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Review Article

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A Review on the Advancement in Hybrid Manufacturing Using Wire Arc Additive Manufacturing

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Abstract

This review paper is written to summarize the scientific efforts made to enhance hybrid manufacturing (HM) technology. The HM technology has gained significant attention both in industry and academia. Additive manufacturing (AM) technology has played a decisive role in this scenario that provides numerous advantages over conventional methods of manufacturing. In general, with the advent of new technologies in the system of manufacturing, there has been an increase in the demand of customers and markets as competition has increased. The paper starts with the advantages and disadvantages of HM and AM, with a focus on the metal additive manufacturing (MAM) and wire arc additive manufacturing (WAAM) systems and their work. From onwards, scientific and engineering efforts to evaluate the surface quality of the part and the heat affected zone effect on the microstructure and mechanical properties during the WAAM process have been discussed. How this technology has evolved over time has been described comprehensively.

Keywords

Hybrid manufacturing, Wire and arc additive manufacturing, Additive manufacturing, Metal additive manufacturing, Direct energy deposition

Introduction

The HM is a manufacturing process that uses and involves two or more different technologies in order to transcend their limitations and profit from their advantageous features [1-3]. The primary challenge for any product designer during the manufacturing process is to reduce the lead time it takes to bring the products to market and improve their ability to manufacture several variations (flexible manufacturing). Keeping costs low means, one must stay current on the cutting edge of technical change and advance at the same pace. During the most recent few years, research efforts have been focused on the production of metal components with the goal of reducing the use of materials, in particular for metals that are either costly to purchase or hard to cut.

With the advent of new technology and new systems, a new method of manufacturing was introduced called AM, which consists of a compilation of different techniques that are used to join the materials together in a layer-by-layer manner to create complex components. This methodology is a blend of different technologies, which include computer-aided design (CAD), computer-aided manufacturing (CAM), and laser and electron energy beam technology, etc. Laser scanning and computer numerical control are also included in this method [4]. The maturity of different technologies started in the 1980s, and this was the advent of additive manufacturing. This method was originally developed around polymers, waxes, and paper laminates, which were used for the process of prototyping, and this term was called rapid prototyping. But nowadays, additively manufactured parts are used as functional ones as they are made up of materials like cremains, composites, and or metals [5]. The AM is the rapidly growing technique of manufacturing, and it is widely utilized in the aviation and aerospace sectors as the interest in the use of technology and digitalization has increased over a period of time. There are different concerns regarding the use of AM, which include precision and accuracy being the crucial factors required for the fabrication of complex metal parts in geometry. This has raised the need for a new manufacturing system, which is known as MAM [6].

The MAM has now become a popular and potential method of manufacturing for its most demanded real-world application. These days, most of the complex and accurate metallic parts are employed by employing MAM technology. It has enabled the building of complex geometry and solved the problems related to accuracy and precision, which were bottlenecks presented in the old methods [7]. MAM has evolved at a very fast rate and is efficiently replacing the traditional methods of manufacturing. In the 1980s, the selective laser sintering technique was developed by Carl Deckard; this technique can print objects with different kinds of materials such as plastic, glass, or ceramics. This has become popular for end-product products, and it was used for the fabrication of metallic parts [8]. In 1994, an electric optical system was developed which describes the prototype machine based on this technology. These were just a few of the many reasons that promoted the extensive use of the MAM process. This process is a tool-less manufacturing system which holds different kinds of advantages, such as the ability to produce versatile parts with minimum human interaction at reduced design and production cycle time. Accordingly, this process has evolved as a compressive area of research.

This technology has the ability to manufacture complex parts that were not possible with the use of the conventional method of manufacturing. It has the unique characteristic that it can manufacture parts directly from the CAD model without the use of any other additional tooling system. Another important feature of this system of manufacturing is that it has a constant cost per unit part which changes with every new batch of manufacturing in the other systems [9]. MAM has a niche market that is growing at a very fast rate; it is an addition to the conventional method. But it has different limitations, like it can be used only for limited applications because when it is utilized post-processing it has a high cost and slow manufacturing speed as compared to the other methods. So, this method works well for applications that can be made economically, are no bigger than a human fist, and have complicated shapes [10].

History and Evolution of MAM

The AM emerged in 1987 with the advent of stereolithography from a 3D system; a process that has the ability to solidify the thin layers of ultraviolent light-sensitive thin liquid polymers by the use of a laser. It is regarded as the first commercial system of AM that has been introduced in the world. It has a precursor, which is the SLA 250 machine [11]. Afterwards, in 1988, there was a collaboration of the 3D systems in the SL market and the commercialization of the first-generation acrylate resins. After this commercialization, there was an introduction of the new version of the technology in Japan termed as CMET and D-MEC. This advancement in stereolithography technology was credited to Charles Hull, who filed the first patent on AM [12]. The selective laser sintering system was introduced in 1992. Both technologies are based on the use of laser radiation to solidify the polymer feedback. These are still in use for prototyping applications. In 1994, the EOS manufacturing company introduced direct metal laser sintering technology. This technology is used to print metal parts from the two components of metal powders in a liquid phase. This has made it possible to make one-step AM by melting the material around the steel particles that has a low melting point [13].

Based on the direct metal laser sintering technology, EOS made their prototype EOCINT M160 machine in 1994, and onwards, in 1995, the M250 was launched. These allowed the rapid production of metal tools and manufacture of metal parts by sintering the powder [14]. In most of the cases, the mechanical characteristics of the materials were comparable to those of metal alloys as there was a combination of low-melting materials with high-resisting materials. In 1998, Optomec, a company, commercialized its laser-engineered net-shaped metal power system that is based on the research efforts of Sandia national labs [15]. In 1999, extrudehone introduced its prometal rapid tooling system with the commercial intensive research work of the MIT process for manufacturing metal parts and tooling. In 2002, there was further evolution in AM as the sales of direct metal disposition laser cladding systems were started by precision optical manufacturing. In this process, parts are produced and repaired employing metal powder [16].

The WAAM is considered an excellent process for metallic component fabrication by aiming for a lower cost and higher deposition rate [17]. It uses an arc as a source of heat, such as in gas tungsten arc welding (GTAW) [18], plasma arc welding (PAW) [19], and gas metal arc welding (GMAW) [20]. These significantly reduce equipment costs. In terms of waste material and contamination, wire deposition provides major advantages over powder deposition. This is due to the fact that all of the metal wire is fed directly into the molten pool, while powder-based methods use recycled powders, which may cause contamination [17].

This evolution remains at the same pace as it has enabled the fabrication of usable parts in a single-step process. It has enabled the manufacturing of almost 100% dense and functional designs, but the efforts were slow yet progressive. In 2003, the TRUMPF company followed its own setup, which is based on the use of lasers for directly melting the metal alloys [12]. After initial success, however, TRUMPF has discontinued its engagement because of the fact that it has a limited market size and has fewer prospects in machine sales. In 2007, NORSK TITANNIUM Company introduced an advanced technology for the conventional plasma arc melding process. They used titanium and focused on aircraft and space applications [4].

In 2013, polymer-based fused deposition molding technology was introduced into the market. In 2015, the hype of these products ended with a decrease in the trade price, but onwards, system sales were increased, and the industry became instrumental in sectors such as aviation, energy, gas, and oil, which were quick in adopting this new technology. Over time, the systems have improved a lot, and nowadays they have become more reliable and efficient with a range of suitable materials offered to the markets that have grown significantly [21]. In 2016, DESKTOP METAL Company entered the market and introduced metal bipolar junction transistor technology, and a second hype was created as compared with the production of PBF (powder bed fusion). Recently, in 2020, a new technique of MAM called LED-based MAM was introduced. This technique is able to solve the two main concerns present in PBF, which include that it allows production in a larger volume and that it allows manual reworking of the components. These issues were causing concern in the market and are expected to be resolved in the coming years [2].

A significant benefit of WAAM production processes is their ability to manufacture large parts at high speeds. This type of manufacturing enables metal parts to be manufactured directly from CAD/CAM systems without the use of moulds. Another critical factor of importance is that we consider that quick prototyping would be a great and low-cost option in the automotive sector for testing innovative prototypes without the need for specialized equipment. It could be important to go through multiple revisions to acquire a new design [3]. Traditional manufacturing practices result in heavier and overweight parts than what is required to safely sustain the construction loads. As a consequence, AM techniques result in efficient and optimal production solutions.

In recent years, AM has now become an important part of the discussion around sustainability in manufacturing. Since it is not necessary to specify a blank geometry or accept fixtures, clamps, jigs, molds, or dies, AM (3D printing) has ushered in a whole new era in the industry that needs limited set-up and prevents unnecessary processing activities. [22]. Although AM technologies have the potential to be used in a wide variety of applications due to their improved simplicity and capability, they have still encountered resistance in traditional industry.

Classification

As far as MAM is concerned, it has three different categories, which include liquid-based, powder-based, and solid-based AM. All of the categories of AM have their own unique features, processes, and advantages. All of the techniques have their own unique manufacturing process and principles. Figure 1 shows the three main categories of these MAM processes and their subtypes.

According to AM standard EN ISO/ASTM 52921 classifies into two identification groups, it's indirect and direct MAM [23].

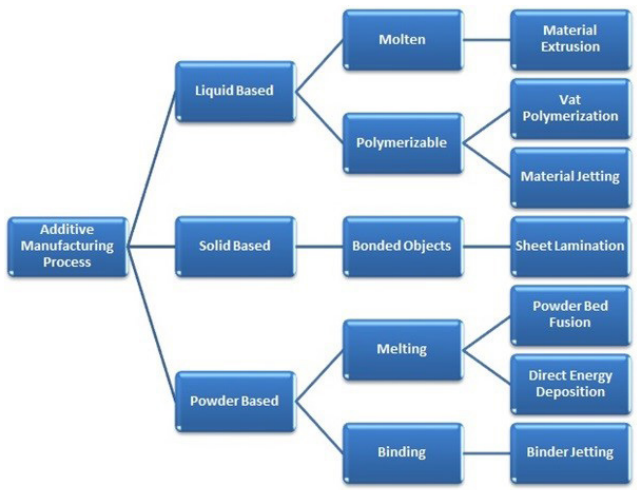

Figure 1: Schematic diagram of **(a)** MAF process for plane surface and **(b)** material removal mechanism.

Direct MAM is comprised of four groups that are currently used to manufacture metal parts (Figure 2): Binder jetting [24], where bind jetting is an established MAM technology with remarkable benefits in respect to variant AM techniques. To avoid furnishing elements from residual stress during intensifying, the use of binding powder layers is beneficial rather than heat-insulation. In the bind jetting techniques, the re-coater machine disseminates a transparent coating of metal powder along the 3D printer build plate. Granular size and size diameter (Dv10, Dv50, and Dv90) are important parameters to consider when selecting metal powders for bind jetting [2].

The PBF [25-28] is a MAM technique in which laser, inflame, or electron beam welding is utilized to liquefy and amalgamate the material while concurrently molding it into multidimensional shapes. With this technique, metal and plastic components can be produced. To melt the material, laser fusion, electron beam fusion, and thermal fusion are used. PBF works through schematic laser sintering techniques. PBF has common characteristics such as low cost, minimal sup-

Figure 2: AM classification and its indirect and direct suitability for the fabrication of metal parts [24].

port, a wide material selection (metal, plastics, and alloys), and powder recycling [12]. Sheet lamination (SL) is a 3D printing manufacturing process, also called laminating object. Manufacturing involves multiple tiers of components of foil in order to produce a subject. Building 3D subject piles, laminating with thin sheets of component, and shaping final products with ultrasonic welding or laser cutting are all examples of 3D subject pile ups. Build material (paper, plastic, and woven fiber) and forming methods (CNC milling and laser cutting) are the types of SL. Thin foil of components is fed from the roller to provide a foundation, where selective deposition lamination and ultrasonic additive manufacturing bind the layers jointly, besides CAM of laminated engineering materials shapes the layers by cutting. Fast printing, integrated HM systems, minimum cost, etc. are the advantages of using SL [9, 23, 29].

Direct energy deposition (DED) [29, 30] is a 3D printing technique that uses an energy surge, such as a plasma arc, electron beam, or laser, to liquefy components that are deposited synchronously by a nozzle. DED processes have the ability to be used for repairs or to build new products along with additional AM technology and add material to current components. Employing CAD software, the DED process commences with the fabrication of a 3D model. To fabricate a finished product model, slice into tiers with the help of software. Multiple materials can be utilized for the purpose of the DED process, such as polymers and ceramics [21, 23].

Indirect MAM is classified into three groups that are mostly used to highly fill polymers and fabricate polymer components from metals or ceramic powders: building models tier by tier in a vat of liquid photopolymerization. To cure liquid, ultraviolet light is utilized, where light is managed beyond the surface of the resin by the enforcement of motor mirrors. Following the stereolithography process and post processing techniques by utilizing plastics and polymer materials [31].

Material jetting produces products by using an identical technique to a 2D inkjet printer. Its comparatively recent 3D printing process employs fluid photopolymer and ultraviolet light to cure the material tiers. To build, the foundation material is hoarded from a nib that acts horizontally. For the process of material jetting, plastics, and polymer (polypropylene) components are used. The material jetting process has high accuracy with minimum waste, but limited material (polymer and waxes) can be utilized [9, 32]. Material extrusion, also known as fused filament fabrication, is an AM process that employs persistent composite material to formulate 3D parts. Plastic filament is ingested from a coil through a horizontal movable heated printer. The heated component is fed to build the layer-by-layer foundation. Plastic and polymers (nylon) are the materials used for this process. Usage of this technique is an extensive and low-cost process, whereas quality, accuracy, and speed are low when compared with other AM processes [23,33]. These methods are seldom applicable to the manufacturing of pure metal or alloyed components. Figure 3 shows what the geometry part can do with WAAM.

The application of the designed parts distinguishes between indirect and direct MAM processes. Metal designed components are the final items of direct MAM and are simply manufactured in compliance with requirements and the design criteria. The designed parts are master designs or instruments that will be used to obtain the metal components, mostly through conventional production methods [34].

Figure 3: Examples of geometry obtained by WAAM [34].

In DED, we can use a laser beam, electron beam, or electric arc as the source of heat energy and have the same operative concepts as arc welding processes. In this paper, the focus is on the electric arc type of DED, the electrical arc called WAAM. The three welding processes that can be used with WAAM are GTAW, PAW, and GMAW [35]. According to the American Welding Society, gas metal arc welding is a welding process using an arc between the weld pool and a continuous filler metal electrode. When we use this process with direct energy deposition technology, it's called GMAW-DED, as shown in figure 4. The mechanism is operated by using a robotic arm, and the model is built on a substrate (base plate) material, which can be cut off after it has been completed. When the wire is molten, it is extruded in the shape of beads on the substrate. As the beads adhere to one another, a sheet of metal material is formed. The procedure is then replicated, layer-by-layer, until the metal component is finished. WAAM can interact with a variety of metals as long as they are in wire shape. The collection contains nickel alloys, aluminum alloys, titanium alloys, and stainless steel. Metals which can be welded are capable of WAAM.

Operation Principle

In principle, an electric arc is used to melt the wire metal. WAAM is driven by robotic arms. When the energy source

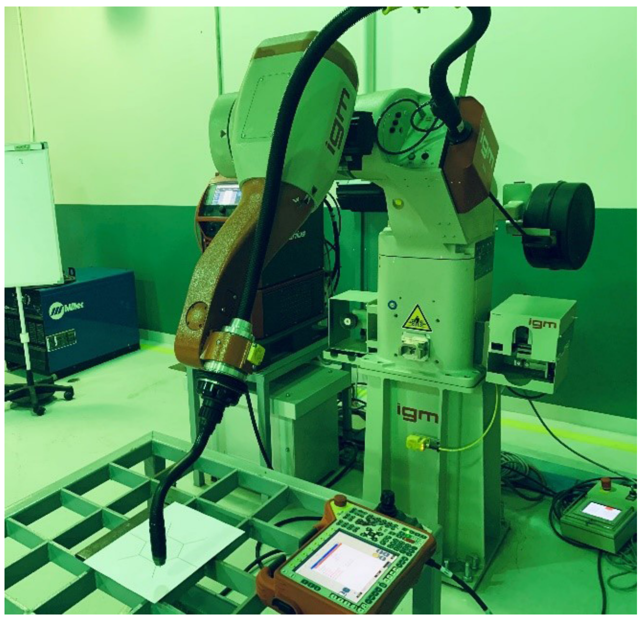

Figure 4: Robotic arm using Gas Metal Arc Welding (Robotic GMAW).

melts the rod, the melted coating over the substrate forms beads that stick together to form a layer. WAAM uses bead extrusion technology, which involves the extrusion of molten metal into beads. These provide additional benefits to WAAM compared to laser-based AM. One of these advantages is that this process and raw materials are less expensive when compared to other forms of AM. It can also be used in the repair process. When working with large components weighing more than 10 kg, we can achieve a high deposit rate. WAAM also looks at the broad spectrum of innovative structure possibilities, such as hybrid techniques with other manufacturing operations, or novel materials that come across internal structures. These innovative restraints and opportunities vary significantly from those endowed by metal powder AM engineering and innovation necessitate a fresh approach [36]. On the other hand, this results in certain limitations, such as residual stress and distortions, as well as the need for shielding gas [8]. In concert with a remissive technique, WAAM is appropriate in order to manufacture fully opaque components in an effective method. As a result, varying technique specifications for this process and intricate component demeanor cause a slew of issues that could be mitigated by a multidimensional procedure [37].

As compared to laser-based powder AM, the primary benefit of WAAM is its capability of molding a wide range of metallic substances and having a high rate of deposition. Figure 5 presents the hardware and the workpieces, while table 1 gives the results of the hardware expansion. Table 1 shows that wire arc additive manufacturing has significant advantages in terms of deposition rate, type of material it can use, and the construction of complex and large metal parts, and that the cost of WAAM is lower than thin laser-based powder AM processes.

Typically, in WAAM, the hardware cost of the device in order of magnitude is quite less than the laser powder system hardware, while the material utilization rate and deposition rate are two times higher. The aerospace industry is one of the

Table 1: Comparison of manufacturing of laser additives with WAAM [38].

	Laser based powder AM	WAAM
Rate of Deposition	0.1 to 0.2 kg/h (Low)	4 kg/h (High)
Rate of Utilization	10 - 60% (Low)	90.0% (High)
Materials that are acceptable	Titanium alloy, alloy steel	Aluminum alloy, magnesium alloy, alloy steel
Manufacturing cost	High	Low
Workpiece Applicable	Complex part, small part	General part, large part
Veracity	0.05 mm (High)	0.2 mm (Low)

modern industries where WAAM is frequently used due to its key strategic benefits relative to conventional technologies. It operates with an electric arc as an energy surge and welding wire as a raw material, and it can operate with available welding equipment. Accordingly, it is economical compared to traditional AM technologies, which require precise equipment and components. 3D CAD model using specific software or reverse engineering technique, such as 3D scanning [39, 40]. If the complexity of the metal structural elements grows, the advantages of WAAM become more important, as shown in figure 6. WAAM has a larger use, lower cost and the potential to produce large, complicated parts than laser-based powder additives, which are usually called a near-net forming process that can vastly expand material use, reduce product cycles, and significantly increase efficiency. This is the primary path for new renewable, low-carbon, and highly efficient manufacturing sectors to grow [38].

The Benefits of Using WAAM

The ability to fabrication large metal component in 3D

Across various AM techniques, WAAM is apparently compatible with the manufacturing of small-to-large scale

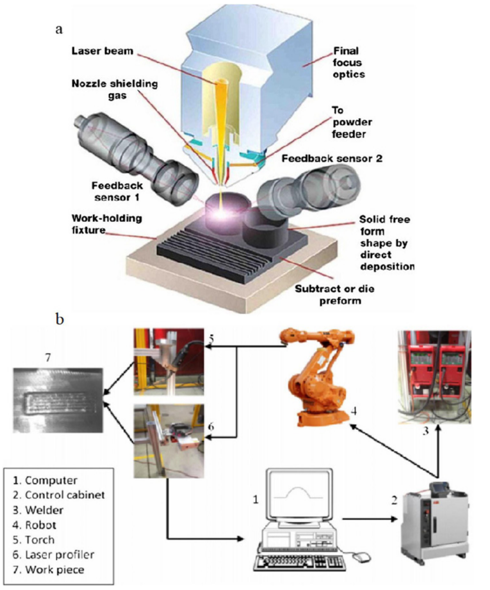

Figure 5: Components of the system **(a)** Powder additive processing using lasers and **(b)** WAAM [38].

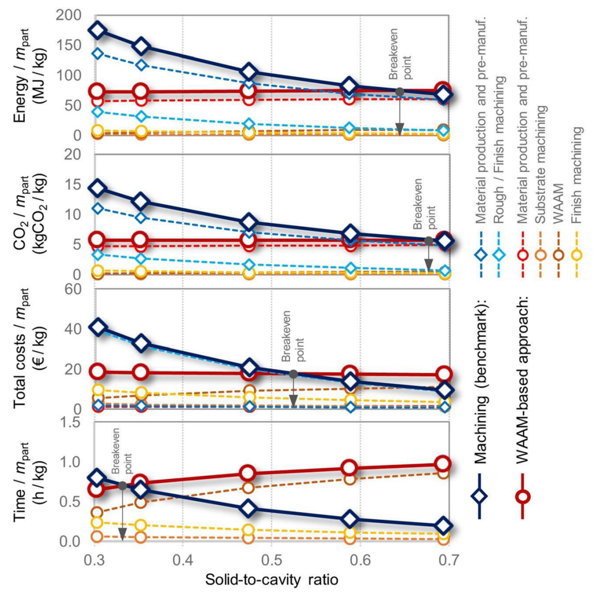

Figure 6: Shows the main effects as a feature of the solid-to-cavity ratio using various production processes [41].

components. Large-sized metal parts are ideal for the machine expansion and automation in this process (Figure 7) and mass-scalatting processes in comparison with PBF metal.

WAAM main economic factors are minimizing waste and enhancing lead time [42]. The WAAM machine's robotic arm has more room, which means it has a bigger build envelope; it can accommodate any size part. This enables the manufacturing of larger parts that would not be possible using PBF processes. The best-known instance of an additive technique is 3D printing [43].

Figure 7: An example of a WAAM component [44].

Cheaper process and materials

The welding wire used in the WAAM process is considerably less costly than the metal powder used in PBF in terms of production costs. This is due to the fact that welding is the basis of WAAM manufacturing, which is a well-established industrial technology in itself. WAAM hardware is normally made up of off-the-shelf welding technology and is less expensive than some other metal 3D printers. Additionally, wire is usually more manageable than powder, which requires the use of advanced protective equipment. Furthermore, by utilizing WAAM, more than 10 kg of steel, titanium, and other components have the potential to be used for depositing rate. For the AM technique, welding instruments and wire are the raw materials. The conventional and current technique of manufacturing from forged and billet [45] is an appropriate process to replace it because the rate of deposition is high, the cost of appliance and material is low, and the dimensional integrity is excellent. Therefore, WAAM is employable in industries like aerospace, automobiles, nuclear energy, peripheral equipment, and fortification. The manufacturing of titanium and nickel components has a complex dimensional and aerospace industry spotlight on this concern, where remissive techniques are used in these fabrics. In the Lockheed SR-71 Blackbird's dimensional substance, 93% of the titanium is comprised and 90% of the forging substance is eliminated during the production process. Norsk Titanium is approved by the federal aviation which is used in the Boeing 786 Dreamliner and its first titanium AM material built through WAAM. This type of technology reduces waste, uses less energy, lowers production costs, and saves up to 70% more time than traditional methods [37, 46].

Perfect for maintenance operations

WAAM is also an excellent choice for repairing and maintaining individual parts such as turbine blades, as well as molds and dies. WAAM may be used to repair worn-out or broken features or components by depositing new material on their surfaces. Figure 8 shows how WAAM can be used to repair metal parts. This will result in considerable cost savings because it will reduce the need for a new part to be manufactured from scratch.

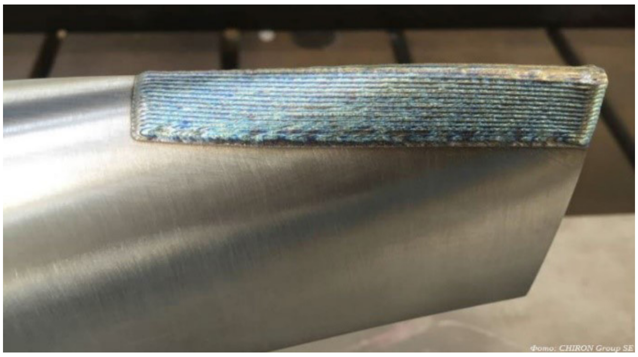

Figure 8: WAAM used to repair metal components [Image credit: CHIRON Group][47].

Limitations of WAAM

Shielding is needed for certain materials

Shielding is used when using such materials, such as titanium, to produce an inert environment and ensure proper building conditions. In other words, the procedure must take place in a gas chamber that is almost devoid of oxygen. However, the chamber reduces the part size that can be made using this technology, and fitting such a chamber raises the cost of the machinery [48].

Residual stresses and distortions

Heat management is one of the difficulties involved with WAAM. Distortions and residual stresses (RS) are major issues for the WAAM mechanism because they do not just affect component tolerance but can also lead to premature failure [49]. The WAAM is a multi-filing procedure that uses a traditional welding arc as a heat source and welding wires as a filler material. Both finite-element modeling and Neutron diffraction RS measurements have confirmed that welded structures experience a large amount of plastic stress during heating, while during cooling, much of the strain is elastically adjusted, resulting in a large RS development in the weld [50, 51].

Poor resolution

WAAM usually produces near-net-shape components with a poor surface finish. As a result, the desired surface roughness is acquired by meatal removal processes. The WAAM process is unpredictable, and the evaluation index method is single, resulting in low precision and poor surface quality of the shaped workpiece. There is significant residual stress and welding deformation, as well as welding defects such as cracks, slag inclusions, and pores. Therefore, meeting the technological specifications for the manufacturing of such large components as aerospace, aviation, nuclear power, and weaponry is challenging [38, 52].

Conclusion

The paper takes readers on a journey through the advent and advancement of AM technology with an overview of the various commercially popular AM techniques and their working principles. A thorough summary of the most prominent advantages and disadvantages has been presented, and finally, the classification and evolution of the hybrid additive processes produced in the past decade have been highlighted.

Overall, the paper demonstrates that combining traditional manufacturing processes with advanced MAM techniques can help to achieve a critical two-fold goal. The first is broadening the scope of applicability and overcoming AM's shortcomings such as low efficiency, metallurgical defects, rough surface consistency, and dimensional precision [53], and the second is increasing flexibility and encouraging new applications across traditional manufacturing processes/routes [54, 55].

The paper in particular emphasizes WAAM technology, a multidisciplinary technology with adequate room and different aspects for enhancing and interposing innovative notions. Using WAAM to create prototypes or mechanical parts is faster and less expensive than laser cladding or electron beam. The paper also demonstrates that implementation of WAAM technology is helpful in enhancing optimization parameters, monitoring of the process, design modification, heat treatment, etc. The WAAM is a multidisciplinary technology with adequate room and different aspects for enhancing and interposing innovative notions. Because using WAAM to create prototypes or mechanical parts is faster and less expensive than using laser cladding or electron beam. The paper demonstrates that implementation of WAAM technology is helpful to enhancing optimization parameters, observing, monitoring of the process, design modification, and heat treatment, and the outcome coherence with previous studies [40, 56].

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Conflict of Interest

None.

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