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Current Trends in Wire Arc Additive Manufacturing: A Review

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ABSTRACT

Wire arc additive manufacturing (WAAM) is a fusion manufacturing process in which the heat energy of an electric arc is employed for melting the electrodes and depositing material layers for wall formation or for simultaneously cladding two materials in order to form a composite structure. This directed energy deposition-arc (DED-arc) method is advantageous and efficient as it produces large parts with structural integrity due to the high deposition rates, reduced wastage of raw material, and low consumption of energy in comparison with the conventional joining processes and other additive manufacturing technologies. These features have resulted in a constant and continuous increase in interest in this modern manufacturing technique which demands further studies to promote new industrial applications.

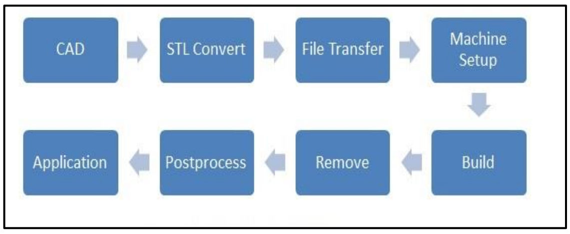
Keywords: *WAAM; Additive; Manufacturing; Welding; Titanium; 3D Printing.*

1.0 Introduction

Additive manufacturing (AM) also known as 3D printing (3DP), rapid prototyping (RP), direct digital manufacturing (DDM), rapid manufacturing (RM), and solid freeform fabrication (SFF) is gaining much importance in recent years owing its ability to manufacture large metal components with high deposition rate and material utilization [1,2]. ASTM defines Additive manufacturing (AM) as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as conventional machining” [3].

Additive Manufacturing is considered more efficient than conventional machining as former creates final product by adding layers followed by finishing processes while latter wastes material by removing material from larger stock. In addition, complex parts can be manufactured without the use of cutting tools and fixtures [4]. Its simplification lies in developing complex 3D objects directly from CAD data without the much needed process planning. While AM successfully reduces the machining cost, minimize the production time and usage of raw material, still it has to overcome structural quality issues [5-7]. The finished product produced by AM has to be passed through or some degree at least following steps as shown in Figure1:

Figure 1: Generic AM Process



Setting up of AM machine includes build variables like the material constraints, energy source, layer thickness, timings, etc. The AM machine does all build up with little supervision to avoid any power or software glitches.

After removal of product from the machine, post processing is done which includes finishing and heat treatment processes [7].

2.0 Classification for AM Processes

ASTM F42 committee had categorized the AM processes according to deposition technique, type of

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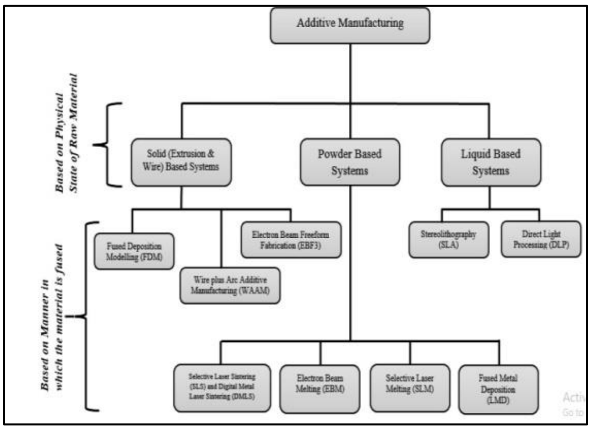
material and the process by which the material is being fused [8, 9]. Basically, For manufacturing of nonmetals, techniques like Vat Photo polymerization, Binder Jetting, material Extrusion and Sheet Lamination are being used, while Powder Bed Fusion and Directed Energy deposition are used to deposit layered metals [10].

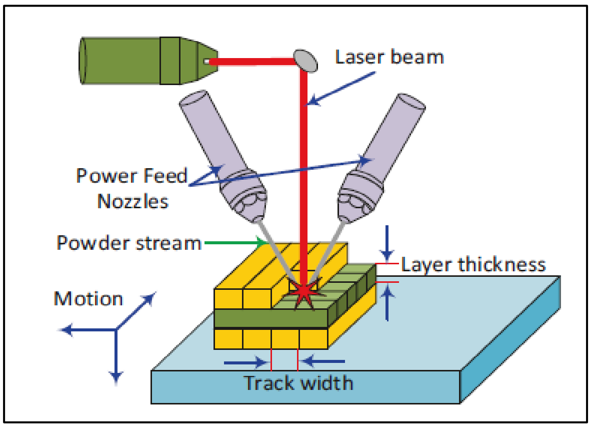
Figure 2: Classification of AM Processes



3.0 Directed Energy Deposition

DED is widely used to deposit almost all metal-alloy system and in addition, nowadays, to remanufacture or restoring the damaged metals components [11, 12]. DED processes direct energy (laser or electron beam) into a narrow region to heat a substrate and simultaneously melting both substrate and material that is being deposited, via layers [13].

Figure 3: A Typical Laser Powder DED Process [13]



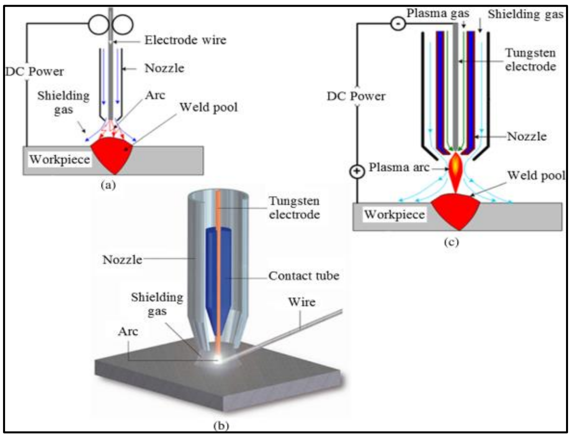
Issues like cracking and delamination are commonly seen during processing of ceramics coatings in a metal matrix due to noticeable property differences at the interphases. To reduce these issues, laser engineered net shaping (LENS) was used to manufacture matrix of Vanadium Carbide in stainless-steel 304. Processing via laser exhibited enhanced hardness and wear resistance due to smaller and homogenous grains of vanadium carbide on the grain boundaries of metal matrix [14]. It is seen that repair done on aerospace parts by DED shows increased corrosion and wear resistance due to layers of different compositions deposited on the build area [15,16].

4.0 Wire-Arc Additive Manufacturing

WAAM is now gaining popularity in field of AM, but it was invented back in 1925, when Baker [21] filed patent of finding a novel process in which electric arc was used to deposit layers of metals to form decorative articles. WAAM uses Wire and arc additive manufacturing (WAAM), variant of Directed energy deposition uses metal wire as a (raw materials) deposition materials and electric arc generated by metal-inert gas (MIG) welding, tungsten inert gas (TIG) welding, and plasma arc (PA) as the heat sources and is suitable to build large metallic parts with less residue issues [17]. In addition, WAAM produces metallic parts with reductions in raw material which in turn reduces cost [18]. In contrast to other DED technique like Laser Engineered net shaping, WAAM offers high deposition rate, making WAAM more suitable for large scale complex parts [19, 20].

According to the type of heat source, WAAM commonly has three types: Gas Tungsten Arc Welding (GTAW)-based, Gas Metal Arc Welding (GMAW)-based and Plasma Arc Welding (PAW)-based. As shown in figure 4 a, GMAW is a welding process in which an electric arc forms between a consumable wire electrodes, usually held normal to the substrate and the work piece metal. Both GTAW and PAW processes used non consumable electrode wire; however difference lies in temperature zones. The temperature in plasma arc is three times than that in arc produced by GTAW causing less weld distortion and smaller welds with higher welding speeds [22].

Figure 4: Schematic Diagram of the a) GMAW, b) GTAW, and c) PAW Process



4.1 Processing challenges in WAAM

Presence of large columnar grains poses a serious material processing challenge in WAAM. In contrast to large columnar grains, fine equiaxed microstructure provides more strength, toughness and corrosion resistance [23]. In WAAM process, grains grow in aggressive manner causing reduction in total number of grains which in turn causes the grain enlargement [24].

Large columnar growth of grains aligned to weld direction occurs due to the low temperature difference between electrode and substrate [25]. Grain refining via post heat treatment process is not possible for materials like austenitic stainless steels that don't undergo solid phase transformations [26].

Both enlarged grains and residual stresses causes cracking during the solidification especially in materials with high coefficient of thermal expansion which affect the structural integrity and service life [27-28, 13].

Changes in temperature due to trapping of atmospheric gasses and evaporation of low melting point elements can develop various microstructures affecting properties of WAAM parts [29]. With the increase in build direction of Inconel 625 by ALM-GTAW , the segregation of elements like Mo and Ni increases causing zones of depletion in γ-matrix.

These depleted zones hinder the growth of strengthening phases which degraded the mechanical properties of deposited Inconel 625. The tensile strength decreases from the base to top layer of deposited wall [30].

Effect of shielding gasses like nitrogen and argon on the mechanical properties as well as on the microstructure of 5356 aluminum alloy manufactured via WAAM was studied.

Under the protection of N2, height of weld bead was smaller because of breakage of N-N bonds under ionization which reduces temperature of arc.

As nitrogen gas reacted with aluminum substrate, flaky striped Nitrides were formed which reduced not only the Ultimate Tensile Strength and plasticity of samples but also changed the mode of fracture to combined ductile and brittle fracture. In contrast, with argon shielding, no flaky nitrides were found as argon does not react with substrate used and exhibit uniform hardness in all directions in deposits [31].

4.2 WAAM applications

Lockett et al. [32] made a set of design rules for WAAM to manufacture aerostructure components. An assessment criteria was also framed to see the optimum build orientation. The assessment criteria included substrate waste, deposited material mass, number of deposition operations, build complexity and symmetry.

Their experiment with a thicker substrate plate with track flanges, built up using two sided WAAM deposition, yielded favorable results. Rounded corners for continuous deposition and elimination of stress induced at the corners were suggested. They concluded that the WAAM process is not adequate for complex 3D lattices and long thin unsupported members.

Bushachi et al. [33] developed a process map for the implementation of WAAM as a compact system for manufacturing applications for defense platforms which operate in potentially hostile environments that may be restrained due to mission criticality. The authors reported the use of plasma torch with localized shielding, argon recovery equipment, heat treatment mechanism, and a fixed gas distribution system.

They addressed the module synchronization to deal with the trade-off between the size of the component and the jig size and suggested the use of anti-vibration bushes to mitigate the issues of vibration. Yuan et al. [34] proposed architecture for a multidirectional WAAM system focused on positional bead modelling, multi directional slicing and deposition process optimization strategy. Parabola model was used to obtain optimum welding parameters and desired bead geometry.

Based on the experiments, they concluded that a low power and low value of WFS and TS will yield higher quality and improved productivity.

5.0 Wire Arc Manufacturing of Different Metals

For manufacturing of alloys especially advanced alloys like titanium, additive manufacturing is considered to be most favorable technique [35]. Processing of titanium with powder metallurgy offers various challenges due to the high ductile-to brittle-transition temperature (DBTT), high recrystallization temperature and low fracture toughness. Wire Arc Additive Manufacturing technology can replace powder metallurgy for manufacturing a defect-free tungsten structure with orientation of front wire feeding approach. In addition tungsten parts were layered with a rate of 1.9 kg/h which is highest among all the additive manufacturing technologies [36].

5.1 Ti-6Al-4V alloy

Ti-6Al-4V has been a popular choice for a number of industrial applications owing to its suitability in the aerospace industry, which is oriented towards more enhancements for optimum performance. WAAM with laser as energy source was experimented [37] and it was found that the globular grain size and column grain width are proportional to laser beam power and wire feed speed, but inversely proportional to weld speed, while the epitaxially grown columnar resulting from nucleation in the microstructure has larger width. Increased weld speed also caused constriction due to rapid solidification. The mechanical properties showed an anisotropic trend, while the characterization of horizontal builds revealed a higher fatigue strength and ultimate tensile strength (UTS) with lower ductility, compared to the wrought materials. The microstructures revealed an anisotropy with columnar grain structure in alignment with the build direction. The microstructural transformations showed coarsening of grains and the gradual formation of a fine equiaxed structure with nucleation that results in epitaxial grain growth.

When the PLASMA source is used as a technique of reversed deposition, a high deposition rate and efficiency, as well as an increase of UTS by 12% and a wider wall width have been obtained. Banding was recorded with an increase in alpha lamellar size between the bands. The enhancement of PLASMA source WAAM, i.e., continuous plasma WAAM with high energy density, was analyzed [38] by reducing the heat input layer by layer. The energy accumulation in the molten pool is diminished and that allows for an easy nucleation, prevents the air oxidation phenomenon and the development of multiple thermal cycles. Equiaxed rectangular grid, representing martensite, new alpha plates, representing basket weave structure, and formation of horizontal bands determined by thermal cycle were also highlighted. These bands show low hardness with formation of alpha colonies.

5.2 Aluminum alloys

Geng et al. [39] explored the geometric limitations and tensile characteristics by investigating the WAAM of 5A06 Aluminum Alloy with 1.2 mm thickness. It was noticed that the tensile properties are obviously influenced by the build direction and the texture orientation, showing isotropy in the build direction, but anisotropy with respect to the texture orientation.

Because of the weld bead overlapping that may occur owing to the large molten pool and to the effect of surface tension, WAAM with a layer width of 7.2 mm cannot be applied for plane shapes with certain geometrical features, such as sharp angles less than 20_ or curvatures greater than 10 mm. In the case of axial loading, acting perpendicular to the texture orientation, a large number of grain boundaries become resistant to deformation, while on parallel loading to texture orientation, a sliding of grain boundary occurred in the bounding region, determining the tensile strength decrease. Horgar et al. [40] studied the feasibility of WAAM for 1.2 mm diameter AA5183 alloy used as wire and AA6082-T6 plates of 20 mm thickness as base material. It was noticed that the tensile and hardness properties were anisotropic with the plane orientation and the deposition direction.

The macro inspection of the weld showed intergranular hot cracks in the high temperature part of the reheated area with equiaxed grains. The dilution of AA5183 with AA6082 generates the formation of hot cracking, which can be reduced with addition of Ti, B, Sc, Er, or Zr in the composition of the wire material.

Due to the grain refinement effect of nanoparticles, the additives have a positive effect on the tensile and ductile properties and minimize the cracking tend.

5.3 Inconel

Xu et al. [41] studied the microstructure and aging response of Inconel 718 alloy determined by the WAAM processes for IN718. The strength of the weld was found to be lower than the strength of the forged material. They proposed the use of inter-pass rolling with the aim of improving the mechanical properties.

The thermomechanical processing serves to enhance the strength and reduce the material anisotropy and the aging response generated by the WAAM process. The macrostructure of the sample, which was subjected to inter-pass rolling, exhibits smaller columnar grains aligned to the wall sides and duplex grain structure with re-crystallized core that extends up to half the wall thickness. The microstructure of the rolled sample achieved after solution plus aging treatment presents fewer dendrite structures grown in random directions, in comparison with the unrolled sample, that determines the improvement of tensile, elongation, and ductility properties.

6.0 Conclusion

Based on a large number of recent articles published in the wire arc additive manufacturing field, this review article provides an overall view of the progress made and information useful to researchers worldwide interested in obtaining new findings. To enhance the acceptability and the applicability of the WAAM process for a wide variety of custom-made large size metallic builds performed from materials such as Ti-6Al-4V alloy, Inconel, Chromium, having properties close to the wrought or cast parts, more experimental research to improve the knowledge is needed. Besides, exploring the possible applicability of the WAAM process for repairing large metallic structures would be advantageous in terms of maintenance and service costs. Further, the capability to fabricate large metal 3D printed components and deployment for light materials increase the attention paid by industry towards the WAAM technique.

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