Investigations on Process Parameters of Wire Arc Additive Manufacturing (WAAM): A Review

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Abstract Wire arc additive manufacturing (WAAM) is an imperative method for fabricating 3D metallic parts. By the large, additive manufacturing (AM) innovation is utilized to prevail over the restriction of conventional subtractive manufacturing (SM) for manufacturing larger parts with a low buy-to-fly ratio. There are mainly three heat sources utilized in WAAM: metal inert gas welding (MIG), tungsten inert gas welding (TIG) and plasma arc welding (PAW). WAAM is picking up a reputation for the manufacturing of 3D parts using metal as raw material but the method is difficult to control because of its implicit residual stress, low hardness, discontinuous deposition, roughness, low grain growth and distortion. These problems create major issues for WAAM since they affect the part's geometric precision and extremely demean the properties of manufacturing parts. In this review paper, the WAAM process for the manufacturing of 3D metal parts along with its process parameters and their effect is reviewed.

Keywords Additive manufacturing (AM) · Wire arc additive manufacturing (WAAM) · Metal inert gas (MIG)

1 Introduction

Additive manufacturing (AM) is a method used in the creation of 3D parts with layer-by-layer material deposition [1]. AM was earlier known as rapid prototyping (RP), rapid tooling (RT) and layered manufacturing (LM). AM may be able to fabricate useful items directly from computer-aided design (CAD) data [2]. AM is developed in three phases. First phase is manual prototyping where prototypes are not very sophisticated, and level of complexity is simple. Second stage is soft or virtual prototyping begun between 1975 and 1980. In this stage, computerized models can be stressed, modelled and tested by a computer and the complexity of items is twice as complex as in the past stage [3]. The third phase is rapid prototyping, which

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started in the mid-1980s, which results in reducing the manufacturing time by using the hard prototype and increase the complexity almost three times higher than the second phase [3].

Despite the fact that there is a couple of variability inside the mechanical behaviour of AM parts which are routinely demonstrated by the heterogeneity and anisotropy developing from the variety in heat supplied [4]. The primary advantages of AM over the traditional conventional methods are high precision, faster manufacturing rate, and reduction in material waste [5]. Most of the added substances utilized were plastic, polymer and ceramic but presently nowadays metals are also being used as raw material in various AM processes. The usage of manufacturing technologies is subordinate to the raw material status during 3D metal printing.

2 Metal Additive Manufacturing

Metal additive manufacturing is known as a deposition of liquid metal in layers. It may be a direct feeding process including combining electrical sources, a movement framework and feedstock based on the wire. It is the improvised form of the fused deposition modelling (FDM) technique. On the basis of raw materials used, metal AM is classified into wire-based, powder-based and sheet-based processes. Among these technologies, the wire-based method leads in terms of structural efficiency and deposition rates. Wire-based methods also suitable for continuous and uncluttered material flow. Hence, wire-based AM is the most suitable for the production of costly components [6]. This technology can proficiently deliver large-scale metal components. However, with regard to accuracy and surface roughness, it is lower than other AM methods [7, 8]. Uses of metal additive manufacturing in recent times increases because of its ability to deliver metal parts at less cost and low buy-to-fly ratio. On the basis of the power source used, metal AM processes can be also classified as:

2.1 Electron Beam Additive Manufacturing (EBAM)

In this method large size, complex and intricate parts are possible to fabricate by an electron beam which uses as a heat source. Also, the use of vacuum in this technique allows the easy deposition of reactive metals like titanium otherwise for the fabrication of reactive materials we required some separate shield arrangement [6] (Fig. 1).

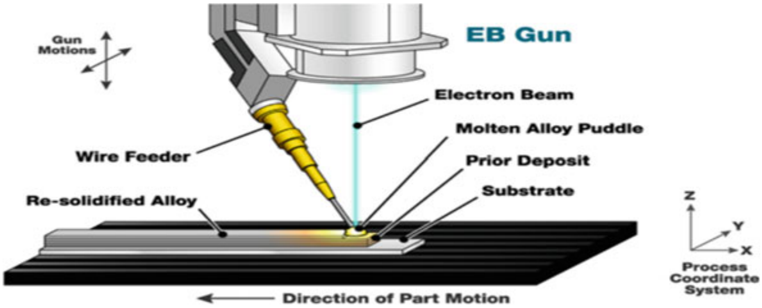

Fig. 1 Schematic diagram of EBAM [9]

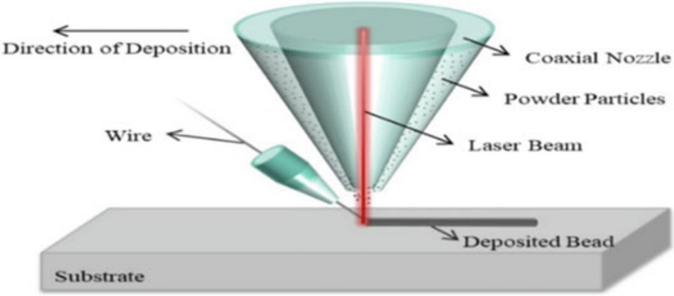

Fig. 2 Schematic diagram of WLAM [10]

2.2 Wire and Laser-Based Additive Manufacturing (WLAM)

WLAM is a process of fabricating 3D complex shape products by continuous feeding of wire into the molten metal pool. Uses of high power density in this technology, small and complex characteristics are easily obtained. High cost and incapability of producing large components are the primary limitation of WLAM [6] (Fig. 2).

2.3 Wire and Arc-Based Additive Manufacturing (WAAM)

In this technique, fabrication of 3D parts was carried out with the help of welding torch to generate weld pool by selecting optimum process parameters and adaptive tool path generating strategy. The main advantage of WAAM over other processes is the high deposition rate which makes this method faster and compatible (Fig. 3).

Metal inert gas (MIG) [12, 13], tungsten inert gas (TIG) [14–16] and plasma arc welding (PAW) [17, 18] are the main source of heat used in the WAAM technology. The afterwards execution of cold metal transfer (CMT) as upgraded MIG it is widely used as the heat source. Due to its capacity to deliver a high rate of deposition with

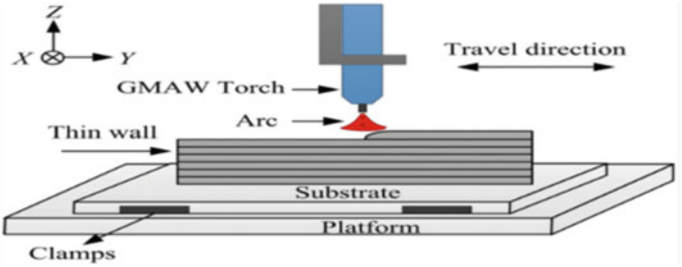

Fig. 3 Schematic diagram of WAAM [11]

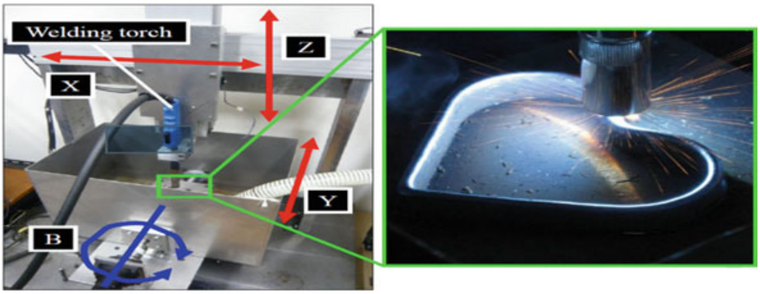

Fig. 4 Specimen fabricated by WAAM machine [26]

lower heat input, CMT has superior execution than MIG [19, 20]. MIG has four welding modes: globular mode, short-circuit mode, splash mode and pulsed-spray mode. In 1920, Shirizly et al. [21] utilized a fusible electrode to form an overlapping metal deposit. Subsequently, Ujiie et al. [22, 23] created the procedure of making a circular cross section through dynamic weld metal deposition. An offline observing framework was created to permitted a computer-aided design (CAD) format to be sliced to encourage weld deposition in layer-by-layer in an indicated to organize [24] (Fig. 4).

3 Parameters Affecting the WAAM Technology

3.1 Wire Feed Speed (WFS)

The study shows that the wire feed rate of Al5Si alloy below 10 m/min and above 45 m/min creates a discontinuous deposit. The best regular bead with a 0.1 mm standard deviation is obtained with 35 m/min wire feed speed [25]. It also shows that bead height of Hastelloy X alloy (nickel-based alloy) is linearly related to wire feed rate [27].

3.2 Travel Speed

Travel speed inversely affects the humping defect, melt through depth and bead width. Study shows that an increase in travel speed of Hastelloy X alloy (nickel-based alloy) results decrease in bead width and melt through depth, due to this the roughness is increased [27]. It also shows that the extreme speed at which humping starts in mild steel wire is 0.6 m/min for 0.8 mm wire diameter [28].

3.3 Heat Input

Results show that the decrease in heat input slows down the grain growth rate of ER5356 (aluminium–magnesium alloy). Also, heat supplied alternatively between layers formed small pores and cracks, large-sized grains and relatively low microhardness [29]. Bead structure of Ti6Al4V alloy in the first few layers differs along with the deposition height due to changes in the heat dissipation route but later it is insignificant of heat input [30]. Also, microstructure, grain size and crystalline stage of the Ti6Al4V sheet due to impacts of heat input vary along the construction direction. Optimum temperature to get favourable mechanical properties of Ti6Al4V is 200 °C [31].

3.4 Deposition Direction

The hardness of AA5183 aluminium alloy in the horizontal direction is approximately 75 kg/mm^2, whereas hardness shown in the vertical direction is about 70–75 kg/mm^2. It is also found that the deposition of multilayers from consequent passes gives cracking in weld [32]. Uniform deposition of molten metal depends on the wire feeding angle. A lower value of wire feeding angle (30°–50°) resulting in cracking of deposition of Ti6Al4V alloy, whereas the wire feeding angle of (70°) causes droplets splattering on the side of deposition [33].

3.5 Bulk Deformation

The study shows that the pores larger than 5 μm in diameter of 2319 Al alloy are dispensed with a rolling load of 45 kN [34]. There are two types of roller used in cold working of ER70S-6 steel, slotted roller and profiled roller. Among them, the slotted roller has a high efficiency of distortion elimination and deposition than later one [35].

4 Applications of WAAM

WAAM is suitable for the production of large-sized costly components with high complexity; hence, it is suitable to be used in areas such as aerospace industry, automotive industry, defence industry, naval industry and nuclear industry [36].

The main applications of WAAM technology are given below:

4.1 *Aerospace Industries*

Manufacturing of titanium and nickel alloys components with high complexity is the main focus in the aerospace industry because subtractive methods seem to be difficult and costly for the production of these material parts [37, 38].

4.2 *Nuclear Industry*

For manufacturing parts in the nuclear industry, WAAM is an appropriate method because it replaces some less useful nickel parts to stainless steel parts so that cost and weight both are reduced [39].

4.3 *Medical Industry*

In the medical industry, different alloys of cobalt, titanium and chromium are used for fabricating human vertebra, hip stem implants, dental implants and treatment of bone fracture with the help of WAAM technology [40, 41].

5 Issues and Challenges

5.1 *Surface and Material Quality*

Excessive heat input is required for achieving a high deposition rate in WAAM but due to high heat input, several challenges like residual stresses and distortions are coming as result, so for the fabrication of large metal components through WAAM these two are the primary concern. To get rid of these problems, post-welding heating is used for releasing residual stress and preheating is used for the problem of surface cracks and distortions.

5.2 Residual Stress and Distortion

Residual stress causes component failure because of uneven heat flow, and also, it is responsible for rough tolerance. For reducing the residual stress, post-processing is applied but the problem of reduced tolerance is remaining. Post-weld heat treatment (PWHT) can be used to reduce the residual stress during the process.

6 Conclusion

Numerous theories on WAAM state that WAAM can essentially decrease costs and enhance manufacturing effectiveness in industrial areas, particularly the aerospace, nuclear industry and automotive areas. Subsequently, numerous researches have focused on upgrading the WAAM process through moderation during 3D printing. Several process variations have been evolving in recent times to improving the microstructure and mechanical properties of the manufactured components. Moreover, the maximum number of alloys like aluminium, titanium and steel are utilized previously in fabricating the component using WAAM technology with fabulous outcomes.

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