent production in the forthcoming Industry 4.0 era.[5,6] In general, the process variables and alloy compositions are two key components for influencing the microstructures of metals produced through AM.[7] Figure 1 depicts the four phases of "plan," "do,"

[1]Department of Mechanical Engineering, Vel Tech Rangarajan Dr.Sagunthala R&D Institute of Science and Technology, Chennai, India
[2]Department of Mechanical Engineering, Aditya Engineering College, Surampalem, 533437, India
[3]Department of Electrical Engineering, College of Engineering, Taif University, Taif, Saudi Arabia
[4]Department of Civil Engineering, College of Engineering, Taif University, Taif, Saudi Arabia
[5]Department of Architecture Engineering, College of Engineering, Taif University, Taif, Saudi Arabia
[6]School of Civil and Environmental Engineering, FEIT, University of Technology Sydney, Broadway, NSW, Australia
[7]Department of Mechanical Design and Manufacturing Engineering, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Adama, Ethiopia

Date received: 9 April 2023; accepted: 10 October 2023

Corresponding author:
Kiran Shahapurkar, Department of Mechanical Design and Manufacturing Engineering, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Adama 1888, Ethiopia.
Email: kiranhs1588@gmail.com

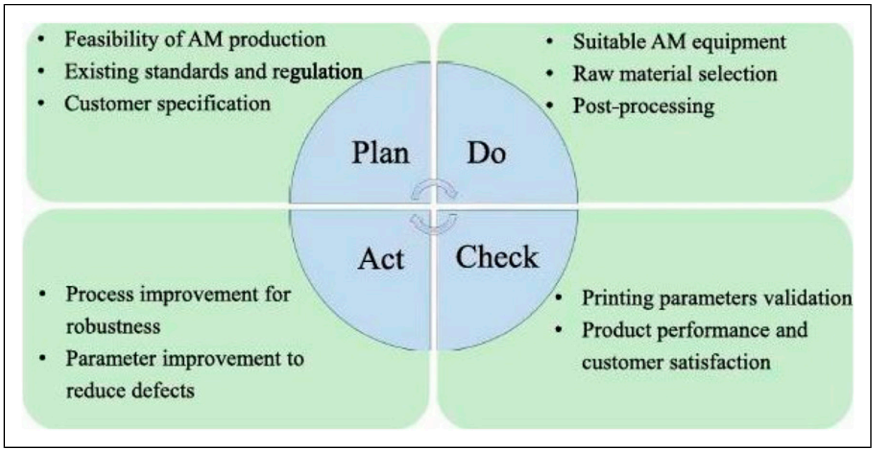


Figure 1. PDCA cycle combined with AM.[110]

"check," and "act" in the framework of AM to continue producing quality and customer satisfaction.

All AM procedures depend deeply on materials because of their inherent ability to influence performance and shape. Metal, polymer, ceramic, and natural materials have all been used in various AM methods, as indicated in Figure 2. Based on these homogeneous material systems, AM methods with heterogeneous materials, such as all varieties of composites, and multiple materials, have been built successfully to get better qualities.

With its characteristics, this technique has achieved significant development for metal materials as well as polymer materials. It is capable of processing an extensive range of metals, alloys, and ceramics.[8–10] It is divided into seven classes based on the stacking mechanism: material extrusion, powder bed fusion (PBF), material jetting, vat photopolymerization, sheet lamination, binder jetting, and direct energy deposition.[11,12]

AM is a valuable method for creating scaffolds that are essential in bone tissue creation.[13,14] It is quickly becoming an extensively acknowledged approach in medicine because it provides high complexity, patient-specific design, on-demand and cost-effective manufacture, and high productivity.[15] Arora et al.[16] have discussed that AM has contributed to the fight against COVID-19 by manufacturing face shields, ventilators for testing, 3-D bio-printing, antimicrobial polymers, face masks, oxygen valves, lung prototypes, and so on. The application of AM in construction has recently received a lot of interest. The big robotic arm and scaffold systems have been developed to print construction parts from comprehensive materials, metals, or polymers.[17] Klimyuk et al.[18] have concluded that the ability to use 3D printing is an alternate technique for producing punch components for single-piece and small-batch manufacture. Nadagouda et al.[19] have highlighted 3D printing applications in four environmental fields, including sustainable engineering, wastewater, air quality, water, and alternative energy sources. Figure 3 represents the diverse industrial adoption of AM.

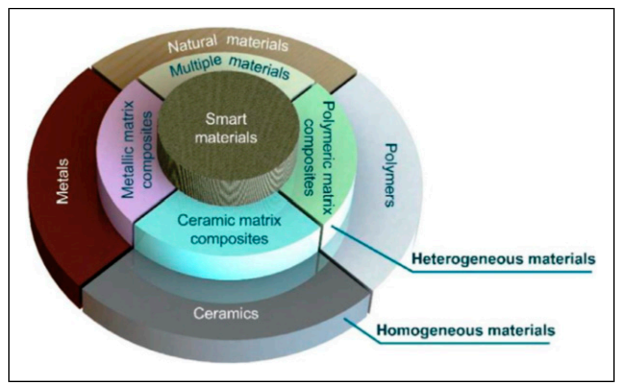


Figure 2. Material system used in AM processes.[111]

The modern world has seen enormous developments in AM research, along with applications and other aspects of it. To fully enable the value of AM, however, some obstacles must be removed. The main problems are the compatibility of raw materials, the absence of testing facilities, and the incidence of numerous flaws in AM-fabricated parts.[20] AM is proficient in creating specialized and high-end products. Energy usage, production costs, and lead times are all improved with the use of AM to meet sustainability standards. Aside from that, AM technologies are seen as being environmentally sustainable because they result in reduced material waste, CO_2 emissions, and a stronger circular economy.[21] The qualification and certification processes for AM have been hampered despite the technology's rapid growth due to the multiple flaws found in printed parts. Contrarily, neural networks have drawn a lot of interest as a deep learning technique over the past 10 years and have proven to be quite effective when processing image data.[22] Since the exceptional post-COVID-19 situation prompted

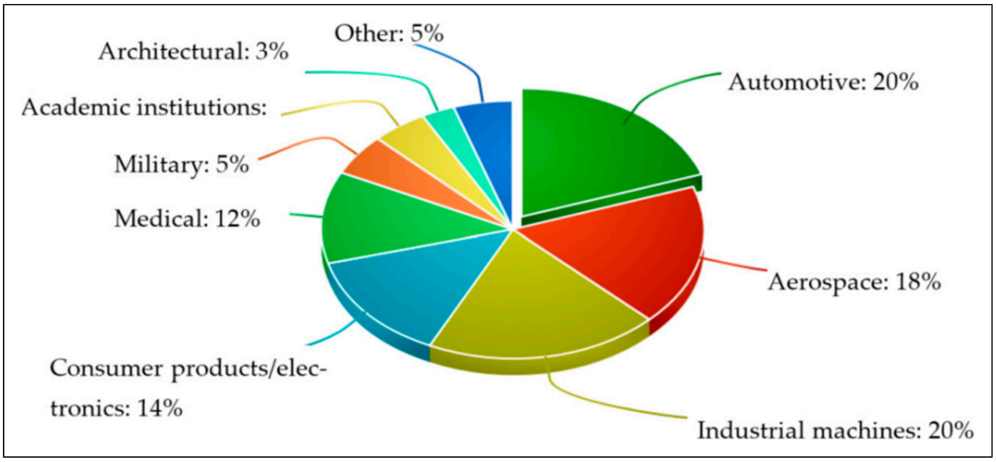


Figure 3. Industrial adoption of AM.[112]

international automakers to adopt on-shoring, Sheriff Muhammad et al.[23] have concentrated on AM implementation in the automotive supply chain's procurement stage to create auto components. To examine the adoption of AM in such settings, future research should take into account the effects of the collaboration amongst AM service providers in the automotive supply chain. It is difficult to recreate the space environment using physical variables like gravity, atmospheric pressure, and temperature in a laboratory setting. Therefore, creating proper AM space technologies is a huge task for scientists.[24] AM methods deal with complicated problems such as poor surface quality, flaws, and decreased corrosion resistance. These issues preclude AM parts from being used in real-time operating applications. These problems are typically solved using post-processing techniques such as laser shock peening, laser polishing, traditional machining techniques, and heat treatments.[25]

Welding methods

Welding is an important manufacturing procedure because it allows for the easy production of complicated structures. Because it is practically incredible and time-consuming to create complicated components as separate parts, the effect of welding technology has expanded dramatically everywhere in current years.[26] It is commonly employed in the last stages of casting production and in the fabrication of connecting components.[27] There are three forms of welding: fusion welding, non-fusion welding, and resistance welding. Because of its fast welding speed, continuous lengthy welding, and strong mechanical qualities of weldments, GMAW is a widely utilized welding technology with widespread application in industries.[28] TIG, TAGS, or GTAW, also known as tungsten arc inert gas shielded welding, is a type of arc welding that uses an inert gas to shield the electrode and a non-consumable tungsten electrode.[29] PAW employs a sharply restricted arc to create a keyhole inside the molten pool. As a result, the PAW technique has a substantially higher process efficiency than the typical TIG welding process.[30] The electric field between the base electrode and anode accelerates electrons generated by the electron gun cathode in EBW. These accelerated electrons are directed to a welding location in the workpiece.[31] In LBM, a unique light composed of photons created either by gas or solid-state is concentrated on an incredibly tiny diameter, resulting in a high energy density that is utilized for welding.[32] Friction Stir Welding (FSW) is a powerful solid-state joining technique. It is deliberated as a green and environmentally friendly welding process because of no requirement for filler material or shielding gas. Furthermore, there is no arc flash, fumes, or dispersion in this welding technique.[33,34] It has certain benefits over conventional fusion welding processes. FSW is a novel and very successful solid-state joining process developed in 1991 by TWI in Cambridge, England, for combining aluminum alloys.[35] Ultrasonic Metal Welding (USMW) is a solid-state welding technology that produces metallurgical bonding between similar or different materials without melting.[36]

Welding and AM are both examples of surface growth difficulties because they both require the deposition of thermally extended material on the surface of a surface and result in the buildup of longitudinal residual stress after the operation.[37] The difference between normal welding and welding-based AM processes was nicely illustrated in Figure 4. Thermal conductivity occurs in more dimensions in welding (Figure 4(a)) than in welding-based AM processes, where heat must be derived in most cases in one direction: to the bottom of the component (Figure 4(b)).

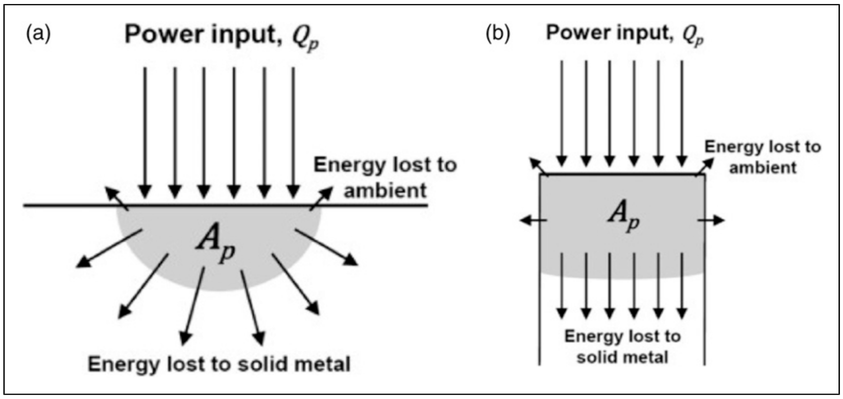


Figure 4. Heat transfer (a) welding (b) welding-based AM.[113]

Arc welding-based additive manufacturing

WAAM is incredibly inexpensive since the equipment is current welding equipment, and the filler metals, which are comparable to those used in welding, can also be purchased off the layer.[38] Because of the rapid deposition rates and minimal geometrical constraints, this is particularly ideal for near-net shape manufacture of large components as well as incremental manufacturing.[39] Figure 5 illustrates how the alternate layers were deposited in opposing directions to maintain the geometric tolerance.

Wire Arc Additive Manufacturing (WAAM) is a metal-part manufacturing technology that uses directed energy deposition and arc welding. The CNC machine or an industrial robot guides the welding flame along a deposition path, allowing 3D forms to be created. The experimental setup for robot-guided WAAM is shown in Figure 6.

The arc welding-based AM can be classified into GMAW, GTAW, and PAW-established technologies. Figure 7 shows the representation of these three heat sources.

Gas metal arc welding-based additive manufacturing process

In GMAW-AM, an electric arc is formed between the consumable electrode and the workpiece, melting the wire electrode and depositing it above the substrate surface as a result of the relative motion of the worktable and the GMAW torch. The feature of metal deposited in GMAW-AM is mainly indicated by surface form, dimensional quality, relative density, mechanical characteristics, hardness, and so on.[40] Vinoth et al.[41] fabricated the stainless steel plate using robot GMAW with ER 316 L consumable wires. The WAAM plate is built one layer at a time on that same plate, as seen in Figure 8.

Reimann et al.[42] used the GMAW welding procedure to create intricate, three-dimensional free-form constructions.

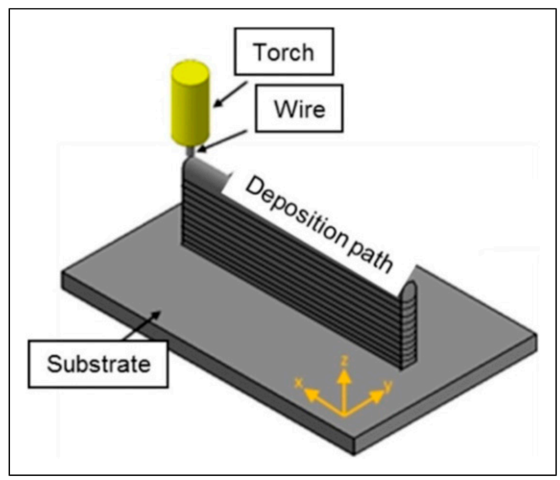


Figure 5. Graphical illustration of the layer sequence.[114]

Figure 9 depicts an additively built, topology-optimized component that has been cleaned but has not yet been taken from the substrate.

Shengfu et al.[43] used YHJ507M wire to create a hollow pipe with many branches (see Figure 10). When compared to the qualities of the casting pipe junction, the tensile strength of the 10-directional pipe joint improved by 12.4%.

Nagamatsu et al.[44] have fabricated the hollow turbine blade using GMAW based AM approach which is presented in Figure 11.

Le and Mai et al.[45] constructed the thin-walled models on SS400 steel plates using an industrial robot GMAW-AM process. The tensile properties of thin-walled 308 L stainless steel are shown in Figure 12.

Lee et al.[46] explored the impact of heat input, current ratio, and voltage ratio on bead shape under nine distinct deposition circumstances. Figure 13 depicts the results of hardness measurements under various situations. Comparisons were made between the maximum and minimum heat input circumstances as well as the current-to-voltage

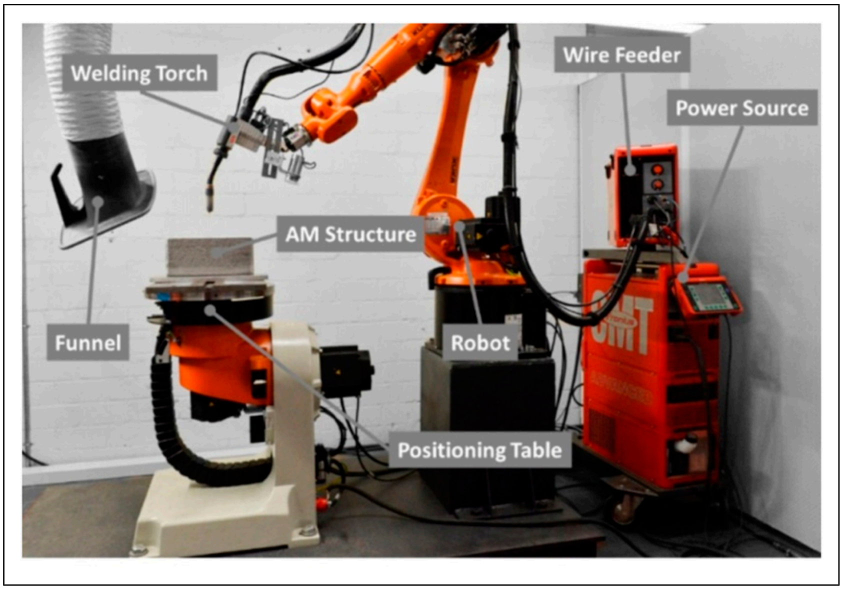


Figure 6. Experimental setup for robot-guided WAAM.[115]

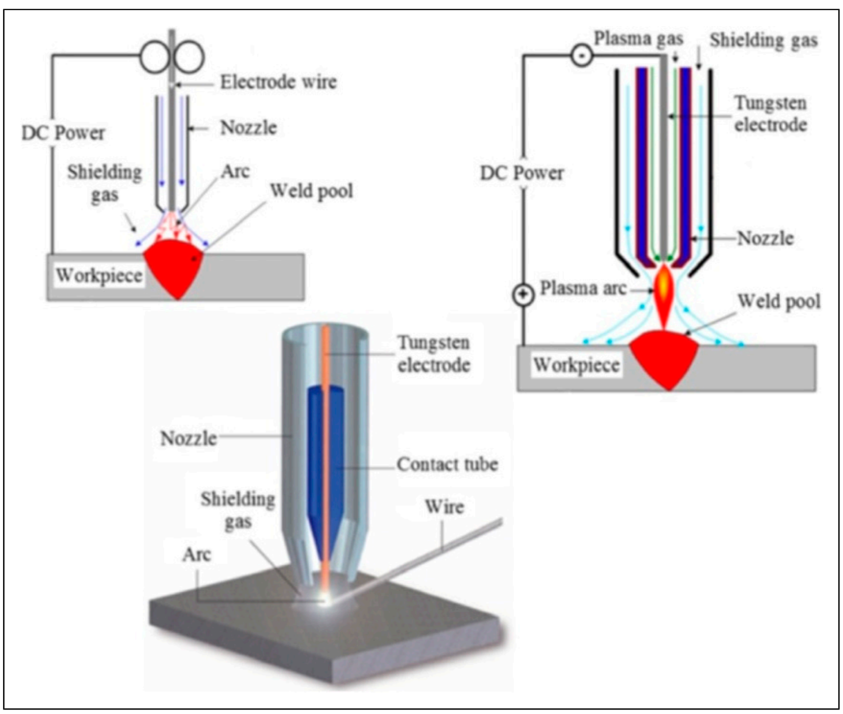


Figure 7. Representation of WAAM: (a) MIG, (b) TIG (c) PAW.[116]

ratio. It displays a current to voltage ratio of 0.21 for the blue line and 0.15 for the red line. The two lines are placed at 80 HV, and no discernible difference is seen despite the different current to voltage ratios. Furthermore, the rate of heat input makes little influence. The hardness test revealed that the hardness did not alter as a result of the welding different heat input and current-to-voltage ratio.

Suarez et al.[47] used the GMAW technique to produce bimetallic walls of mild steel and 316 L stainless steel in both overlying and stacked solutions. The manufacture of defect-free bi-metallic walls from various sheets of steel is a novel procedure that is detailed here for the first time. The superimposed wall and the intermetallic structure were shown in Figure 14. They have found the finer bainitic structure on the SS-ER70 sample.

Figure 8. Cross-sectional view of the GMAM Plate.

Figure 9. Additively manufactured component.

Colegrove et al.[48] used a rolling technique on GMAW-AM of ER70S-6 steel to minimize residual stress and grain size. The microstructure of the AM-ed wall is shown in Figure 15. The rolling technique flattened the columnar grains generated during deposition by applying compressive force.

Yuan et al.[49] invented a multi-directional WAAM technology for producing complicated metal components with robotic GMAW. The suggested multidirectional WAAM technology can greatly reduce production time and cost when compared to current WAAM approaches. According to Pattanayak and Sahoo,[50] high deposition is a substantial advantage of GMAW-AM, but it is also related to higher heat input, causing residual strains and distortions. As a result, intensive testing and process modeling are required to analyze the thermal characteristics of GMAW-AM to diminish residual stresses and distortions.

Cold metal transfer (CMT) arc welding-based additive manufacturing

WAAM is a reasonably simple method for enabling non-vertical material deposition, as welding apparatus paired with an industrial robot manipulator established in various labs and industries. Figures 16(a)–(b) illustrate the distinction between raising the welding gun's height incrementally over a few centimeters versus all at once.

Wall constructions were created utilizing CMT arc welding-based AM utilizing two types of ER2319 welding wires, one with and one without Cd components. With Cd elements, the yield strength in the deposition and building directions is raised by 5.5% and 9.3%, respectively, as compared to without Cd elements.[51] Mohiuddin and Mohideen[52] employed robotic CMT technology to additively build the 1.25Cr 0.5Mo 14 mm wall component. In various zones and orientations, the microstructure and mechanical

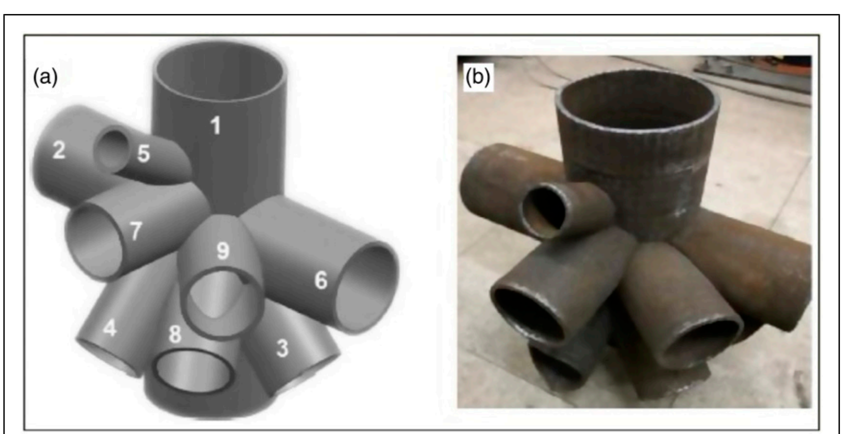


Figure 10. Hollow pipe (a) CAD model (b) fabricated part.

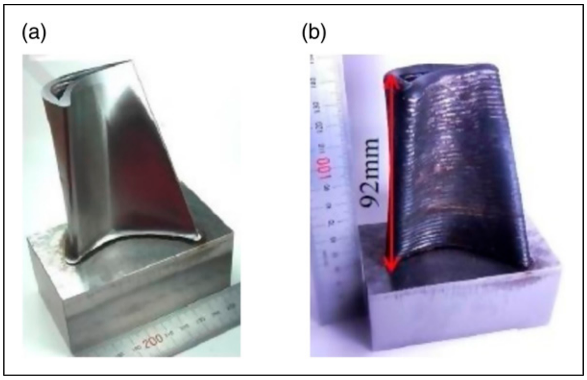


Figure 11. Turbine blade (a) fabricated part (b) after finishing.

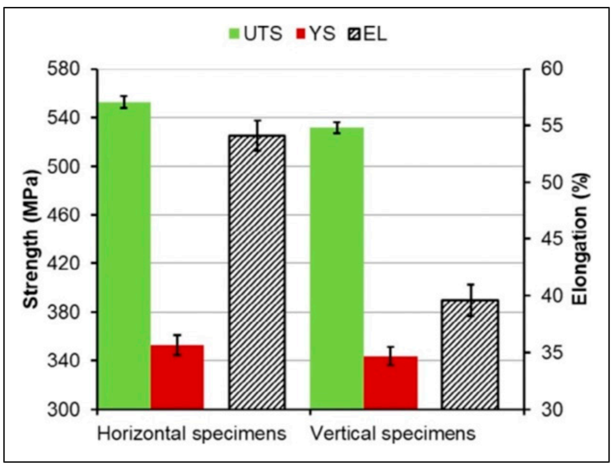


Figure 12. Tensile properties of 308 L stainless steel.

characteristics of fabricated wall sections were investigated. Plangger et al.[53] studied the viability of immediately producing a near-net form structural part on a subassembly for use in crane building without post-machining. The hardness values vary from 220 Hv to 440 Hv, with a single outlier of 180 Hv for the middle region. Tian et al.[54] employed direct current CMT welding with Ti-6Al-4V and AlSi5 wires for WAAM. Ti alloy was placed initially, followed by Al alloy on top of the Ti layer. Figure s17(a)–(d) depict the component's cross-sectional microstructure, which may be separated into three areas: the Al alloy region (area A), the interface layer between the Al and Ti alloys (area B), and the Ti alloy (area C). Figure 17(a) shows the component's morphology. Al and Ti alloys contact was clearly visible. Area A contained the porosity. The round pores had an average diameter of 70 microns. A lengthy, discontinuous strip of $Ti(Al_{1-x}Si_x)_3$ was shown in Figure 17(b). During the flow process, the strips were struck by the liquid Al alloy, resulting in the breakage of some strips and the formation of $Ti(Al_{1-x}Si_x)_3$ phases with varying lengths. Strip and block-shaped intermetallic compounds were created in the interface layer, as seen in Figure 17(c). The basket-wave structure of the Ti alloy during deposition is depicted in Figure 17(d).

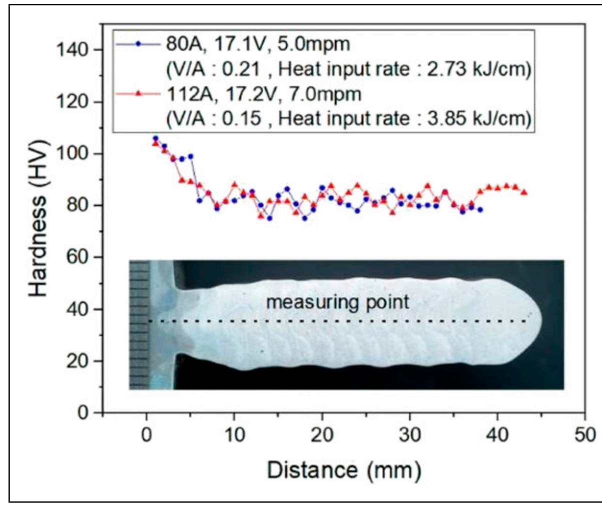


Figure 13. Hardness comparison.

Ti alloy was placed initially, followed by Al alloy on top of the Ti layer. Using the CMT welding machine, Xu et al.[55] created the Ti-6Al-4V wall. The columnar grain structure of the WAAMed Ti-6Al-4V was observed all beside the build direction (Figure 18). The microstructure inside the grains was made up of fine laths, and the breadth of the paths was significantly finer than in the wrought plate sample.

Gas tungsten arc welding based additive manufacturing process

An arc forms between a non-consumable tungsten electrode connected to the negative and the substrate connected to the positive terminal in GTAW-AM, resulting in a molten pool on the substrate surface. The filler wire is inserted via its leading edge into the molten pool, where it melts and is deposited on the substrate surface.[56] Gokhole et al.[57] investigated the use of a GTAW-based AM technique to create thin-walled metallic constructions. They investigated the impact of control factors on output metrics including deposition height and breadth. According to their findings, 80∘ is the better decision, and as the tilt angle increases, the deposition width and height decrease. Rodriguez et al.[58] have performed GTAW-based AM for fabricating the stainless steel parts. Table 1 includes the average mechanical properties determined in those samples.

Veeman et al.[59] have studied the mechanical and microstructural characterization of functionally graded material walls using GTAW-based AM. According to the experimental results, the fabricated wall possesses superior

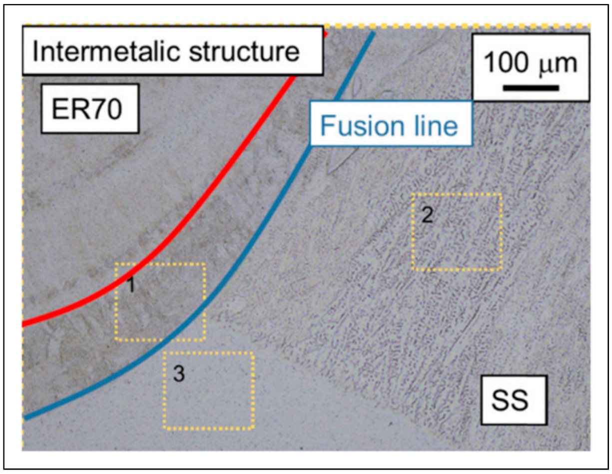


Figure 14. Microstructure analysis of the GMAM-ed SS-ER70.

attributes such as tensile strength and hardness. Paskual et al.[60] have studied the capabilities of AM and mechanical properties obtained by the TIG-AM. Tensile strength tests reveal that anisotropy reappears in terms of elongation at break, which is below the limit in the transverse direction (PT). However, yield and ultimate strengths transcend this limit and exhibit uniformity in both directions. Oropeza et al.[61] used TIG welding to evaluate the characteristics of nanoparticle-enhanced aluminium 7075 wire on overlay and 3D-printed component samples. When 3D printed and single-layer overlay microstructures are compared, the printed condition has bigger grains with a textured structure, as seen in Figure 19.

Plasma arc welding-based additive manufacturing process

AM applications that employ arc welding technologies are becoming increasingly widespread due to the higher productivity that these processes may achieve when compared to laser deposition. Among these methods, plasma transferred arc (PTA) deposition requires less heat than GTAW and GMAW and allows for more precise control of the feed rate. Martina and colleagues.[62] Alberti et al.[63] studied the possibility of PTA for AM thin wall production. They determined that PTA may be utilized to successfully create thin walls of Ni-based superalloys without crack nucleation caused by stacked deposition heat cycles. Wang et al.[64] used plasma arc AM to create crack-free Ti-Al alloy samples, and the influence of substrate temperature on as-deposited TiAl alloy was also examined. They discovered that as substrate temperature rises, microstructural lamellar spacing and colony size tend to increase. Li et al.[65] effectively deposited the metal portion in the shape of the Chinese character “中” using the self-adaptive double electrode micro PAW control system. Thus, it was established that the system shields the PAW deposition process from interferences caused by torch stand-off distance and that this method has the potential to be used to repair complicated surface metal components.

Veiga et al.[66] investigated the mechanical qualities of the PAW-WAAM wall constructed in compliance with aviation requirements. The tensile test results of specimens retrieved from the titanium alloy wall were generated under the identical PAW-WAAM process parameters. According to the results of the testing, UTS and yield stress are lesser in the vertical compared to the horizontal direction. Artaza et al.[67] used WAAM-PAW to build Ti6Al4V walls to study the deposition process under various air conditions. The impacts of relating heat treatment to WAAM-produced components in various media have been investigated. The core microstructure of all three heat-treated materials under consideration displayed fine acicular alpha and beta phases.

High-energy density (HED) welding-based additive manufacturing

Many firms depend on HED beam welding methods including laser beams and electron beams. Patterson et al.[68] state that these methods are widely employed in many welding and AM applications containing a wide-ranging of materials Table 2 lists the advantages of HED methods over arc welding procedures.

Electron beam welding (EBW) based additive manufacturing

Individually fabricating pieces using Laser Additive Manufacturing (LAM) and electron beam welding (EBW) is a viable method for creating big components with less internal stress. Fortuna et al.[69] created the bulk components on austenitic stainless steel by using the electron beam wire-feed additive technique. Figure 20 depicts the overall appearance of cylindrical blanks on substrates that were created using various process settings.

Weglowski et al.[70] used a universal EB machine to conduct the EBAM with a wired procedure. A wire feeder and a 4.9 m^3 working chamber are included in the apparatus. Figure 21 displays the macrostructure images of the EBAM LNM 307 plate.

Wanjara et al.[71] performed the additive repair using an electron beam gun with a 60 kV accelerating voltage. For the construction of the wall structure (Figure 22), 142 layers of single beads were needed to achieve a bead height of 50 mm with a wire deposition rate of 25 mm^3/sec.

Bimetallic structural gradient material was created by Osipovich et al.[72] utilizing an in-house AM wire-feed EBW machine. The substrate was a rectangular AISI 304 plate with a thickness of 12 mm, and the feedstock materials were

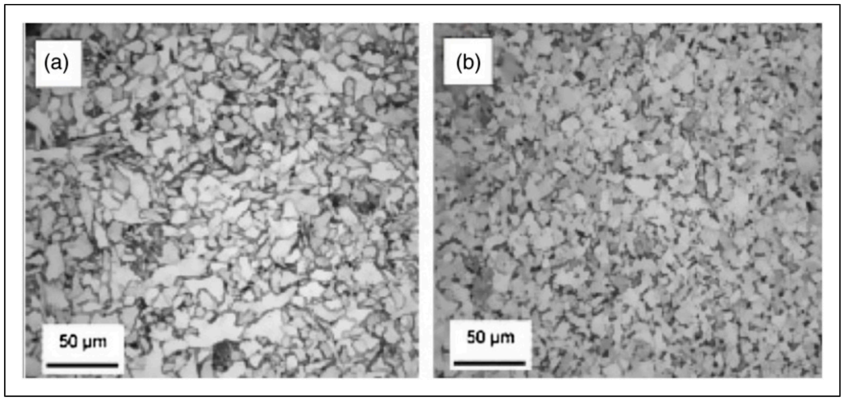


Figure 15. Microstructure of wall (a) GMAW deposited (b) rolled.

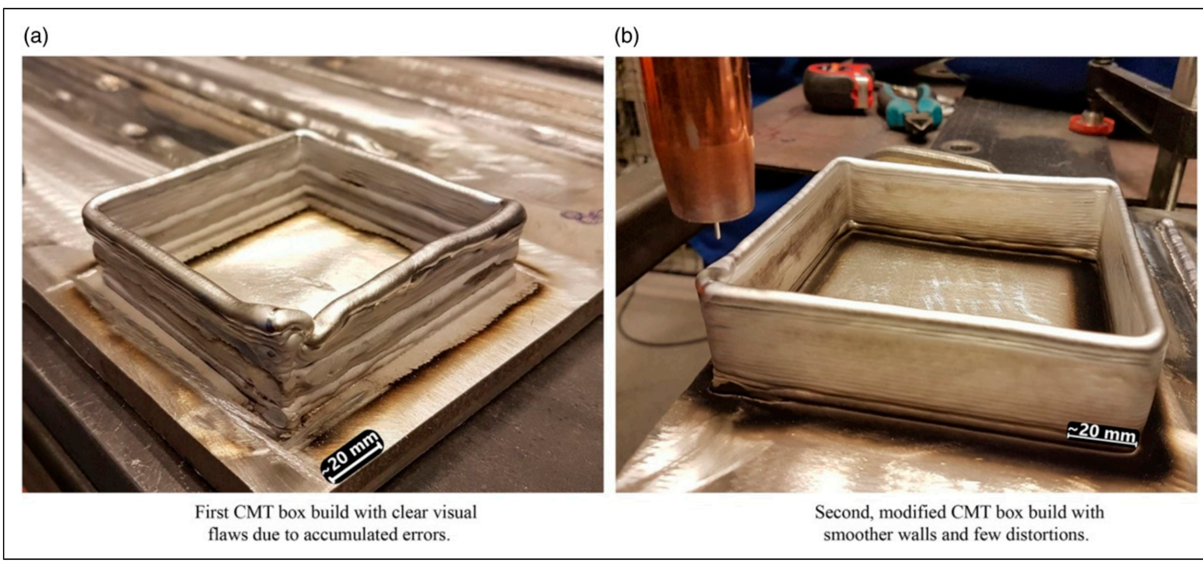


Figure 16. (a–b) Construction of square box using WAAM.[117]

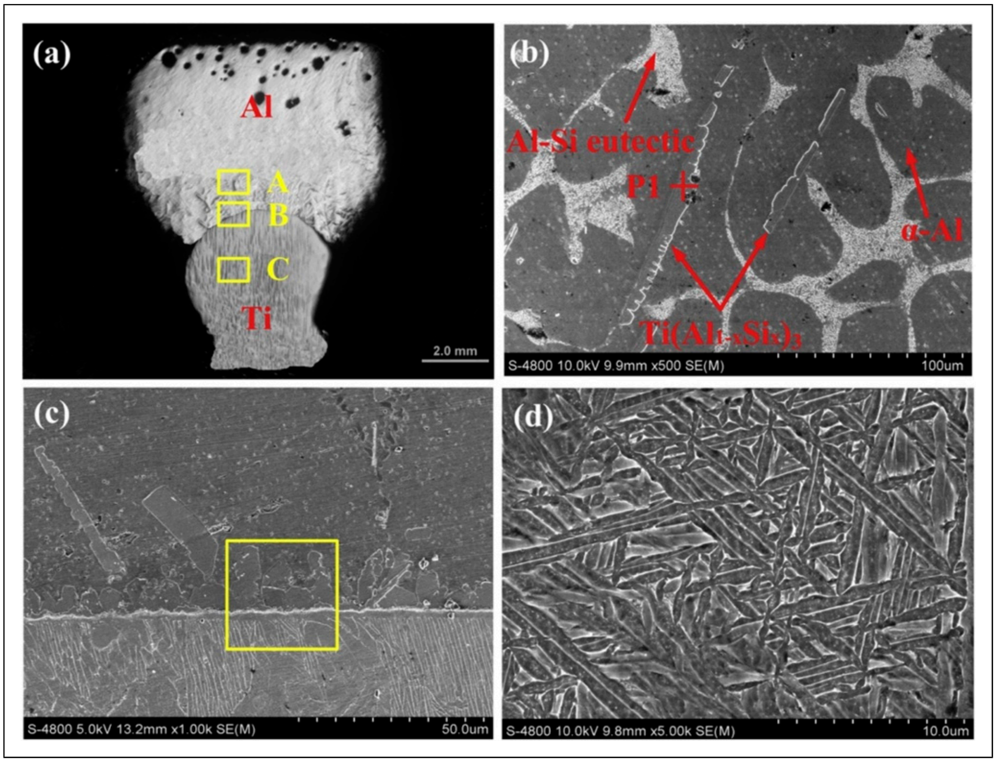
copper C11000 and 304 SS wires with a diameter of 1 mm. Figure 23 depicts the height disparity of microhardness in the SS/copper wall cross-section.

The substrate was a rectangular AISI 304 plate with a thickness of 12 mm, and the feedstock materials were copper C11000 and 304 SS wires with a diameter of 1 mm. Figure 31 depicts the height disparity of microhardness in the SS/copper wall cross-section. Panchenko et al.[73] explored the phase composition, microstructure, mechanical characteristics, and fracture processes in EBAM-produced chromium-nickel stainless steel before and after post-built Solid Solution Treatments (SST). Coarse Nb-based particles had little effect on the deformation pattern but do help with pore development (Figure 24).

Kalashnikova et al.[74] used their self-developed wire-feed EB-based AM equipment to create block-shaped samples. The hardening patterns of aluminum-silicon alloy A04130 and aluminium magnesium alloy AA5056 produced using EBM technology were investigated. After the EBAM process, the base metal of the AA5056 alloy is represented by big elongated grains that develop epitaxially. The average grain size ranges from 132.5 m to 76.1 m in height and breadth to 52.7 m and 30.4 m in height and width, respectively (Figure 25).

Laser beam welding-based additive manufacturing

It is a fabrication method that is an important part of Industry 4.0, which seeks to use numerous sensors for continuous process control. The geometric inaccuracy of produced components is the current LBAM difficulty. Francis and Bian et al.[75] created the Deep Learning



Figures 17. (a–d) Cross-sectional morphology of component.

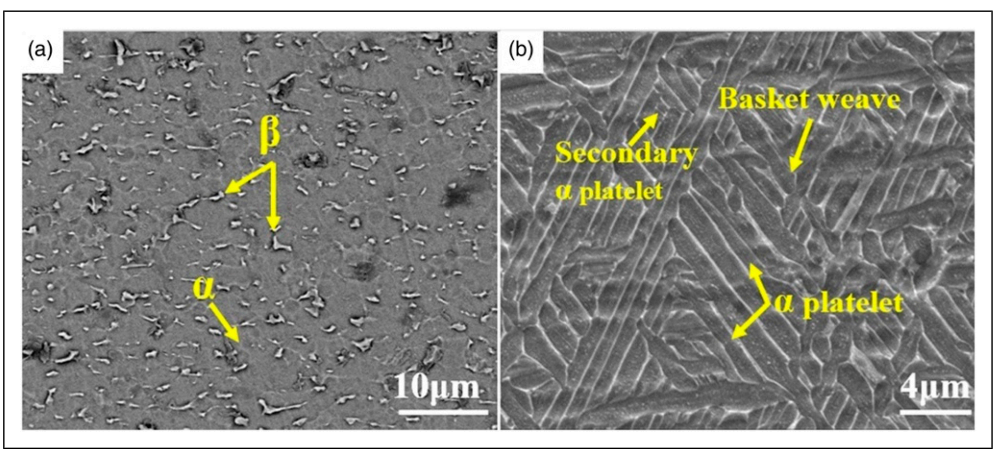


Figure 18. Microstructure of BM: (a) Wrought Ti-6Al-4V; (b) WAAMed Ti-6Al-4V.[118]

technique to improve accuracy and forecast distortion. Du et al.[76] used wire-based laser AM to investigate the dimensional properties of thin-walled Ti-6Al-4V components. The outcome demonstrates that as the number of layers is increased, the thickness of the layer on thin-walled parts progressively rises at first before stabilizing quickly. Zhang et al.[77] developed a novel AM method that uses low-power pulsed laser-assisted welding to fabricate metal components. The results show that the rational range of the laser power in LBW-based AM was about 200W to 400W, to assure the forming quality. Caiazzo[78] studied the effects of changing the laser power and processing speed while depositing a single trace of Ti-6Al-4V wire across a substrate. The geometrical responses, including dilution, trace height, breadth, and depth, were taken into consideration. It was determined that, for a particular processing speed, laser power has no influence on trace height but noticeably has an effect on trace width. Miao et al.[79] have investigated the

Table 1. Mechanical properties of stainless steels parts.

Direction	YS (MPa)	UTS (MPa)	Elongation (%)
Vertical	322.2	539.9	43.1
Horizontal	365.5	590.3	42.3

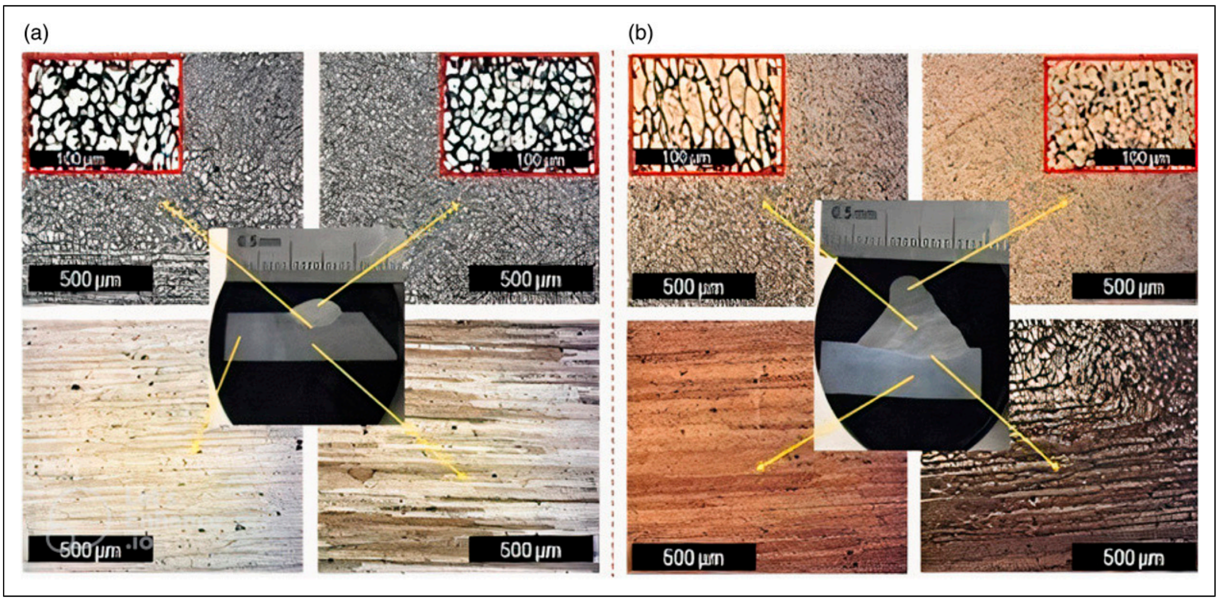


Figure 19. Microstructure (a) single layer overlay (b) 3D printed parts.

microstructure advancement and mechanical properties of the LAHAM sample. Figure 26 depicts the microstructure of a LAHAM sample perpendicular to the scanning direction. They discovered that the laser Zone (LZ) contains finer granules than the HAZ, which is due to the increased cooling rate and enhanced fluid movement in the laser zone.

Brandl et al.[80] created the Ti-6AL-4V cylinder using laser-based WAAM and assessed the mechanical characteristics of the deposited plates concerning aerospace material requirements. They have acquired an average hardness rating of 355 ± 28 HV0.5 in constructed conditions. The effects of laser amplification with both a leading and the following laser beam on CMT-based WAAM have been researched by Nasstrom et al.[81] The topological capabilities of WAAM are found to be best enhanced by a trailing laser beam.

Comparison study

The applicability of WAAM in numerous areas has increased the need for study in this area. According to the Web of Science, more than 60 review articles (including conferences and proceedings) on this topic have been published in the last 4 years (2018–2021), with the majority of them published in 2021. Almost 40% of the evaluations in these review articles focused on wire arc additive manufacturing of any given alloy as shown in Figure 27.

Due to its benefits, including the capacity to manufacture complicated parts and the ability to save material throughout the manufacturing process, AM technology is outstanding for welding technology. It's a novel development in the industry that AM-produced components may be combined with welding and small-to medium-sized pieces.[82] The features of different types of arc welding heat sources used in AM including GTAW, GMAW, and PAW are shown in Table 3.[83,84]

Table 4 summarizes the parameters that were considered for the arc and beam welding-based AM technique. In comparison to alternative laser-based deposition techniques, Kindermann et al.[85] showed that CMT-based WAAM-produced heat-treatable in 718 alloys demonstrates greater strength and adequate responsiveness.

Elmer et al.[86] employed several wire-feed AM methods to compare the high deposition rate disparities between laser and electron beam heat sources. They concluded that laser-wire AM utilized the least amount of energy per unit length of weld and provided the most control over the melt pool and surface quality. Table 5 displays the hardness, tensile, and qualitative parameters of various WAAMs.

Nagasai et al.[87] developed 308 L austenitic stainless steel cylindrical components using two separate arc welding

Table 2. Advantages and disadvantages of HED welding.[68]

Advantages	Disadvantages
Low heat input	Difficulty in improving fusion zone characteristics by employing filler material
Narrow heat-affected zone	High solidification rates
Deep penetration	Difficulty in employing filler material to increase fusion zone properties
High depth-to-width aspect ratios	Higher initial equipment investment
Reduced distortion	
Extraordinary energy transfer efficiency	
Less consumable costs	

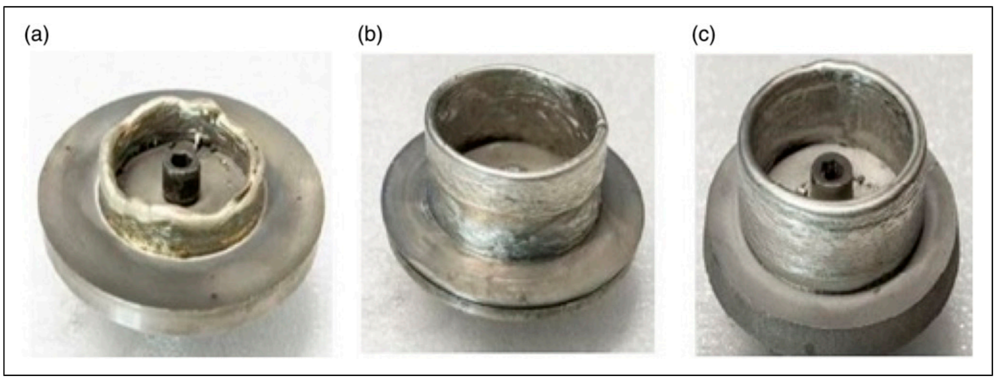


Figure 20. Cylindrical blanks with different deposition velocities (a) 0.10 (b) 0.23 (c) 0.18.

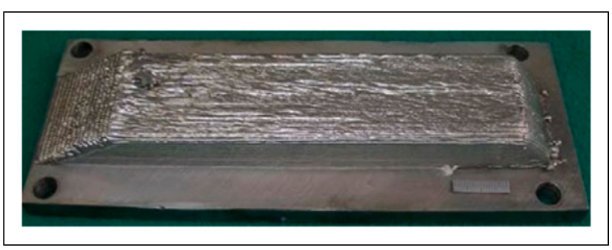


Figure 21. Macrostructure of EBAM LNM 307 plate.

Figure 22. EBW-AM fabricated Ti6Al4V wall.

techniques. The mechanisms and effects of the processes on the microstructure and mechanical properties were investigated. Figure 28 depicts micrograph images of GMAW and CMT components generated by the image analysis tool ImageJ. The photos clearly illustrate that the volume fraction of the phase in the GMAW is substantially smaller than in the CMT.

Aldalur et al.[88] investigated the thermal expansion behavior of Invar specimens made with GMAW-based and PAW-based WAAM technologies. Because of the lower heat input of the deposition process, the Invar material generated by PAW included a larger concentration of niobium carbides than the sample produced by GMAW. The microstructure images for the WAAM process are shown in Figure 29.

Recent developments in welding-based additive manufacturing

Initially, AM may combine multiple fusion welding processes such as GMAW, CMT, GTAW, PAW, EBW, and LBW. It entails melting followed by solidification, whereas solid-state AM techniques include substantial plastic deformation. Currently, the widespread acceptability of fusion welding-based AM is limited. Moreover, these techniques typically yield extremely textured columnar grains with anisotropic mechanical properties. Because they overcome the difficulties associated with fusion welding-based AM techniques, solid-state welding-based AM methods are gaining appeal as an alternative to these

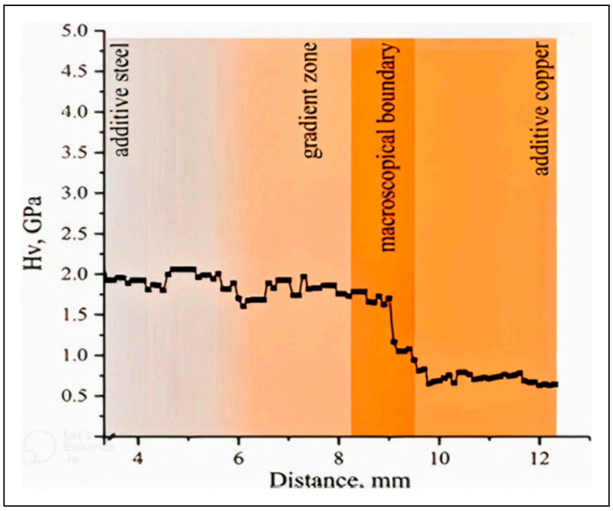


Figure 23. Microhardness with the distance from the substrate.

approaches.[89] Some of the solid-state AM methods are friction stir additive manufacturing (FSAM), ultrasonic additive manufacturing (UAM), and additive friction stir deposition (AFSD).[90–92] AFSD provides a deformation processing path to metal, with material addition and bonding accomplished by severe plastic deformation at extreme temperatures.[93] In recent years, FSAM based on the FSW principle has been developed as one of the revolutionary solid-state AM technologies, and preliminary research has shown that it can overcome restrictions, particularly for light alloy additive manufacturing.[94] Table 6 depicts an approximate history of research in the field of friction-based additive methods (FATs). The list is not full, but it clearly shows that, despite the early introduction of FATs, fewer academics have investigated this highly novel topic.

There are two approaches to FSAM: stacked-based FSAM and powder-based AFSD. Both methods have the same principle, but their processing is different. Metal plates or layers are linked one by one in stacked-type FSAM. To assure the connecting of two stacked layers at the same time, the tool pin is made longer than the created layer. The graphical procedure of the FSAM technology is shown in Figure 30.[95]

Figure 31 depicts a macrograph of the weld and a hardness profile along the material's center line. They determined that a significant improvement in hardness may be

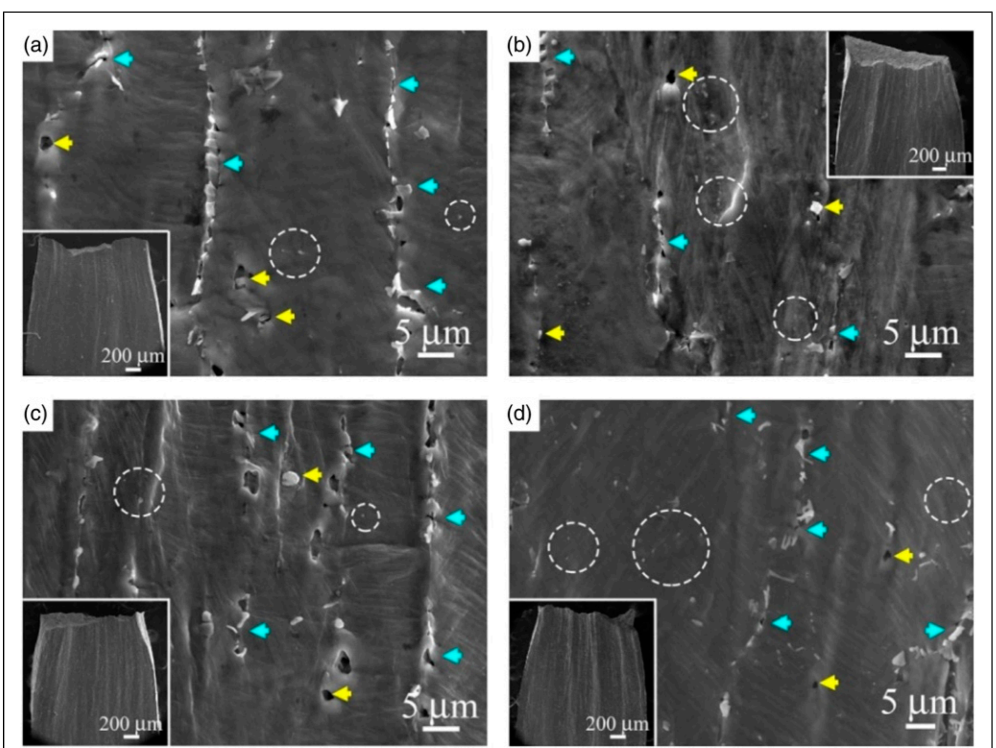


Figure 24. SEM pictures of the EBAM specimens: (a) as-built (b) SST for 1 h (c) SST for 5 h (d) SST for 10 h.

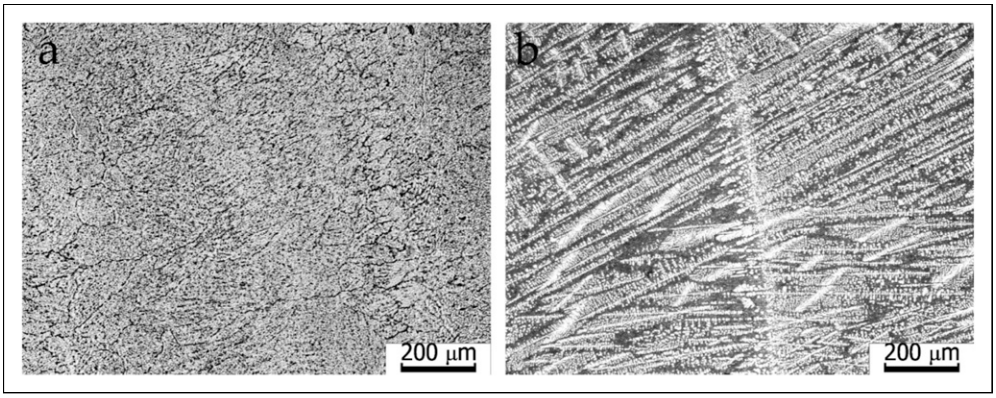


Figure 25. Base metals in as-built samples of (a) AA5056 and A04130 (b) after EB-AM.

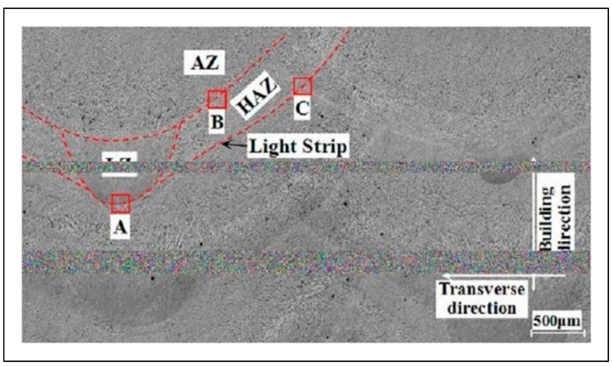


Figure 26. Microstructure of LAHAM sample.[79]

detected over the whole layer thickness when related to the base material.

Zhang et al.[96] created an integrated model in FSAM to forecast microstructures and mechanical characteristics. They concluded that re-heating and re-stirring in FSAM enhanced hardness and yield strength. Zhao et al.[97] conducted the FSAM on 2195-T8 aluminum–lithium alloy sheets with a thickness of 2 mm. The impact of tool pin parameters on interfacial bonding properties among additively built layers has been explored. Figure 32 depicts microstructure pictures of the five tools' constructions.

They discovered that cylindrical pins and conical pins with three flats are unsuitable for the FSAM method because they provide extremely poor material mixing characteristics along the bonding contact. Ultrasonic additive manufacturing (UAM) is a solid-state AM method that uses metal foil feedstock to generate near-net-form objects. Han et al.[98] explored how the welding power affects the strength of as-welded UAM steel. The shear strength of a cobalt-chromium-coated sonotrode is increased. Batista et al.[99] investigate and develop a unique resistance spot welding process in zinc-coated steel sheets using additive manufacturing (AMSW), which is used in the car industry. In contrast, spot welding was also accomplished using the usual resistance spot welding process (RSW). The outcomes demonstrated that when the best settings were used, the AMSW had 34.47% greater shear tensile stress and 28.57% higher tensile stress with a transverse load to the weld spot than the standard RSW.[100–109]

Insights, discussions, and future perspectives

The manufacturing industry is being revolutionized by AM, which enables the layer-by-layer deposition process to fabricate structures in almost net shape and with minimal material waste. But there are dimensional restrictions on parts made using the AM technique. According to current studies, to solve this issue, metal materials produced using AM can be combined with various welding techniques. This article intends to review the basic concepts, the effect of process parameters, possible materials, and an understanding of defect formation of the welding-based AM. In addition, the effects of these methods on the mechanical properties and microstructures have been addressed. AM technique differs from the welding technique in that it offers advantages such as sophisticated component manufacturability, material savings, and configurable components throughout the process. AM is closely related to welding, and the collaboration is helpful to the progress of both technologies. This manufacturing technique has significantly increased as a result of the strong economic and scientific interest. In general, the use of welding-based AM to create parts with non-porous, and good fatigue strength is promising for many industries.

The previous sections of this review article detail the many aspects of the state of the research in the area of welding-based AM. In summary, numerous concepts are being introduced in AM that has been widely employed in arc welding with filler material. As a result, clarification of fundamental terminology is critical to creating a shared

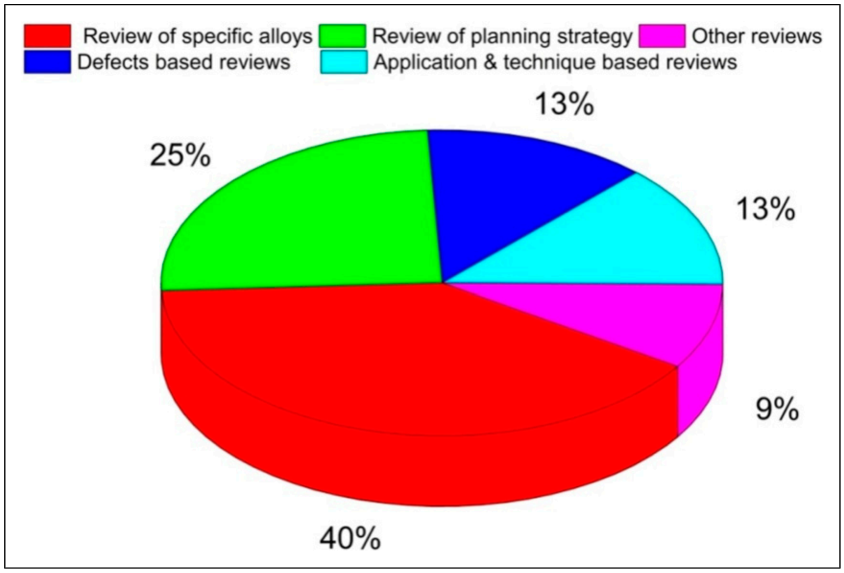


Figure 27. Emphasis of review articles of WAAM process.[119]

Table 3. Characteristics of various WAAM processes.

WARM	Heat source	Features
GMAW-based	GMAW	Low arc stability, wire electrode, deposition rate: 3–4 kg/h, and spatter
	CMT-GMAW	Low heat input, wire electrode, deposition rate: 2–3 kg/h, zero spatters, and high process tolerance
	TandemGMAW	Easy control, two-wire electrodes, deposition rate: 6–8 kg/h
GTAW-based	GTAW	Separate wire feed process, wire, and torch rotation are needed, non-consumable electrode, deposition rate: 1–2 kg/h and
PAW-based	Plasma	Distinct wire feed process, wire, and torch rotation are desirable, non-consumable electrodes, and deposition rate: 2–4 kg/h

Table 4. Process parameters for different welding based AM process.

Sl No	Welding-based AM process	Process parameters	Ref.
1	GMAW-AM	Current, arc voltage, wire feed rate, deposition rate, contact tip-to-layer angle, stand-off distance, and gas flow rate	Rajkumar et al.[122]
2	GTAW-AM	Current, wire feeding speed, frequency, gas flow rate, the electrode to filler wire, travel speed, and gas flow rate	Guo et al.[123]
3	PAW-AM	Deposition rate, wire travel speed, intensity, and average energy	Martina et al.[62]
4	LBW-AM	Defocusing amount, power, wire feeding speed, and scanning speed	Ning et al.[124]
5	EBW-AM	Accelerating voltage, beam current, scanning frequency, beam rate, beam sweep, and wire-feed rate	Fuchs et al.[125]

backdrop between welding and AM. In general, there has been less research into beam welding-based AM techniques than arc welding-based AM techniques. One of the biggest problems is that fusion welding-based AM cannot produce incredibly complicated structures. The hybridization of the arc with beam welding-based AM was discovered to increase the process capabilities and support the production of high-quality metallic parts. However, the hybridization of beam and arc for AM has not received much attention. Welding and AM have many characteristics, and this complementarity is advantageous to the development of both technologies. Therefore, it is hoped that research into

Table 5. Summary of AM builds parameters and resulting properties.

Sl.No	Description	Properties	LBW-AM	EBW-AM
1	Build properties	Microhardness (HV)	214	172.6
		Microhardness (HRB)	92.5	83.1
2	Tensile test results in the longitudinal direction	Yield stress	444.0	283.4
		UTS	617.8	565.4
		Elongation to failure (%)	47.7	46.3
3	Tensile test results in transverse direction	Yield stress	482.0	342.0
		UTS	657.8	584.0
		Elongation to failure (%)	46.2	49.6
4	Qualitative	Cost of equipment	Medium	High
		Deposition rate	Low	Medium
		Surface finish	High	Low

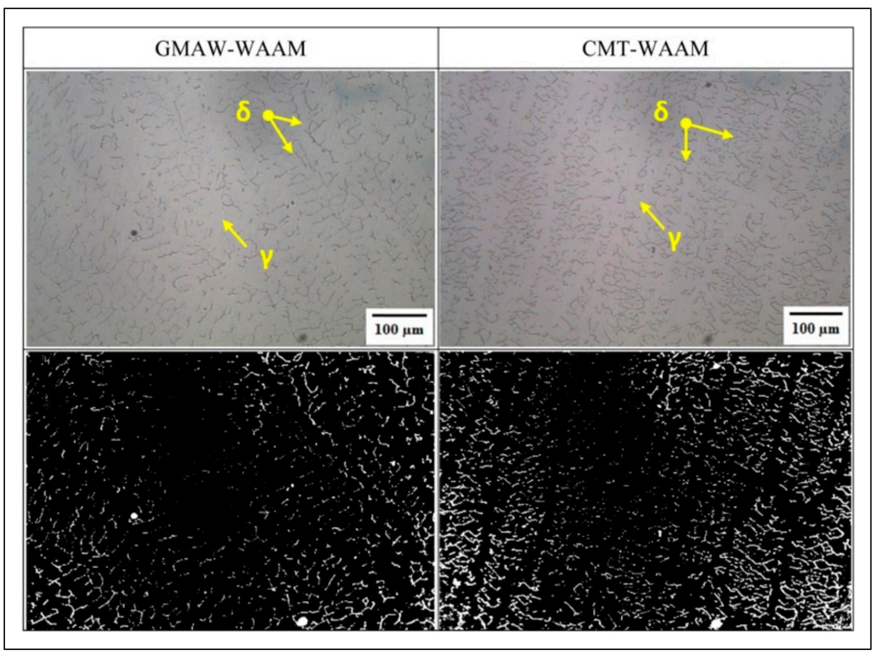


Figure 28. Austenite and ferrite phases (a) GMAW (b) CMT

the application of various welding techniques for the various materials produced by AM will increase. Future research predicts that combining AM technology with welding techniques will increase in popularity.

This technology has very promising prospects. The main areas of research in the near future will be on the development of newer materials, the fabrication of intricate patterns, the management of grain and phase changes, and microstructure through a greater variety of alloys and composites, among other things. Optimization and neural networks have demonstrated outstanding successes over the past 10 years in a variety of fields, particularly those involving applications involving image data, which offers up new opportunities for the subject of welding-based AM. The FSAM process has numerous advantages, such as good mechanical and microstructural characteristics, structural efficiency, and environmentally friendly processing, which is evident after examining the existing literature. The FSAM

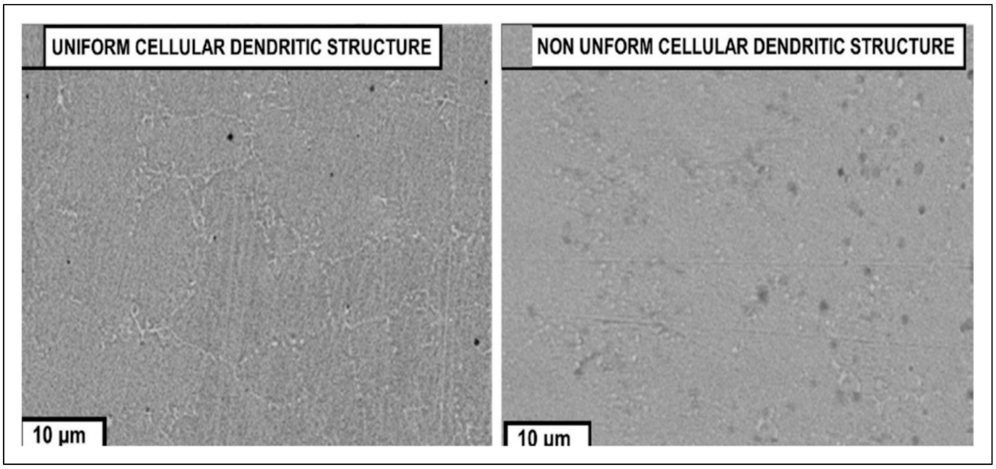


Figure 29. SEM micrographs for WAAM process (a) GMAW (b) PAW

Table 6. Timeline of friction additive techniques.[121]

Sl.No	Year	Development
1	2002	Patented friction joining for AM
2	2005	Stated the additive FSW method
3	2006	FSW/P applied for AM of components
4	2011	Friction-based AM and termed friction deposition
5	2012	FSAM can achieve components with low production and low waste
6	2015	Fabrication of magnesium-based alloys using FSAM
7	2016	Granted patent on AFS
8	2017	Fabrication of Inconel 625 using AFS

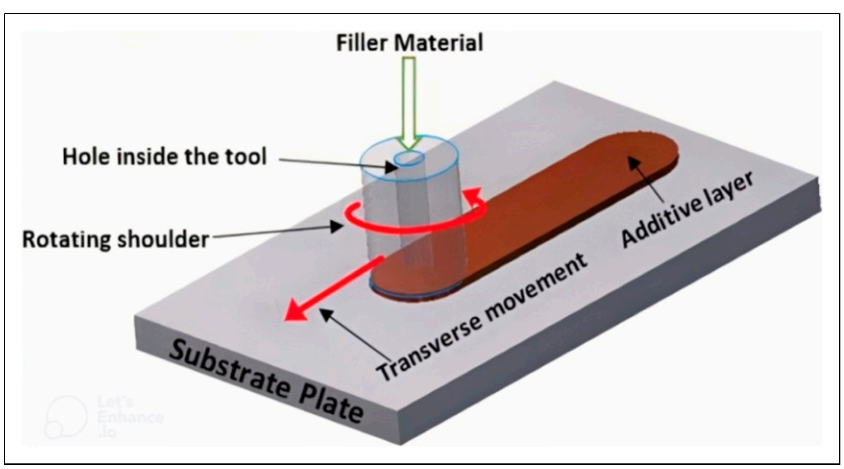


Figure 30. Schematic arrangement of FSAM technique.

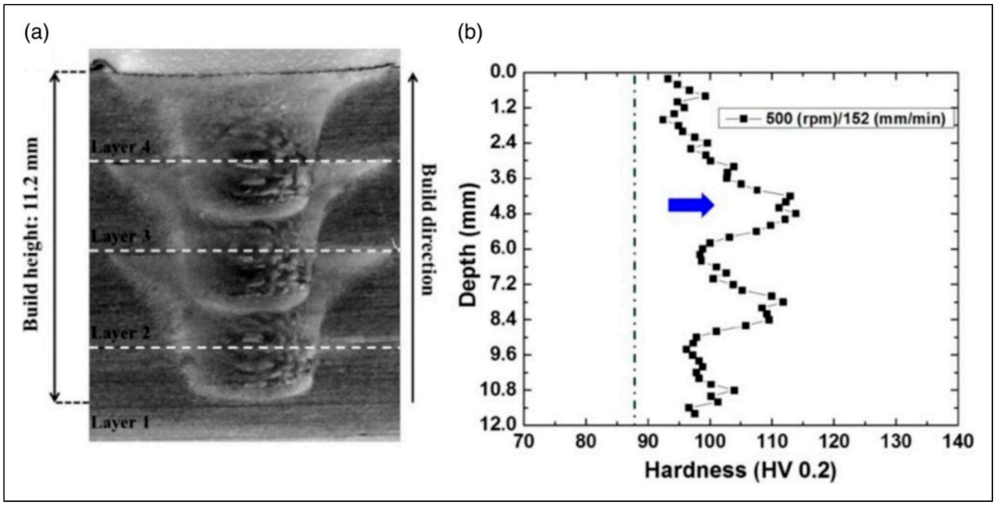


Figure 31. Macrograph and hardness profile of AA5083 alloy fabricated using FSAM.[120]

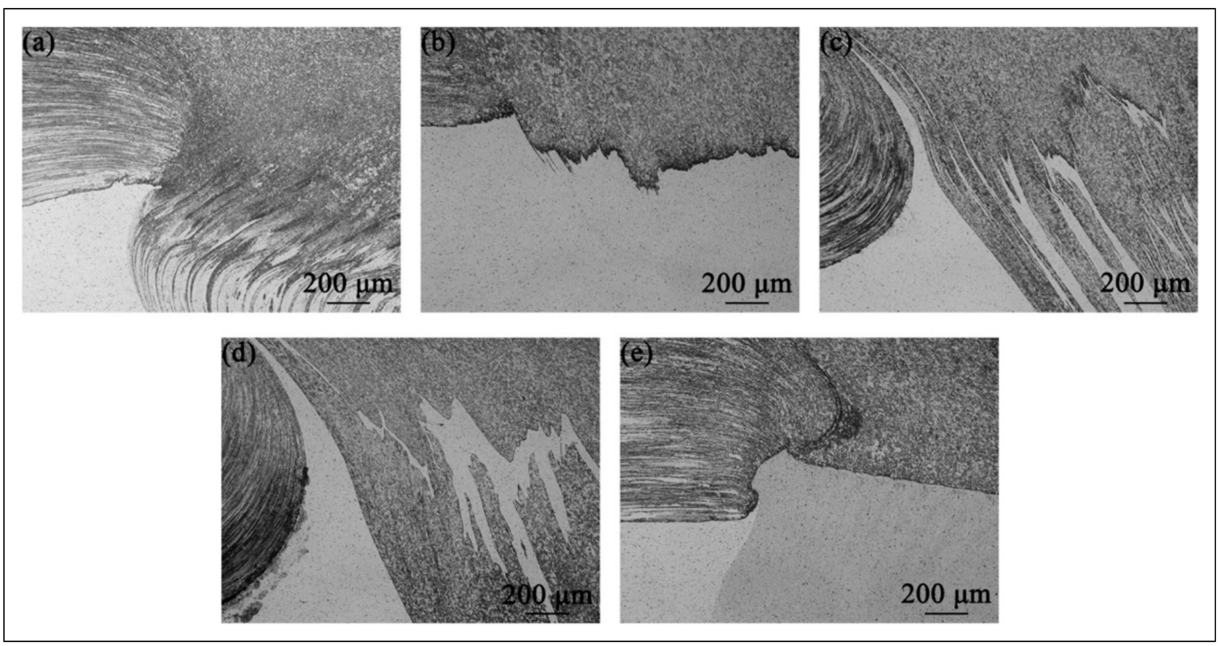


Figure 32. Interfacial formations of the builds manufactured with different tools (a) convex (b) conical (c) cylindrical pin with concave (d) flared pin and (e) cylindrical pin.[97]

process is more flexible in the future for engineering applications because of these characteristics. Further study is needed to develop FSW-based AM technologies that may overcome the limitations of fusion welding. To develop cutting-edge methods, researchers should focus on building FSW-based AM processes.

Conclusion

The application of AM processes in combination with standard welding processes such as GMAW, CMT, GTAW, EBW, LBW, FSW, and USW on raw materials including wire, plates, and sheets (excluding powder) has been investigated. The following findings may be drawn from this review article:

(i) A high deposition is a key advantage of GMAW-based AM, but it is also accompanied by higher heat input, which results in residual strains and distortions. AM based on CMT welding is appropriate for large-scale stainless steel products with low-medium mechanical characteristics needs. TIG and PAW-AM techniques might be utilized for small-medium titanium and stainless steel with medium-high mechanical needs.

(ii) AM based on laser beam welding used the minimum amount of energy and provided the best control over the melt pool and surface quality. The LBW-AM component has greater hardness, tensile strength, and qualitative characteristics than the EBW-AM component.

(iii) FSW-based AM can convert raw materials into functional products with improved mechanical and microstructural properties while consuming little material, emitting minimal emissions, and wasting minimal energy.

Acknowledgements

The researchers would like to acknowledge Deanship of Scientific Research, Taif University, for funding this work.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Taif University, for funding this work.

ORCID iDs

J Bharani Chandar https://orcid.org/0000-0001-7380-3064
Kiran Shahapurkar https://orcid.org/0000-0002-6089-2616

References

1. Lu J, He H, Shi Y, et al. Quantitative prediction for weld reinforcement in arc welding additive manufacturing based on molten pool image and deep residual network. *Addit Manuf* 2021; 41: 101980.
2. Oliveira JP, Santos TG and Miranda RM. Revisiting fundamental welding concepts to improve additive manufacturing: from theory to practice. *Prog Mater Sci* 2020; 107: 100590.
3. Shahrubudin N, Lee TC and Ramlan R. An overview on 3D printing technology: technological, materials, and applications. *Procedia Manuf* 2019; 35: 1286–1296.
4. Dhawale NM, Chavan NR, Patil DA, et al. 3D printing technology and its applications in real-world scenario. *Int j innov res technol sci eng*.2022; 11: 1167–1174.
5. Tofail SA, Koumoulos EP, Bandyopadhyay A, et al. Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Mater Today* 2018; 21(1): 22–37.
6. Dilberoglu UM, Gharehpapagh B, Yaman U, et al. The role of additive manufacturing in the era of industry 4.0. *Procedia Manuf* 2017; 11: 545–554.
7. Liu Z, Zhao D, Wang P, et al. Additive manufacturing of metals: Microstructure evolution and multistage control. *J Mater Sci Technol* 2022; 100: 224–236.
8. Derekar KS. A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium. *Mater Sci Technol* 2018; 34(8): 895–916.
9. Nurhudan AI, Supriadi S, Whulanza Y, et al. Additive manufacturing of metallic based on extrusion process: a review. *J Manuf Process* 2021; 66: 228–237.
10. Gibson I, Rosen D, Stucker B, et al. Materials for additive manufacturing. In: *Additive Manufacturing Technologies*. Cham: Springer, 2021, pp. 379–428.
11. Park SJ, Lee JE, Lee HB, et al. 3D printing of bio-based polycarbonate and its potential applications in eco-friendly indoor manufacturing. *Addit Manuf* 2020; 31: 100974.
12. Wang Y, Tan Q, Pu F, et al. A review of the application of additive manufacturing in prosthetic and orthotic clinics from a biomechanical perspective. *Engineering* 2020; 6(11): 1258–1266.
13. Haleem A, Javaid M, Khan RH, et al. 3D printing applications in bone tissue engineering. *J Orthop Trauma* 2020; 11: S118–S124.
14. Dogan E, Bhusal A, Cecen B, et al. 3D printing metamaterials towards tissue engineering. *Appl Mater Today* 2020; 20: 100752.
15. Li C, Pisignano D, Zhao Y, et al. Advances in medical applications of additive manufacturing. *Engineering* 2020; 6(11): 1222–1231.
16. Arora PK, Arora R, Haleem A, et al. Application of additive manufacturing in challenges posed by COVID-19. *Mater Today Proc* 2021; 38: 466–468.
17. Paolini A, Kollmannsberger S and Rank E. Additive manufacturing in construction: a review on processes, applications, and digital planning methods. *Addit Manuf* 2019; 30: 100894.
18. Klimyuk D, Serezhkin M and Plokhikh A. Application of 3D printing in sheet metal forming. *Mater Today Proc* 2021; 38: 1579–1583.
19. Nadagouda MN, Ginn M and Rastogi V. A review of 3D printing techniques for environmental applications. *Current opinion in chemical engineering* 2020; 28: 173–178.
20. Srivastava M, Rathee S, Patel V, et al. A review of various materials for additive manufacturing: recent trends and processing issues. *Journal of Materials Research and Technology* 2022; 21: 2612–2641.
21. Hegab H, Khanna N, Monib N, et al. Design for sustainable additive manufacturing: a review. *Sus Mat and Tec* 2023; 35: e00576.
22. Valizadeh M and Wolff SJ. Convolutional neural network applications in additive manufacturing: a review. *Adv Ind Manuf Eng*, 2022; 4: 100072.

23. Muhammad MS, Kerbache L and Elomri A. Potential of additive manufacturing for upstream automotive supply chains. *Supply Chain Forum Int J* 2022; 23(1): 1–19.
24. Zocca A, Wilbig J, Waske A, et al. Challenges in the technology development for additive manufacturing in space. *Chin J Mech Eng: Additive Manufacturing Frontiers* 2022; 1(1): 100018.
25. Mahmood MA, Chioibasu D, Ur Rehman A, et al. Post-processing techniques to enhance the quality of metallic parts produced by additive manufacturing. *Metals* 2022; 12(1): 77.
26. Rathinasuriyan C, Muniamuthu S, Mystica A, et al. Investigation of heat generation during submerged friction stir welding on 6061-T6 aluminum alloy. *Mater Today Proc* 2021; 46: 8320–8324.
27. Sai MS, Dhinakaran V, Kumar KM, et al. A systematic review of effect of different welding process on mechanical properties of grade 5 titanium alloy. *Mater Today Proc* 2020; 21: 948–953.
28. Gupta SK, Raja AR, Vashista M, et al. Effect of heat input on microstructure and mechanical properties in gas metal arc welding of ferritic stainless steel. *Mater Res Express* 2018; 6(3): 036516.
29. Rathinasuriyan C and Kumar VS. Mechanical and metallurgical properties of GTAW, GMAW and FSW lap joints on AA6061-T6 Alloy. *Advances in Materials and Processing Technologies* 2021: 1–17.
30. Das B, Yadaiah N, Ozah R, et al. A perspective review on estimation of keyhole profile during plasma arc welding process. *Mater Today Proc* 2018; 5(2): 6345–6350.
31. Dhanaraj PS and Rathinasuriyan C. Selection of intense energy welding process for high strength aluminum alloy using AHP. *Mater Today Proc* 2021; 46: 8254–8259.
32. Dhanaraj PS and Rathinasuriyan C. Optimization of fiber laser welding parameters for high strength aluminium alloy AA7075-T6. *Mater Today Proc* 2022; 52: 283–289.
33. Rathinasuriyan C, Pavithra E, Sankar R, et al. Current status and development of submerged friction stir welding: a review. *Int. J. Precis. Eng. Manuf. -GT* 2021; 8(2): 687–701.
34. Rathinasuriyan C and Senthil Kumar VS. Submerged friction stir welding and processing: insights of other researchers. *Int J Appl Eng Res* 2015; 10(8): 6530–6536.
35. Chandran R, Ramaiyan S, Shanbhag AG, et al. Optimization of welding parameters for friction stir lap welding of AA6061-T6 alloy. *Mod Mech Eng* 2018; 8(1): 31–41.
36. Anand K, Elangovan S and Rathinasuriyan C. Modeling and prediction of weld strength in ultrasonic metal welding process using artificial neural network and multiple regression method. *Mater Sci Eng A Mat Sci Eng A-Struct* 2018; 2(2): 40–47.
37. Zaza D, Ciavarella M and Zurlo G. Strain incompatibility as a source of residual stress in welding and additive manufacturing. *Eur J Mech Solid* 2021; 85: 104147.
38. Frazier WE. Metal additive manufacturing: a review. *J Mater Eng Perform* 2014; 23(6): 1917–1928.
39. Hauser T, Da Silva A, Reisch RT, et al. Fluctuation effects in wire arc additive manufacturing of aluminium analysed by high-speed imaging. *J Manuf Process* 2020; 56: 1088–1098.
40. Majeed A, Ahmed A, Lv J, et al. A state-of-the-art review on energy consumption and quality characteristics in metal additive manufacturing processes. *J Braz Soc Mech Sci Eng* 2020; 42(5): 1–25.
41. Vinoth V, Sathiyamurthy S, Natarajan U, et al. Examination of microstructure properties of AISI 316L stainless steel fabricated by wire arc additive manufacturing. *Mater Today Proc* 2022.
42. Reimann J, Henckell P, Ali Y, et al. Production of topology-optimised structural nodes using arc-based, additive manufacturing with GMAW welding process. *J Civ Eng* 2021; 10(2): 101–107.
43. Yili D, Shengfu Y, Yusheng S, et al. Wire and arc additive manufacture of high-building multi-directional pipe joint. *Int J Adv Des Manuf Technol* 2018; 96(5): 2389–2396.
44. Nagamatsu H, Sasahara H, Mitsutake Y, et al. Development of a cooperative system for wire and arc additive manufacturing and machining. *Addit Manuf* 2020; 31: 100896.
45. Mai DS. Microstructural and mechanical characteristics of 308L stainless steel manufactured by gas metal arc welding-based additive manufacturing. *Mater Lett* 2020; 271: 127791.
46. Lee HK, Kim J, Pyo C, et al. Evaluation of bead geometry for aluminum parts fabricated using additive manufacturing-based wire-arc welding. *Processes* 2020; 8(10): 1211.
47. Suárez A, Panfilo A, Aldalur E, et al. Microstructure and mechanical properties of mild steel-stainless steel bimetallic structures built using wire arc additive manufacturing. *CIRP J Manuf Sci Technol* 2022; 38: 769–773.
48. Colegrove PA, Coules HE, Fairman J, et al. Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. *J Mater Process Technol* 2013; 213(10): 1782–1791.
49. Yuan L, Ding D, Pan Z, et al. Application of multidirectional robotic wire arc additive manufacturing process for the fabrication of complex metallic parts. *IEEE Trans Ind Inf* 2019; 16(1): 454–464.
50. Pattanayak S and Sahoo SK. Gas metal arc welding based additive manufacturing—a review. *CIRP J Manuf Sci Technol* 2021; 33: 398–442.
51. Dong MY, Yue ZHAO, Quan LI, et al. Effects of Cd addition in welding wires on microstructure and mechanical property of wire and arc additively manufactured Al− Cu alloy. *Trans Nonferrous Metals Soc China* 2022; 32(3): 750–764.
52. Mohiuddin MD and Mohideen SR. Investigation on the fracture behaviour of wire arc additive manufactured rotor steel weldments after heat treatment. *Theor Appl Fract Mech* 2022; 119: 103342.

53. Plangger J, Schabhüttl P, Vuherer T, et al. CMT additive manufacturing of a high strength steel alloy for application in crane construction. *Metals* 2019; 9(6): 650.
54. Tian Y, Shen J, Hu S, et al. Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V and AlSi5 dissimilar alloys using cold metal transfer welding. *J Manuf Process* 2019; 46: 337–344.
55. Xu M, Chen Y, Zhang T, et al. Microstructure evolution and mechanical properties of wrought/wire arc additive manufactured Ti-6Al-4V joints by electron beam welding. *Mater Char* 2022; 190: 112090.
56. Benakis M, Costanzo D and Patran A. 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* 2020; 60: 61–74.
57. Gokhale NP, Kala P and Sharma V. Thin-walled metal deposition with GTAW welding-based additive manufacturing process. *J Braz Soc Mech Sci Eng* 2019; 41(12): 1–12.
58. Rodriguez N, Vázquez L, Huarte I, et al. Wire and arc additive manufacturing: a comparison between CMT and TopTIG processes applied to stainless steel. *Weld World* 2018; 62(5): 1083–1096.
59. Veeman D, Alruqi M, Subramaniyan MK, et al. Fabrication of functionally graded material via gas tungsten arc welding based wire feeding additive manufacturing: mechanical and microstructural characterization. *Mater Lett* 2022; 324: 132786.
60. Paskual A, Álvarez P and Suárez A. Study on arc welding processes for high deposition rate additive manufacturing. *Procedia Cirp* 2018; 68: 358–362.
61. Oropeza D, Hofmann DC, Williams K, et al. Welding and additive manufacturing with nanoparticle-enhanced aluminum 7075 wire. *J Alloys Compd* 2020; 834: 154987.
62. Martina F, Mehnen J, Williams SW, et al. Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V. *J Mater Process Technol* 2012; 212(6): 1377–1386.
63. Alberti EA, Bueno BMP and D'Oliveira ASCM. Additive manufacturing using plasma transferred arc. *Int J Adv Des Manuf Technol* 2016; 83(9): 1861–1871.
64. Wang L, Zhou W, Shen C, et al. Effect of substrate temperature on microstructure and mechanical properties of TiAl alloy fabricated using the twin-wire plasma arc additive manufacturing system. *J Mater Sci* 2022; 57(19): 8940–8955.
65. Li N, Fan D, Huang J, et al. Self-adaptive control system for additive manufacturing using double electrode micro plasma arc welding. *Chin J Mech Eng* 2021; 34(1): 1–14.
66. Veiga F, Gil Del Val A, Suárez A, et al. Analysis of the machining process of titanium Ti6Al-4V parts manufactured by wire arc additive manufacturing (WAAM). *Materials* 2020; 13(3): 766.
67. Artaza T, Suárez A, Veiga F, et al. Wire arc additive manufacturing Ti6Al4V aeronautical parts using plasma arc welding: analysis of heat-treatment processes in different atmospheres. *J Mater Res Technol* 2020; 9(6): 15454–15466.
68. Patterson T, Hochanadel J, Sutton S, et al. A review of high energy density beam processes for welding and additive manufacturing applications. *Weld World* 2021; 65(7): 1235–1306.
69. Fortuna SV, Filippov AV, Kolubaev EA, et al. Wire feed electron beam additive manufacturing of metallic components. In: AIP conference proceedings, Tomsk, Russia, 1–5 October 2018.
70. Węglowski MS, Błacha S, Pilarczyk J, et al. Electron beam additive manufacturing with wire–analysis of the process. In: AIP conference proceedings, Palermo, Italy, 23–25 April 2018.
71. Wanjara P, Watanabe K, De Formanoir C, et al. Titanium alloy repair with wire-feed electron beam additive manufacturing technology. *Adv Mater Sci Eng* 2019; 2019: 3979471.
72. Osipovich KS, Astafurova EG, Chumaevskii AV, et al. Gradient transition zone structure in "steel–copper" sample produced by double wire-feed electron beam additive manufacturing. *J Mater Sci* 2020; 55(22): 9258–9272.
73. Panchenko MY, Maier GG, Moskvina VA, et al. Microstructure and mechanical properties of Nb-alloyed austenitic CrNi steel fabricated by wire-feed electron beam additive manufacturing. *Mater Char* 2022; 190: 112063.
74. Kalashnikova T, Chumaevskii A, Kalashnikov K, et al. Regularities of friction stir processing hardening of aluminum alloy products made by wire-feed electron beam additive manufacturing. *Metals* 2022; 12(2): 183.
75. Francis J and Bian L. Deep learning for distortion prediction in laser-based additive manufacturing using big data. *Manufacturing Letters* 2019; 20: 10–14.
76. Du F, Zhu J, Ding X, et al. Dimensional characteristics of Ti-6Al-4V thin-walled parts prepared by wire-based multi-laser additive manufacturing in vacuum. *Rapid Prototyp J* 2019; 25(5): 849–856.
77. Zhang Z, Sun C, Xu X, et al. Surface quality and forming characteristics of thin-wall aluminium alloy parts manufactured by laser assisted MIG arc additive manufacturing. *Int j lightweight mater manuf* 2018; 1(2): 89–95.
78. Caiazzo F. Additive manufacturing by means of laser-aided directed metal deposition of titanium wire. *Int J Adv Des Manuf Technol* 2018; 96(5): 2699–2707.
79. Miao Q, Wu D, Chai D, et al. Comparative study of microstructure evaluation and mechanical properties of 4043 aluminum alloy fabricated by wire-based additive manufacturing. *Mater Des* 2020; 186: 108205.
80. Brandl E, Baufeld B, Leyens C, et al. Additive manufactured Ti-6Al-4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications. *Phys Procedia* 2010; 5(Pt 2): 595–606.

81. Näsström J, Brueckner F and Kaplan AF. Laser enhancement of wire arc additive manufacturing. *J Laser Appl* 2019; 31(2): 022307.
82. Karayel E and Bozkurt Y. Additive manufacturing method and different welding applications. *J Mater Res Technol* 2020; 9(5): 11424–11438.
83. Çam G. Prospects of producing aluminum parts by wire arc additive manufacturing (WAAM). *Mater Today Proc* 2022; 62: 144582.
84. Zeli WANG and Zhang Y. A review of aluminum alloy fabricated by different processes of wire arc additive manufacturing. *Mater Sci* 2021; 27(1): 18–26.
85. Kindermann RM, Roy MJ, Morana R, et al. Process response of inconel 718 to wire+ arc additive manufacturing with cold metal transfer. *Mater Des* 2020; 195: 109031.
86. Elmer JW, Vaja J, Carpenter JS, et al. Wire-based additive manufacturing of stainless steel components. *Weld J* 2020; 99: 8. LLNL-JRNL-771645; LA-UR-19-23147).
87. Nagasai BP, Malarvizhi S and Balasubramanian V. Mechanical properties and microstructural characteristics of wire arc additive manufactured 308L stainless steel cylindrical components made by gas metal arc and cold metal transfer arc welding processes. *J Mater Process Technol* 2022; 30: 188.
88. Aldalur E, Suárez A and Veiga F. Thermal expansion behaviour of Invar 36 alloy parts fabricated by wire-arc additive manufacturing. *J Mater Res Technol* 2022; 19: 3634–3645.
89. Kobryn PA, Ontko NR, Perkins LP, et al. Additive manufacturing of aerospace alloys for aircraft structures. Air force research lab wright-patterson afb oh materials and manufacturing directorate. *Cost Effective Manufacture via Net-Shape Processing. Meeting Proceedings RTO-MP-AVT-139, Paper 3*. Neuilly-sur-Seine, France: RTO, 2006, pp. 3-1–3-14.
90. Mishra RS, Haridas RS and Agrawal P. Friction stir-based additive manufacturing. *Sci Technol Weld Join* 2022; 27(3): 141–165.
91. Tuncer N and Bose A. Solid-state metal additive manufacturing: a review. *Jom* 2020; 72(9): 3090–3111.
92. Yin S, Cavaliere P, Aldwell B, et al. Cold spray additive manufacturing and repair: fundamentals and applications. *Addit Manuf* 2018; 21: 628–650.
93. Yu HZ and Mishra RS. Additive friction stir deposition: a deformation processing route to metal additive manufacturing. *Materials Research Letters* 2021; 9(2): 71–83.
94. Tan Z, Li J and Zhang Z. Experimental and numerical studies on fabrication of nanoparticle reinforced aluminum matrix composites by friction stir additive manufacturing. *J Mater Res Technol* 2021; 12: 1898–1912.
95. Srivastava AK, Kumar N and Dixit AR. Friction stir additive manufacturing–an innovative tool to enhance mechanical and microstructural properties. *Mater Sci Eng B* 2021; 263: 114832.
96. Zhang Z, Tan ZJ, Li JY, et al. Experimental and numerical studies of re-stirring and re-heating effects on mechanical properties in friction stir additive manufacturing. *Int J Adv Des Manuf Technol* 2019; 104(1): 767–784.
97. Zhao Z, Yang X, Li S, et al. Interfacial bonding features of friction stir additive manufactured build for 2195-T8 aluminum-lithium alloy. *J Manuf Process* 2019; 38: 396–410.
98. Han T, Kuo CH, Sridharan N, et al. Effect of weld power and interfacial temperature on mechanical strength and microstructure of carbon steel 4130 fabricated by ultrasonic additive manufacturing. *Manufacturing Letters* 2020; 25: 64–69.
99. Batista M, Furlanetto V and Duarte Brandi S. Development of a resistance spot welding process using additive manufacturing. *Metals* 2020; 10(5): 555.
100. Eazhil KM, Sudhakaran R, Venkatesan EP, et al. prediction of angular distortion in gas metal arc welding of structural steel plates using artificial neural networks. *Metals* 2023; 13: 436. DOI: 10.3390/met13020436
101. Zubairuddin M, Chaursaia PK and Ali B. Thermo-mechanical analysis of laser welding of Grade 91 steel plates. *Optik* 2021; 245: 167510.
102. Kumar P, Kumar R, Arif A, et al. Investigation of numerical modelling of TIG welding of austenitic stainless steel (304L). *Mater Today Proc* 2020; 27: 1636–1640.
103. Akhtar MN, Sathish T, Mohanavel V, et al. Optimization of process parameters in CNC turning of aluminum 7075 alloy using L27 array-based taguchi method. *Materials* 2021; 14: 4470. DOI: 10.3390/ma14164470
104. Sathish T, Mohanavel V, Ansari K, et al. Synthesis and characterization of mechanical properties and wire cut edm process parameters analysis in AZ61. *Materials* 2021; 14: 3689. DOI: 10.3390/ma14133689
105. Sharath BN, Venkatesh CV and Afzal A. multi ceramic particles inclusion in the aluminium matrix and wear characterization through experimental and response surface-artificial neural networks. *Materials* 2021; 14: 2895. DOI: 10.3390/ma14112895
106. Sathish T, Kaladgi ARR, Mohanavel V, et al. Experimental investigation of the friction stir weldability of AA8006 with zirconia particle reinforcement and optimized process parameters. *Materials* 2021; 14: 2782. DOI: 10.3390/ma14112782
107. Chairman CA, Ravichandran M, Mohanavel V, et al. mechanical and abrasive wear performance of titanium di-oxide filled woven glass fibre reinforced polymer composites by using taguchi and edas approach. *Materials* 2021; 14: 5257. DOI: 10.3390/ma14185257
108. Rethnam GSN, Manivel S, Sharma VK, et al. Parameter study on friction surfacing of AISI316Ti stainless steel over EN8 carbon steel and its effect on coating dimensions and

bond strength. *Materials* 2021; 14: 4967, DOI: 10.3390/ma14174967
109. Sathish T, Mohanavel V, Arunkumar T, et al. Investigation of mechanical properties and salt spray corrosion test parameters optimization for Aa8079 with reinforcement of tin + Zro2. *Materials* 2021; 14: 5260. DOI: 10.3390/ma14185260
110. Chen Z, Han C, Gao M, et al. A review on qualification and certification for metal additive manufacturing. *Virtual Phys Prototyp* 2022; 17(2): 382–405.
111. Tian X, Wu L, Gu D, et al. Roadmap for additive manufacturing: toward intellectualization and industrialization. *Chin J Mech Eng: Additive Manufacturing Frontiers* 2022; 1(1): 100014.
112. Jimenez A, Bidare P, Hassanin H, et al. Powder-based laser hybrid additive manufacturing of metals: a review. *Int J Adv Des Manuf Technol* 2021; 114(1): 63–96.
113. Treutler K and Wesling V. The current state of research of wire arc additive manufacturing (WAAM): a review. *Appl Sci* 2021; 11(18): 8619.
114. Artaza T, Bhujangrao T, Suárez A, et al. Influence of heat input on the formation of laves phases and hot cracking in plasma arc welding (PAW) additive manufacturing of inconel 718. *Metals* 2020; 10(6): 771.
115. Köhler M, Fiebig S, Hensel J, et al. Wire and arc additive manufacturing of aluminum components. *Metals* 2019; 9(5): 608.
116. Li Z, Liu C, Xu T, et al. Reducing arc heat input and obtaining equiaxed grains by hot-wire method during arc additive manufacturing titanium alloy. *Mater Sci Eng* 2019; 742: 287–294.
117. Evjemo LD, Langelandsvik G, Moe S, et al. Wire-arc additive manufacturing of structures with overhang: experimental results depositing material onto fixed substrate. *CIRP J Manuf Sci Technol* 2022; 38: 186–203.
118. Cunningham CR, Flynn JM, Shokrani A, et al. Invited review article: Strategies and processes for high quality wire arc additive manufacturing. *Addit Manuf* 2018; 22: 672–686.
119. Tomar B, Shiva S and Nath T. A review on wire arc additive manufacturing: processing parameters, defects, quality improvement and recent advances. *Mater Today Commun* 2022: 103739.
120. Palanivel S, Sidhar H and Mishra RS. Friction stir additive manufacturing: route to high structural performance. *Jom* 2015; 67(3): 616–621.
121. Srivastava M, Rathee S, Maheshwari S, et al. A review on recent progress in solid state friction based metal additive manufacturing: friction stir additive techniques. *Crit Rev Solid State Mater Sci* 2019; 44(5): 345–377.
122. Rajkumar V, Vishnukumar M, Sowrirajan M, et al. Microstructure, mechanical properties and corrosion behaviour of Incoloy 825 manufactured using wire arc additive manufacturing. *Vacuum* 2022; 203: 111324.
123. Guo Y, Quan G, Jiang Y, et al. Formability, microstructure evolution and mechanical properties of wire arc additively manufactured AZ80M magnesium alloy using gas tungsten arc welding. *J Magnesium Alloys* 2021; 9(1): 192–201.
124. Ning J, Yu ZS, Sun K, et al. Comparison of microstructures and properties of X80 pipeline steel additively manufactured based on laser welding with filler wire and cold metal transfer. *J Mater Res Technol* 2021; 10: 752–768.
125. Fuchs J, Schneider C and Enzinger N. Wire-based additive manufacturing using an electron beam as heat source. *Weld World* 2018; 62(2): 267–275.