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Review Article

Additive manufacturing method and different welding applications

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ABSTRACT

Additive manufacturing (AM) technology, in other words "layered manufacturing" or "3D printer technology" has been developing rapidly in recent years. Unlike the traditional manufacturing method (TM), the working principle of AM technology is to create layer-based production by deposition the layers on top of each other. Owing to its advantages such as material saving, lower cost, the ability to produce parts without the need for molds and the design flexibility in complex shaped parts, it has brought a breath of fresh air to the areas where it is used primarily medical, aerospace and automotive. However, the parts produced by AM method have dimensional limitations. According to recent studies, in order to eliminate this problem, metal materials produced with AM can be combined with commonly used by different welding methods so that large parts can be obtained. In this study, these welding methods are explained and recent researches are examined. AM technology and methods are introduced. The usage areas of the method are described. In addition, the welding parameters and the effects of this new method on the mechanical properties and microstructures are investigated.

Prof. Yahya BOZKURT graduated from Marmara University, Faculty of Technical Education, Department of Metal Education in 2000. In December 2000, he became a research assistant at the Department of Metal Education, Faculty of Technical Education, Marmara University. He became Assistant Professor in 2009, Associate Professor in 2012 and Professor in 2018. He still continues to work at Marmara University, Technology Faculty, Department of Metallurgy and Materials Engineering. However, He is Head of Mechanical Metallurgy Department. He has more than 100 article and proceeding about mainly welding technology and different area. He teaches courses on welding technologies, plastic forming, manufacturing methods, work accidents and protection, materials science, etc. at undergraduate, graduate and doctoral levels. Recently he started publishing articles about additive manufacturing. He started to give master's and doctoral theses on additive manufacturing. He advised the project prepared by the undergraduate students in this regard and their projects were entitled to the top tour.

1. Introduction

Additive manufacturing (AM) is the production process which can be identified as a 3D printer or rapid prototyping, where

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the parts are created layer-by-layer deposition which is digitally controlled [1]. AM method is a technology that promises to reduce the cost of parts by reducing material waste and time to market. In addition, AM can provide an increase in design flexibility and option, which saves weight and also facilitates complex part production [2,3]. This technology was used not only for polymer materials, but also has made great progress for metal materials with its features. It can process a wide variety of metals, alloys, ceramics [4,5]. AM technology has different methods that can be classified among themselves and can be used for different materials and applications. Some of the most commonly used methods are selective laser sintering (SLS), selective laser melting (SLM), stereolithography (SLA), material jetting, binder jetting and material extrusion, etc. [5–7]. The use of different techniques for different materials provides advantages for many applications and is promising for many industries, especially; biomedical, aerospace, defense and automotive [8,9]. Since it provides the production of parts that cannot be produced with TMM easily and with rapid prototyping, it has a lot of advantages compared to TMM [10,11]. Besides, AM technique has some disadvantages. One of these is that the parts produced by this method have dimensional limitations. In order to eliminate this problem, the parts produced in small size can be combined with welding method to become larger parts [12]. Therefore, the use of welding techniques in AM technology is constantly increasing [13]. Parts produced with AM are thin layers of material and the addition of these layers can be accomplished with different welding techniques. Some of the most common welding processes for metal AM are laser beam welding, gas metal arc welding (GMAW/MIG), gas tungsten arc welding (GTAW/TIG), plasma arc welding (PAW), friction stir welding (FSW), ultrasonic welding and electron beam welding. Recent studies and future trends show that parts with good structural and mechanical properties and efficiency are used more. Unlike conventional processes, parts with such different properties can be produced in a single component and therefore good joining provided by welding methods can give the manufactured components the necessary properties [14–16]. Considering its usability AM by welding methods to assemble small parts and examining the studies, AM techniques are thought to have the ability to reveal the next industrial revolution. Therefore, AM technology also called the 4th industrial revolution is thought to revolutionize production just as the printing press revolutionizes traditional printing [17–19].

Recently, the growing popularity of AM technology methods, materials and different welding applications are comprehensively explained in this study because of insufficient report encountered apart from a few detailed reviews as known by the authors [20,21]. However, this study targets different welding technology applicable to AM of metals, highlighting the similarities between both technologies and the procedures used in welding that can be directly applicable in AM. Therefore, recent research and trends in the use of the AM method, including the different welding processes and the microstructure properties of the resulting connections are being reviewed.

2. Additive manufacturing

2.1. *Additive manufacturing process*

AM is the officially defined by ASTM Standard F2792. It is defined, unlike subtractive manufacturing methodologies such as traditional machining, it is the process of joining materials into layers, often overlapping, to make objects from 3D model data. AM method has some process steps. The first step of the process is usually 3D modeling of the object planned to be produced for this computer-aided design (CAD) software is often used. The part to be produced can be modeled on the computer, downloaded if it has been modeled before. If there is an existing part, it can be produced with a 3D printer by scanning. If an original product is modeled, modeling is the step that best reflects your imagination. There are various programs used for modeling, these programs are also used for engineering and architecture. After modeling, the software slices this model cross sectional layers and creates a digital file. In the printing process, the object is created by adding it over each layer another in layers [22–26].

3D printer technology has brought a breath of fresh air to every area which used. Owing to this technology, it is possible to produce objects that were difficult or even impossible to produce using traditional methods (TM). In addition, some limitations and problems related manufacturing or shaping method are invalid for 3D printer. In fact, this means that the object to be produced depends on our imagination [27–29].

Although 3D printers are mentioned as a so new miracle technology, they have been for a long time in our life. In fact, the reason why it is said to be new is that it is now available at a lower cost. These lower-cost 3D printers can provide making the product-development process much more efficient. Not only product-development process but also it can be useful to enabling distributed manufacturing. Considering the success of the 3D printer in the areas where it is used and promises to benefits for the future, what is done is only minor clues for the future. In addition, sheer charm of seeing something built from nothing have influenced us and it gives a different way of thinking therefore we can predict that these 3D printers will affect us more in the future and perhaps become an indispensable technology. AM process, unlike many TMM forms parts by laying the materials. TMM is based on cutting and reduction. TMM process usually starts with the block of material and followed by cutting away the material. Thus material is produced in desired sizes and shapes. AM is the opposite of this, because AM starts with nothing. The desired object is produced with additions, so it is not a subtractive like TM. It also has the ability to produce minimal waste compared to TMM. There are many examples of AM process in nature and in everyday life. If a very simple example is given, it may be a brick wall. Before building a brick wall some steps are followed which can be compared to the AM method. Initially, architects or engineers draw a formal plan for building the wall and then the wall is built by arranging the bricks step by step. This is just like AM. In AM, the desired final product is designed and after that executes the part as a layer at a time, such as building brick walls [30–32].

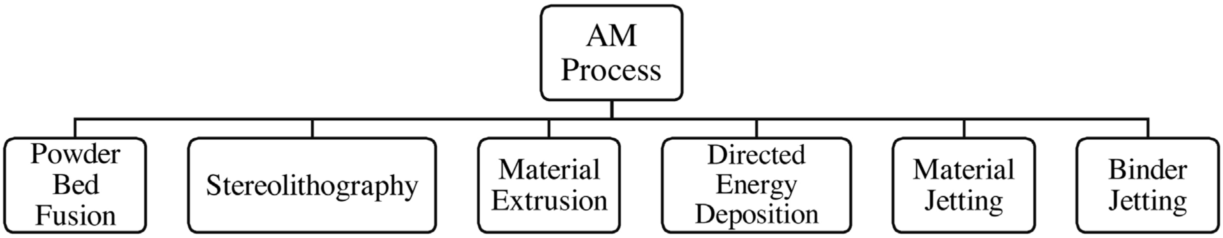

Fig. 1 – AM process techniques.

AM includes many methods in itself. The differences between the methods are due to the material used and the method of processing layers. Each method has its own advantages and disadvantages. Therefore, while choosing the one of the methods of layered manufacturing technology, the material used and the parameters depending on the method should be taken into consideration and the most appropriate method should be chosen. These methods can be classified differently [33–36]. The classification of AM methods is shown in Fig. 1. Some of these methods are powder bed fusion, stereolithography (SLA), material extrusion, directed energy deposition, material jetting, binder jetting. The main principle of the SLA is the curing of the liquid photopolymer with a light source. In this way, a large number of small molecules are connected and a cross link is formed. The resin layer adheres to the first layer and the curing process continues in order and the layered manufacturing of the part is made [37–41]. DED is based on the principle that the energy source (laser beam or electron beam) melts the substance locally and accumulates the molten substance on the layer [42,43]. In the material extrusion method, the filament is fed into the extruder then pushed through the nozzle, the material is liquefied in a heat chamber. With the movement of the extrusion head the filament is laid on the ground where it cools and solidifies so that layered production occurs [44–47].

2.1.1. *Selective laser sintering*

Powder bed fusion includes selective laser sintering (SLS), Selective laser melting (SLM) and Electron Beam Melting (EBM) [44,48,49]. SLS is a technology commonly used for polymer materials but it can also be used for ceramics, vax, nylon, metal-polymer powders and steels or alloys. The power source used for sintering the powdered material is laser. The expression "Powder bed" in the name of the process actually gives information about the process. A portion of the powdered polymer is heated to a temperature below the melting point of the polymer. In this process, the powder is spread in a thin layer, CO_2 laser beam scans the surface. With the temperature formed in the regions where the laser beam hits, the powder material melts partially, the powder in the selected regions is sintered. The moving platform is pulled down a layer thickness. To create a layered structure, a thin layer of powder is layered on top of the last scanned layer. The experimental laser manufacturing system taken from one of these studies is shown in Fig. 2. Moreover the method is suitable for mass production and it is among the advantages of the method that the powder used in the form of a bed can be largely recycled. On the other hand, post-processing may be required to improve the surface and mechanical properties [44,47–52].

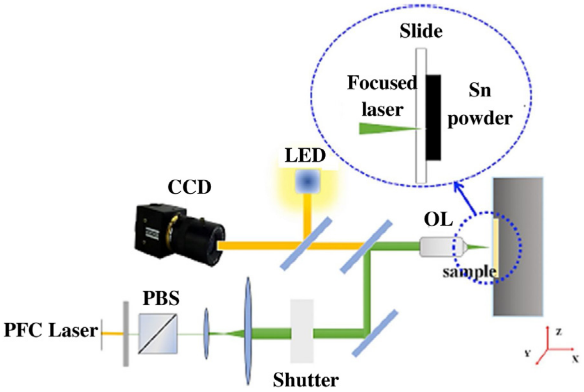

Fig. 2 – Laser manufacturing working system. OL: objective lens, PBS: polarization beam splitter, CCD: coupled charge devices [52].

2.1.2. *Selective laser melting*

SLM is a frequently used method for metal materials. It is particularly functional for common metals such as stainless steel. The basic principle of the method is the shaping of the thin powder layer by laser scanning. The desired part shape is obtained by laser beam. Laser power and scanning speed are important parameters in order to have optimum part properties such as low porosity, high strength, hardness and good mechanical properties. Unlike TMM techniques, there are few restrictions on the production of complex-shaped parts, but there are still limitations on the use of support structures and the possibility of deformation. These restrictions and shape of the part affect the cost. In addition to post-processing is commonly required. SLM does not have a very different mechanism than SLS but SLM uses the laser to achieve a full melt of the material forming so the material is completely melted. Polymer materials are preferred in SLS while metal materials are used in SLM. Another difference between them is related to the use of supporting structures. Although the powder bed in both methods gives physical support to the process, this is insufficient for the SLM method, it needs supporting structures. On the other hand, apart from removing the supports, dense parts can be produced without the need for any other post-processing. Owing to the solid state sintering in process, high strength and low porosity parts can be produced by SLM, this makes the SLM method superior to SLS. There are points

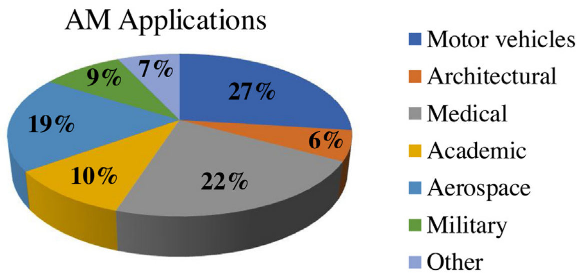

Fig. 3 – AM applications worldwide market share [62].

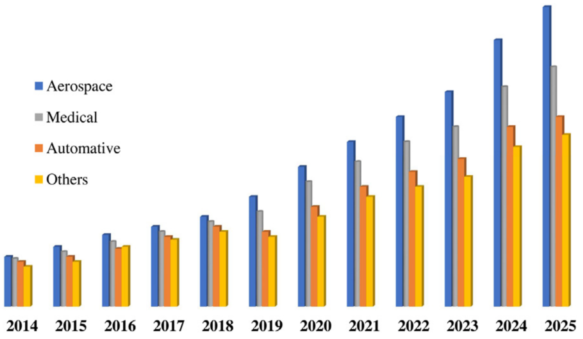

Fig. 4 – Estimates of market by application [63].

where both processes are superior or weak from each other [44,53–56].

2.1.3. *Electron beam melting*

EBM method is often the preferred method for reactive metal materials such as Ti and its alloys. If the EBM method is simply expressed, it is the melting and solidification process that takes place in a certain cross-sectional area, just like other fusion methods in the powder bed. But this time a high energy beam is used instead of a laser. Just like the laser, the electron beam scans the layer of powder, first the part melts with the heat provided by the beam followed by solidification. EBM method is generally used for metal materials, in practice it is achieved in high conductivity materials. It has some advantages such as high efficiency compared to other powder bed fusion methods. But it basically has the same principle: It starts with laying a thin metal powder on the platform. The powder is scanned with electron beams instead of laser, this process is faster than other methods. Owing to the moving platform, a thin layer of powder is laid on top of the last layer of powder so that the layered structure is obtained. This process is repeated until the part is created. Oxidation precautions are of great importance since there is melting and cooling during the process [57–60].

2.2. *Applications*

Since AM has been used and subjected to many research, it has been tried in different sectors and new AM sectors have been developed. The adoption of AM technologies has been a preferred method in many fields such as aerospace, automotive, medicine, architectural etc. as it provides many advantages for each industry. In 2012 application areas of AM technology ratio were reported as shown in Fig. 3. It is expected to increase rapidly by 2025 as shown in Fig. 4 [61–63].

2.2.1. *Aerospace*

AM technology is a preferred technology for aerospace applications. Aerospace components are often complex and the success of AM technology in complex structures provides a great advantage for use in this industry as well [64–68]. Many leading companies in the field support the use of this technology in the aerospace industry and continue their studies. One of these companies is Airbus, it produced the hinge bracket component of the aircraft with the Direct Metal Laser Sintering (DMLS) method. These Ti brackets produced with DMLS are some of the advantages of energy consumption and CO_2 emissions over the entire life cycle compared to steel brackets produced by conventional methods. Also most importantly, using DMLS to create the hinge is a significant savings. Ti brackets as shown in Fig. 5(a). Owing to the material selection and the advantages of the AM method, it has total mass saved %65. Thereby their studies on the success of AM technology in aircraft components continue. Rolls-Royce Trent is the largest airspace/engine part produced by EBM. It has a front bearing bed made of Ti, approximately 1.5 m in diameter and 0.5 thickness thick, and 48 aero f. Also each LEAP engine has 19 fuel nozzles as shown in Fig. 5(b) [69]. Owing to the success of the AM method in complex parts, parts can be produced without joining operations. One of the best examples of this is the Liquid Oxygen Flange, which is used in the upper stage of the United Launch Alliance Launch Vehicles. Fuel flow characteristics are very important to performance of this component and AM technology enables unique interior flow configurations that would be almost impossible for TMM. Liquid oxygen flange produced by AM as shown in Fig. 5(c) [70]. Hinge is one of the examples of success in complex components that are difficult to produce with TMM. AM provides capability of the process to create geometry and features that cannot be produced easily or economically using TMM. Hinge product has been redesigned to function by altering the part's topology, and then fabricated using an AM Laser Powder Bed Process is shown in Fig. 5(d) [71]. Nasa is another organization that adapts to new technological developments, there are many studies on the use of AM technology in the production of aircraft components, one of which is the production of the gas turbine engine. Faster cycle time and complex design features are aimed in the nickel added gas turbine engine produced with the AM in Australia. Gas turbine engine is shown in Fig. 5(e) [72]. Another work of Airbus Company is the production of Ti bracket connector with SLM. Bracket connector used in the Airbus A350 XWB. The part made of titanium using SLM has a bone-like porous structure, which allows it to significantly reduce its weight. It is lighter than traditional designs 30%, thus reducing the weight significantly, reducing fuel consumption and increasing the aircraft's load capacity. In addition, it provides savings and reduces development time by up to %75, thanks to SLM operation. Ti Bracket connector as shown in Fig. 5(f). The part previously made from aluminum using conventional methods can be made with Ti using the SLM method, thereby reducing weight and saving fuel [73]. The use of AM method in production of leap motor is becom-

Fig. 5 – Aerospace components produced by AM technology: (a) Hing holder produced by Airbus with AM technology, (b) Rolls Royce Trent XWB engine manufactured with EBM method, (c) liquid oxygen flange produced by AM, (d) aerospace hinge part produced with laser powder bed method, (e) gas turbine engine by 3D printing, (f) bracket connector produced by Airbus, (g) leap engine fabricated with AM, (h) bald bracket manufactured by EBM, (i) complex shape Bracket designed with AM [69–76].

ing widespread as shown in Fig. 5(g) [74]. The motor contains 19 3d printed fuel nozzles, is 5 times more durable than previous models. In another study, A Bleed Air Leak Detect (BALD) bracket used in the hot side of the engine on Lockheed Martin's Joint Strike Fighter platform was selected. The BALD bracket is machined from the Ti-6Al-4V plate to certain geometry with TMM. In the production of BALD brackets with EBM, the cost and the mechanical properties are improved while minimizing the cost. Bald brackets are produced with the EBM method as shown in Fig. 5(h) [75]. One of the aircraft components that are difficult to design with TMM is brackets. Thanks to AM, brackets with design flexibility can be produced, at the same time these parts are harder and lighter. Bracket which is produced by AM, is 23 stiffer than the originally designed part under the same load conditions, and was also 15% lighter in weight as shown in Fig. 5(i) [76].

2.2.2. *Automotive*

Decreasing density and increasing force-to-weight ratio are significant in many industries. Production of low density parts will also reduce manufacturing cost and fuel consumption. One of the industry where density reduction can be very useful is the automotive industry. AM technology is used in the automotive industry due to its advantages in low-density part production, less material waste and energy saving. In addition AM technology enables the production of complex shaped parts at low density and is therefore preferred for many studies in the automotive industry. Some of these studies are shown in Fig. 6. In one of these studies, the body panel was produced with AM to evaluate production time and cost and compare with TMM, shown in Fig. 6(a) [77]. One of the major advantage of the AM processes is their ability to create hollow structures which is a unique opportunity for some car parts such as tailpipe. Tail pipe that is commonly produced by forging and casting methods, two metal sheets formed by deep drawing are joined by a welding seam. In a study, a tail pipe powder bed for a Porsche GT2 RS was produced by powder bed fusion process, as shown in Fig. 6(b) [78]. The hydraulic manifold, which has a small size and complex structure, it was produced at the MDF in Oakridge National Laboratory through an ONR-sponsored project as shown in Fig. 6(c). Another an example is a turbocharger for an auto engine shown in Fig. 6(d) [79]. There are many similar examples, it will be understood that the use of the AM method is now common in the auto-

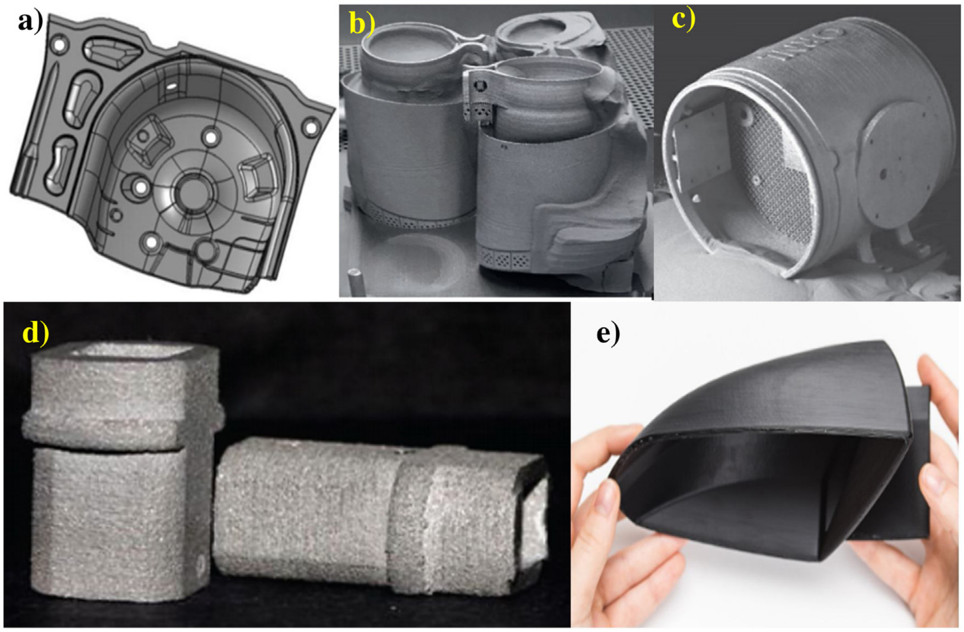

Fig. 6 – Automotive components produced by AM: (a) model for body panel to be manufactured by AM method, (b) Ti tailpipe was produced with powder bed fusion, (c) hydraulic manifold was produced with EBM, (d) turbocharger by 3D printer, (e) motorcycle wing mirror by FDM [77–80].

Fig. 7 – Medical applications using AM: (a) prosthetic hands in different colors, (b) cranial implant built with EBM, (c) a prosthesis socket produced with 3D printer for a little girl, (d) tibial tray produced by SLM, (e) femoral component, (f) acetabular cup built with 3D printer, (g) knee implant manufactured by AM, (h) hip stem manufactured by AM, (i) 4 Ti prosthesis was produced for a cat [88–96].

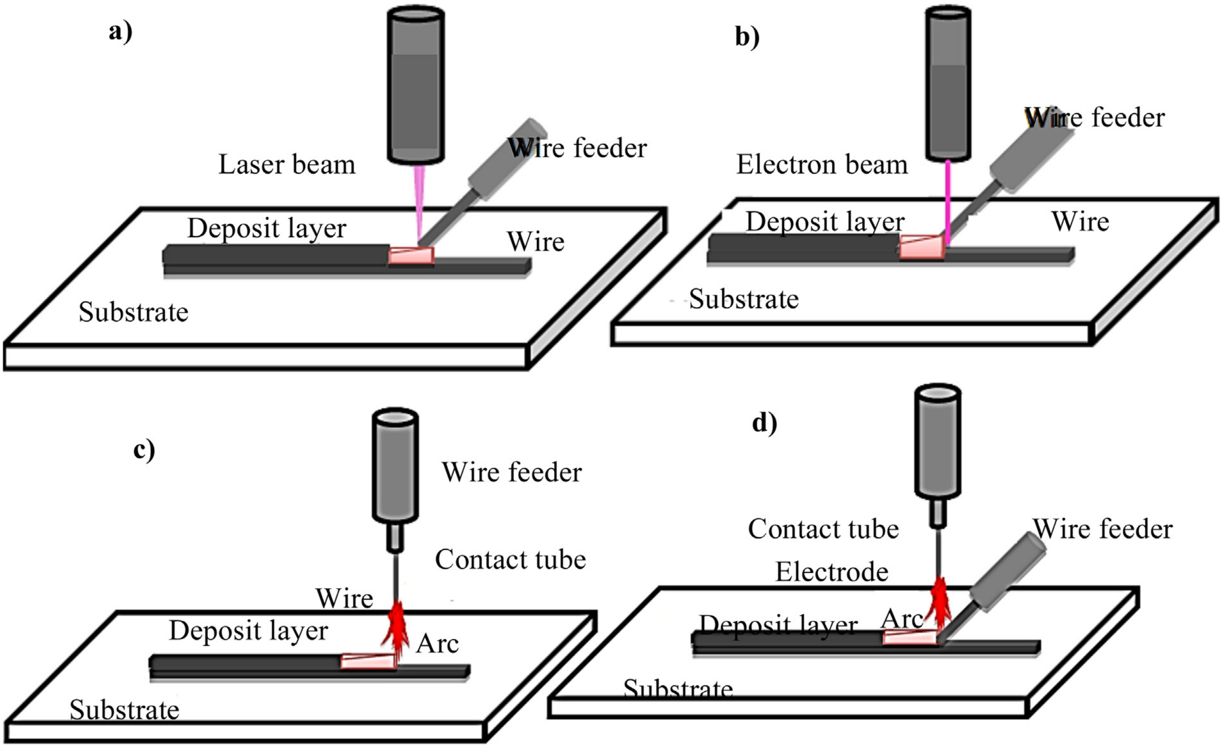

Fig. 8 – Combination of welding methods with AM: (a) LAM, (b) EBM, (c) GMAW, (d) GTAW [102].

motive industry. As shown in the Fig. 6(e), many examples can be given, such as the wing mirror or full-color dashboard [80].

Other studies have also explored the use of AM technology to produce low volume automotive components. In addition to these studies, many leading automotive companies in their business conduct extensive research on this method. Especially tire companies state that it is not far to produce tires with a 3D printer suitable for seasonal transitions in the near future.

2.2.3. *Medical*

AM technology offers important advantages for tissue engineering and biomedical devices thanks to its ability to produce different parts on demand for specific patient needs. For instance, surgical planning with the AM has developed imaging procedures that provide surgeons with better imaging and better understanding of the patient's anatomy and pathology. Today, CAD-based AM technology helps produce 3D template models and guides that enable accurate planning and control during surgery. A new area where the AM is planned to bring revolution is the pharmaceutical industry. Once a suitable AM method is determined and the most suitable material for applications is selected, the drug itself can be developed and printed [81–87].

There are many successful applications and many studies on medical use of AM and some of these applications are shown in Fig. 7. Especially, the production of dental implants and patient-specific prostheses have a big role. The success of the system on complex parts has many advantages for this sector due to its design flexibility and customizability. The design process of AM for prostheses is similar to the traditional process, only more affordable and accessible. Prostheses that can be produced in different colors and different size are shown in Fig. 7(a) [88,89]. One of the implant applications produced with am technology is the cranial implant made to improve the psychological state of the patient after skull injury. As shown in Fig. 7(b), the implant with porous surface can be built with EBM [90]. Nowadays, AM technology has been started to be used for the prostheses produced with TMM, usually with casting methods. There are several studies on this area, one of these examples is the prosthesis produced with AM for a little girl, Rosaline, as shown in Fig. 7(c) [91,92]. It is actively considered for the production of orthopedic implants and scaffolds due to the advantages of AM technology such as the possibility of combining different materials, material saving, full dense part production, moldless production opportunity, production time and cost savings. The hip replacement parts produced with the SLM technique are shown in Fig. 7(d–f and h) [93]. Thanks to AM, implants are produced for the patient. In the studies, the implants tried in different patients are tested and developed day by day. One example that can be given is the knee implant shown in Fig. 7(g) [94]. The advantages of technology are promising not only for humans, but also for animals. In today's world, millions of animals are disabled due to trauma, fracture and other medical problems. Due to their different successful applications, this technology also provides application for veterinary field. One of these applications is shown in Fig. 7(i), Ti prosthesis was produced for a cat who lost all four of her paws [95,96].

3. Welding technology in additive manufacturing

AM technology is remarkable for welding technology due to its some advantages such as the manufacturability of the complex parts, material saving during the process. The combinability of the parts produced with AM with the welding method with the small-medium sized parts is new in the sector. AM technology not only avoid some problems encountered during the welding process, but also provides parts with high precision dimensional tolerances. Thus, high strength, non-porous and high fatigue resistant parts can be produced. Parts produced with AM have dimensional limitations. There are some drawbacks to expanding the production platform to eliminate this problem. When more than one source is used to manufacture large volumes of parts, partial differences in the mechanical properties of the part may occur if there is a possible calibration difference between these sources. For these reasons, AM parts produced in small volumes can be converted into larger volumes using different welding technique. Therefore it is tried to combine AM technology with different welding methods and it is aimed to become widespread. It is not yet possible to commercialize as it is a new technology and it have some restrictions but there are some studies in order to improvement this technology. Using AM with welding methods can be classified like welding based additive manufacturing (WAM) processes like wire arc additive manufacturing (WAAM), laser additive manufacturing (LAM) and electron beam additive manufacturing (EBAM). LAM, EBM, GMAW and GTAW methods are shown in Fig. 8 [97–102].

3.1. *Wire arc additive manufacturing*

The success of the welding technology in joining parts is the solution for limited size part produced by AM, which is one of the disadvantages of the AM. In fact, it has been understood that with AM, parts can only be produced in limited sizes, so that the produced parts can be combined with the welding method to achieve larger sizes. Therefore welding technology is used effectively with AM techniques. Techniques such as WAAM are based on material melting, similar to beam-based techniques. WAAM process is shown in Fig. 9. The wire is welded using an electric arc as a heat source near the net shape pieces in the layers. Owing to WAAM technologies, higher print resolution, high deposition rate, surface quality, low production cost and production of large-scale components are achieved. Also suitable for many different materials and its alloys, Ti, Al, Ni, steel are some of these materials. The WAAM process can use GMAW/MIG (metal inert gas), GTAW/TIG or PAW. Many studies are carried out, especially by changing parameters, an optimized result can be obtained. For example, adjusting the operating procedure by controlling the heat input can be used to change the microstructure of the resident components during WAAM [103–109].

There are several studies about the use of GMAW technique in parts produced with AM. High efficiency and low cost are the most important benefits. Despite the many benefits it provides, it is not common to use it now, due to disadvantages such as stresses and deterioration from excessive heat input. For GMAW-based WAAM processing, owing to the natural properties of the method, a weld transition, weld geometry is not uniform, especially at the start and end parts. This can give rise to poor surface quality and part precision. Many studies aim to improve the use of layered manufacturing and welding methods. Previous studies using GMAW welding as AM have shown that results are expressly related by the materials and equipment used [110–114].

When high deposition rates are preferred, the production process with compressed powder will be better if the wire is wanted to produce more complex parts. Compared with other metal AM methods, WAAM process has low cost, high material usage and high deposition rate. Besides it has environmental friendliness and cost competitiveness therefore it can will replace TMM in near future. This technology can be used in the manufacture of complex parts, especially for aerospace, automotive and biomedical applications. WAAM method, which uses arc as a heat source and wire for raw material, has been the subject of research for AM processes since the 1990s. This method has recently proven to have the potential to produce large-scale engineering structures. The WAAM process has been a remarkable method for the production of customized large parts at low cost compared to other metal additive methods. This method can be applied to the arc welding equipment by adding a numerically controlled milling machine or a robot. WAAM process can be built parts including a computer controlled robotic system, a welding power source, a welding torch and a wire feed system. In one of studies, the combinability of a machine part broken with AM and MIG welding method was examined. The easy application of the MIG-MAG welding method has benefited the AM. The workpiece is connected to the tray of the 3D metal printer used in the study and the table moves, while the filling torch remains stationary. No failure were observed in the junction area of the assembled parts and the operation was successful. It is an example of the use of AM technique in repair welding applications. In another study, the surface properties of aluminum alloy parts produced with laser-assisted MIG–AM were examined. As a result of its study, the system for metal parts was successful and it was proposed for the manufacture of metal parts. Some of the studies about the use of MIG welding method with AM system have analyzed the toughness and impact resistance of the parts produced in this way and the results of the studies supported that the method was appropriate [115–120].

In the MIG method, equipment requirements are low and it have low capital cost, so it is an economical method. In addition, component geometry and welding positions are not limited, they are suitable for parts with complex geometry. It has numerous applications and uses for many materials. It has wide usage especially for low alloy stainless steels, aluminum and its alloys and some non-ferrous alloys. It has become a preferred method for many applications from different sectors owing to its advantages. There are many studies about production of metal parts by desired size and shape by AM and their combinations with welding. Since MIG is the common welding methods of TIG, its use with AM has been considered important. The use of MIG welding and AM provides joining efficiency and low cost. There are successful studies about using the MIG method together with AM by determining the optimum parameters. Welding parts produced with the

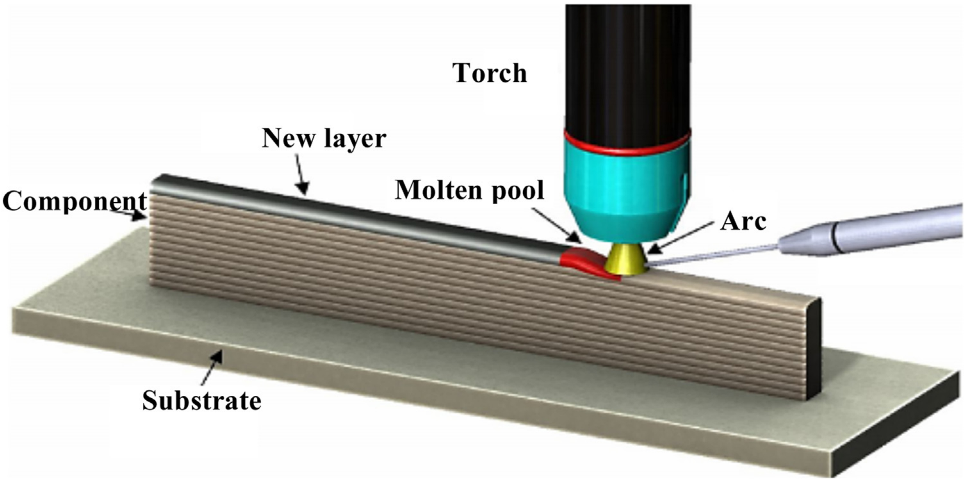

Fig. 9 – WAAM process [109].

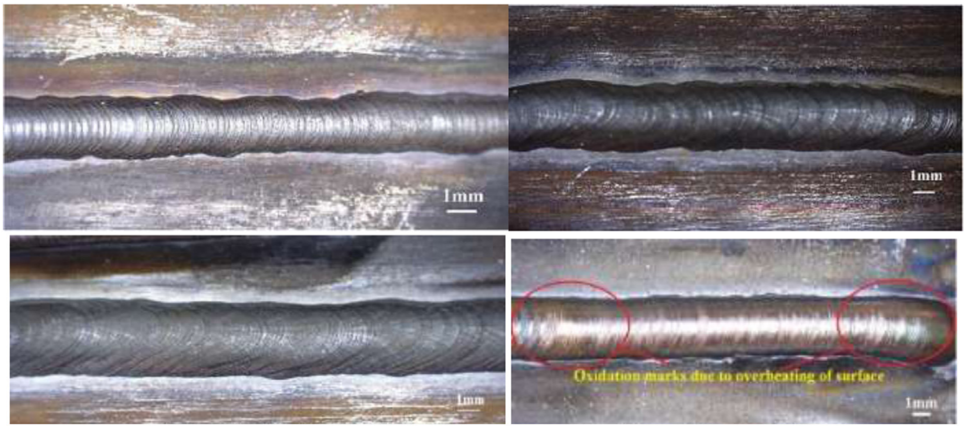

Fig. 10 – Welding surface effects of different touch angles: (a) 60°, (b)70°, (c) 80°, (d) 90° [133].

AM technique increases design flexibility, especially for industries such as aviation, any welding equipment can be used with AM, but is currently a commercially available deficiency. It is thought that its use will be widespread especially for Ti and steel materials. Compared to TMM this technology prevent casting defects, reduce material consumption and thus reduce costs [121,122].

Materials produced by WAAM used by the TIG welding method generally shows better mechanical properties than similar ones and they also do not exhibit a high porosity problem that reduces fatigue life. Therefore, the WAAM-TIG manufacturing process is a low-cost method for the rapid production of medium-large-scale components and structures. Another advantage is that the molds are not used in the WAAM-TIG method compared to TMM. For example, it has been mentioned that large mold parts are widely used in ship applications, and this situation causes problems such as design and production time of the dimensions of the tool and mold elements, and the WAAM-TIG method may be an alternative for the solution of the mentioned problems. The WAAM-TIG method is a good option for repairing special parts such as turbine blades and molds. With this method, new material can be deposited on the surface of the damaged parts to repair the parts. In this way, significant economic savings are achieved without the need for a new part production [123–130].

WAAM has some parameters such as arc voltage, working distance, wire feed rate, travel speed and deposition strategy or path planning. Malcom et al. studied on TIG based WAAM and they examined the impact of some of these process parameters on the resultant sample characteristics such as bead roughness, bead shape and size and the microstructure. As a result of the study, they indicated through depth and roughness are free of wire feed speed. Increasing travel speed or reducing current deduces a reduce in melt through depth and an increment in roughness [131]. Liberini et al. studied on optimum selection of process parameters for WAAM. They examined the effect of heat input and feed rate during deposition of the weld beads on the microstructure and mechanical properties of the sample [132]. There are several studies about the effect of optimization of parameters on parts produced by WAAM. Gokhole et al. studied on GTAW-based AM process for producing thin walled metallic constructs. They examined effect of process variables on the output parameters, such as deposition height and width. Welding process with different torch angles is as shown in Fig. 10 Welding surface

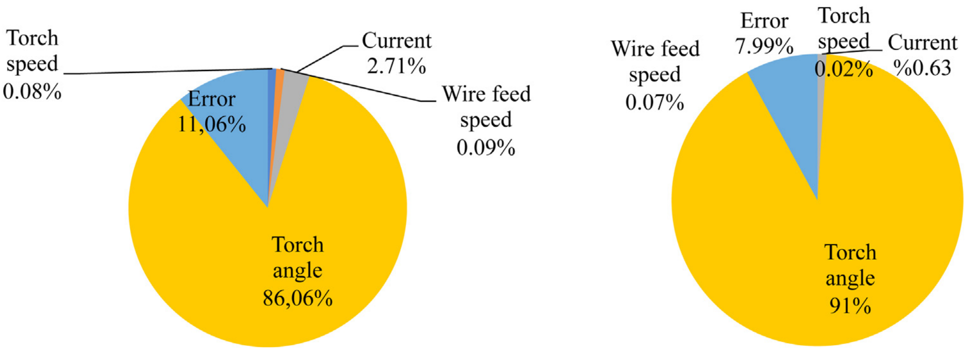

Fig. 11 – Percentage effect of process parameters: (a) change in deposition width (mm), (b) change in deposition height (mm) [133].

Table 1 – Comparison of LAHAM and WAAM tensile test result [142].

Sample	Tensile strength (MPa)	Yield strength (MPa)	Elongation %
LAHAM	163.39 ± 1.68	75.60 ± 4.91	17.38 ± 5.44
WAAM	151.91 ± 1.28	69.71 ± 4.01	16.80 ± 0.61

effects of different touch angles; a60,b70,c80,d90 133. Fig. 11 Percentage effect of process parameters;a Change in deposition widthmm,b C Fig. 10. As a result of their study showed that 80° is better option and as the tilt angle rises the deposition width increases and the deposition height decreases. Percentage contribution process parameters on change in deposition width and height are shown in Fig. 11(a and b) [133].

WAAM is a suitable method for many metals and their alloys such as Ni [134,135], steel [136,137], Ti [138,139], Al [140–142] and their alloys which are frequently used in sectors that are always need to developments such as automotive and aerospace. Miao et al. studied on the effect of laser energy on 4043 Al/Si parts produced with laser arc hybrid AM (LAHAM) and WAAM. They made microstructure evaluation and examined the mechanical properties. They determined that the yield and tensile strength and elongation after the introduction of laser energy are higher than the without laser as shown in Table 1. The microstructures of the LAHAM and WAAM samples are compared as shown in Fig. 12. They observed the arc zone (AZ), laser zone (LZ), heat affected zone (HAZ) in the LAHAM sample. When comparing LAHAM and WAAM samples, they stated that the important difference in their microstructure is the LZ in finer grains and decreased HAZ in LAHAM sample due to high cooling rate and enhanced fluid flow in the LZ. In addition, they defined that thick grain boundaries or Si eutectic gathering to form large discrete particles observed in the structure. They found that the distribution of Si is more uniform in LZ, while the Si phases in HAZ are large in the grain boundary and form large discrete particles. The back scattering images of Al and Si and the element distribution are shown in Fig. 12(a and d). The Al distribution is shown in Fig. 12(b and e) and the Si distribution is shown in Fig. 12(c and f). They observed less Si segregation and a more homogeneous structure in the parts produced with LAHAM [142].

3.2. *Electron-beam additive manufacturing*

Comparing the welding capabilities of materials produced with AM and welding capabilities of materials manufactured with different manufacturing techniques is a preferred method for determining welding success. Rosenthal et al. studied on combining and comparing the A356-T6 produced by SLE and the AlSi10Mg produced by the casting method with EBW. As a result of the study, they established the region affected by an insignificant heat in the sample produced by SLE and they observed that this caused an unexpected deterioration in the mechanical properties of the welded structure. On the other hand, A356- T6 observed the presence of a partially molten region adjacent to the weld metal, but the presence of a specific heat affected area could not be determined. They stated that the hardness value of SLE material was higher compared to the cast material [143,144]. Chen et al. examined the differences in post-weld microstructure and mechanical properties of materials showing anisotropic properties produced with SLE. They combined the parts with the EBW as the longitudinal and transverse direction. Consequently they stated that the strength of longitudinal direction welded samples was found to be higher than that of transverse direction welded samples, but the ductility of transverse direction welded samples was higher than that of longitudinal direction welded samples [145].

3.3. *Friction stir additive manufacturing*

The fusion welding process has a wide molten weld and HAZ zone, resulting in various solidification related problems such as strength loss and distortion. Today, the laser beam provides very narrow molten weld zone and HAZ zones. In the FSW (friction stir welding) method, the workpieces are compressed to move relative to each other. Joining is achieved by applying pressure without melting [146–151]. FSW method has some advantages compared to fusion welding methods such as energy efficient, environmental friendly, weldability of similar or dissimilar alloys, reduced of distortion. FSW is very useful and efficient welding process to join dissimilar materials to produce final products of light weight and high performance. There are many studies on the potential use of the FSW method for different materials and applications. FSW

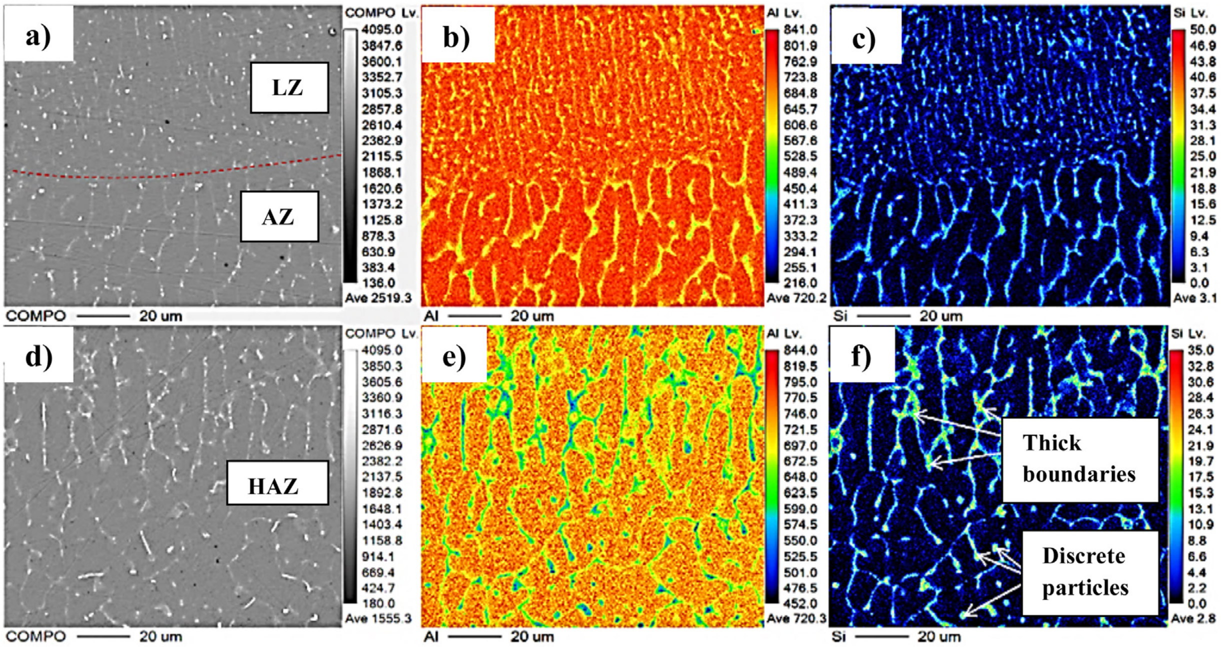

Fig. 12 – Comparison of parts produced with LAHAM and WAAM: (a) back scatter image of LAHAM sample, (b) distribution of element Al of LAHAM, (c) distribution of element Si of LAHAM sample, (d) backscatter image of WAAM sample, (e) distribution of element Al of WAAM sample, (f) distribution of element Si of WAAM [142].

overcomes the problems associated with fusion welding processes. Hence FSW is a revolutionary development in welding technology and it can be used with AM technology [151–157]. Friction stir additive manufacturing (FSAM) is a combination of AM and FSW. Thanks to this method, the desired layered structure is obtained by using one of the AM techniques, and then friction mixing welding is made on the layered structure. The use of friction stir welding is examined to add small to medium-sized parts to parts produced with AM. The formation of residual stresses in materials produced by layered manufacturing significantly reduces the mechanical properties of the material. To overcome this problem, heat treatment process is applied to metallic materials produced by layered manufacturing. Sensitivity analysis can be made according to process parameters affect to part qualities so that some problems can be solved. It is possible to successfully manufacture high-strength parts using FSAM, because the method enables the production of parts with fine structures. In this way, higher ductility and structural performance are improved compared to the main metal. In addition, the method has the ability to achieve microstructural modification and significantly improve, therefore it is unique [158–163].

4. Conclusion

The use of AM for many areas such as medical, automotive, and aerospace is widespread but it is still a new technology. Despite its advantages such as the ability to produce parts with complex geometry that it is impossible produced with TMM, it provides lower costs thanks to material savings, low density and high strength parts production, it has some limitations in serial production and large part production. In this study, recent studies have been examined and the use of AM technology with common welding methods such as GMAW, GTAW, FSW, EBW has been investigated. Samples in which these methods are applied are evaluated. Generally speaking, it is obvious that it is promising for many sectors parts with non-porous, high fatigue strength and good mechanical properties produced by AM achieve successful harmony by welding processes. While the advantages of the system can be used for many areas, it is possible to solve the size limitation by suitable welding methods and optimized welding parameters since it has been found that successful connections can be achieved when optimum parameters are provided for welding methods. Therefore, it is hoped that for different materials produced by AM, studies on the use of different welding methods will increase. It is thought that the use of AM technology and welding methods together will become a more common method in the future.

Conflicts of interest

The authors declare no conflicts of interest.

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