The Innovation in wire arc additive manufacturing (WAAM): A review

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Keywords: Wire Arc Additive Manufacturing (WAAM), Hybrid Manufacturing (HM), Additive Manufacturing (AM), Metal Additive Manufacturing (MAM), Hybrid Additive Manufacturing (HAM), Metal Additive Manufacturing (MAM), Direct Energy Deposition (DED)

Abstract. This review or research paper is illustrated to analytically assess and address one of potential industrial revolutions, which is Wire Arc Additive Manufacturing (WAAM). WAAM is classified from Hybrid Manufacturing (HM) processes. Thus, one of the Hybrid Manufacturing ultimate goals has always been to transcend the limitation aspects associated with the tradition process. As Artificial Intelligence (AI) has evolved and expanded all over the globe, Additive Manufacturing (AM) has been gradually developed and introduced to the world to be one of a distinguished innovative impact in the history of manufacturing. Additive Manufacturing (AM) has been improved over the conventional methods in the manufacturing world due to its advanced complexity, consistency, quality of work, and various advantages and contribution that satisfy the costumers needs and requirements. Various applications in the industry have proven the AM applicability to replace the conventional processes such as casting and machining as it can deal with very coplex shapes [3]. In spite of the fact that there are numerous materials that can be manufactured in the modern technologies of AM, such as polymers, metals, ceramic, and composites, the contribution of Metal Additive Manufacturing (MAM) arguably has been a significant influence in the industries in comparison to the others [1]. In this review paper the detailed deliverable information and materials which will be established and communicated in this paper will concentrate on the history of (WAAM) including its pros and cons, latest contribution to the industries, AM classifications, materials, and primary materials and practices in industry.

Introduction

Referring to the technological developments that have been occurring to the old age of manufacturing industry, additive manufacturing (AM) has distinguished its self from and among the rest of conventional manufacturing methods by gradually eliminating human errors and interference, increase quality of work, and increase productivity. AM technology goes all the way back to the 1980s. HM has contributed to manufacture very complex and complicated materials with different geometries including internal structures to potentially allow to achieve higher productivity, quality, and mass production. In this paper, the definition of Hybrid Manufacturing (HM) has been a major controversy among researchers as it has gained its popularity back in 1990's. HM can be defined as the incorporation and merging of two manufacturing processes or technologies into one for the benefit of exceeding the limitation associated and gaining the ultimate and fundamental advantages [2].

History and classification of mam

Any produced metallic materials or wire-feed AM, it definitely has been produced by one of the three types of energy sources, which are electron beam, electric arc, or laser [31]. However, electric are welding has defeated the other two types due to its benefits of higher energy efficiency and deposition rate. The arc welding AM deposition rate is 50-130g/min, whereas the deposition rate for both electron beam and laser is 2-10 g/min [32]. Additive manufacturing has provided various types of real life examples in the industries since its beginning of revolution, such as Selective Laser Melting (SLM). SLM has been classified as a type of metal additive manufacturing (MAM) and the way SLM works is that a 3D model is being produced via melting the particles of metallic powder through a complete laser procedure. The part manufactured via this process can have percentage of porosity less than 0.1% [9]. In addition, SLM has the ability to produce material with high efficiency as well as the ease of building complex geometries free of constrains, which the conventional manufacturing processes could not have [8]. However, the researchers have agreed that initially SLM could not contribute to the huge demand in aerospace and transportation industries due to limitation of size in the building chamber with approximate dimension of 300 mm x 300 mm for the single laser system. When it comes to the widely used materials in SLM technology, 24 CrNiMo has great tribology, structural, and mechanical properties as it one type classified from High Strength Low Alloy (HSLA). Another example of that has been evolving drastically over the past years, which is the 3D printing using natural fiber. The agricultural term of natural fiber is referring nowadays to the environmental friendly materials, such as rice shells, nut shells, reeds, wood fiber, gels, solutions, thermoplastics, polymer, polylactide, polypropolene, and crop straws, which they have been widely utilized in health care, machinery, and aerospace. Natural fiber composite materials are made from the addition of natural fibers as reinforcers and other agents as compatibilizers and flexibilizers into the polymer or gel matrix. Various methods can be applied in the 3D printing industry, but there are countable common ones, such as Fused Deposition Modelling (FDT), Stereo lithography Apparatus (SLA), Direct Ink Writing (DIW), Selective Laser Sintering (SLS), and Digital Light Processing (DLP) [10].

Discussion

Classification

Various industries have been benefiting from AM mostly in the medical, automotive, railway, and aerospace sectors and the popularity was gained during the late 20th century [26, 45]. An interesting fact about AM in aerospace, the heaviest part produced via AM weighed roughly 750 kg, its width was 1.7 m, its length was 4.7m, and the height was 0.5 m [44]. In 2016, AM aerospace sales was \$ 6.7 billion and was classified as one of fastest growing among others [54]. Also, AM has been widely used in the medical field to fabricate part for their patients, such as respiratory parts [52]. AM is also coming to be part of the railway environment as the spare parts are requiring immediate alternative fabrication methods like AM since light weight, low cost, and lead time is the ultimate goal [60]. Metal additive manufacturing (MAM) has been classified as Direct Additive manufacturing with four processes, such as powder bed fusion (PBF), binder jetting (BJ), direct energy deposition (DED), and sheet lamination (SL). (fig.7) illustrates the categories for metal materials AM [29]. Also the other classification is Indirect Additive Manufacturing with three processes, such as material jetting (MJ), vat photopolymerization (VP), and material extrusion (ME) (fig.1). As per the standards of ISO/ASTM 52900, materials used, feedstock, and deposition methods are the main differences among them [57]. Also, there is a major difference between direct and indirect MAM. MAM can be classified as direct whenever the parts are fabricated directly based on provided design, specifications, or certain requirements, whereas, the indirect MAM involves certain outlines to be followed in order to eventually acquire ultimate metal parts. Some examples to indirect MAM are sand casting, injection moulding, and die casting [2,56].

DIRECT MAM

Powder bed fusion (PBF) is one of the techniques utilized in metal additive manufacturing (MAM) where metal powder particles (ranges from 20 – 100 micrometres) are positioned in a bed are being melted layer by layer through a thermal source such as electron beam or laser [42]. Additionally, few practices are associated with PBF that play a big role in producing metals and plastics, such as Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). Having said that, PBF has several advantages in terms of materials, such as the powder is recyclable, the availability of wide variety of materials (plastics, metals, and alloys), and it is low in cost [25]. Schematic is presented in (fig 2).

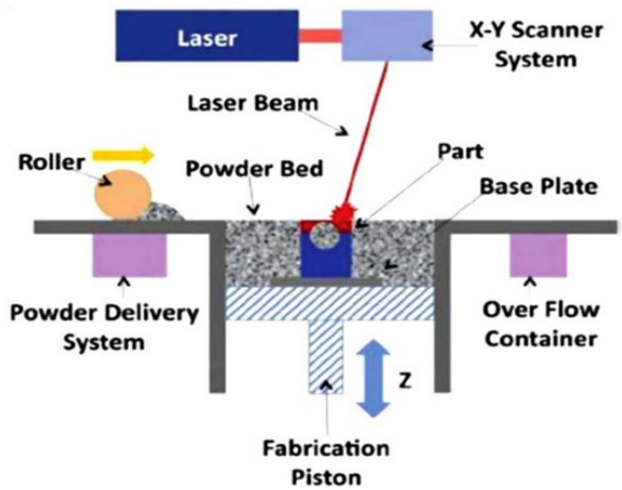

fig.2 – PBF process schematic

Binder jetting (BJ) is a liquid binder selectively deposited on a powder bed with a print head, which produces a final product of cohesive powder particles. It is a growing process that allows the production of part for the manufacturing, medical, and dental industries. This technique enables the production of metallic and ceramic parts as well as the sand moulds for castings. Furthermore, the materials used in this process is the form of powder particles that is being spread across the platform in a certain thickness and being evened out by the help of a roller. Then the liquid binder is being deposited over the build material via the inkjet printhead to form the desired layer by linking the substrate particles. Then, the operator lowers the platform to build the next layer, and the process keeps repeating until the desired object is completed. Thus, there are numerous distinct advantages for BJ, which are production of coloured objects, greater shape volume, high speed, discreet residual stresses, and astronomical material compatibility. On the other hand, BJ can have particular disadvantages linked to it such as, object shrinkage, non-sustainability for physical segments, and porosity defects [27]. Schematic is presented in (fig 3).

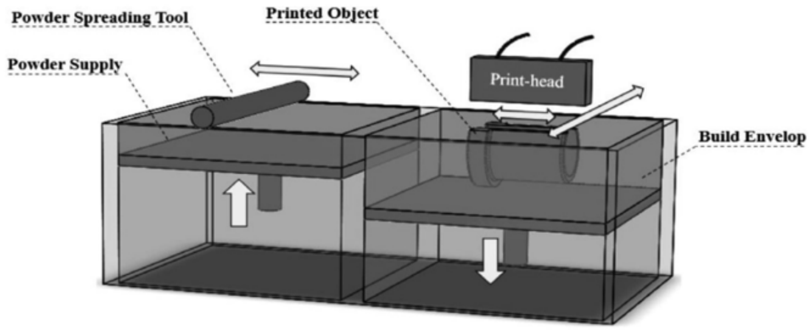

fig 3 – schematic of binder jetting

Direct energy deposition (DED) is one of MAM processes that is fully reliant on the assistance of other multi axis equipment, such as Computer Numerical Control (CNC) or robots [26]. DED is a 3D method used to fabricate metals, ceramics, and polymers objects via melting powder or wire through a thermal energy source (electron beam, laser beam, and electric arc) This kind of method has also various alternative names since the 90s, such as, Laser metal deposition (LMD), laser solid forming (LSF), and laser engineered net shaping (LENS) [55]. Although DED can manufacture large metallic materials due to its advantage of higher deposition rate, DED is only able to produce parts with lower finishing resolution than PBF [29, 48]; in the case of DED, nozzle is in use here, likewise of electron beam, laser, or plastic arc. It is important to shed the light on the fact that DED is capable of repairing existing part, or deposit additional layers on existing part through the backing of CAD software [2].

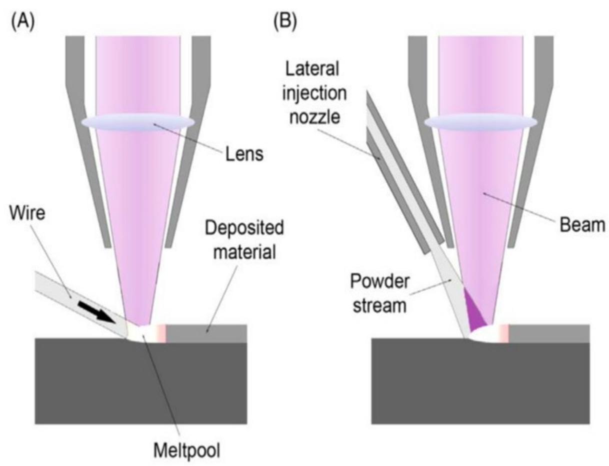

fig 4 – schematic DED process (a) wire based & (b) powder stream based DED

INDIRECT MAM

Additive manufacturing is utilized to fabricate prototypes in a direct approach, however, this process can be used and considered an indirect method whenever tools, or master patterns are manufactured, which are designated as the assistance to produce the required final parts. Favourable examples are, die casting, injection moulding tools, sand casting, casting, and vacuum casting [17]. Moreover, when it comes to indirect MAM, highly filled polymer and polymer with ceramic powders and metals incorporated are the main materials associated with MAM, which also consist of three main categories; material jetting (MJ), vat photopolymerization (VP), and material extrusion (ME) (Fig 1). material jetting (MJ), is a 3D printing method that produces very precise objects with massive variety of materials and colours. MJ jets small drops of liquid plastics and ultraviolet light exposure instantly cures the plastics solidifying it, and so, layer by layer, compound objects take shape. Nevertheless, in this process, material properties can be adjusted, such as durability or heat resistance, therefore, designers can predict future needs and serve them now. Vat photopolymerization (VP), produces a 3D models. VP uses a Vat (large tank to hold plastic liquid) to melt and solidify the resins through ultraviolet light exposure to finally form polymers (photopolymer) [2,47]. Material extrusion (ME), it is 3D process in which the material is selectively dispensed through a nozzle to form a three dimensional object, normally at elevated temperature. Also, material extrusion (ME) is also know as fused filament fabrication (FFF) with a wide range of materials to be fabricated, such as ceramics, metals, composites, and biomaterials. [2]

Wire arc additive manufacturing (WAAM)

The first invention of arc welding goes back to 1881[39]. WAAM involves only low investment compared to the rest of AM methods [51]. Wire and arc additive manufacturing (WAAM) is a three dimensional production process that works by rapidly melting metal layer by layer through a thin wall component, which has a high efficiency in deposition rate and low cost process. Usually, the standard thickness of the wire ranges between 0.8 mm to 1.2 mm [41]. Thus, the material usage can exceed 90%, 85 % - 90% of energy efficiencies, and high deposition rate that can reach 4 kg/h [40]. WAAM possesses the capability to manufacture massive part with zero reliance on moulds via the use of CAD / CAM software. However, WAAM production is highly dependent upon additional positioning systems, such as a robot, or CNC milling machine [16]. Additionally, WAAM main components are motion system, material deposition system, and heat source [28]. Studies have shown various ways of adopting and implementing heat sources during the WAAM operation, such as Cold metal transfer (CMT), Plasma Arc Welding (PAW), Gas Tungsten Arc Welding (GTAW), and Gas Metal Arc Welding (GMAW) [15].

CMT technology used in WAAM has the advantage of fabricating large scale structural parts as the the cost of materials is low and the deposition rate is high. CMT technology in WAAM and its products are widely used in the industries, especially in biomedical, aerospace, and chemical fields. Nevertheless, when it comes to the best suited materials to be produced via CMT-based WAAM, a high strength with low density titanium alloy (Two-phase α/β Ti-6Al-4V) is produced. However, the quality surface improvement after machining is lacking due to the methodology implemented (layer-by layer deposition) and it has become one of the main challenges out there, whereas the the recent studies and experimentation were concentrating mainly on tensile properties, evolution, and microstructure [15,58].

Moving on to Plasma Arc Welding (PAW), PAW is one of the most modern and advanced manufacturing process and it is well known for its high efficiency and low production cost, lower cost in operation as well as lower equipment cost compared to other advanced welding technologies. Plasma Arc Welding (PAW) is a modified type of TIG Welding and it is nothing but the ionized gases. The word Plasma is nothing but the forth state of matter after solid, liquid, and gas. PAW has proven its ability to exert an extreme high welding currents and deep penetration during the appearance of keyhole mode. Furthermore, Plasma Arc Welding (PAW) has the ability to produce gas as a heat source with an exceeding gas temperature of 20,000 K [20], which creates a narrow constricted arc pattern and the heat can easily transfer to the bottom of the work piece via the keyhole, also PAW has the tendency to concentrate on high flux and pressure [21]. Refer to below (fig 11).

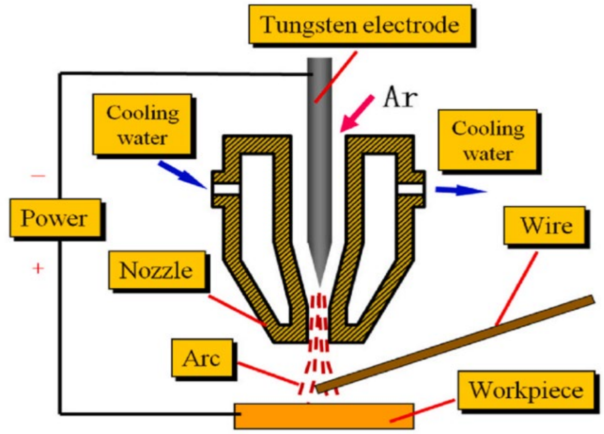

fig 11 – PAW [29]

Gas Tungsten Arc Welding (GTAW) is also same type as Tungsten Inert Gas (TIG). GTAW is an arc welding process where arc is constituted between a non-consumable electrode and conductive base metal. Additionally, the main function of inert shielding gas such as helium or argon is to eliminate any possible atmospheric pollution and oxidation in the welding area and contribute to solidify the work piece. Also, the gas plays a vital role in increasing the electric arc strike due to conductivity increase between the work piece and the electrode. Having said that, the main function of electrode is to melt the metal with a melting temperature up to 3422 Celsius. Moreover, this specific process is strictly applicable to certain materials, such as Carbon, magnesium, stainless steel, and titanium. However, when it come to the aspect of heat addition of this process, welding speed, current, and voltage are main three factors that GTAW is extensively dependant upon to achieve extraordinary excellent welds, spatter free, and low distortion. On the other hand, there are few disadvantages associated with GTAW, which are the method is sensitive for airflow, time consuming, and pricy [22]. Refer to below (fig 10).

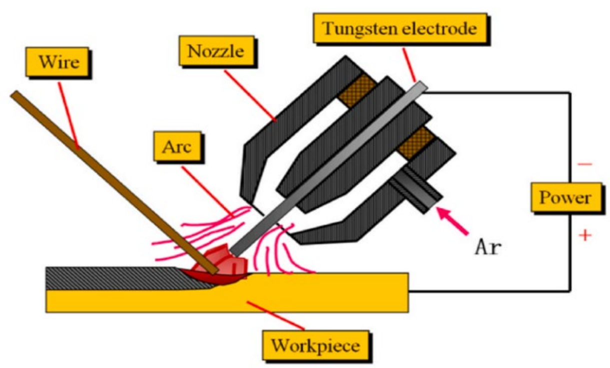

fig 10 – GTAW [29]

Gas Metal Arc Welding (GMAW) is one such arc welding process where the arc is constituted between a consumable wire electrode and the conductive base plate. This process also known as GMAW-DED due to the use of the technology of direct energy deposition, which can be deposited layer by layer in the form of beads. One of the biggest advantages of GMAW is its high deposition rate (3 – 4 kg/h) [14]. Nevertheless, this process is popularly used in the industry and could be applied in a wire form shape non-ferrous and ferrous metals, such as nickel, titanium and aluminium alloys, as well as stainless steel due to its reliability, flexibility, and high efficiency [24]. Refer to below figures (8 & 9&14).

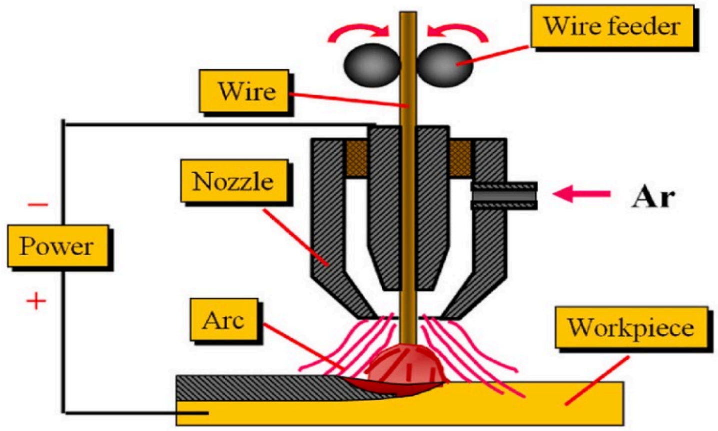

fig 8 – GMAW

Table 1
Approximate cost of different metal materials in wire and in powder [4].

Feedstock	Ti–6Al–4V	Inconel 718	Inconel 625	Stainless Steel 316L
Wire (£/kg)	120	58	49	12
Powder (£/kg)	280	80	80	40

fig 9 – Approximate cost of materials

fig 14 – Real world example of fabricated part (WAAM)

Conclusion

In conclusion, this paper's main objective was to introduce the readers to the establishment and development of AM and WAAM. Looking over the innovative idea behind this part of AM/WAAM, it could be clearly perceived that as AM/WAAM continues to expand, various tangible benefits are gradually appearing, such as, the reduction of human error and interference, reduction of exposure to polluted chemicals or dirt, and the decrease in materials usage. There is no doubt that WAAM is considered one of the tremendous transition of AM in the industrial revolution 4.0. As science and technology evolves, there is no doubt of what AM/WAAM could bring further to our future to make it a better world for us. As I went through uncountable journals and e-books, I found so much of rich information about this topic, and there are yet more to come. I am very optimistic and excited to dip deep into the development of this topic and consider it as part of my thesis. There is no suspicion that it is going to be certainly a challenging topic to deliver, but it should be fun.

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