Recent Research and Future Opportunities for Stainless Steel 3D Printing in Construction

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Abstract

Metallic additive manufacturing (AM), also referred to as 3D printing, is becoming increasingly popular in the aerospace and biomedical industries, due to its many advantages over traditional manufacturing techniques. Metallic additive manufacturing is now starting to be explored as a viable manufacturing method in the construction sector, with prototype façade and connection nodes having been built and a stainless steel pedestrian bridge currently being constructed using these techniques. There has been significant effort to date in characterising the mechanical properties of additively manufactured stainless steel, although there has been limited research with a construction focus. Additive manufacturing presents many opportunities in the construction sector, but challenges still need to be overcome; with anticipated advances in manufacturing technology, lower material costs, increased regulation and development of new standards, these novel manufacturing techniques could play an important role in the future of construction.

Keywords

3D printing; additive manufacturing; metal; stainless steel; review; research; applications.

1 Introduction

Additive manufacturing has the potential to revolutionise the construction industry. Construction is generally considered to lag behind the aerospace and automotive industries in terms of uptake of technology, innovation and productivity levels [1]. Construction projects are transient, with the workforce disbanding after project completion, leading to a loss of knowledge, which is particularly unique to the construction sector. Many construction sites still use predominantly traditional methods, such as controlling the placement of concrete by hand, which is essentially unchanged from when the Romans started using concrete in approximately 100 BC [2]. The major new advancement in construction has been the move towards offsite manufacture, although this only moves the traditional techniques away from the building site. Diminishing workforce skills, an increased appreciation of health and safety and construction techniques which limit imagination, and restrict innovation, provide an opportunity for '3D printing', or more formally termed additive manufacturing (AM), techniques to be adopted.

Additive manufacturing increases the component mass during the manufacturing process, typically building an object layer-by-layer from 3D model data through an automated process. Conventional manufacturing techniques are either subtractive, i.e. they reduce the amount of material within an object, such as machining a metallic block, or are formative, where the amount of material used is conserved, such as shaping (e.g. hot-rolling or cold-forming) or casting using a mould [3]. The concept of additive manufacturing can be traced back to photo sculpture in the 1860s, where three-dimensional sculptures were produced from a series of two-dimensional photos [4]. Significant research effort in the 1960s and 1970s led to the development of photopolymerisation for polymers, powder bed fusion for ceramics, metals and polymers, and sheet lamination for ceramics, metals, paper, polymers and wood. Stereolithography, a type of photopolymerisation, where an ultraviolet sensitive liquid polymer is cured using a laser, was the first additive manufacturing technique commercialised in the late 1980s [3].

The rapid development of additive manufacturing (AM) has led to many different names for the field, including 3D printing (3DP), additive fabrication (AF), additive layered manufacturing (ALM), rapid casting, rapid manufacturing (RM), rapid prototyping (RP), rapid tooling and solid free form fabrication (SFF) [3,5]. An attempt to standardise the terminology has been made in ISO/ASTM 52900 [6] where the general term additive manufacturing has been adopted for all processes of making parts from 3D models and materials, and seven key groups of technologies have been identified: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat polymerisation, covering ceramics, composites, metallic materials and polymers. These methods all broadly follow the same workflow process: firstly, a 3D CAD model is created; this is then sliced into a series of building layers; this information is then sent to the processing machine, defining the location of the building head; and finally, the part is built up layer-by-layer. Today a wide range of materials can be used in additive manufacturing processes including ceramics, chemicals, composites, concrete, foodstuffs, metallic materials (including aluminium, cobalt-chrome, copper, gold, iron alloys (including stainless steels), magnesium, nickel based alloys, titanium and tungsten), paper, plastics, sandstone, silicones, wax and wood [4,7–16].

Metallic additive manufacturing is currently used in the biomedical and aerospace industries to produce high value end use parts that are highly customised or produced in small quantities [3,17]. The total AM market was estimated to be worth over $4 billion in 2014, with the market for end use parts being $1.7 billion, and is anticipated to grow to more than $21 billion by 2020 [3]. Beyond the high value sectors, additive manufacturing is starting to be explored in the construction sector to build concrete bridges, houses and offices [18,19], plastic houses [20] and stainless steel metallic connection nodes and bridges [21,22]. These new forming methods offer tremendous potential within the construction

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industry to build structural components, or even entire structures, with geometric freedom, engineered material properties and reduced waste.

In Section 2 of this paper, the various techniques of metallic additive manufacturing are described, and their suitability for use in construction is discussed. A review of existing metallic additive manufacturing research is then presented in Section 3, while early applications are set out in Section 4. Finally, the opportunities and challenges ahead for metallic additive manufacturing are discussed in Section 5.

2 Metallic Additive Manufacturing Techniques

Metallic materials, such as carbon steel, stainless steel and aluminium, are widely used in the construction industry, but the products are typically manufactured using traditional techniques such as hot-rolling, cold-forming and extrusion. This naturally leads to structural elements that are prismatic (i.e. with uniform cross-section along their length), owing to their ease of manufacturing using these methods. In this section, an overview of the various metallic additive manufacturing methods, which could be adopted within the construction sector and allow greater flexibility in the geometry of structural elements are outlined. Powder bed fusion (PBF), directed energy deposition (DED) and sheet lamination are the forms of metallic additive manufacturing included in ISO/ASTM 52900 [6]; electrochemical additive manufacturing is in the very early stages of development and is not yet commercially viable. Each process has its own specific characteristics that make them more suitable for certain applications, such as the maximum built part size and the building speed [23]. The practicality and scalability of these methods are also discussed.

2.1 Powder bed fusion (PBF)

Powder bed fusion (PBF) is a method of additive manufacturing in which material within a powder bed is selectively fused together using thermal energy, from either a laser or electron beam. This method is suitable for small parts with complicated geometries [23]. The build time can currently be lengthy, taking tens of hours and depositing roughly 50 g/hour, as objects are built up with individual layers, tens of microns thick. The surface roughness is typically less than 20 μm [24]. An inert atmosphere, or vacuum, is required to prevent metallic powders from oxidising [4]. This requirement has implications on the building space size and therefore the maximum dimensions of a single part, which is typically a 250 mm cube. Powder bed fusion can be used with polymers, combinations of metals, combinations of metals and polymers and ceramics. Any unused powder can also be recycled and reused [10].

2.2 Directed energy deposition (DED)

Directed energy deposition (DED) features metallic powder or wire being fed directly into the focal point of a laser or electron beam, resulting in a molten pool that can be selectively deposited [4]. This technique is suitable for high complexity parts and can be used to repair damaged components [4,23]. Like powder bed fusion, directed energy deposition also requires an inert environment to prevent oxidation [10] and has maximum part size limitations, along with long build times (depositing roughly 1 kg/hour). The surface roughness is typically 20-100 μm [24].

Wire and arc additive manufacturing (WAAM), also known as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and plasma arc welding (PAW) [25], is a directed energy deposition technique that uses arc welding tools and wire to build up a component. The final structure is formed entirely from the deposited weld material. Although the first patent was filed in 1926 [26], this method has only been investigated as a viable manufacturing technique since the 1990s. This technique is suitable for medium to large scale parts, that would typically be forged or machined, with low to medium geometric complexity. Wire and arc additive manufacturing allows high deposition rates (4 kg/hour), good structural integrity and can be used to produce virtually unlimited part sizes, with a 0.5 mm surface roughness [23]. Wire and arc additive manufacturing is considered to be a near net shape process, which means, depending on the design requirements, the built parts may entail some additional machining to achieve the desired final shape and surface finish. Compared with other metallic additive manufacturing processes, wire and arc additive manufacturing is much cheaper due to the use of standard off-the-shelf equipment and low material costs, with the wire feedstock being an order of magnitude cheaper than metallic powder [3], making WAAM more suited to the cost-sensitive construction industry. The placement of the wire is controlled by a robotic arm or computer controlled gantry. The surface tension of the molten metal can be used to produce horizontal features without a supporting structure, which are typically necessary with other metallic additive manufacturing techniques.

A major challenge with WAAM relates to the high residual stresses and distortion that can result from the high heat input. The residual stresses arise from shrinkage during cooling and are largest along the deposition direction. Symmetrical building (moving outwards from a line of symmetry), back to back building (two identical components built symmetrically back to back at the same time) and heat treatment can be used to reduce the residual stresses [23]. The temperature must also be carefully controlled to ensure consistent deposition conditions, which can lead to the equipment sitting idle to allow cooling during building [3]. Non-destructive testing (NDT) and online monitoring (OLM) can be used to check the building process by measuring the voltage, current, porosity level, grain size and shape during deposition [23].

2.3 Sheet lamination

In the sheet lamination method, individual cross-section layers are cut out and then laminated together using diffusion binding, low melting point alloys, adhesive polymers or ultrasound [4,27]. This method is compatible with ceramics, cork,

foam, metals, paper, polymers, rubber and wood [3], and multiple materials can be used in one build depending on the lamination method used. Advantages of sheet lamination include the low material and equipment costs, the sheets can be cut by a laser or milling machine, and its high strength and good quality surface finish [4,27]. Sheet lamination can also be used to embed sensors and electronics within objects. The geometry of the final part is only limited by the layer thickness and machining capabilities of the cutting device [28].

2.4 Electrochemical additive manufacturing (ECAM)

Electrochemical additive manufacturing (ECAM), not covered by ISO/ASTM 52900 [6], is a new alternative metallic additive manufacturing process which is being developed that is similar to electroplating, where the part is built up at the atomic level. This process is in the early stages of development, with the maximum dimension of parts currently around 600 μm. A major advantage of ECAM is that since it is a non-thermal process, parts can be built with lower internal residual stresses [29].

2.5 Discussion

The two metallic additive manufacturing techniques that are most likely to be adopted in the construction sector are powder bed fusion and directed energy deposition methods. Sheet lamination is unlikely to allow the geometric forms that will attract architects, structural engineers and clients to use these new forming techniques, or be viable for producing parts at a construction scale. ECAM is still in the very early stages of development, although again it is not anticipated to be used for construction sized parts soon.

Powder bed fusion and laser and electron beam based directed energy deposition methods allow for very accurate parts to be built, although with current technology the maximum dimensions are small, relative to typical structural elements, and the build times are lengthy. These techniques can still be used within construction, as discussed later in Section 4 with prototype façade and connection nodes already being produced; nevertheless, currently they do not scale to full-sized structural members. Future advancements in manufacturing equipment will allow larger parts to be built and likely lead to shorter build times, although for the foreseeable future these techniques will most likely still be used for specialised, small components where the material or geometric benefits outweigh the economic cost and long build times.

Wire and arc additive manufacturing significantly expands the maximum part size that can be built and has sufficient building speed that typical structural elements, and even entire structures, can be built, such as the MX3D bridge discussed in Section 4.3. However, the dimensional accuracy and surface finish will likely require additional post-processing techniques for many construction applications. Process advances are deemed unlikely to be able to improve the dimensional accuracy and surface finish; the manufacturing technique inherently produces a rough surface and has a minimum thickness of 2-3 mm, which is slightly larger than that of conventionally produced structural components. This method does have the potential to allow new geometric forms that can be produced relatively cheaply and quickly, provided the dimensional and surface variability is acceptable.

3 Research on Additively Manufactured Metallic Products

There has been significant research effort devoted to the advancement of metallic additive manufacturing processes and products over the past twenty years. An overview of the research into the properties of iron alloy metallic additively manufactured material and elements is presented in this section. Iron alloy based metallic materials are commonplace in construction due to their combination of strength, stiffness and relatively low cost.

3.1 Powder bed fusion (PBF) manufactured material

Tensile coupon tests investigating the stress-strain properties of powder bed fusion manufactured Grade 316L stainless steel material in different building orientations have been undertaken in a number of previous studies [30–35]. Compressive coupon tests have also been carried out [35]. The measured stress-strain curves from Buchanan et al. [35] are reproduced as Figure 1 for the tensile coupons and Figure 2 for the compressive coupons. The anisotropic behaviour, arising from the novel manufacturing method, is immediately apparent from these two figures.

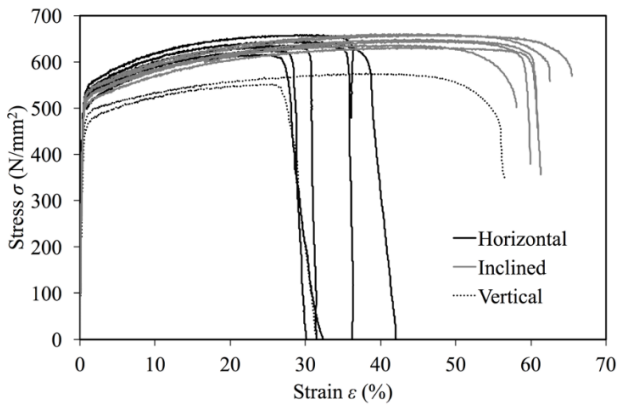

Fig. 1 Measured stress-strain curves from tensile coupon tests on Grade 316L stainless steel reported by Buchanan et al. [35]

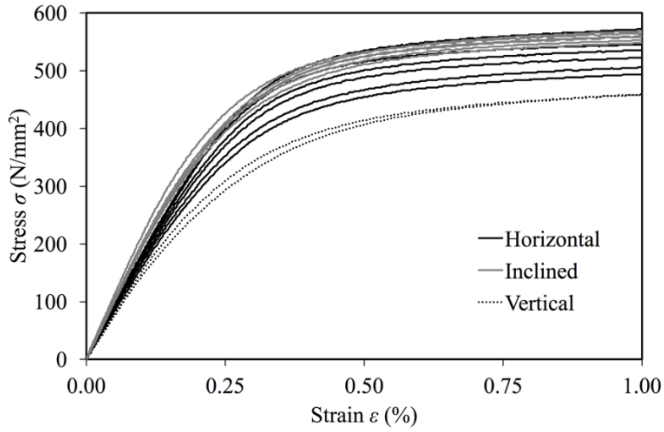

Fig. 2 Measured stress-strain curves from compressive coupon tests on Grade 316L stainless steel reported by Buchanan et al. [35]

The variation with building orientation θ in Young's modulus E, 0.2% proof stress $\sigma_{0.2}$, ultimate stress σ_u and fracture strain ε_f, considering available data from the literature, are shown in Figures 3-6 respectively. For each series of tests, the value of E, $\sigma_{0.2}$, σ_u or ε_f at orientation θ has been normalised by the average value across all orientations. The building orientation θ is defined as the angle measured from the horizontal building plane to the longitudinal axis of the coupon (i.e. $\theta = 0°$ is a coupon parallel to the building plane, $\theta = 45°$ is an inclined coupon and $\theta = 90°$ is a vertical coupon).

The Young's modulus E is seen to have minimal variation with building orientation, as shown in Figure 3 for both tension and compression, whereas the 0.2% proof stress $\sigma_{0.2}$ and ultimate stress σ_u is observed to decrease with an increase in building orientation θ, as seen in Figures 4 and 5 respectively. This is attributed to the elongated grains in the vertical direction, resulting in lower strength when loaded in this direction.

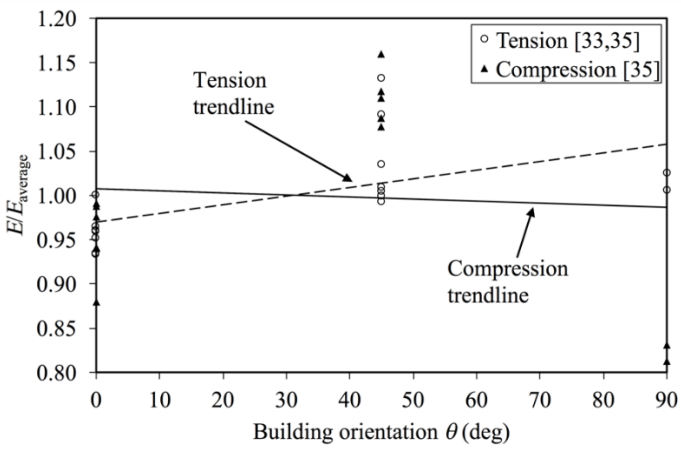

Fig. 3 Variation in normalised Young's modulus E with building orientation θ for PBF manufactured Grade 316L stainless steel [33,35]

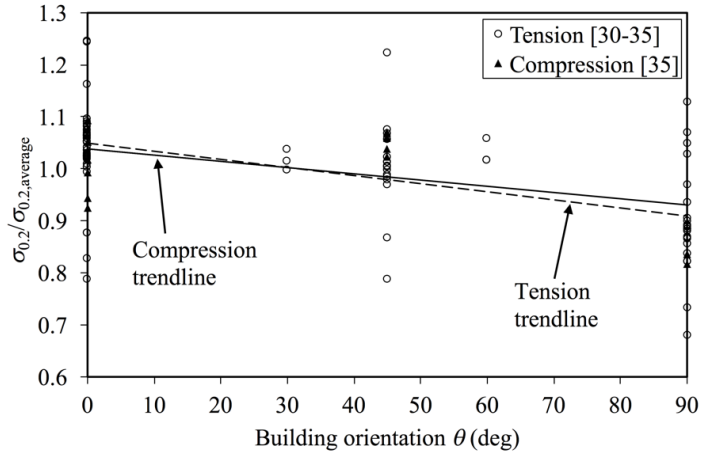

Fig. 4 Variation in normalised 0.2% proof stress $\sigma_{0.2}$ with building orientation θ for PBF manufactured Grade 316L stainless steel [30–35]

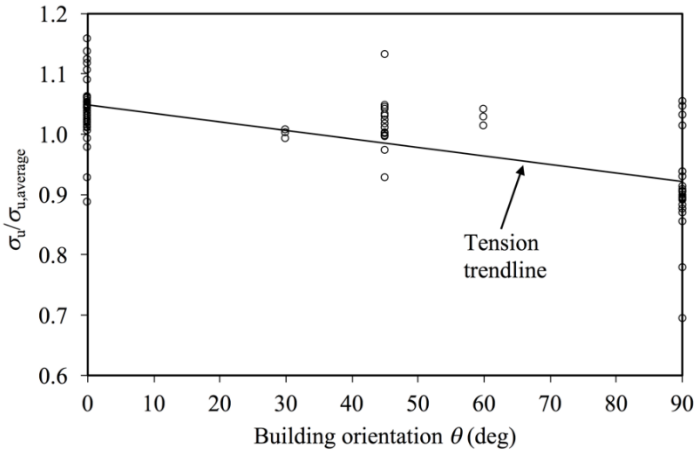

Fig. 5 Variation in normalised ultimate stress σ_u with building orientation θ for PBF manufactured Grade 316L stainless steel [30–35]

The variation of the fracture strain ε_f with building orientation θ is shown in Figure 6. The results are highly scattered, with the vertically orientated coupons showing higher fracture strains in some test series [30,33,35], but lower in others [31,32,34].

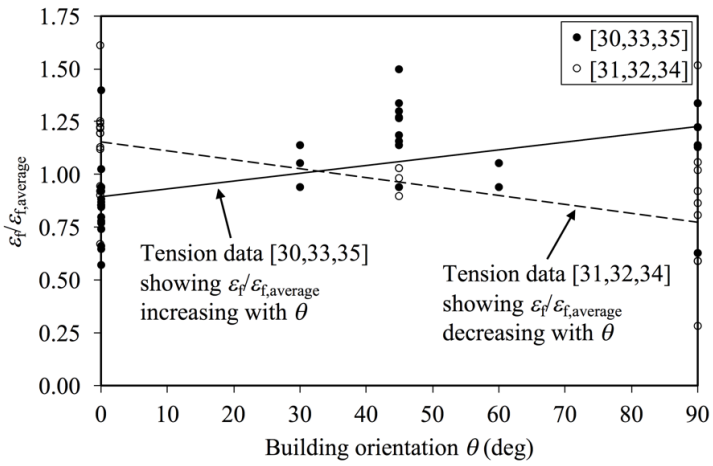

Fig. 6 Variation in normalised fracture strain ε_f with building orientation θ for PBF manufactured Grade 316L stainless steel [30–35]

Heat treatment may reduce the degree of anisotropy, as observed by Mower and Long [33], but only horizontal ($\theta = 0°$) and inclined ($\theta = 45°$) coupons were tested in the study, so further investigation is required.

In terms of the absolute values for the key material properties of PBF manufactured Grade 316L stainless steel [30–36] relative to equivalent conventionally produced material [37,38], PBF manufactured material has a slightly lower average Young's modulus ($E \approx 180{,}000$ N/mm^2), a significantly higher yield stress and a more variable fracture strain than

conventionally produced material. The lower Young's modulus is associated with a higher degree of porosity than conventional stainless steel. The higher strength is attributed to the rapid cooling and solidification from the manufacturing process, which leads to a fine crystalline structure [30,33,34].

The effect of laser power [8], powder particle size [32] and building layer thickness [32,34] on the mechanical properties of PBF manufactured Grade 316L stainless steel has been explored, while the level of residual stresses in PBF manufactured material was measured in [39,40] and found to be significant. The corrosion resistance of powder bed fusion manufactured 316L stainless steel has also been investigated and, provided full relative density is attained, the resistance is similar to conventionally formed material [41]. The tensile properties of PBF manufactured Grade 304 stainless steel with varying layer thickness, laser overlap, laser scanning angle and building direction have also been studied in [42].

The tensile and fatigue behaviour of heat-treated powder bed fusion manufactured PH1/15-5PH martensitic stainless steel has been studied in [43]. The variation in tensile stress-strain responses of with building orientation for PH1/15-5PH material was investigated by Buchanan et al. [35]. Anisotropic behaviour was again observed, as shown in Figure 7, although in contrast to the 316L tests, the ultimate stress and fracture strain reduced with increasing build orientation, varying by up to 5% and reducing by up to two thirds respectively, while the Young's modulus and 0.2% proof stress showed minimal variation with build angle.

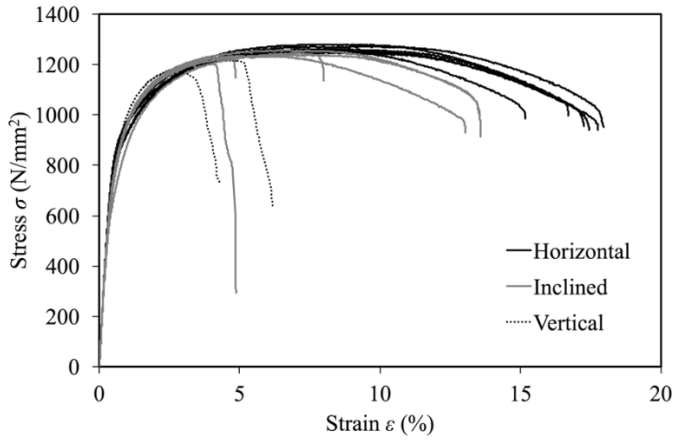

Fig. 7 Measured stress-strain curves from tensile coupon tests on PH1 stainless steel reported by Buchanan et al. [35]

The fatigue performance of powder bed fusion manufactured Grade 316L and PH1/15-5PH stainless steel has been explored in [44], while that of aluminium alloy AlSi10Mg, titanium alloy AlSi10Mg and Grade 316L and 17-4PH stainless steel has been examined in [33]. For stainless steel, fatigue behaviour similar to conventionally produced material was observed if the principal stresses aligned with the build planes, otherwise premature fatigue failed occurred due to separation between the layers.

Studies into the structural applications of powder bed fusion metallic materials have included examining Grade 316L stainless steel open cellular lattice structures [45–47], negative Poisson's ratio structures [48] and square hollow section (SHS) compression elements [35]. A photograph of the specimen building process of the SHS and their deformed shapes, following failure under concentric compression loading, are shown in Figures 8 and 9. The normalised ultimate axial cross-sectional resistance $N_u/A\sigma_{0.2}$ (where N_u is the ultimate axial resistance and A is the cross-sectional area) of the five tested powder bed fusion SHS compared with conventionally produced austenitic, duplex and ferritic SHS for varying EN 1993-1-4 [37] cross-section slenderness $c/(t\varepsilon)$ (where c is the element width, t is the thicknesses and $\varepsilon=[(235/\sigma_{0.2})(E/210{,}000)]^{0.5}$) is shown in Figure 10. The stockier additively manufactured cross-sections had slightly greater normalised axial resistance, using the averaged vertical material properties, compared with conventionally formed stainless steel SHS. The most locally slender SHS had a normalised resistance slightly below the existing conventional test data, which may be the result of internal defects or high residual stresses. The EN 1993-1-4 [37] cross-section resistance predictions were calculated for the additively manufactured SHS and were found to offer suitable predictions for the non-slender cross-sections and slightly unconservative predictions for the slender cross-section, overestimating the cross-section resistance by 13%. The continuous strength method (CSM) resistances were also determined, and these were found to be more accurate in predicting the resistances of the non-slender cross-sections.

Further studies are currently underway, by the authors, into the structural response of other additively manufactured stainless steel cross-sections, including those with internal structures. The fracture behaviour, shear properties and Poisson's ratio of powder bed fusion manufactured stainless steel also require additional investigation.

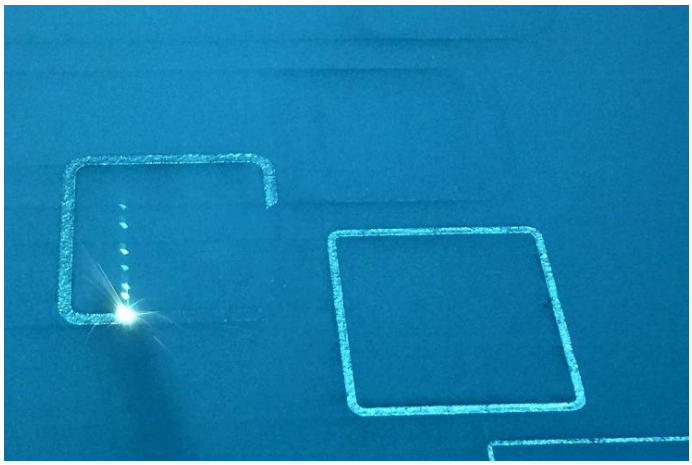

Fig. 8 Grade 316L stainless steel SHS stub columns being built by powder bed fusion [35]

Fig. 9 Deformed additively manufactured SHS test specimens [35]

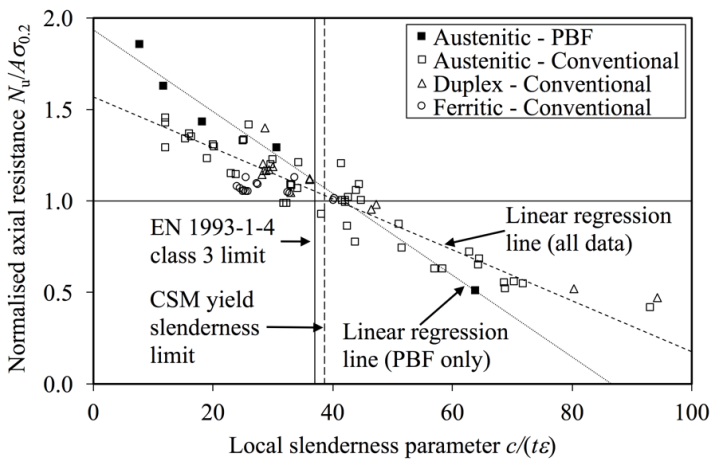

Fig. 10 Normalised ultimate axial resistance $N_u/A\sigma_{0.2}$ varying with local slenderness $c/(t\varepsilon)$ [35]

3.2 Additive manufactured material from directed energy deposition (DED)

The effect of heat treatment and thermal history on the tensile and compressive properties of directed energy deposition manufactured Grade 316L stainless steel material has been investigated in [49]. Heat treatment was found to lower the yield and ultimate strength, but increase ductility, like annealing. Early work also looked at the effect of the laser power and powder delivery rate on the mechanical properties of Grade 304 stainless steel [50].

Early research on metallic additive manufacturing using three-dimensional welding was undertaken by Spencer et al. [51] who built a hollow box, vertical wall and horizontal plate using mild steel wire and investigated the surface finish, microstructure and residual stresses. An additive manufacturing technique that combines gas metal arc welding and CNC machining, to produce mild steel tensile coupons in varying orientations, has also been explored [52]. Anisotropic behaviour was observed, with the average ultimate strength varying by up to 15% with orientation, although this was later reduced with a higher arc current.

The applications of wire and arc additive manufacturing in structural engineering have also been explored as part of the preparatory work for the MX3D stainless steel bridge [26]. Tensile coupons were built from 308LSi and 316LSi stainless steel wire, with slight anisotropic material relationships observed (a variation in the ultimate strength of 10%) from the test results; fatigue tests and buckling tests on rods were also undertaken. Further tensile coupon tests on wire and arc additive manufactured 304 stainless steel and ER70S mild steel were carried out in [53]. Tensile coupons in two perpendicular orientations were built for mild steel, with no significant difference in yield strength observed, while the stainless steel coupons were built in the same direction. The authors are currently undertaking tests on tensile and compressive coupons and stub columns built, using wire and arc additive manufacturing, from Grade 308LSi stainless steel.

3.3 Other

Research into sheet lamination has been much more limited than for powder bed fusion or directed energy deposition. A variety of complex shapes, cooling channels, honeycomb structures and spherical shells with holes, with sheet metal and polymer adhesives, have been built [27]. The feasibility of electrochemical additive manufacturing (ECAM) has been established by building nickel microstructures with cantilevering overhangs [29].

4 Metallic Additive Manufacturing in Construction

Since the early 2000s, architectural firms have adopted additive manufacturing for model making, resulting in significant time and cost savings, with reports of the model making process being shortened from months to hours and costs reducing fiftyfold [17,54]. Metallic additive manufacturing is still less common further down the design and build process. A review of publicised metallic additive manufacturing projects is presented in this section.

4.1 Nematox façade node

The Nematox façade node was developed to show how additive manufacturing processes could be used to enable more complicated façade geometry (shown in the rendering in Figure 11), allowing for substantial innovation and greater geometric freedom [55]. The developed solution moves the structural connections outside of the node, reducing the likelihood of defects affecting the environmental sealing. A full-size prototype (shown in Figure 11) was built using powder bed fusion and aluminium powder, which required 120 hours of CAD design, including ten hours to convert the model into an appropriate AM file format and a further two hours to place the node within the AM equipment software. The building process took 76.5 hours, with an additional four hours of finishing work required at the end. This additive manufactured node is seen as an example of how a high technology component can be used with existing verified and tested façade systems [56].

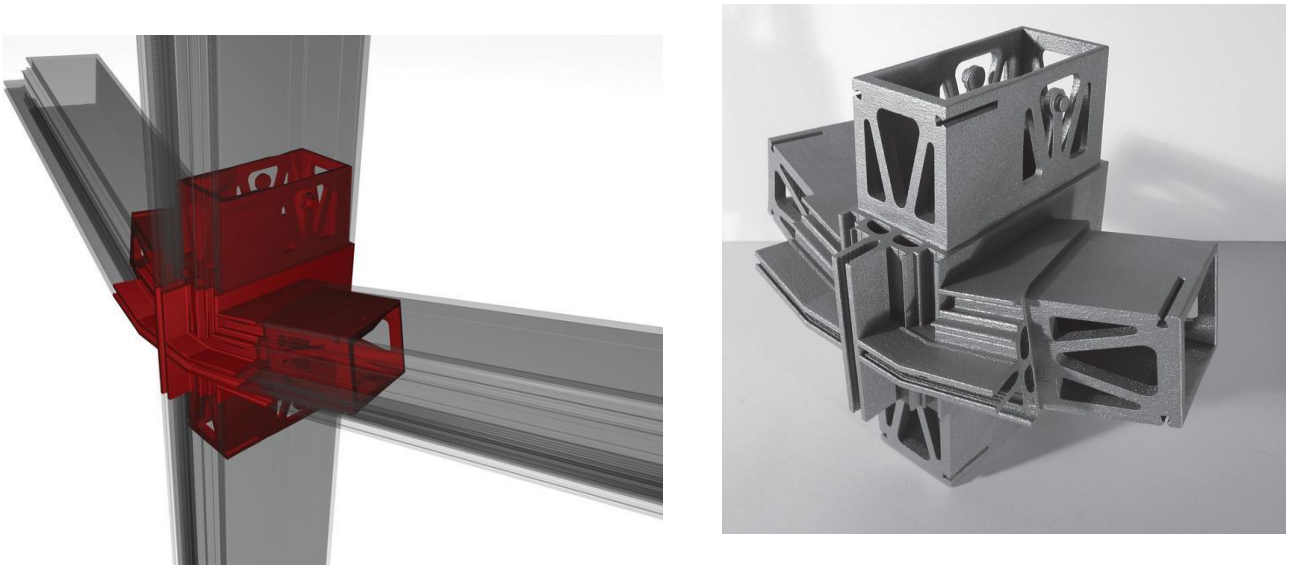

Fig. 11 A rendering of a Nematox façade node (left) and a full size aluminium prototype node (right) [55]

4.2 Arup lighting node

Arup redesigned a tensegrity structure lighting node to take advantage of the opportunities presented by additive manufacturing. The conventionally fabricated design comprised up to seven unique machined plates welded to a central tube. Topology optimisation was applied to this previous design, with the starting point and boundary conditions prescribed and then software used to develop a geometrically optimised node. The design was then rationalised for manufacture – reducing the amount of material used, to minimise cost and speed up manufacture, and moving elements to act as support structures, to prevent the need for support structure removal. The final design is an organic structure which aligns with the internal forces. 40% scale models of the original and optimised nodes were produced (as shown in Figure 12), the latter using powder bed fusion with ultra-high strength steel powder.

It was noted, in 2014, that the new additively manufactured node cost roughly three times that of a conventionally produced node, but that it is expected to become cheaper through manufacturing developments within five years. Developments such as more powerful powder bed fusion equipment and a further optimised node design, considering the higher strength of additively manufactured metallic materials and undertaking manufacturing optimisation in parallel with topology optimisation, will lead to reduced build times and lower costs [57].

A second optimised node was developed to take advantage of the lessons learned from the first node. The design objective was to minimise the total weight, with material removed where it was subjected to lower stresses. The node was again built using powder bed fusion, although with Grade 316L stainless steel powder. This second iteration was 75% lighter than the conventionally fabricated node, half the height and with its integrated connections allowed the entire tensegrity lighting structure to be 40% lighter. It was highlighted that there were high level demands on computational skills and that the post-optimisation steps were time consuming [22].

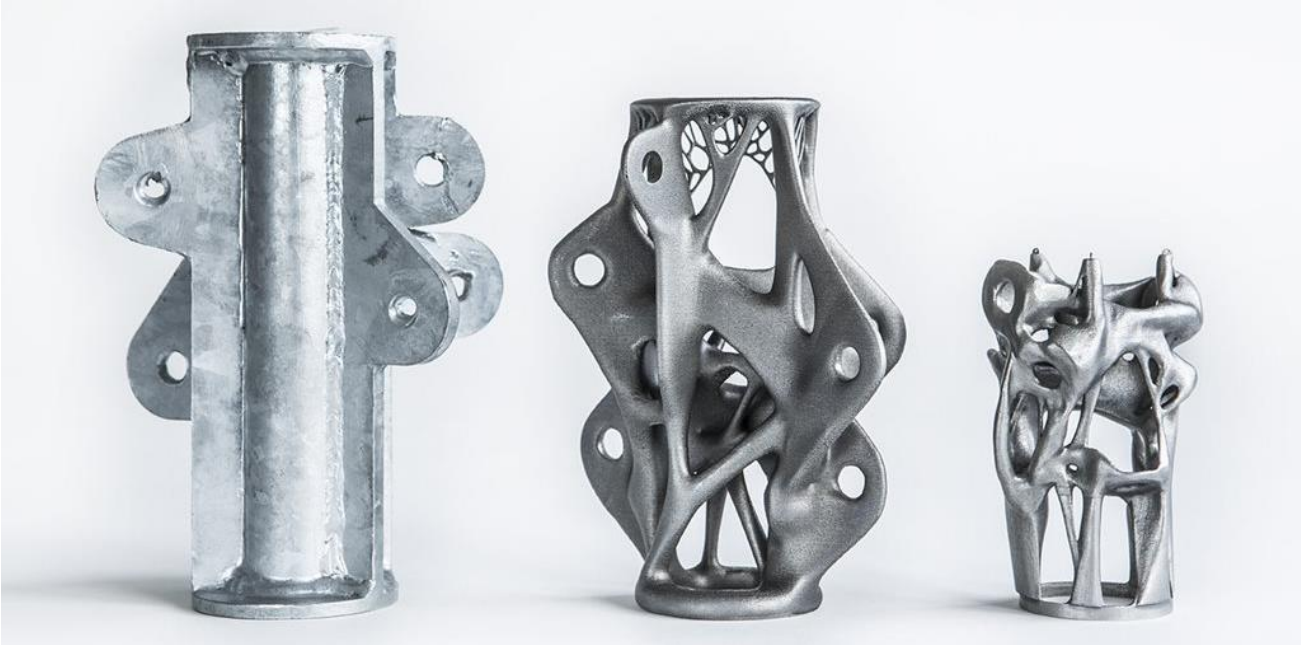

Fig. 12 The progression from a conventional lighting node to the two AM optimised lighting nodes [58]

4.3 MX3D bridge

MX3D are building the first additively manufactured stainless steel metallic bridge. The bridge has a 10 m span, and a 2.5 m wide deck, and is being built using wire and arc additive manufacturing with a 6 axis robotic welding arm [59]. An architectural rendering of the bridge is shown in Figure 13. The bridge is anticipated to be completed by summer 2018 and will be located within the centre of Amsterdam, Netherlands.

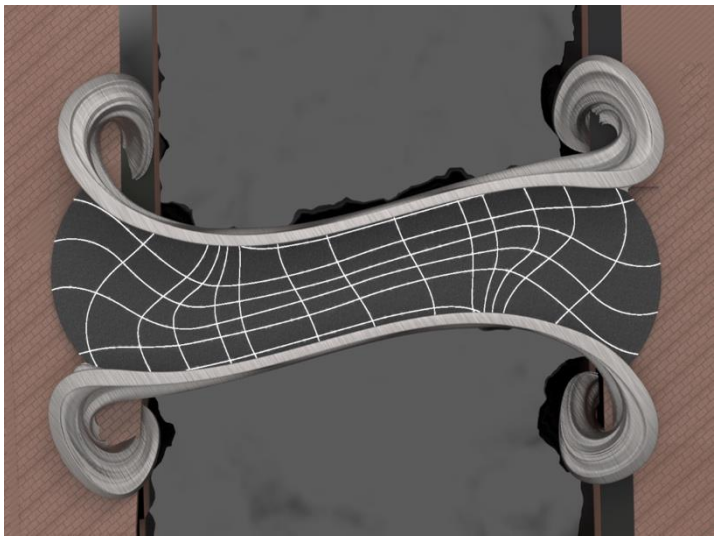

Fig. 13 A plan view architectural rendering of the MX3D bridge [21]

These metallic additive manufacturing projects highlight several important considerations for the wider adoption of these techniques in construction. The CAD design process and post-processing after manufacture can be particularly time consuming, as seen with the Nematox façade node. There is also a need to consider the limitations of the manufacturing technique whilst undertaking any optimisation processes, otherwise an unbuildable or sub-optimal form

will be attained, requiring additional human intervention. Structural engineers will require, or at least need access to, high level computational skills to incorporate additive manufacturing within existing structural design workflows. The optimised Arup lighting node has shown that metallic additive manufacturing can enable highly optimised, lightweight, efficient structural forms that would be excessively time consuming and costly to manufacture with traditional forming techniques.

5 Opportunities and Challenges from Metallic Additive Manufacturing in Construction

Metallic additive manufacturing offers tremendous opportunities for innovation within construction. The geometric and material flexibility, customisation and potential to lower costs through reduced waste, shortened construction time and the repair and strengthening capabilities, are described in Section 5.1. Additive manufacturing also brings challenges, some of which are inherent to the manufacturing technique and others that relate to the current state of the technology, which may be alleviated as the manufacturing capabilities advance. These challenges are discussed in Section 5.2.

5.1 Opportunities

5.1.1 Geometric and material flexibility

The main opportunity that additive manufacturing offers over traditional manufacturing processes is the geometric flexibility at both the macro and microscales, allowing for highly optimised structures and engineered materials. Designers are no longer limited to working with simple low complexity geometries, with non-re-entrant shapes and constant wall thicknesses, due to the limitations of existing manufacturing processes at the macroscale. This unlocks a limitless variety of new structural cross-sections and forms, such as cross-sections and members with varying wall thicknesses around the perimeter or along the length, or hollow sections with internal strengthening features that could simply not be produced with conventional methods.

At the microscale, the material properties can be modified to produce engineered materials with controlled mechanical behaviour. As an example, in the biomedical industry, the porosity of implants is deliberately increased in key locations to lower the material stiffness to improve compatibility with adjoining elements [60]. Within construction this could be used to distribute forces and moments in the most favourable way by reducing the stiffness to attract less force in certain areas, or used to produce sacrificial energy absorbing elements for structures in seismic areas.

Residual stresses are generally regarded as an unwanted ‘imperfection’, typically resulting in premature yielding and a reduction in load-carrying capacity. However, if they are arranged to be of the opposite sense to the stress arising from the applied loading they can delay yielding and have a positive influence on load-carrying capacity. Additively manufactured metallic materials can also benefit from improved material properties, such as higher strength, that are inherent to the manufacturing process.

5.1.2 Customisation

Additive manufacturing offers a high degree of customisation that has not previously been attainable in a low margin industry, such as the construction sector. Small production runs are possible, with no tooling requirements in many scenarios, enabling the fulfilment of custom orders for niche markets [2]. Structural engineers could make every structural component unique with no additional manufacturing costs; the cost to produce two identical or different variants of an object is essentially the same [15,17]. Design changes could also be rapidly incorporated. This customisation will likely create additional demand for additive manufacturing, which in turn will help to lower costs. Customisation has been used, since the 1990s, as a marketing strategy in the Korean house-building sector [1].

5.1.3 Construction time, material use and environmental advantages

Construction uses vast resources; in the US it has been estimated to consume 36% of the total energy, 30% of raw materials and 12% of the potable water [61]. Traditional construction techniques use standardised components for beams, columns, floors and walls that have unique dimensions. The components must therefore be cut down to size, ultimately producing waste and increasing the economic and environmental costs [15]. Additive manufacturing provides opportunities to reduce this waste by allowing bespoke components to be produced for each project, reducing the amount of raw material required and unwanted material that needs to be disposed of. For metallic powder bed fusion methods, up to 98% of the remaining ‘waste’ powder can be recycled and reused [5]; in general, additive manufacturing techniques can lead to a 40% reduction in waste over subtractive techniques [17]. The environmental impact of an additively manufactured component has been estimated to be up to 70% lower than that of an equivalent component produced with conventional techniques [62].

In construction, generally the longer the length of time between the start of a project and the finished structure, the greater the financial cost of the project. Additive manufacturing offers several opportunities for this construction time to be shortened. Firstly, there is reduced setup time for manufacturing components with these new techniques [63]. The time to build the individual structural elements can also be reduced, the build time for a structural concrete wall built using concrete printing was reduced to 65 hours compared with 100 hours for a conventional wall [2], which ultimately helps to reduce construction costs. For metallic additive manufacturing, faster build times can be achieved through consideration of the build orientation [2]; taking into account the characteristics of the building process; and by keeping the build height low [4]. Additive manufacturing will likely initially feature predominantly in offsite manufacture and modularisation which will help to increase quality, but also allows for reduced costs, through economies of scale.

Geometric complexity can be obtained at minimal, or in some cases no, additional manufacturing cost, whereas with conventional manufacturing there is always a direct link between design complexity and cost [4,64]. Additive manufacturing techniques also offer the opportunity to repair damaged or corroded structural elements, or be used to strengthen a structure in-situ, reducing the cost of the repairs or strengthening work.

Finally, additive manufacturing enables just-in-time manufacture, which can reduce inventory storage costs, in addition to providing structural engineers with a limitless array of cross-sections and forms that are not restricted by uncertain demand and low inventory turnover [17].

5.2 Challenges

5.2.1 Costs

While additive manufacturing offers considerable potential for material and cost savings in the future, there is currently likely to be an economic penalty in the early adoption of this technology. The construction industry is highly cost sensitive. The opportunities for major innovation are severely limited with projects predominantly awarded based on cost, with the lowest bidder winning. The cost implication of additive manufacturing in the construction industry is still unclear, and some have commented that it is too early for it to be utilised in the construction industry [1]. The raw material cost can be higher than for conventional processes – for aluminium the material cost can be ten times greater, and with powder bed fusion the material cost can be up to half of the total cost [3]. There are also costs associated with failed builds that need to be considered. The cost of additive manufacturing equipment, particularly for laser or electron beam based methods, can be high and costs do not decrease with increased production runs [17]. Energy costs vary depending on the technique used; stereolithography uses as little as 100 W, whereas electron beam melting directed energy deposition can use 3000 W [5].

Additive manufacturing processes, while heavily automated, are not entirely labour-free; there are significant pre-processing and post-processing steps to undertake, such as file repair, build machine cleaning, removal of support structures and heat and surface treatment [3,5]. While faster construction is possible with additive manufacturing over conventional techniques, this requires increased deposition rates that generally result in lower placement precision and resolution, affecting the geometric accuracy and the surface finish. Typically, a better surface quality is attained from building with thinner layers, which takes more time and therefore increases the economic cost.

5.2.2 Variability in geometric and material properties

A second major challenge is the wide range of additive manufacturing technologies that lead to a lack of standardised design methods, manufacturing guidelines and practices. The same 3D CAD file can produce a wide range of results with different additive manufacturing methods. This lack of standardisation is commercially beneficial for equipment manufacturers through vendor lock-in, although it hampers more widespread adoption of additive manufacturing techniques. There is a clear requirement for material, process, calibration, testing and file format standards despite the range of materials, equipment and processes currently available [4]. Variability across builds [4] and between machines using the same process [3] will require new quality assurance measures during, and after, the building process to ensure that parts built meet appropriate strength and reliability requirements. The International Organization for Standardization (ISO) and American Society for Testing and Material (ASTM) has formed working groups to solve these problems, and in 2013 set the goal of developing a single set of global standards to be applied to the majority of additive manufacturing materials, processes and applications [3]. For construction, a rigorous inspection and testing regime would need to be established.

5.2.3 Manufacturing process limitations

Parts which are additively manufactured behave differently to conventionally formed components, as seen in Section 3.1 from prior stainless steel research. The inherent material anisotropy, due to the novel manufacturing process, may be reduced with heat treatment, although this requires further investigation. The long-term behaviour of additive manufactured components is also unknown [1].

For most metallic additive manufacturing methods, special techniques are required for overhanging parts, due to the need to support its self-weight during manufacture. This can be achieved in three ways: i) a support structure can be utilised, which is fabricated with the final part, and cut away before use [5]; ii) a second material, that is easy to remove, can be deposited to provide support; or iii) the unconsolidated powder can be used for support [15]. Support structures are also typically required to dissipate heat into the build platform, reducing warping and curling of the built components [4].

The actual building process can be slow for some metallic additive manufacturing processes, as the parts are built up in very thin layers. There are still size limitations with some methods, particularly the non-wire-based methods, which limits the maximum size of built components, without some additional form of assembly. Both limitations can be expected to reduce in prominence over time, with further developments in the building processes and advancements in manufacturing technology.

The surface finish can also be very different to conventional material, with a ‘stair-stepping’ effect from the layer-by-layer building process and a rough surface which may require additional processing, such as polishing or sanding [4]. The ‘stair-stepping’ effect may be improved with further development of the building techniques, while the rough surface is an inherent outcome from the manufacturing process.

6 Concluding Remarks

Additive manufacturing (AM) can trace its history back to the 1860s, although it has only been in the last twenty years that these new novel manufacturing techniques have been commercialised. A wide range of materials and techniques can be used, covering polymers, concrete and metallic materials that are melted, extruded, adhered or chemically hardened to form objects in a layer-by-layer manner. Metallic additive manufacturing is starting to gain traction in the aerospace and biomedical industries for high value, end part manufacturing. There has been significant research to date into the material properties of additively manufactured stainless steel, but there has been limited research undertaken with a construction focus, considering cross-sections, connections and full structural systems. Further work is currently underway in these areas.

Metallic AM techniques are starting to be considered as a viable technique for use in the construction industry. Powder bed fusion methods have been used to build prototype façade and connection nodes and directed energy deposition techniques are currently being used to build a stainless steel pedestrian footbridge in Amsterdam. Additive manufacturing offers the potential to produce bespoke individual components with high geometric complexity, engineered material properties and optimised structural forms. These components are impossible, or uneconomic, with conventional subtractive and formative manufacturing techniques. Significant challenges remain in the adoption of additive manufacturing techniques in construction. There is a lack of standardisation in design methods and between equipment vendors, inherent variability between builds with the same equipment, higher material costs and a lack of suitable standards and regulations covering construction using these new techniques. It is also unclear how these new manufacturing methods will be utilised – entire structures could be built using these techniques, or they may be used only for high complexity components or even internal fixtures and fittings. However, what is clear, is that additive manufacturing offers tremendous opportunities and potential for the construction industry, as these challenges are overcome.

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