Metal Additive Manufacturing Technique in Construction Industry: A Review Paper

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1 Introduction

Additive manufacturing or 3D printing is the technique of manufacturing which employed the concept in which finite section of the element are attaching to each other in a well-organized pattern so as to develop a full structure. With this concept of manufacturing at the finite level of an element, properties of the structure can be altered and modified accordingly from the ground level. AM offers great benefits in terms of much efficient structure, freedom in adopting geometrical shapes, utilization of lesser material and reduction of material wastage, opportunity for developing new functionally graded material and prestressing, additionally for repair and strengthening benefits.

Traditional method of manufacturing is subtractive by nature meaning when any structure is developed such as either concrete or steel block, extra materials are removed during shaping or machining which leads to reduction in the overall integrated mass. Additive manufacturing adds material progressively [1], the concept of building layer over layer from 3D model data. The technical concept has been observed in 1860s from a three-dimensional sculpture developed from a two-dimensional sculpture portrait [2].

Comparing with concrete, steel can be molded and shaped depending on our desirable aesthetical views and purposes. Applying the concept of additive manufacturing in steel manufacturing will be great boom in terms of freedom of choosing shapes and sizes, generating more optimized structure, utilizing the undesired residual stress in a beneficial manner, etc. Wire and Arc Additive Manufacturing (WAAM) is suitable for steel construction. Here wire electrode serves as printing material to produce large

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components layer by layers. This level of manufacturing rate can be applied successfully in commercial field for making connections and joining technology rather than fabrication.

In milling process, materials are removed from the structure, on the other hand additive manufacturing creates structure by adding materials. With additive manufacturing in metal, the concept of thermal and mechanical behaviors of the material used to play an important role. Traditional welding has a limited number of deposition tracks whereas AM has thousands of such weld tracks overlapping each other. In normal welding a large temperature variation is developed around the melt pool due to high-energy concentric heat. The thermal effect due to deposition of material and non-uniform cooling is associating with residual stress which is responsible for unexpected failure, strength of the build structure, fatigue life, and dimensional inaccuracy. The undesirable residual stress can be converted into desirable pre-stress by controlling the moving heat source manually in additive manufacturing. The heat is introduced layer after layer which is termed as 'thermal cycle'. This method helps to control cooling effect rather than non-uniform cooling as observed in traditional welding.

2 Additive Manufacturing in Construction

2.1 3D Printing in Concrete

Concrete is the very basic and widely used raw material in construction and it is of low cost and locally available easily. Concreting requires huge expenditure for the arrangement of scaffolding and formwork accounting half of the construction cost.

WinSun, a Chinese advanced materials supplier turned architectural business, originally began investigating additive manufacturing in 2005. By 2013, WinSun had constructed the first residential building made using additive printing. The first AM office structure, depicted in Fig. 1, was constructed in China and shipped to Dubai in 2016. [3].

In 2016, concrete pedestrian bridge [4] spanning 12 m was also completed in urban park of Castilla-La Manicha near Madrid, Span (Fig. 2). In 2017, a bicycle bridge was also built in Gemert, Netherland (Fig. 3), printed using concrete layer of 1 cm thick from an AM nozzle with zero formwork [5, 6].

2.2 Polymer Printing

Using polymer as printing material a canal house of 6 m tall designed in 2014 by DUS Architects developed blocks and built in Amsterdam [7], Netherland resembling the traditional Dutch gabled canal house (Fig. 4).

Fig. 1 Winsun Building, Dubai [3]

Fig. 2 Castilla-La Mancha Pedestrian bridge [4]

Fig. 3 Gemert Bicycle Bridge [6]

Fig. 4 3D print canal house in Amsterdam [7]

2.3 Metal Printing

Initially metal printing was used for smaller components such as connections and facade nodes. The Nematox facade node [8] (Fig. 5) gives an example of how metal AM helps to optimized the façade geometries by giving connection outside the nodes, reducing drawbacks due to the effect of sealing condition. The Arup Lightning node [9] which was redesigned by Arup by topology optimizing the previous structure is shown in Fig. 6. In the optimized structure materials are reduced or removed wherever lower stresses occur. This reduces the total weight to 75% of the previous model.

The MX3D bridge (Fig. 7) of Amsterdam, Netherland [10] is the most recently developed full size metal additive manufacturing masterpiece completed in the year 2019 built using WAAM technique. The 2.5 m wide bridge with 10 m spanning was designed with engineers in partnership with Arup in collaboration with researchers from Imperial College London. Numerical simulation and load test are also completed.

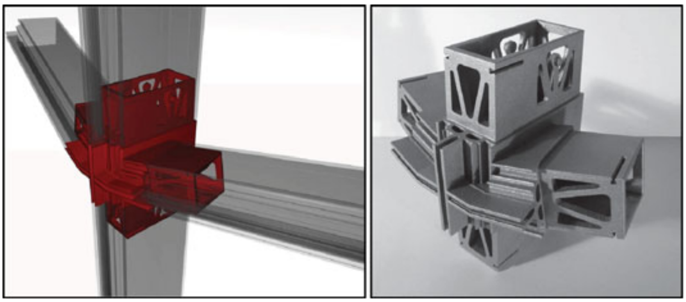

Fig. 5 Nematox node [8]

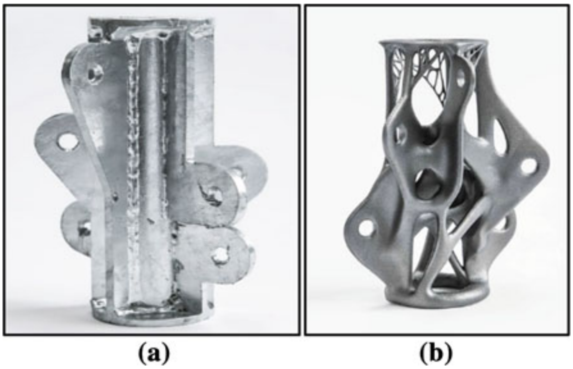

Fig. 6 **a** Conventional lightning node **b** Arup optimized node [9]

Fig. 7 MX3D bridge, Amsterdam [10]

3 Technologies in Metal Additive Manufacturing

Based on the standard of ISO/ASTM 52900 [11] powder bed fusion and directed energy deposition are the popular and easily available methods for metal additive manufacturing.

3.1 Powder Bed Fusion (PBF)

Laser or electron beam source heat energy is incorporated and material contained in a powder bed is selectively fused and create molten pool of metal and bonded together. Pieces with complicated geometries are a good fit for this technique [12]. The existing build time for items may be tens of hours, and the building rate is roughly 50 g/hour because they are constructed in tens of micron-thick individual layers. It can give a very smooth surface finish with roughness lesser than 20 μm [13]. A very inert and vacuum atmospheric condition is required to prevent oxidation of metallic powder [2]. So PBF is solely adopted in Lab rather than using in-situ construction.

3.2 Directed Energy Deposition (DED)

As the name suggests, energy deposition as directed by the laser or electron beam. The wire or metal powder are deposited directly at the focal point of the beam of electron or laser [2]. They form molten pool of metal and form mass as it cooled down. Identical to powder bed fusion, powder-based DED has a maximum component size limitation, requires an inert atmosphere to avoid oxidation, and has lengthy build periods (currently depositing at a rate of roughly 1 kg/hour). Typically, it gives not a smooth surface with values ranging from 20 to 100 μm [13].

4 Researches in Metal Additive Manufacturing

Additive manufacturing products have been mostly in the researching stage. In the past 5–6 years significant researches have been conducted based on metal additive manufacturing building components and parts. Numerical finite element modeling of the scale model, optimization, and load testing are also carried out. Comparative studies between machined components and printed components with varying cross-sectional dimensions such as square hollow section (SHS) and circular hollow section (CHS).

4.1 Research Based on Powder Bed Fusion (PDF)

Using powder bed fusion method for manufacturing Grade 316L stainless steel material with different orientation of building, the stress–stain properties were evaluated in many previous studies [14]. Buchanan et al. [14] investigated the stress–strain curve of the AM PBF shown as in Fig. 8. Three building orientations were investigated. The angle between the building's horizontal surface and the coupon's center line is known as the building orientation. A significant degree of porosity in PDF produced material than in ordinary stainless steel was shown to be related with a lower elastic modulus. Yet, the fabrication process's quick cooling effects and crystals result in a higher strength.

Marouene Zouaou et al. [15] developed a finite element model of a fused filament fabricated (FFF) specimen made up of new polymeric pre-structured material using Abaqus software. Three angles of building orientation (0°, 45°, and 90°) were adopted. Tensile strength as predicted by the software matches very closely to the experimental results. The longitudinally oriented specimen (0°) attains the maximum

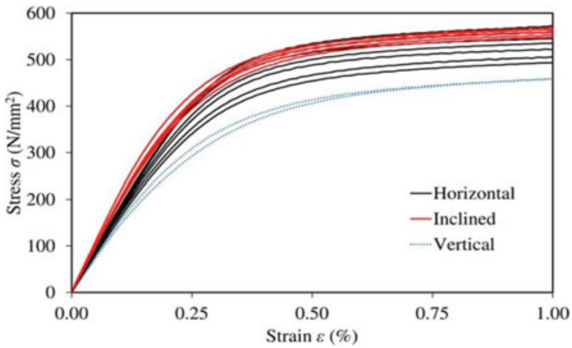

Fig. 8 Measured stress–strain curves by Buchanan et al. [14]

tensile yield strength with good ductile behavior while the transversal (90°) one has the weakest and exhibit fragile behavior at the yielding point.

Grade 316L stainless steel open cellular lattice structures [16], circular hollow section as well as square hollow section compression elements [14] have all been studied in the structural application of powder bed fusion metallic materials. Generally stockier AM cross-sections had stronger axial resistance compared with conventional formed stainless steel SHS when same vertical material properties are used in both cases. However, in the case of slender section, AM specimens have slightly lower resistance than the conventionally built section which may due to residual stress effect.

4.2 Research Based on Directed Energy Deposition (DED)

Prior to the work of MX3D bridge, researches based on the use of wire and arc additive manufacturing (WAAM) applications were carried out. Two perpendicular orientations of tensile coupons for mild steel were developed, with no notable change in yield strength detected, although stainless steel coupons were constructed in the same way. Full sized load test experiment as well as the numerical simulation of the elements of the MX3D were also conducted.

Research based on AM metal components such as beam hook, stiffener, clamping elements for diagonal bracing, end plate replacement, node for space frame were also carried out following the concept of optimization [17] (Fig. 9).

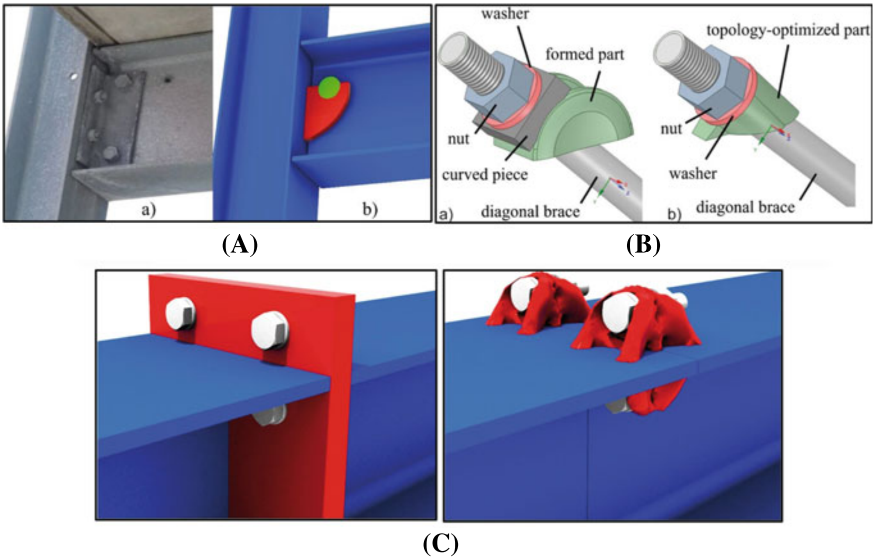

Fig. 9 **A** Conventional connection versus beam hook, **B** conventional versus optimized clamp **C** conventional versus optimized T-stub end plate [17]

5 Opportunities and Challenges

5.1 Flexibility in Geometry and Material Optimization

With the introduction of additive manufacturing, a new system of structural components such as hollow cross-sectional elements are readily fabricated. These elements are designed to obtained sections with unregular thicknesses at the same time without compromising the strength. Additionally, these hybrid type of elements when coupled with the conventional type of material can produced much higher strength.

The idea of additive manufacturing implies not only for the freedom of customization but also the concept of selective deposition of material to the region subjected to higher stresses. This concept drastically reduces the material consumption and hence the cost. Materials are supplied to only wherever needed to fulfill the bending moment diagram's and hence produces a geometrically more ductile cross-section.

By using high strength material in areas with a large stresses and moments, like the middle of beams, and higher ductility in areas with higher ductility needs, such connections, by controlled cooling system a good ductile and strengthen material can be produced [18]. The porosity nature of the biomedical human implant in order to reduce material stiffness within the neighboring human bone [19] is extracted and applied to the concept of addictively manufactured elements. AM elements have greater advantages in terms of forces and moment distribution with lower stiffness to attract lower forces in specific locations. The porosity nature gives tremendous benefit in energy dissipation capacity for seismically subjected structures.

5.2 Degree of Customization

Additive manufacturing allows for levels of customization previously unattainable in a low-margin business like construction. Structural engineers might make each structural component distinctive without incurring printing expenses; the cost of producing two identical or different variations of the same product is practically the same [20]. Design modifications might also be implemented quickly. This customization is anticipated to increase demand for additive manufacturing, which will assist to reduce prices.

5.3 Construction Time

Additive manufacturing provides various potential to reduce building time. With additive manufacturing in construction, the duration of project can be reduced to 65% when compared with the conventional method of building [21].

5.4 Hybridization and Strengthening

Additive manufacturing is thought to enhance rather than replace traditional construction approaches. Additive manufacturing techniques may also be used to repair damaged or corroded structural parts or to reinforce a structure in-situ, lowering the cost of repairs or strengthening. Any repair procedure gives a chance to upgrade the structural element's design.

5.5 Environmental Effects

Construction accounts about 30% of global greenhouse gas emissions [18]. Elements such as walls, columns, beams, and floors with definite proportions, traditional building procedures employ standardized components such as steel structural cross-sections or reinforcing bar. By producing specific, optimal structural components for each project, additive manufacturing minimizes the amount of raw materials used and waste that has to be disposed of. In general, additive manufacturing processes may reduce waste by 40% when compared to subtractive approaches [20].

5.6 Human Factors

Labor expenditures are predicted to account for 15–50% of overall building costs [22]. Some claim that by increasing automation and working in adverse weather and at night, many worksite operations may be completed more safely, correctly, and quickly [22]. Building procedures in additive manufacturing are often highly automated, lowering labor costs and lowering the danger of human mistake throughout the production process. However, because there are fewer possibilities for human intervention during manufacturing, 3D CAD models must be of high quality and mistake free [1]. This growth in automation will represent a significant departure from traditional, more manual system.

5.7 Challenges

The initial cost of machineries and installation would be very expensive with this current technology. And there is limitation of manufacturing process such as PBF is completely confined to laboratory only which requires very inert environment. With regard to design methodology and digital workflow, advanced computational tools are required and as these advances further, the cost of production will decrease. Besides there is a fear in the general people mind regarding this robotic technology will give unemployment also.

6 Conclusion

This article examined ongoing metal AM techniques, current research, early applications in construction, and application in many technical industries, as well as the numerous potential and difficulties that lie ahead for widespread metal AM adoption in the construction industry. For use in constructing, powder bed fusion and directed energy deposition are the two best metal additive manufacturing technologies (DED). Quality construction is possible using PBF and DED technologies, though there are drawbacks on expense, lead time, and maximum size. Practically unbounded item sizes are possible using wire and arc additive manufacturing DED, but dimensional precision and surface polish are restricted.

Using the technique of metal additive manufacturing (AM), massively scalable structural that are conventionally not possible, costly and time-consuming are now coupled with traditional structural parts to produce hybrid structures. Modifications in the microstructure can alter the basic mechanical behavior, and functionally graded materials can be used to regulate the internal dispersion of forces and moments.

Initially AM is to cost more than conventionally developed section. It will be necessary to develop new digital design processes, focus more toward functionality rather than manufacturing and adapt codified structural methodological approaches to factor in different material properties and more variable shape.

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