

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

Adnan A. Ugla, Hassan J. Khardair, Ahmed R. J. Almusawi

**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].

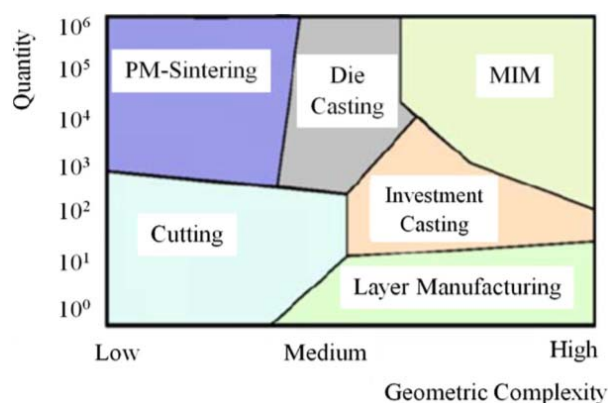


Fig. 1 Qualitative Stations of the AM metal components made comparable with the usual options (MIM metal injection molding, PM-Sintering Powder metallurgy sintering) [11]

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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 <sup>3</sup> , 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-EBF<sup>3</sup>: 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<sup>3</sup>) [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<sup>3</sup>);
- 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<sup>3</sup>) system

[45]. The actual EBF<sup>3</sup> 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<br>2- Robotic machine<br>3- Manipulator's arms<br>4- Gantry machine   |
|--------------------------|--|--|
| Heat Supply technique    | Electric Arc process<br>Power Beam process | 1-TIG/GTAW process<br>2-MIG/GMAW process<br>3-Plasma process<br>Laser<br>1-DMD<br>2-DED<br>Electron<br>EBF3                                    |
| Metal deposition process | Wire-Feed process                          | WAAM<br>1- TIG-Wire welding<br>2- MIG- Wire welding<br>3- P- Wire welding<br>WLAM Laser- Wire (DMD)<br>WEAM Electron- Wire (EBF <sup>3</sup> ) |
|                          | Powder-Feed                                | 1-DMLS<br>2-EBM<br>3-SLS<br>4-SLM  |

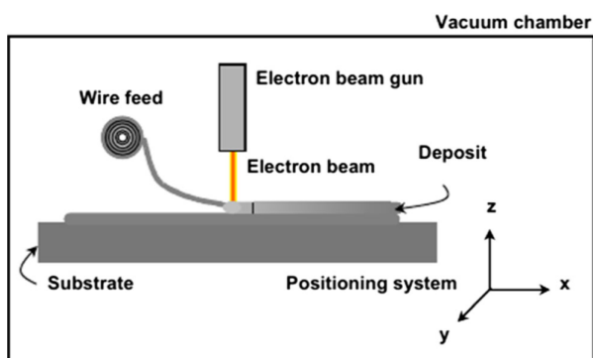


Fig. 2 A primary schematic part in an electron beam Freeform fabrication (EBF<sup>3</sup>) system [45]

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<sup>3</sup>-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<sup>3</sup> 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].

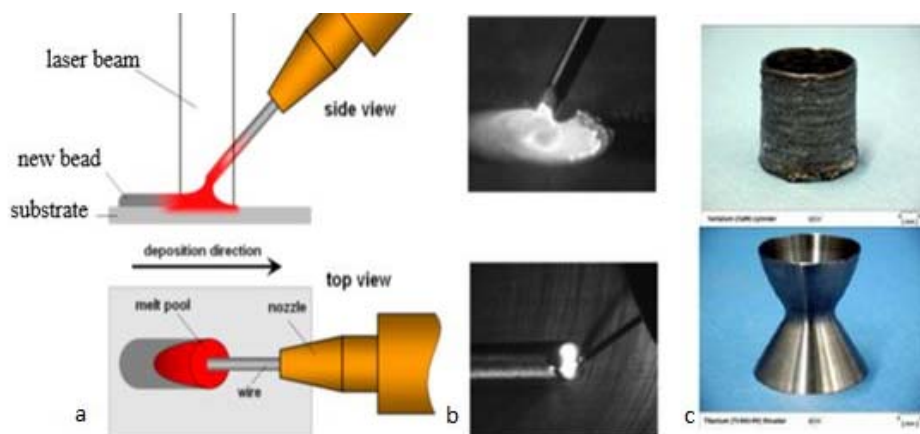


Fig. 3 (a) Schematic drawing of the process; (b) top and side view images of a real process; and (c) Exemplary components: Ta-20W cylinder (as-built surface) [43]

### 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.

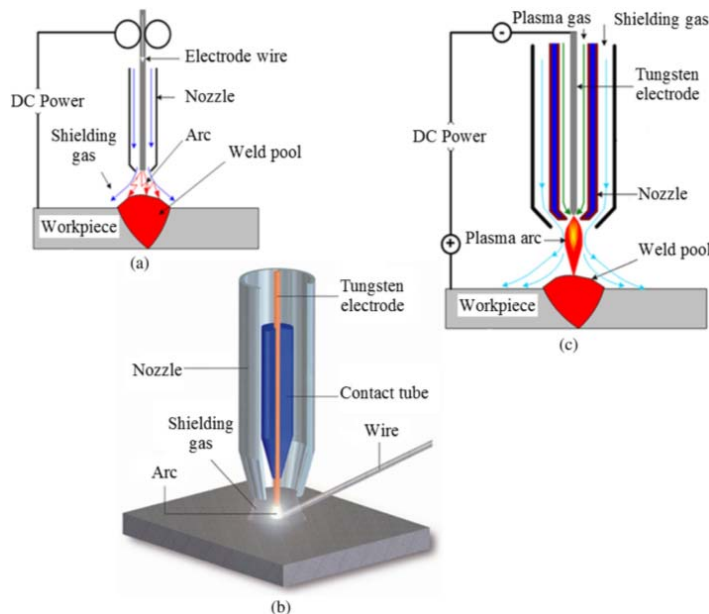


Fig. 4 Schematic diagram of the (a) GMAW, (b) GTAW, and (c) PAW process [13]

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.

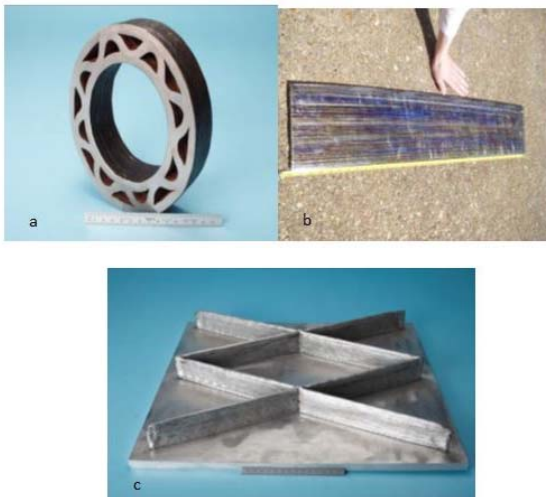


Fig. 5 WAAM components: (a) mild steel honeycomb structure; (b) aluminum stiffened Panel structure; (c) 1 meter long Ti64 wall structure [84]

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.

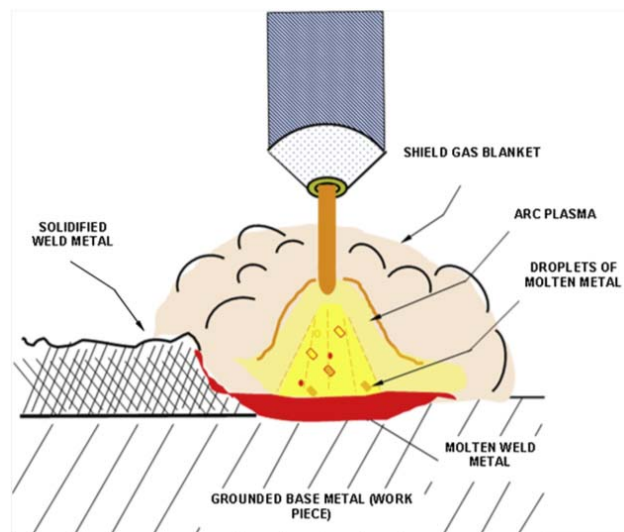


Fig. 6 Schematic of GMAW [87]

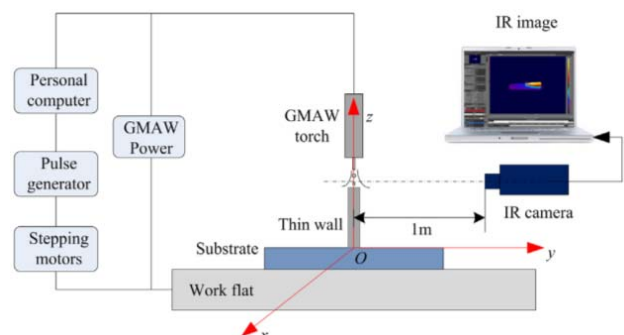


Fig. 7 Schematic diagram of GMAW based AM system with the IR camera [97]

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.

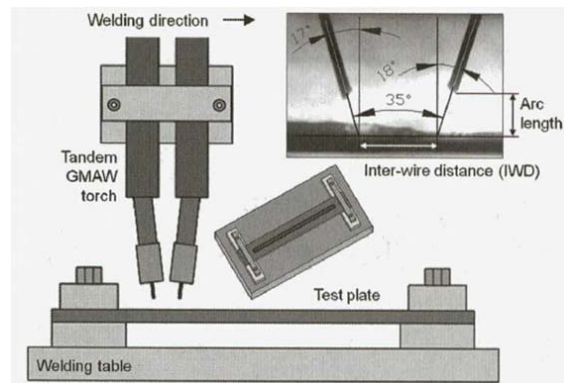


Fig. 8 Schematic illustrates rig used for evaluating the Tandem Pulsed GMAW arcs [102]

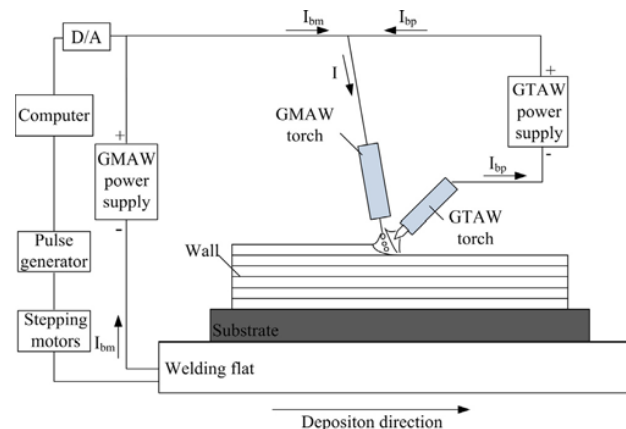


Fig. 9 Schematic diagram of double electrode GMAW-based AM system [105]

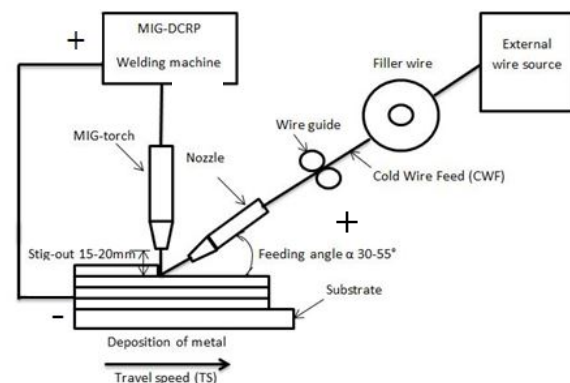


Fig. 10 Schemes illustrate the external CWF plus MIG-welding of SMD system

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.

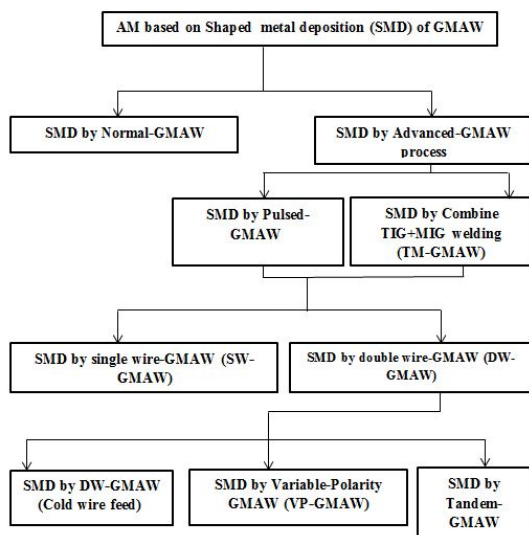


Fig. 11 Classification of SMD for GMAW process

#### 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 COMMERCIALY USED IN AM PROCESSING [67]

| Ti-alloys           | Al-alloys | Tool Steels | Superalloys | Stainless steel        | Refractory   |
|---------------------|-----------|-------------|-------------|------------------------|--------------|
| Ti-6Al-4V<br>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 2<sup>nd</sup> 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]:

$$AE = \frac{60VI}{1000v} \quad (1)$$

$$HI = \eta AE \quad (2)$$

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  $\eta$  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.

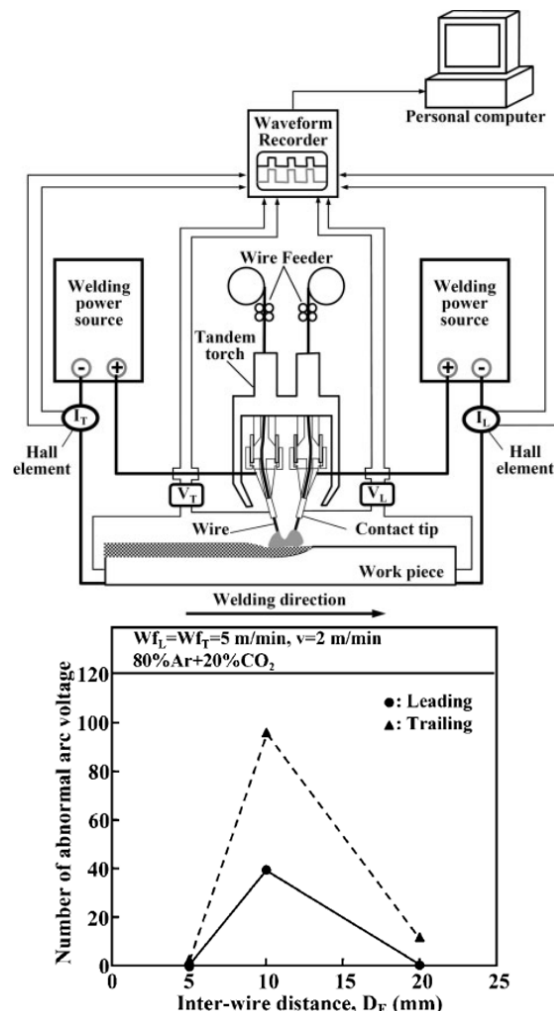


Fig. 12 The effect of Interwire the electric arc which in turn affects HI and efficiency [128]

## 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<sup>3</sup>) 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 (EBF<sup>3</sup>) 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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