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Metal Inert Gas Welding-Based-Shaped Metal Deposition in Additive Layered Manufacturing: A Review

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***Abstract*—**Shaped Metal Deposition (SMD) in additive layered manufacturing technique is a promising alternative to traditional manufacturing used for manufacturing large, expensive metal components with complex geometry in addition to producing free structures by building materials in a layer by layer technique. The present paper is a comprehensive review of the literature and the latest rapid manufacturing technologies of the SMD technique. The aim of this paper is to comprehensively review the most prominent facts that researchers have dealt with in the SMD techniques especially those associated with the cold wire feed. The intent of this study is to review the literature presented on metal deposition processes and their classifications, including SMD process using Wire + Arc Additive Manufacturing (WAAM) which divides into wire + tungsten inert gas (TIG), metal inert gas (MIG), or plasma. This literary research presented covers extensive details on bead geometry, process parameters and heat input or arc energy resulting from the deposition process in both cases MIG and Tandem-MIG in SMD process. Furthermore, SMD may be done using Single Wire-MIG (SW-MIG) welding and SMD using Double Wire-MIG (DW-MIG) welding. The present review shows that the method of deposition of metals when using the DW-MIG process can be considered a distinctive and low-cost method to produce large metal components due to high deposition rates as well as reduce the input of high temperature generated during deposition and reduce the distortions. However, the accuracy and surface finish of the MIG-SMD are less as compared to electron and laser beam.

***Keywords*—**Shaped metal deposition, additive manufacturing, double-wire feed, cold feed wire.

I. Introduction

ADDITIVE layered manufacturing (ALM), also known as three dimensional (3D) printing is a novel technique could be allowed to fabricate fully dense metal objects by depositing materials in a layer by layer manner, compared to traditional machining procedure [1]. Additive manufacturing (AM) has shown great potential to minimize material wastes, life-cycle impacts, and energy consumptions [2]. At the same time ALM has been marked as an innovative technology to produce net or near-net-shapes. The technology was used to develop the final solid parts by depositing successive cellular layers of the material (powder or wires). The whole process is done by melting the metal using the heat that comes out of an electron beam, laser beam, plasma or electric arc [3]-[5].

In the last twenty years, AM offers acquired an increasingly more interest within the production business, particularly to produce component versions as well as prototypes. A brief history associated with AM may be summarized lately within the report [6]. The original AM techniques include stereolithography apparatus [7] and 3D printing [8]. These AM processes are initially applied to fabricate polymer as the connection or perhaps inspection equipment, and recently even in last manufacturing. The ability of generating the prototype, directly from computer aided design (CAD) models in a short period, is a significant factor that reduces the steps of the production process [7], [8]. It is well known that there are several troubles in machining of some materials like titanium, nickel alloys etc. via conventional production techniques. Therefore, there is a requirement for an alternative manufacturing technique that will offset most of those troubles. Candidate manufacturing method is the AM technology where there is no individual tooling necessary. Thus, AM is definitely a perfect technology for rapid manufacturing [9], [10].

Fig. 1 highlighted the fact that AM is appropriate to fabricate components with medium to high geometrical difficulty at relatively low quantities [11].

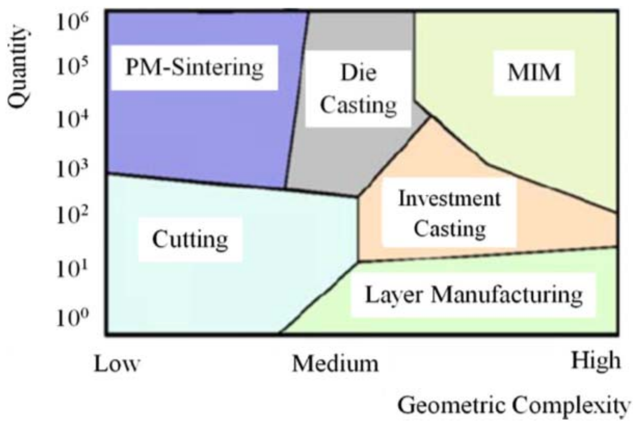

Fig. 1 Qualitative Stations of the AM metal components made comparable with the usual options (MIM metal injection molding, PM-Sintering Powder metallurgy sintering) [11]

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Throughout 1990, this particular technology surfaced within European countries and now it pioneers in the exact same region [12]. In contrast to the traditional subtractive manufacturing (e.g. Computerized Numerical Control) CNC machining), it offers several benefits. First, it is easy to automate the AM process completely right from a part design to fabrication in a CAD/Computer aided manufacturing (CAM) environment. This particular decreases both the production time and the quantity of human input needed for each new part. Even though program for CNC machining could be produced from CAD models automatically at the same time, with regard to complicated geometries multiple re-fixturing is necessary, resulting in time-intensive and expensive re-fixturing and calibration methods. Second, AM is a cost competitive strategy for fabricating components that are made from costly materials just like titanium and nickel alloys in the aerospace industry, where such components often suffer a really lower fly-to-buy ratio. Additionally, AM is achievable to generate single component structures with a complicated form that would neither practical nor even possible to build with traditional approaches [13].

As AM is classified as a young method by American Society for Testing and Materials (ASTM) and the American Society of Mechanical Engineers (ASME), they began the actual improvement associated with AM standardization procedure [3]. ASTM offers described AM as ‘‘a procedure associated joining materials to build products from 3D model data, typically layer upon layer, compared to subtractive manufacturing techniques” [14], [15]. Likewise VDI 3404 standard, AM is the manufacturing process in which the workpiece is built up in successive cellular layers [16]. During the past years, Bourell et al. [17] released a roadmap for AM depending on a workshop on 65 key people in AM. Their own report investigated essential aspects of the AM including:

- Design and style
- Progression modeling and control
- Material Components, techniques, and also equipment
- Biomedical purposes
- Energy source and sustainability applications

Similar industrial sectors might be interested from working with this approach technology by shortening the actual manufacturing period, manufacturing complicated geometries with internal features, creating regarding consolidated parts as a substitute for several sub-parts, decreasing materials usage and manufacturing costs. AM requires a number of steps that move from the virtual CAD explanation to the physical resultant part. The generic AM processes require these steps [18]:

- A computer-aided design and style (CAD)
- Transformation in order to standardize tessellation language (STL)
- File exchange and also treatment
- The device set up and work planning
- Development
- Elimination and clean up
- Post-processing

Building on the previous discussion, the aim of the present paper is to review the studies of the researchers who have conducted their experiments and research in the field of metal deposition processes and their classifications, including SMD process using WAAM which divides into wire + TIG or MIG, besides that, SMD used SW-MIG welding and SMD used DW-MIG welding. Additionally, this paper studies the materials used in the SMD processes, the efficiency of the arc energy, and heat input of the SW-MIG and DW-MIG in SMD process.

II. Classification of AM Processes for Fabricating Metal Components

The International Organization for Standardization (ISO)/ ASTM 52900:2015 classifies the AM technique into seven strategies [19]:

1. Binder jetting (BJ) strategies;
2. Directed energy deposition (DED) strategies;
3. Material extrusion (ME) strategies;
4. Material jetting (MJ) strategy;
5. Powder bed fusion (PBF) strategies;
6. Sheet lamination (SL) strategies; and
7. Vat photopolymerization (VP) strategy.

TABLE I
Classification and Comparison of AM Processes

	Technique of layering		Types	Properties				
				Quality	Deposition rate	Surface finish (Working surface)	Energy efficiency	Cost
Arc beam process	Wire- Feed	TIG-Process	TIG-SMD	-	++	-	++	+++
		MIG-Process	MIG-SMD	0	+++	+	++	+++
	Powder-feed	Plasma-Process	P-SMD	+	++	+	+	+
Electron beam processing	Powder-bed		EBAM, EBM, EBSM	0	+	+	++	-
	Wire-feed		SMD, EBF^3, WAAM	-	+++	-	++	+
Laser beam processing	Powder-bed		DMLS, SLS, SLM	++	-	+++	-	-
	Wire-feed		DMD, DED, SMD	0	++	0	-	-
	Powder blown		LMD, LMDS, DLD, LAM, LENS	+	++	+	-	0

DMLS: direct metal laser sintering; SLS: selective laser sintering; SLM: selective laser melting; LENS: laser-engineered net shaping; LAM: laser additive manufacturing; DLD: direct laser deposition; LMDS: laser metal deposition shaping; LMD: laser metal deposition; SMD-DMD: shaped metal deposition–direct metal deposition; EBSM: electron beam selective melting; EBM: electron beam melting; EBAM: electron beam additive manufacturing; SMD-EBF3: shaped metal deposition–electron beam freeform fabrication; SMD-WAAM: shaped metal deposition– WAAM; UC: ultrasonic consolidation; SLAM: sheet lamination additive manufacturing; DED: direct energy deposition; TIG: tungsten inert gas welding; MIG: gas metal arc welding; + + : excellent; + : good; 0: neutral; -: negative [4], [19]-[27].

Generally, AM processes can be classified into three types according to feedstock material types: (I) powder bed processes, (II) powder fed processes, and (III) wire feed processes [11]. Table I highlights metal AM classification depending on the heat source and material additive technique, and as well indicates a comparison of the characteristics of these techniques [4], [19]-[27].

AM strategies are used in various industries such as medical, automotive, aerospace, design and tooling industry [18]. Hence, AM could be favored in several locations of manufacturing, including tooling process, medical process, aerospace, art, education, architecture, visualization, nanotechnology, automobile and sports, energy, and electronics.

Previously, many authors have conducted researches in the field of wire feed additive manufacturing, including wire and laser additive manufacturing (WLAM) [21]-[24], electron beam freeform fabrication (EBF^3) [26], [27], and WAAM [28]-[32].

There are a large number of researchers in this field of WAAM, for example Spencer et al. [33] investigated the effect of heat on the surface finish, residual stresses and mechanical properties of producing parts in robotic GMAW based AM system and enhanced the surface quality through managing and controlling the layer temperature via an infrared thermometer. They studied the effect of temperature and how it affects the properties of the metal in terms of smoothness of the surface and the remaining stresses as a result of deposition of the metal and how to improve the properties of the surface by controlling the temperature of the layer added to the metal precipitate. In addition, Mughal et al. [34] indicated that the welding arc GMAW dependent on AM is well-known because of its higher deposition rate and reduced manufacturing cost regardless of the surface quality, dimensional accuracy, and reliability. They conducted their work through a 3D thermo-mechanical FE model of direct metal deposition using a moving thermal source and sequential metal deposition. During their work, they used ANSYS program to find the deformation results and compared with experimental results obtained from single layers, plate-shaped building. Furthermore, metallic objects deposited with GMAW operate to have a lot of advantages of excellent mechanical performance, high density and good bonding strength. Also, Mughal et al. [35] formulated a thermo-mechanical model to anticipate the deformations and residual stress. In fact, it has been discovered that ongoing deposition rate without inter pass cooling final results in a smaller amount deformation as it equivalently offers a preheating for the substrate. While Zhang et al. [36] developed a robotic weld that is dependent on rapid prototyping (RP) technique and endorsed the feasibility of utilizing GMAW technique for creating 3D-parts. As well, some research recommendations, such as droplet transfer, heat input, and developing appearance control had been additionally presented for GMAW-based on AM [37]. Xiong et al. [38] developed inclined thin-walled parts or objects using GMAW with flat position deposition free from a turntable. Additionally, the effects of process variables on geometrical attributes are usually introduced. Within the modern times, there is hard work put by researchers to utilize wire feed and powder together to meet the challenges and difficulties, as well as to reduce the problems in the systems, for example, Syed et al. [39], [40] analyzed a combined technique, wire and powder were delivered to the melt pool simultaneously utilizing laser energy. They indicate that the overall mass deposition rate technique and efficiency might be improved and little porosity is acquired.

Brandl et al. [41] performed a comparative study utilizing wire-feed and powder-bed Ti6Al4V. They showed that the wire-feed samples produce high mechanical properties and low porosities and contaminations than the powder-bed samples.

Some literature investigated the combining process of AM with the milling process. Karunakaran et al. [42] produced a hybrid layered manufacturing technology that mixes GMAW for layered deposition and CNC machining as a subtractive technique to build metallic objects. Furthermore, AM can be used in the medical application, so it is essential to review the most important researches, and in particular those that used AM in the medical applications:

Jamieson et al. [43] suggested that AM is an appealing marketplace in the area of orthopedics. Comparing with the manufacturing of surgical equipment with the aid of machining technique and RP strategies, bone geometry is also analyzed and proved to be allowable for the building of the implant model with the help of a machining technique. Hieu et al. [44] indicated the AM in medical technique and methods which depend on medical health-related imaging data and opposite engineering. The 3D prototype of anatomical has constructed. These techniques are effective for the design and production of medical devices, surgical aid equipment, implant, and bio-prototype.

Liu et al. [45] showed that AM played a substantial part in the medical area. It can produce anatomical parts which are more complex in a form directly from the various scanning techniques, like CT images.

In recent years, many studies were completed in the AM, which concentrated on utilizing metallic wire feedstock as a deposition material and using a laser beam, electron beam, or arc beam as a heat supply for melting the metal wires and depositing the shaped metal objects. Presently, the definition of SMD is the term for all techniques which utilize a metal wire/feed as a deposition material related to one of the main energy sources like as electron beam, laser beam, and electric arc beam. Within the mid-1990s, at Welding Engineering Research Center (WERC) in Sheffield University, more development was made on the SMD process, which was copyrighted by Roll-Royce [46].

III. SMD Process

SMD is a revolutionary manufacturing technique produced by Rolls-Royce PLC and certified by the University of Sheffield [47]. SMD enables difficult metal parts to be immediately produced from a CAD model. SMD offers a rapid, versatile and cost-effective substitute for traditional production techniques, and is perfect for the production of short runs of parts, mass customization or one-off repair solutions [48]. SMD process is conducted by externally providing a cold wire of metallic material into a weld pool layer by layer to be able to acquire a designed element form [46], [59]. SMD has the natural possibility to outshine polycrystalline castings of the same chemistry when it comes to mechanized properties, because of the more constant solidification problems that might be made by a deposition technique.

Actually, SMD can be viewed as a net or a near net shaped part manufacturing method when compared with the modern AM techniques. This method may be used specifically for the quick production of metal components exactly. The SMD process creates completely thick components and guarantees excellent benefits of using any welded materials which are hard-to-machine and to make alloys. Nevertheless, it ought to be obvious that the microstructure of the SMD components comparing with deposited parts are different by the large temperature ranges and the high cooling rates [1], [50]-[52]. The key positive aspects of SMD are outlined whenever components are made along with costly supplies such as titanium. Titanium is popular within commercial industries such as aerospace, medical, sporting activities, automobiles and also maritime. The actual most favored titanium alloys are Ti-6Al-4V, which accounts for 60% of titanium production [53]-[56].

Up to now, to be able to acquire a desired final shape, the standard production techniques, such as machining, are in line with the materials getting rid of the workpiece. There are many apparent disadvantages with this procedure, such as the big waste associated with the material in scraps and the consequent increase in the costs, with respect to the materials utilized.

Hensinger et al. [57] and Zhang et al. [58] demonstrated that absolutely no procedure leftovers tend to be created, reducing the actual materials utilized to the strict amount required by the ultimate workpiece form. SMD process is already introduced to the aerospace producing market as a unique low-cost solution with regard to the big structural element because of their high deposition rate and efficiency. These types of methods may considerably enhance product improvement, fund's expense, as well as buy to fly (BTF) ratios [59].

Mechanized qualities of the element created by way of a good SMD procedure (WAAM or DMD) differ significantly based on the deposition parameters, like arc plasma energy, speed, wire feedstock, etc. Typically, mechanized properties of deposited parts are restricted to cast such as the properties of wrought materials and they might involve some appealing qualities for aerospace sectors [60]. Lastly, microstructure examination associated with generating components confirms that one will find absolutely no drawbacks from top quality viewpoint [1]. The key positive aspects and also limits regarding SMD strategies could be summarized as:

- Depositing procedure utilizing WAAM techniques can be achieved utilizing chamber or outside the chamber as well as that you don't have to have a vacuum environment such as in the EBM process [61], [62].
- It is ideal for complete automation [1], [28], [49], [53], [54].
- Higher depositing rates, low-cost components, as well as much less period associated with manufacturing because of the much less cooling period [59], [63], [53], [22]-[27]
- It is able to manufacture large structural components, especially for the aerospace and defense industry components [59], [56].
- It might attain substantial curiosity about the actual modern times because of its higher depositing rates as well as greater effectiveness [69], [64].
- It usually requires, additional machining procedures to obtain a much better surface [65].
- It is restricted to mass manufacturing [66].
- The WAAM methods cannot be accustomed to create little elements and very intricate portion geometries [4].

IV. Classification of SMD Techniques

AM system can be classified in terms of stocks of raw materials, energy sources, construction volume, etc. There are four standard SMD fundamental programs in this technique such as powder bed techniques, powder feed techniques, wire feed techniques, and control method [67]. In addition, there is a computer software method which usually permits adding components in line with the identified way. Table II shows the main units in the SMD system, addition presents a fresh group for the SMD technique based on the heat source employed for melting the metal wire which can be independently fed into the melting pool in either both very hot or perhaps cool state. This kind of techniques tends to be managed by way of the possibly automatic robot, CNC machines, manipulator arms as well as gantry type routers.

Presently, two standard heat resources are already found in SMD methods, i.e. electric arc and power beam acquired through the laser and electron beam. These types of heat sources are utilized with regard to melting the supplied material as wire. Even though the powder materials, which is one of the AM techniques, is very common, wire-based SMD processes are usually getting a lot more favor because of the increased deposit rate and also increased efficiencies in comparison to other [59].

The most common SMD techniques often, tend to use these methods:

- SMD using an electron beam heat source (EBF^3);
- WLAM (DMD-Laser wire feed); and
- SMD using a *WAAM*.

A. SMD Process Using Electron Beam Freeform Fabrication Process

Electron beam freeform fabrication is really a NASA trademarked AM procedure fabricating complicated parts, near-net-shape components, which need considerably much less raw materials as well as complete machining compared to conventional production techniques [13], [63], [68]. Fig. 2 shows an electron beam freeform fabrication (EBF^3) system

[45]. The actual EBF^3 system includes a good electron-beam gun, wire feeder, positioning system enclosed and vacuum chamber as demonstrated in Fig. 4.

The procedure presents metal wire feedstock into a molten swimming pool that is produced as well as continual utilizing a concentrated electron beam in a higher vacuum environment.

TABLE II
SMD TECHNIQUE

SMD techniques	Path Generating machine			1- CNC machine 2- Robotic machine 3- Manipulator's arms 4- Gantry machine
	Heat Supply technique	Electric Arc process		1-TIG/GTAW process 2-MIG/GMAW process 3-Plasma process
		Power Beam process	Laser	1-DMD 2-DED
			Electron	EBF3
	Metal deposition process	Wire-Feed process	WAAM	1- TIG-Wire welding 2- MIG- Wire welding 3- P- Wire welding
			WLAM	Laser- Wire (DMD)
			WEAM	Electron- Wire (EBF^3)
		Powder-Feed		1-DMLS 2-EBM 3-SLS 4-SLM

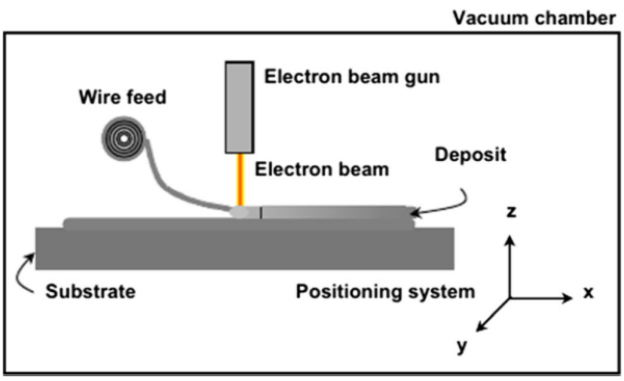

Fig. 2 A primary schematic part in an electron beam Freeform fabrication (EBF3) system [45]

The actual electron beam couples successfully along with any kind of electrically conductive materials, such as extremely reflective alloys, for example, lightweight aluminum as well as copper. The actual size of the wire feedstock may be the managing element identifying the tiniest function achieved by using this procedure: good size wires can be utilized with regard to including better particulars, as well as the bigger size wire may be used to improve the depositing rate with regard to mass depositing. Taminger et al. [69] disclose that there is trade-off in between the actual depositing rate and grain dimension size with regard to supplies transferred while using BEF procedure. However, the tensile properties regarding BEF^3-deposited Ti-6Al-4V and 2219 Al had been really consisting of more than an array of the procedural condition, showing how the tensile properties are not affected towards the variants associated with heat input. Other researches on EBF^3 could be found [45], [70], [71].

B. SMD Process Using WLAM Process

WLAM is a good AM procedure to create metal elements with complete denseness utilizing metal wires like the ingredient materials as well as laser beam as the power source. The actual WLAM techniques usually include a laser, a computerized wire-feed program, some type of computer numerically managed worktable or perhaps an automatic robot program and a few accessorial mechanisms (e.g. shielding gas, preheating or cooling system). Therefore the lasers can be categorized as gas, solid-state, semiconductor or diode, liquid, fiber and free-electron X-ray [72]. As schematically shown in Fig. 3, the actual laser beam creates a melt pool about the substrate material till the metal wire is actually achieved, forming a metallurgical bond with the substrate [43].

WLAM is really a flexible procedure which has the capacity to fabricate an array of alloys as well as other metals. Usually, laser beam splits into three primary kinds, three standard procedures when using laser sintering (LS), laser melting (LM) and laser metal deposition (LMD) has been developed [4], [19]-[27].

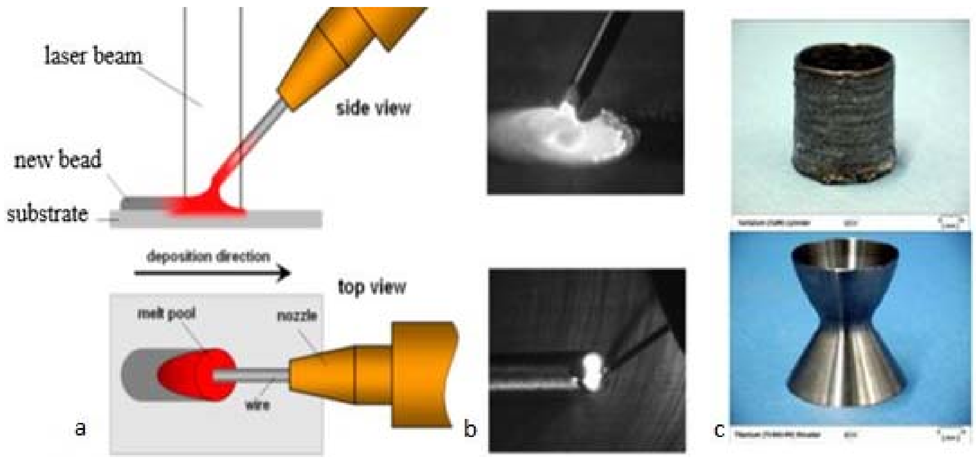

Fig. 3 (a) Schematic drawing of the process; (b) top and side view images of a real process; and (c) Exemplary components: Ta-20W cylinder (as-built surface) [43]

C. SMD Using WAAM

WAAM systems offer brand new paths in order to produce close form metal components. WAAM signifies the switching stage within the metal AM systems because it brings together the actual electrical arc heat sources with a metal wire giving a system to produce 3D metallic parts by depositing beads of weld metal in a layer by layer style [48]. WAAM technique can classify into three strategies based on the type of electric arc torch utilized to melt the filler wire: (i) 3D-TIG welding process (TIG or GTAW + wire feedstock) [73]-[75], (ii) 3D-MIG welding process (MIG or GMAW + wire feedstock) [76]-[79] and (iii) 3D-Plasma Welding process (Plasma + wire feedstock) [80], [81], as shown in Fig. 4.

Within the GMAW, electric arc welding is produced from two poles, one of which is the consumable wire electrode and the other is from a workpiece metal. The wire is normally perpendicular to the substrate. You will find four main ways of metal movement within GMAW, called globular, short-circuiting, spray and pulsed-spray, each type of them provides specific characteristics. In addition to, cold metal transfer (CMT), a modified GMAW variant depended on controlled dip transfer mode mechanism, has additionally already been broadly put in place with regard to AM procedures [82], [83], due to its high deposition rate with and low heat input. GTAW and PAW utilized a non-consumable tungsten electrode to create the weld as shown in Fig. 4. Different in GMAW, the wire feed orientation in GTAW and PAW is various and has an effect on the grade of the deposit, which makes the process preparing more difficult. Contemporary automation technique enables high geometric flexibility.

Using the local protecting method, extremely reactive metallic elements could be created within an out-of-chamber atmosphere [82]. Different components may be utilized in the WAAM process, like steel, aluminum alloy, and titanium alloy. Mehnen et al. [84] discussed the design of the WAAM process, in particular, the non-traditional stiffeners design as shown in Fig. 5. A study is presented with different designs of stiffeners to determine the best structures. Different building techniques have been explored via experiments. Thermo-mechanical FE models have been developed to predict thermally induced stress and distortions.

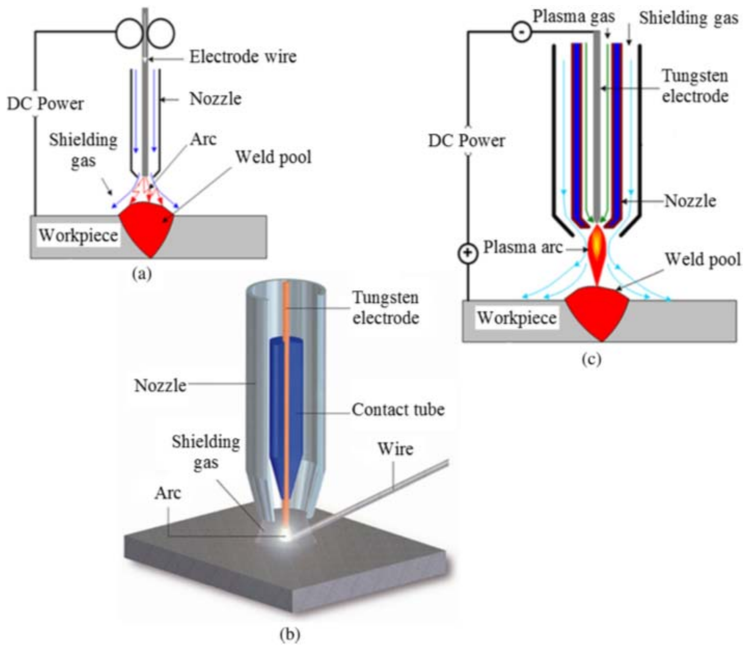

Fig. 4 Schematic diagram of the (a) GMAW, (b) GTAW, and (c) PAW process [13]

At the beginning of 1990s, WAAM technologies acquired a substantial significance within the Welding Engineering Research Centre of Cranfield University. The works of Ribeiro and Norish et al. [85], [86] launched a brand new manufacturing strategy by creating a manufacturing technique for Rolls-Royce plc. Their own technique had been effective at making strong metal components straight from the CAD models.

The present study reviewed the researchers who used the SMD method in the different conventional method of GMAW, Single Wire-GMAW (SW-GMAW), Double Wire-GMAW (DW-GMAW).

1. SMD Using Single Wire-GMAW (SW-GMAW)

The gas metal arc welding GMAW is a popular electric arc depended on SMD technique. GMAW is also known as the MIG welding process. SW-GMAW (convention MIG welding) is applicable the actual consumable wire as the electrode forming an electric arc for depositing the metal layers as shown in Fig. 6 [87]. The actual angle between torch arc and the substrate usually is actually 90 degrees.

A deposition of material using SW-GMAW is managed by an automatic robot controller. This particular regulates not just the actual actions for the automatic robot used to position the welding torch, but also the weld deposition parameters and a tilt and rotate manipulator onto which the weld is deposited. Orientating the part prior to welding enables the geometries to be created with no need for supports [48]. A number of researches on the GMAW-based AM have been explored. Zhang et al. [58] applied a metal transfer control technique to manipulate the size and frequency of the droplets to be able to enhance the deposition accuracy utilizing SW-GMAW. Xiong et al. [88] indicated that the bead thickness within the multilayer depositing procedure may be held consistent to enhance the dimensional accuracy resulting in reducing the waste material and energy by modifying the deposition velocity under a passive vision sensor system using the SW-GMAW technique. There are also many scientists who have worked in the modeling of machines used for deposition of metals. Domandes and Kwak [89] developed the procedure of modeling and modifying the multivariate adjustment of the grain size in the deposition of gamma materials with application in solid free manufacturing and produced cylindrical metal parts.

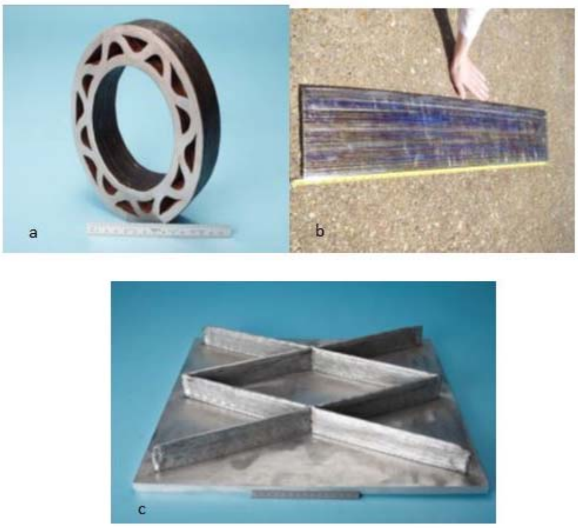

Fig. 5 WAAM components: (a) mild steel honeycomb structure; (b) aluminum stiffened Panel structure; (c) 1 meter long Ti64 wall structure [84]

GMAW mainly possesses the benefit of higher travel speed, less distortion, higher deposition rate, and higher quality of deposited parts. Nevertheless, the high spatter rate comparable with GTAW technique is one of the issues to solve [90]. Xiong et al. [30] indicated that the nozzle to the top surface distance in GMAW depended on AM also offers already being monitored and the procedure stability could be enhanced.

Some researchers in the field of Pulse-GMAW (P-GMAW) and alternating current gas metal arc welding (AC-GMAW) developed many researches and studies in this area, for example, Vilarinho et al. [91]. In their study, they extended the use of the AC-GMAW technique for depositing different steel parts, utilizing various current waveforms; however, a well-balanced arc was not accomplished. Harada et al. [92] indicated that the AC-GMAW technique offers the desired features of higher material depositing with reduced input heat. The technique may be mainly created for the joining of thin aluminum alloy sheets approximately 3-mm thickness. Also, there are many researchers investigated the field of Pulse-GMAW and Pulse-GTAW [31], [93], [94]. Besides, some researchers have focused on their research on the infrared (IR) thermography to record the surface temperature during the deposition process, for example, Bai et al. [95]. They utilized the IR imaging with regard to calibrating input material thermal parameters to enhance the prediction precision of the thermal finite element analysis for GMAW depended on AM, with no immediate evaluation of the thermal behavior while utilizing the IR imaging. IR is really a much better option with regard to heat measurement for weld-based additive production. IR imaging can report the actual heat distributions on the surface of both base plate and also the deposited element with high resolution of time and space [96].

The IR thermography can be used to capture the surface temperature in GMAW based AM with high accuracy With the increase of depositing height, the higher-temperature area rears the molten pool became bigger gradually as shown in Fig. 7.

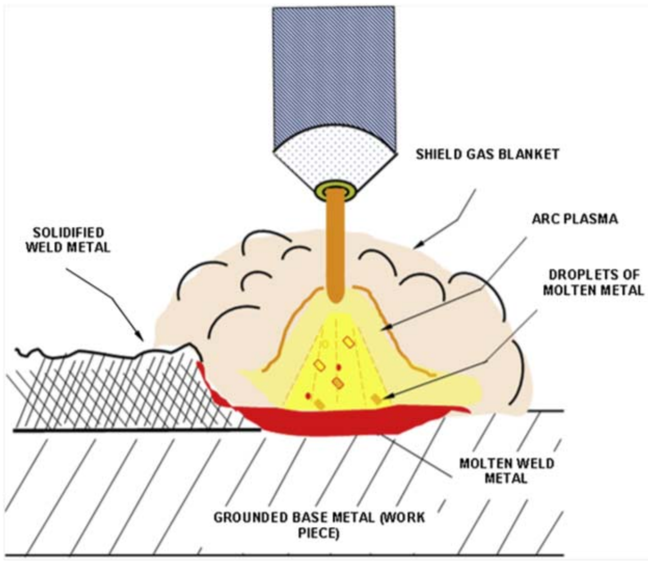

Fig. 6 Schematic of GMAW [87]

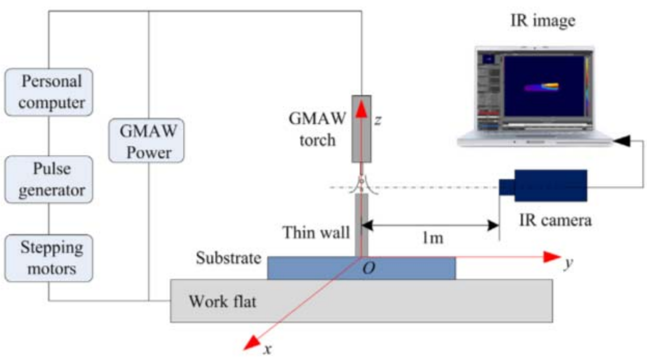

Fig. 7 Schematic diagram of GMAW based AM system with the IR camera [97]

Seppala and Migler [98] utilized the IR thermography in order to measure the actual heat profiles of a model polymer through AM using polymer extrusion during SMD. All the aforementioned researches dealt with SW-GMAW technique. Recently, a new trend developed in the field of DW-GMAW.

2. SMD Using Double Wire-GMAW (DW-GMAW)

To resolve distortions and crack problem and find a way to substantially increase the productivity and reduce the heat input, two technologies have been created to modify GMAW for faster deposition: Tandem-GMAW [99]-[102] and Variable-Polarity GMAW (VP-GMAW) [92]. Tandem-DE-GMAW, a good innovation known as consumable double-wire GMAW (DW-GMAW) and also called double-electrode GMAW, has been developed at the University of Kentucky.

In Tandem GMAW, a pair of torches is integrated into one large torch, and a couple of shuts arcs are usually separately proven between their own wire and workpiece in parallel and are modified by their own GMAW power source as shown in Fig. 8.

DW-GMAW is used to increase the deposition rate and to increase the speed of production and to obtain parts with a good surface finish. Pires et al. [103] compared the DW-GMAW technique with pulse-GMAW and conventional GMAW technique and detailed a few benefits as the:

1) Wide modifying range.
2) The ability to control all weld positions compared to the conventional method.
3) Control the settings of the control system wider than the conventional mode.
4) Decrease the overall heat input.
5) Enhancing combined properties.
6) Powerful weld pool, mixing, and
7) Decrease crack sensitivity.

Ueyama et al. [99] discussed the problems of the configuration of the double wires, the selection of welding currents and wire feed rates with the a couple wires that affect weld bead formation through the tandem pulsed MIG welding technique, in which two wires are fed with pulsed welding currents supplied individually, to be able to explain the essential requirements for sound weld beads without undercut and humping in the higher speed welding of steel sheets. Besides that, there are researchers who have been able to combine the two GMAW-torch and GTAW-torch to minimize the heat input of the base metal. Li et al. [104] suggested the DE-GMAW a variation of conventional GMAW to decrease the base metal heat input and maintain the wire melting current regular through presenting (GTAW) bypass torch. Yang et al. [105] investigated developing features within GMAW multi-layer, single-bead AM by DE-GMAW and supplies a theoretical foundation for its technique as shown in Fig. 9. Wu et al. [106] indicated that the torches' relative position acquired a fantastic effect on the balance of the arcs and metal transfer in the DE-GMAW technique. Some researchers also studied the numerical analysis of DE-GMAW for optimizing the process welding. Other researchers [107] investigated the applying of numerical analysis in the DE-GMAW in order to produce guidelines for optimizing the method experimentally.

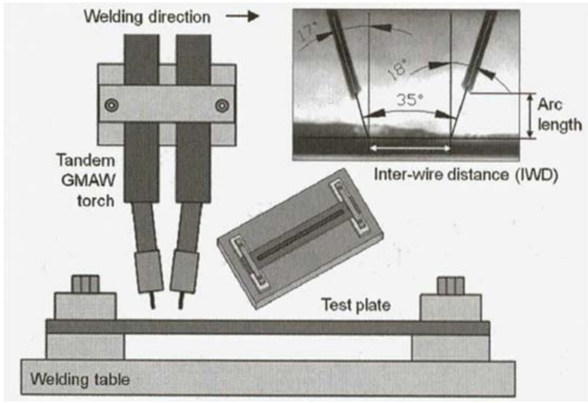

Fig. 8 Schematic illustrates rig used for evaluating the Tandem Pulsed GMAW arcs [102]

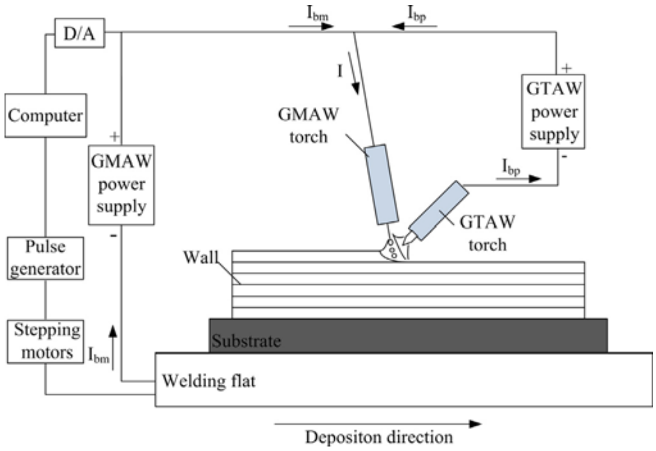

Fig. 9 Schematic diagram of double electrode GMAW-based AM system [105]

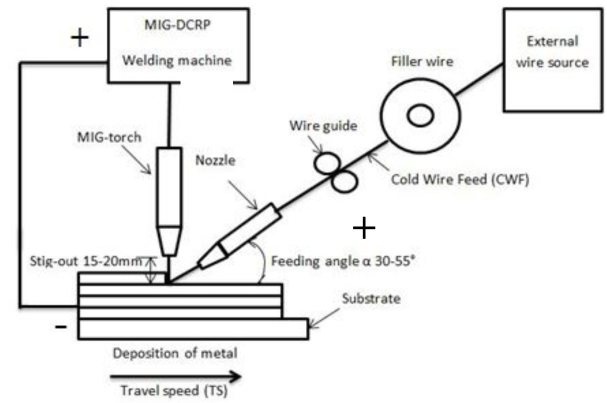

Fig. 10 Schemes illustrate the external CWF plus MIG-welding of SMD system

Through this literary survey conducted by researchers who have used SW-GMAW and DW-GMAW, it is obvious that there is a lack in the research studies concerned using externally cold wire as minor feed way to the deposition area. Thus, a new technology for metal deposition can be obtained through system consisting of a cold feed wire (filler wire) equipped through an external device by wire guide plus MIG-welding. It is considered as a new and important technique in this field since the cold wire reduces the heat input and increases the rate of metal deposition in addition to reducing the production time (see Fig 10). Fig 10 shows that a technology called cold wire feed (CWF) is added plus MIG-welding based on SMD process in AM field.

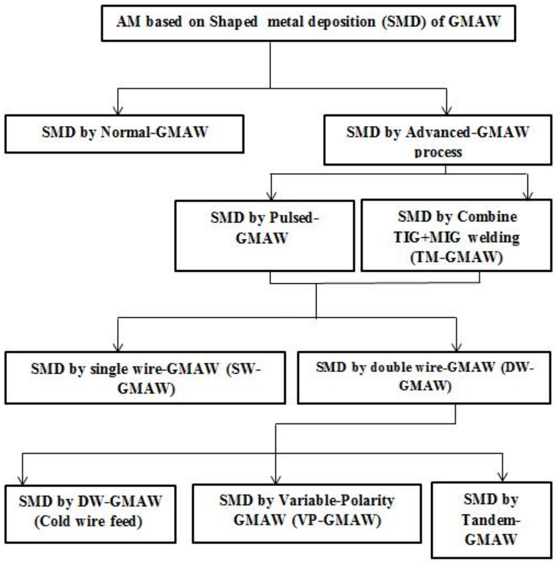

Fig. 11 Classification of SMD for GMAW process

V. MATERIALS USED IN THE CWF OF SMD PROCESS

A wide range of metallic alloys, such as Fe-based [108], stainless steel 308L, 316L [73]-[75], [108]-[110], Ti-based [111], [112] and Al-based [113] materials have been investigated in the SMD process. A lot of researchers focused on the Ti-6Al-4V because of its recognition within the aerospace component manufacturing. The metal alloys of Ti–6Al–4V (Ti6Al4V ELI (extra low interstitial) may be welded by a wide variety of conventional fusion and solid-state processes, although its chemical reactivity typically requires special measures and procedures) are probably the most essential Ti alloys which are utilized in a lot more 50% of all industrial Ti applications [114]. Up to now, there has been merely a restricted quantity of industrial alloys utilized in SMD. A few of these are offered within in Table III. Since the SMD process is evolving, it is obvious that new alloys will have to be developed in order to be able to take advantage of the benefits of SMD. The size of the wire most commonly used in the MIG welding technique is usually between 0.6 to 1.6 mm.

Austenitic stainless steel is commonly utilized within contemporary sectors, for example, biochemistry manufacturing, steamship constructing, higher temperature bolt and nuclear reactor because of its good corrosion resistance, adequate high-temperature mechanical properties, excellent fabricated and welding processing capability [108]-[110]. Skiba et al. [56] stated for the first time the microstructure and mechanical properties for a 308 austenitic stainless steel element created through SMD, the goal is to obtain steel parts with higher corrosion resistance as well as higher ductility. The microstructure of 308 stainless demonstrates that ferrite seems in the form of vermicular and Widmanstätten austenite is available at the top of the elements. Skiba et al. [115] checked out the microstructure and also the qualities associated with SMD 300M metal within the as-produced situation. Yilmaz and Ugla [73] demonstrated for the first time effect of high pulse frequency on the metallurgical characteristics of deposit parts of SS308LSi alloy and also investigated the effect of pulse frequency with other process parameters for the change of primary ferrite grain framework, surface morphology, and microstructure of the deposited AISI 308LSi components in the TW-SMD procedures.

TABLE III
SELECTED ALLOYS COMMERCIALLY USED IN AM PROCESSING [67]

Ti-alloys	Al-alloys	Tool Steels	Superalloys	Stainless steel	Refractory
Ti-6Al-4V γ-TiAl	Al-Si-Mg	H13	IN625	316, 316L, 308L, 309L,	More Alumina
ELI Ti	Al-Si-Mg	Cermets	IN718	202, PH 17-4	Ta-W
CP Ti			Satellite	420, 347,	CoCr

Additionally, there has been extensive research conducted on many minerals in the SMD process, for example, the work of Wang et al. [116] looked into the microstructures and properties of 4043 Al-alloy components using a novel layer-deposition method depending on a variable polarity GTA-AM technique.

Some studies showed that the microstructure is usually in the dendritic framework. In the same way, Amine et al. [117] utilized the laser beam source in order to dissolve as well as deposit the filler metal powders for 316 stainless steel. Other studies investigated the influence of the process parameters on the deposition characteristics, such as microhardness and microstructure. Sudhakaran et al. [118] indicated that the influence associated with gas tungsten arc welding (GTAW) parameters about the pitting corrosion on AISI 202 chromium manganese stainless steel had been investigated. There is a small amount of releasing data available with regard to the modeling of penetration in 202 and 303L grade stainless steel MIG plates. Sudhakaran et al. [119] indicated that the 2nd order quadratic style could be successfully utilized to predict the depth of penetration within GTAW of stainless steel 202-grade plates.

VI. ARC ENERGY AND HEAT INPUT FOR THE CONVENTIONAL MIG AND TANDEM-MIG

Arc energy (AE) and heat input (HI) in arc SMD processes are both measures of the amount of energy that is provided to the workpiece to complete the deposition process; both are measured in units of energy per unit length. European countries use KJ/mm units, America uses KJ/in units [120]. AE it is the energy that the arc of welding prepares for the workpiece before considering the efficiency of the process, while the HI (term, prefers the exercise at present because it provides a way to the most appropriate to compare the deposition process by the electric arc). AE and HI are given by [121]:

$$\mathrm{AE} = \frac{60\mathrm{VI}}{1000\mathrm{v}} \tag{1}$$

$$HI = \eta \mathrm{AE} \tag{2}$$

where V is the voltage used, in volts I is the current used, in amperes, v is the travel speed of the deposition process is measured in KJ/mm or KJ/in and $\boldsymbol{\eta}$ is the process efficiency.

The thermal behavior of metal deposition is very complex when studied, either by experimental or numerical methods and for this reason, there are many aspects still not fully understood in addition to that there are still a large number of uncertainties remaining to date but still not reported. These errors or their sources are caused by irregular temperature of samples within the period of time that lies between beginning and the end of the SMD process. As described by Stenback [122], loss results from the process of deposition of minerals (from the surface of the sample to the environment or conservation system), as well as during transport (when necessary) from the sample to the calorimeter.

In metal deposition processes when traditional MIG techniques are used, there are several problems raised such as HI problems or AE. One of these problems is the lack of attention or suspicion of calorie restrictions of controversial results which, in turn, affect the efficiency of mineral deposition. For example, tests conducted by Bosworth [123], using the water calorimeter have been weakened or inaccurate due to the long time elapsed, 15 seconds, between the beginning of the deposition and the end of the measurement whereas, Quentino et al. [124] pointed out the importance of considering the effect of heat loss through the backside of the deposition by radiation for complete deposition of the sample penetration, using the parameters of HI efficiency instead of the general parameters in the MIG process.

Kumar et al. [125] showed that the thermal input during deposition of metals by the MIG process was higher than the thermal input in the case of TIG process, which means that the energy consumption or the temperature was about 27.06% higher in the MIG than the TIG.

Sometimes a non-consumptive torch is added to reduce HI in the component and thus led to reduced distortions as well as improved tolerance bridging ability; this process is called double electrode or Tandem deposition process. There are many researchers who have done research in this field such as Choi et al. [126]. They indicated that, increasing the efficiency of deposition and reducing HI can be done by using a new control system of industrial PLC. The tandem deposition process was used for aluminum metal. The automatic control system was developed to make it more secure and provide greater comfort and efficiency as well as reduce operator workload.

Ueyama et al. [127] found that the interrupting of the electric arc process using the MIG-Tandem process resulted from the electromagnetic interaction between the adjacent arcs and their effect on the HI and the efficiency of the deposition where, it was found that the HI or AE changes according to the distance between the adjacent arcs due to a break in the arc because of the distance between the brackets in turn. It affects the deposition efficiency, where the arc interruption is found in the excess when the interwire distance is 10 mm, because the deviated length of the excess arc with the electromagnetic interaction becomes longer but does not occur at 5 mm as shown in Fig. 12.

Li et al. [104] suggested tandem deposition process by adding the non-consumable tungsten electrode in the conventional GMAW to form an overflow loop, thus reducing the input of heat or AE to the metal base. Experiments have shown that the use of a sophisticated control system can adjust the current flow in a wide range to maintain the core metal current at the level required.

Sproesser et al. [128] proved that the increasing efficiency and performance of metal deposition of the GMAW process was achieved by a high power tandem process.

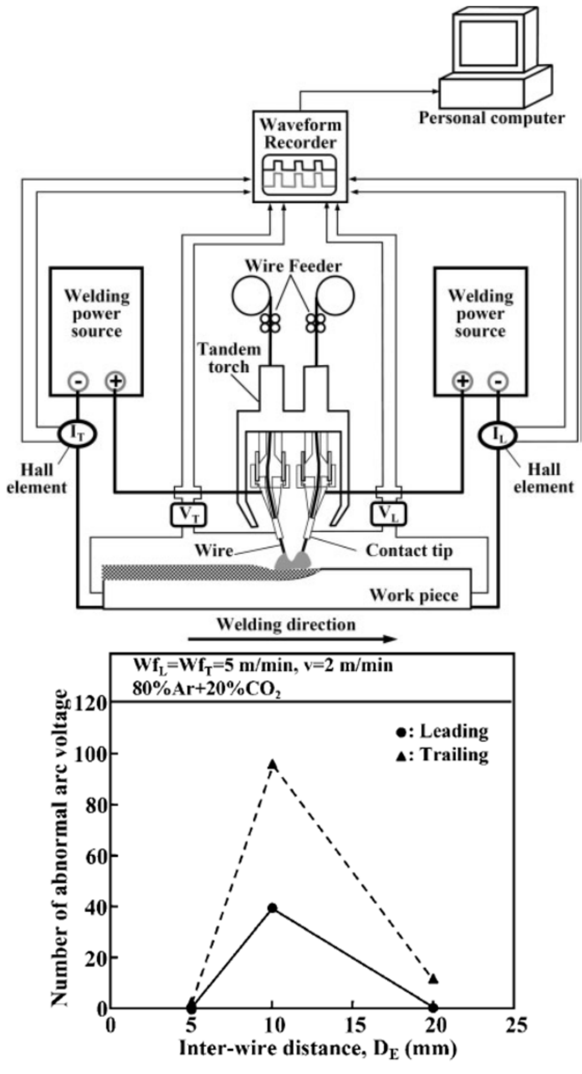

Fig. 12 The effect of Interwire the electric arc which in turn affects HI and efficiency [128]

VII. Summary, Conclusions and Future Recommendations

A. Summary

SMD based on ALM is a new technology of the most popular techniques in the manufacture of products that are difficult to form and cut in the normal operating machines. SMD is a new technology that is able to produce net-shaped or near net-shaped of products by depositing a filler metal (mostly of metallic wires) in the form of a layer on a layer. In this study, there are many types of research that used the electric arc, laser beam, and electron beam as a method of welding or deposition of metals to form the part to be manufactured.

Due to the high deposition rate, SMD is a promising technique for producing large features with high complexity, such as balanced cruciform, flanges and stiffened panel. One of the purposes of this study is to provide an overview of the AM and its classification such as description of SMD. The classification of SMD includes SMD process using Electron beam Freeform fabrication (EBF^3) process, SMD process using WLAM Process and SMD using WAAM. WAAM is divided into SMD using single wire-GMAW (SW-GMAW) and SMD using double wire-GMAW (DW-GMAW). In addition to SMD process, there is new technology, which is CWF plus MIG-welding. Furthermore, the paper studied the materials used in the CWF, the efficiency of the AE, and HI of the conventional MIG and Tandem-MIG in SMD process.

B. Conclusion

The main remarks and findings from the present work can be summarized as follows:

- AM has become a competitive partner of traditional manufacturing techniques such as a metal deposition process, casting, and precision metal parts manufacturing which are used in critical industrial sectors such as aerospace, automotive and medical.
- AM enjoys a market position with tremendous growth potential in modern manufacturing if the major obstacles to this approach can be addressed.
- WAAM process is a term or concept that creates a wide range of options for manufacturing or forming large and lightweight structures. WAAM process is particularly useful for example in manufacturing or repairing parts of aerospace industry where complex and lightweight structures are required. Due to the high flexibility offered by the WAAM process, these parts can be specially designed.
- SMD processes are suitable for fabricating the aerospace parts. In addition, it has been provided as a unique and low-cost solution for the manufacture or formation of structural components within a wide range due to high deposition rate, high efficiency, and high density. This technique is surrounded by many weldable materials such as, for example, Ti-6Al-4V, stainless steel 304, 308L, 309L, 316L and Inconel 718.
- The SMD process represented by MIG-3D welding technique usually produces very dense parts, but the quality and accuracy of the surface are not good compared with the other techniques such as electron beam freeform fabrication (EBF3) process and laser beam processing (LBP).
- MIG welding with CMT is an innovative process for depositing material to be widely formed and based on excellent quality, high efficiency compared to other welding processes such as TIG welding and heat source efficiency are high compared to TIG welding.
- There are some of the improved techniques such as Tandem-GMAW, Variable-Polarity GMAW (VP-GMAW) and DW-GMAW were invented to solve the problems of distortions and cracking due to reducing the HI as well as increase the deposition rate and hence doubling the production rates.
- CWF plus MIG-welding technology is one of the most modern techniques for metal deposition since it reduces HI and AE increases the metal deposition rate and reduces the time needed to manufacture components.
- The deposition efficiency when using a DW-GMAW is higher than the deposition using an SW-GMAW because the HI and AE that is equipped into the workpiece are few.

C. Future Recommendations

- In order to increase the production rate, control the HI, and reduce the required time for manufacturing process with the use of pulsed currents, deep study is required about the possibility of adding cold feed wire with the MIG welding process.
- Study the metallurgical properties of the deposited parts producing using double filler materials from similar and non-similar fillers in cold feed state. Moreover, investigate the effect of double wire cold feed on the residual stresses behavior.

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References

[1] Baufeld, B., Biest, O.V.D., Gault, R., 2010. Additive manufacturing of Ti-6Al-4V components by shaped metal deposition: microstructure and mechanical properties. Mater. Des. 31, S106-S111.W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.

[2] Huang, R.Z., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2016. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. J. Clean Prod. 135, 1559-1570.

[3] Gebhardt A. (2011). Understanding additive manufacturing, rapid prototyping, rapid tooling, rapid manufacturing, 1st edition, Carl Hasner Verlag, Munich- Germany.

[4] Antonysamy AA. (2012). Microstructure, texture, and mechanical properties evolution during additive manufacturing of Ti6Al4V alloy for aerospace applications. University of Manchester, Ph.D. thesis.

[5] Buckner, M.A., Lonnie, J.L. (2012). Automating and accelerating the additive manufacturing design process with multi-objective constrained evolutionary optimization and HPC/Cloud computing. In: *Proceedings of the 2012 IEEE Int Conf on Future of Instrumentation International*

Workshop (FIIW). Gatlinburg, NT, USA, 8-9October, pp. 1-4.

[6] Wohlers T, Gornet T (2014) History of additive manufacturing. Wohlers Report. http://wohlersassociates.com/history2014.pdf

[7] Jacobs PF (1992) Rapid prototyping & manufacturing fundamentals of stereolithography. Society of Manufacturing Engineers, Dearborn. First edition. US

[8] Sachs E et al (1990) Three-dimensional printing: rapid tooling and prototypes directly from a CAD model. CIRPAnn Manuf Technol 39:201–204

[9] Mahmood, R.M., Akinlabi, E.T., Shukla, M., Pityana, S. (2013). Laser Metal Deposition of Ti6Al4V: A Study on the Effect of Laser Power on Microstructure and Microhardness In: *Proceedings of the International Multi Conference of Engineers and comp Scientists, IMECS* 2013, March 13-15, Hong Kong, Volume 11.

[10] Klahn, C., Leutenecker, B., Meboldt, M. (2014). Design for Additive Manufacturing-Supporting the Substitution of Components in Series Products, in *Proceedings of the 14th CIRP Design Conference*, 21:138-143. Available online at www.sciencedirect.com

[11] Levy GN et al (2003) Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRPAnn Manuf Technol 52:589–609

[12] Wohlers, T. (2009). Wohlers report 2009, State of the industry, Annual worldwide progress report, *Wohlers.*

[13] Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: technologies, developments, and future interests. *The International Journal of Advanced Manufacturing Technology*, *81* (1-4), 465-481.

[14] J. Alcisto, A. Enriquez, H. Garcia, S. Hinkson, T. Steelman, E. Silverman, P. Valdovino, H. Gigerenzer, J. Foyos, J. Ogren, J. Dorey, K. Karg, T. McDonald, and O.S. Es-Said, Tensile Properties and Microstructures of Laser-Formed Ti-6Al-4V, JMEP, 2011, 20 (2), p 203–212

[15] ASTM F2792-12 A Standard Terminology for Additive Manufacturing Technologies, doi: 10.1520/F279-12A.

[16] VDI 3404 (2014). Additive Manufacturing: Basics, Definitions, Processes.

[17] D.L. Bourell, M.C. Leu, and D.W. Rosen, Ed., Roadmap for Additive Manufacturing, the University of Texas at Austin, Austin TX, 2009

[18] Gibson, I., Rosen, D., Stucker, B. (2010). Additive manufacturing technologies, Second Edition, Springer, New York, Heidelberg Dordrecht, London, do: 10.1007/978-1-4939-2113-3.

[19] Tofail, S. A., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., & Charitidis, C. (2017). Additive manufacturing: scientific and technological

[20] Van Niekerk G.J. (2007). A model for transparent data exchanging in layered manufacturing. Faculty of Science – the University of Johannesburg, Ph.D. thesis.

[21] Griffith, M.L., Ensz, M.T., Puskar, J.D., Robino, C.V. (2000). Brooks, J.A., Philliber, J. A, et al. Understanding the microstructure and properties of components fabricated by laser engineered net shaping (LENS). In: *Proceedings of MRS Spring Meeting Conference*; San Francisco, CA, US, 24-27 April.

[22] Zhang, K., Liu, W., Shang, X. (2009). Study on scanning pattern during laser metal deposition shaping. In: *Proceedings of the 2009 IEEE Second IntConfon Intelligent Computation Techn and Auto*; Changsha, Hunan, 10-11 October, 4, 668-671.

[23] Jardini, A.L., Larosa, M.A., Bernardes, L.F., Zavaglia, C.A.C., Maciel F. R. (2011). Application of direct metal laser sintering in titanium alloy for cranioplasty. *6th BRAZILIAN Conf on Manf Eng*; CaxiasdoSul-RS-Brazil, 11-15 April.

[24] Zhang, K., Liu, W. (2009). Microstructure evolution of stainless steel during laser metal deposition shaping.In: *Proceedings of the 2009 IEEE Int Conf on Measuring Techn and Mechatronics Auto*, Zhangjiajie, Hunan, 11-12 April, 2, 93-96.

[25] Kloosterman, A., Wentzel, C., Carton, E. (2006). SLAM, A fast high volume additive manufacturing concept by impact welding; application to Ti6Al4V alloy. SAE International, Aerospace Man. And Auto. Fast. Conf. & Exhibition; Toulouse, France, 12-14 September.

[26] Taminger, K. M., & Hafley, R. A. (2003, September). Electron beam freeform fabrication: a rapid metal deposition process. In Proceedings of the 3rd annual automotive composites conference (pp. 9-10).

[27] Taminger, K.M., Hafley, R.A. (2006). Electron beam freeform fabrication for cost-effective near-net-shape manufacturing. In NATO/RTOAVT-139 specialists' meeting on cost-effective manufacture via net shape processing 2006, NATO: Amsterdam (The Netherlands).

[28] Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). A practical path planning methodology for wire and arc additive manufacturing of thin-walled structures. *Robotics and Computer-Integrated Manufacturing*, *34*, 8-19.

[29] Wang F et al (2013) Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V. Metall Mater Trans A 44:968–977

[30] Xiong, J., Zhang, G., Hu, J., & Wu, L. (2014). Bead geometry prediction for robotic GMAW-based rapid manufacturing through a neural network and a second-order regression analysis. Journal of Intelligent Manufacturing, 25 (1), 157-163.

[31] Yilmaz, Oguzhan, and Adnan A. Ugla. "Shaped metal deposition technique in additive manufacturing: A review." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 230.10 (2016): 1781-1798.

[32] Brandl, E., Baufeld, B., Leyens, C., & Gault, R. (2010). 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, 5(Pt 2), 595-606.

[33] Spencer, J. D., Dickens, P. M., & Wykes, C. M. (1998). Rapid prototyping of metal parts by three-dimensional welding. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *212*(3), 175-182.

[34] Mughal, M.P., Fawad, H., Mufti, R.A., 2006. Three-dimensional finite-element modeling of deformation in weld-based rapid prototyping. Proc. Inst. Mech. Eng. Part C-J. Eng. Mech. Eng. Sci. 220, 875–885.

[35] Mughal M et al (2005) Deformation modeling in the layered manufacturing of metallic parts using gas metal arc welding: effect of process parameters. Model Simul Mater Sci Eng 13:1187

[36] Zhang, Y.M., Li, P.J., Chen, Y.W., Male, A.T., 2002. Automated system for welding-based rapid prototyping. Mechatronics 12, 27–53.

[37] Zhang et al. (2003), in which guidelines, including droplet transfer, heat input, and forming appearance control were also presented for GMAW-based additive manufacturing.

[38] Xiong, J., Lei, Y., Chen, H., & Zhang, G. (2017). Fabrication of inclined thin-walled parts in multi-layer single-pass GMAW-based additive manufacturing with flat position deposition. *Journal of Materials Processing Technology*, *240*, 397-403.

[39] Syed, W.U.H., Pinkerton, A.J., Li, L. (2006). Combining wire and coaxial powder feeding in a laser direct metal deposition for rapid prototyping, *J. Applied Surface Science,* 252, 4803-4808.

[40] Syed, W.U.H., Pinkerton, A.J., Li, L. (2006). Simulation wire- and powder-feed direct metal deposition: An investigation of the process characteristics and comparison with single-feed methods, *J. Laser Applications*, 18 (1), 65-72

[41] Brandl, E., Layens, C., Palm, F. (2011). Mechanical properties of additive manufactured Ti6Al4V using wire and powder-based processes, *IOP Conf. Series:*

[42] Karunakaran, K.P., Suryakumar, S., Pushpa, V., & Akula, S. (2010). Low cost integration of additive and subtractive processes for hybrid layered manufacturing. *Robotics and Computer-Integrated Manufacturing, 26*, 490–499.

[43] Jamieson R, Holmer B, Ashby A. How rapid prototyping can assist in the development of new orthopedic products: a case study. Rapid Prototype J. 1995;1:3841.

[44] Hieu LC, Zlatov N, VanderSloten J, et al. Medical rapid prototyping applications and methods. Assembly Automation. 2005;25:284–292.

[45] Liu Q, Leu MC, Schmitt SM. Rapid prototyping in dentistry: technology and application. Int J Adv Manuf Technol. 2006;293:317–335.

[46] RAPOLAC Project home page. [Online]. Available: http:// www. RAPOLAC.eu.

[47] Escobar-Palafox, G., Gault, R., & Ridgway, K. (2011). Robotic manufacturing by shaped metal deposition: state of the art. Industrial Robot: An International Journal, 38(6), 622-628.

[48] Escobar-Palafox, G., Gault, R., & Ridgway, K. (2011). Robotic manufacturing by shaped metal deposition: state of the art. Industrial Robot: An International Journal, 38(6), 622-628.

[49] Bonaccorso, F., Bruno, C., Cantelli, L. (2009). Control of a shaped metal deposition process. In: Physcon 2009; Catania, Ital y, 1-4 September

[50] Clark, D., Bache, M. R., & Whittaker, M. T. (2008). Shaped metal deposition of a nickel alloy for aero engine applications. Journal of Materials Processing Technology, 203 (1-3), 439-448.

[51] Baufeld, B., Van der Biest, O. (2009). Mechanical properties of Ti-6Al-4V specimens produced by shaped metal deposition. *Sci-Tech Adv Mater,* 10(1), 10.

[52] Baufeld, B., Van der Biest, O., Gault, R., Ridgway, K. (2011).

Manufacturing Ti6Al4V components by shaped metal deposition: microstructure and mechanical properties. *IOP Conf. Series: Mat. Sci. and Eng,* 26(1).

[53] Bonaccorso, F., Cantelli, L., Muscato, G. (2011). An arc welding robot control for a shaped metal deposition plant: modular software interface and sensors. *IEEE Transactions on Industrial Electronics,* 58(8): 3126-3132.

[54] Muscato, G., Spampinato, G., Cantelli, L. (2008). A closed loop welding controller for a rapid manufacturing process.In: Proc.13th IEEE Conf; EFTA, Hamburg, Germany, 15-18 September2008; 1080-1083.

[55] Merz, R., Prnnz, F.B., Ramaswami, K., Terk, M., Weiss, L.E. (1994). Shape deposition manufacturing. In: Proceedings of the Solid Freeform Fabrication Symposium, Texas University in Austin, 8-10 August.

[56] Skiba, T., Baufeld, B., Vander-Biest, O. (2009). Microstructure and mechanical properties of stainless steel component manufactured by shaped metal deposition, ISIJ Int, 49(10), 1588-1591

[57] Hensinger, D. M., Ames, A. L., & Kuhlmann, J. L. (2000). Motion planning for a direct metal deposition rapid prototyping system. In Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on (Vol. 4, pp. 3095-3100). IEEE.

[58] Zhang, Y., Chen, Y., Li, P., & Male, A. T. (2003). Weld deposition-based rapid prototyping: a preliminary study. Journal of Materials Processing Technology, 135 (2), 347-357.

[59] Sequeira-Almeida, P.M. (2012). Process control, and development in wire and arc additive manufacturing. School of Applied Sciences, Cranfield University, Ph.D. thesis.

[60] Brandl, E., Baufeld, B., Leyens, C., Gault, R. (2010). Additive manufacturing Ti6Al4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications. J Physical Procedia 2010; 5: 595-606.

[61] Terrazas, C.A., Gaytan, S.M., Rodriguez, E., Espalin, D., Murr, L.E., Medina, F., et al. (2014). Multi-material metallic structure fabrication using electron beam melting. Int J Adv Manuf Technol, 71,33-45.

[62] Gong, X., Anderson, T., Chou, K. (2014). Review on powder-based electron beam additive manufacturing technology. Manufacturing Rev., available online at http://mfr.edp-open.org

[63] Wanjara, P., Brochu, M., Jahazi, M., 2007. Electron beam free forming of stainless steel using solid wire feed. Mater. Des. 28, 2278–2286

[64] Ding, J. (2012). Thermo-mechanical analysis of wire and arc additive manufacturing process. School of Applied Science, Cranfield University, Ph.D. thesis.

[65] Shames, H. (2010). Development of a selection program for additive manufacturing system. Stellenbosch University, Master thesis.

[66] [Online].Available:http://3dprintingindustry.com/wpcontent/uploads/2013/05/Atlantis-Report-on-3D-printing.

[67] Frazier, W. E. (2014). Metal additive manufacturing: a review. *Journal of Materials Engineering and Performance*, *23*(6), 1917-1928.

[68] [online]. Available: http://.www.nasa.gov 2009.

[69] Taminger KMB et al (2003) Electron beam freeform fabrication: a rapid metal deposition process. In: Proceedings of third annual automotive composites conference, Society of Plastic Engineers, Troy, MI; 9–10

[70] Zalameda JN, et al. (2013) Thermal imaging for assessment of electron beam freeform fabrication (EBF3) additive manufacturing deposits. SPIE Defense, Security, and Sensing, International Society for Optics and Photonics

[71] Rännar LE et al (2007) Efficient cooling with tool inserts manufactured by electron beam melting. Rapid Prototyp J 13: 128–135.

[72] Medina, J. A. I. (2012). Development and application of CFD model of laser metal deposition. Ph.D. thesis, University of Manchester.

[73] Yilmaz, O., & Ugla, A. A. (2017). Microstructure characterization of SS308LSi components manufactured by GTAW-based additive manufacturing: shaped metal deposition using pulsed current arc. The International Journal of Advanced Manufacturing Technology, 89(1-4), 13-25.

[74] Yilmaz, O., Almosawi, A. R. J., & Ugla, A. A. (2015). Design, Construction, and Controlling of A Shaped Metal Deposition Machine Using Arc Metal-Wire System. Pulse, 1, T1G.

[75] Ugla, A. A., Yilmaz, O., & Almusawi, A. R. (2016). Development and control of shaped metal deposition process using tungsten inert gas arc heat source in additive layered manufacturing. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 0954405416673112.

[76] Bai, X. W., Zhang, H. O., & Wang, G. L. (2013). Electromagnetically confined weld-based additive manufacturing. Procedia CIRP, 6, 515-520.

[77] Dos Santos, E. B., Pistor, R., & Gerlich, A. P. (2017). High-frequency pulsed gas metal arc welding (GMAW-P): the metal beam process. Manufacturing letters, 11, 1-4.

[78] Knezović, N., & Topić, A. (2018, June). Wire and Arc Additive Manufacturing (WAAM)–A New Advance in Manufacturing. In International Conference "New Technologies, Development and Applications" (pp. 65-71). Springer, Cham.

[79] Zhang, Z., Sun, C., Xu, X., & Liu, L. (2018). Surface quality and forming characteristics of thin-wall aluminum alloy parts manufactured by laser-assisted MIG arc additive manufacturing. International Journal of Lightweight Materials and Manufacture

[80] Martina, F., Mehnen, J., Williams, S. W., Colegrove, P., & Wang, F. (2012). Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V. Journal of Materials Processing Technology, 212(6), 1377-1386.

[81] Sawant, M. S., & Jain, N. K. (2018). Investigations on Additive Manufacturing of Ti-6Al-4V by μ-Plasma Transferred Arc Powder Deposition Process.

[82] Almeida, P. S., & Williams, S. (2010, August). Innovative process model of Ti–6Al–4V additive layer manufacturing using cold metal transfer (CMT). In Proceedings of the twenty-first annual international solid freeform fabrication symposium, the University of Texas at Austin, Austin, TX, USA.

[83] Ding, J., Colegrove, P., Mehnen, J., Ganguly, S., Almeida, P. S., Wang, F., & Williams, S. (2011). Thermo-mechanical analysis of wire and arc additive layer manufacturing process on large multi-layer parts. Computational Materials Science, 50 (12), 3315-3322.

[84] Mehnen, J., Ding, J., Lockett, H., & Kazanas, P. (2014). Design study for wire and arc additive manufacture. International Journal of Product Development 20, 19(1-3), 2-20.

[85] Ribeiro, A.F., Norrish, J., McMaster, R.S. (1994). A practical case of rapid prototyping using gas metal arc welding. In: *Fifth International Conference on "Computer Technology in Welding*", The Welding Institute, printed by Crampton's Printers, 15-16th June, Paris, France, 55, 1-6.

[86] Ribeiro, A.F., Norrish, J. (1996). Rapid prototyping process using metal directly. In: Proceedings of the 7th Annual Int Solid Freeform Fab Symposium, 12-14 August, The University of Texas at Austin, Austin, Texas, USA, 249-256.

[87] Larry, J. (1999). Welding: Principles and Applications. *Albany: Thomson Delmar*, 904.

[88] Xiong, J., Zhang, G., Qiu, Z., & Li, Y. (2013). Vision-sensing and bead width control of a single-bead multi-layer part: material and energy savings in GMAW-based rapid manufacturing. Journal of cleaner production, 41, 82-88.

[89] Doumanidis, C., & Kwak, Y. M. (2002). Multivariable adaptive control of the bead profile geometry in gas metal arc welding with thermal scanning. International Journal of Pressure Vessels and Piping, 79(4), 251-262.

[90] Dong, B. (2017). Fabricating copper-rich Cu-Al binary alloy by wire-arc additive manufacturing.

[91] Vilarinho, L. O., Nascimento, A. S., Fernandes, D. B., & Mota, C. A. M. (2009). Methodology for parameter calculation of VP-GMAW. Welding Journal, 88(4), 92S-98S.

[92] Harada, S., Ueyama, T., Mita, T., Innami, T., & Ushio, M. (1999). The state-of-the-art AC-GMAW process in Japan. IIW Doc. XIII-1589, 99, 1-10.

[93] Meco, S., Pardal, G., Eder, A., & Quintino, L. (2013). Software development for prediction of the weld bead in CMT and pulsed-MAG processes. The International Journal of Advanced Manufacturing Technology, 1-8.

[94] Pal S, Samantaray A (2008) Artificial neural network modeling of weld joint strength prediction of a pulsed metal inert gas welding process using arc signals. J Mater Process Technol 202:464–474.

[95] Bai, X., Zhang, H., & Wang, G. (2013). Improving prediction accuracy of thermal analysis for weld-based additive manufacturing by calibrating input parameters using IR imaging. *The International Journal of Advanced Manufacturing Technology*, *69*(5-8), 1087-1095.

[96] Schwerdtfeger, J., Singer, R. F., & Körner, C. (2012). In situ flaw detection by IR-imaging during electron beam melting. *Rapid Prototyping Journal*, *18*(4), 259-263.

[97] Yang, D., Wang, G., & Zhang, G. (2017). Thermal analysis for single-pass multi-layer GMAW based additive manufacturing using infrared thermography. *Journal of Materials Processing Technology*, *244*, 215-224.

[98] Seppala, J. E., & Migler, K. D. (2016). Infrared thermography of welding zones produced by polymer extrusion additive manufacturing. *Additive Manufacturing*, *12*, 71-76.

[99] Ueyama, T., Ohnawa, T., Tanaka, M., & Nakata, K. (2005). Effects of torch configuration and welding current on weld bead formation in high-speed tandem pulsed gas metal arc welding of steel sheets. *Science and Technology of Welding and Joining*, *10*(6), 750-759.

[100]Tsushima, S., & Kitamura, M. (1994). Tandem electrode AC-MIG welding-Development of AC-MIG welding process (Report 4).

[101]Harwig, D. D., Dierksheide, J. E., Yapp, D., & Blackman, S. (2006). Arc behavior and melting rate in the VP-GMAW process. *Welding Journal*, *85* (3), 52-62.

[102]Reis, R. P., Souza, D., & Ferreira Filho, D. (2015). Arc interruptions in Tandem pulsed gas metal arc welding. Journal of Manufacturing Science and Engineering, 137 (1), 011004.

[103]Pires, I., Quintino, L., & Miranda, R. M. (2007). Analysis of the influence of shielding gas mixtures on the gas metal arc welding metal transfer modes and fume formation rate. *Materials & design*, *28* (5), 1623-1631.

[104]Li, K. H., Chen, J. S., & Zhang, Y. (2007). Double-electrode GMAW process and control. *Welding Journal-New York-*, *86* (8), 231.

[105]Yang, D., He, C., & Zhang, G. (2016). Forming characteristics of thin-wall steel parts by double electrode GMAW based additive manufacturing. *Journal of Materials Processing Technology*, *227*, 153-160.

[106]Wu, C. S., Hu, Z. H., & Zhong, L. M. (2012). Prevention of humping bead associated with high welding speed by double-electrode gas metal arc welding. *The International Journal of Advanced Manufacturing Technology*, *63* (5), 573-581.

[107]Wu, C. S., Zhang, M. X., Li, K. H., & Zhang, Y. M. (2007). Numerical analysis of double-electrode gas metal arc welding process. *Computational Materials Science*, *39* (2), 416-423.

[108]Song, R. B., Xiang, J. Y., & Hou, D. P. (2011). Characteristics of mechanical properties and microstructure for 316L austenitic stainless steel. *Journal Of Iron And Steel Research, International*, *18*(11), 53-59.

[109]Ma, M., Wang, Z., Wang, D., & Zeng, X. (2013). Control of shape and performance for direct laser fabrication of precision large-scale metal parts with 316L Stainless Steel. *Optics & Laser Technology*, *45*, 209-216.

[110]Xie, F., He, X., Cao, S., & Qu, X. (2013). Structural and mechanical characteristics of porous 316L stainless steel fabricated by indirect selective laser sintering. *Journal of Materials Processing Technology*, *213*(6), 838-843.

[111]Mok, S. H., Bi, G., Folkes, J., Pashby, I., & Segal, J. (2008). Deposition of Ti–6Al–4V using a high power diode laser and wire, Part II: Investigation of the mechanical properties. *Surface and Coatings Technology*, *202*(19), 4613-4619.

[112]Baufeld, B., Brandl, E., & Van der Biest, O. (2011). Wire-based additive layer manufacturing: Comparison of microstructure and mechanical properties of Ti–6Al–4V components fabricated by laser-beam deposition and shaped metal deposition. *Journal of Materials Processing Technology*, *211*(6), 1146-1158.

[113]Xiao, R., Chen, K., Zuo, T., Ambrosy, G., & Huegel, H. (2002, September). Influence of wire addition direction in C02 laser welding of aluminum. In *Lasers in Material Processing and Manufacturing* (Vol. 4915, pp. 128-138). International Society for Optics and Photonics.

[114]Leyens, C., & Peters, M. (Eds.). (2003). *Titanium and titanium alloys: fundamentals and applications*. John Wiley & Sons.

[115]Skiba, T., Baufeld, B., & Van der Biest, O. (2011). Shaped metal deposition of 300M steel. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *225*(6), 831-839.

[116]Wang, H., Jiang, W., Ouyang, J., & Kovacevic, R. (2004). Rapid prototyping of 4043 Al-alloy parts by VP-GTAW. *Journal of Materials Processing Technology*, *148*(1), 93-102.

[117]Amine, T., Newkirk, J. W., & Liou, F. (2014). An investigation of the effect of direct metal deposition parameters on the characteristics of the deposited layers. *Case Studies in Thermal Engineering*, *3*, 21-34.

[118]Sudhakaran, R., Sivasakthivel, P. S., Nagaraja, S., & Eazhil, K. M. (2014). The effect of welding process parameters on pitting corrosion and microstructure of chromium-manganese stainless steel gas tungsten arc welded plates. *Procedia Engineering*, *97*, 790-799.

[119]Sudhakaran, R., Vel-Muruganb, V., & Sivasakthivelc, P. S. (2012). Effect of Process Parameters on Depth of Penetration in Gas Tungsten Arc Welded (GTAW) 202 Grade Stainless Steel Plates Using Response Surface Methodology. *TJER 2012*, *9*(1), 64-79.

[120]FAQ: What is the difference between heat input and arc energy? 13/11/2017

[121]Weman, K. (2011). Welding processes handbook. Elsevier.

[122]Stenbacka, N., Choquet, I., & Hurtig, K. (2012). Review of arc efficiency values for gas tungsten arc welding. In *IIW Commission IV-XII-SG212, Intermediate Meeting, BAM, Berlin, Germany, 18-20 April 2012* (pp. 1-21).

[123]Bosworth, M. R. (1990). Effective heat input in pulsed current gas metal arc welding-solid wire electrodes

[124]Quintino, L., Liskevich, O., Vilarinho, L., & Scotti, A. (2013). Heat input in full penetration welds in gas metal arc welding (GMAW). *The International Journal of Advanced Manufacturing Technology*, *68*(9-12), 2833-2840.

[125]Kumar, A., Gautam, S. S., & Kumar, A. (2014). Heat Input & Joint Efficiency of Three Welding Processes TIG, MIG, and FSW Using AA6061. *International Journal of Mechanical Engineering and Robotics Research*, *1*, 89-94.

[126]Choi, S. G., Kim, J. J., Ryu, S. H., & Kwon, B. J. (2009, August). Development of tandem MIG welding control system. In *ICCAS-SICE, 2009* (pp. 820-823). IEEE.

[127]Ueyama, T., Ohnawa, T., Tanaka, M., & Nakata, K. (2007). The occurrence of arc interaction in tandem pulsed gas metal arc welding. *Science and Technology of Welding and Joining*, *12*(6), 523-529.

[128]Sproesser, G., Pittner, A., & Rethmeier, M. (2016). Increasing performance and energy efficiency of gas metal arc welding by a high power tandem process. *Procedia CIRP*, *40*, 642-647.