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Structural performance of additive manufactured metallic material and cross-sections

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ABSTRACT

Additive manufacturing, a common example of which is 3D printing, has become more prevalent in recent years with it now being possible to form metallic structural elements in this way. There are, however, limited available experimental data on the material behaviour of powder bed fusion (PBF) additive manufactured metallic structural elements and no existing data at the cross-section level; this is addressed in the present paper through a series of tests on additive manufactured stainless steel material and cross-sections. Tensile and compressive coupon tests were used to assess anisotropy, symmetry of stress-strain behaviour and the influence of building direction on the material properties. The yield and ultimate tensile strengths were seen to generally decrease in magnitude with increasing build angle, while a reduction in ductility was observed in some building orientations, and the Young's moduli were typically insensitive to the build angle. The structural behaviour of PBF additive manufactured cross-sections was investigated through a series of square hollow section (SHS) stub column tests, and the results compared with conventionally produced stainless steel SHS. The generated test results have been used to evaluate the applicability of existing design guidance for conventionally produced sections to additive manufactured sections.

1. Introduction

Additive manufacturing is the overarching name for any form of manufacturing where an object is produced in an additive manner, whether this be through the laying down of material, melting and binding of material, selective curing of a liquid or the adhering of existing layers. '3D printing' is a term that generates tremendous excitement in society, although strictly applies only to methods which lay down material, and is itself a type of additive manufacturing. Additive manufacturing first emerged in the 1980s with rapid prototyping techniques, initially through stereolithography, which is the process of solidifying ultraviolet sensitive liquid polymer with a laser [1]. Significant advancements have been made since then with a wide range of materials able to be utilised 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 [1–10]. The end products are equally varied from customised sports footwear [11] to building plastic tools on the International Space Station [12], the production of titanium rocket nozzle components [13] and even personalised chocolate confectionary [7].

1.1. Metallic additive manufacturing

Metal additive manufacturing is increasingly popular in the aerospace, automotive, defence and medical industries [14,15] due to its many advantages over traditional manufacturing techniques, such as casting, fabrication, machining, rolling and stamping. Conventionally manufactured objects often have simple geometries to aid manufacturing [4] whereas with new production techniques this need not be the case. Additive manufacturing enables automated and repeatable rapid prototyping or small production runs of objects with complex geometries and shapes that would otherwise be time and cost prohibitive, or even impossible with other manufacturing methods. Structural components can take highly optimised lightweight forms to carry loads more efficiently, including the possibility of internal stiffening structures and specific weight-saving porosities with parts as thin as 100 microns [16]. There are also a number of wider benefits including reduced material waste, reduced energy input and rapid incorporation of design changes. Parts can be built essentially anywhere, just-in-time if required and with the same processing parameters, predictably and reliably. Additive

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manufacturing techniques can even be used to repair worn and damaged metallic components [4,15]. This new manufacturing process has also been found to yield advantageous mechanical properties due to the rapid cooling over conventionally produced metallic materials [17]; this has been observed in the material tests undertaken in this study.

To date, compared with plastic additive manufacturing, which has benefited from the introduction of low cost production equipment in the late 1990s [18], equipment suitable for use with metallic materials has been prohibitively expensive [19]. Currently, production time can be excessively lengthy since, with some building methods, objects are built up using individual layers that are tens of microns thick. Support structures are typically required to mechanically restrain the part being manufactured to the rigid building platform, in order to reduce the distortion arising from the residual stresses [20], and these need to be later manually removed. The surface finish is different from conventionally produced metallic objects which, for some applications, may necessitate additional finishing processes, such as sanding or bead blasting, and consequently parts may need to be manufactured slightly oversized. Significant design times within computer aided design (CAD) software packages can also be required. The maximum dimensions of a single part are limited by the build envelope of the equipment which, for powder bed fusion, is typically a 250 mm cube, while some direct energy deposition methods allow a single dimension up to 5 m. These size limitations will be overcome in time; Big Area Additive Manufacturing (BAAM) is being developed with the intention to build components as large as aircraft wings that are 30 m in length [21]. While additive manufactured metallic materials exhibit some beneficial mechanical properties over conventionally produced materials, they can also exhibit anisotropy [17,22-29] which for some materials can be partially remediated through heat treatment [26-28,30-32], and high residual stresses [3,33].

ISO/ASTM 52900 [34] provides an outline of metallic single-step additive manufacturing methods, where the key process categories are: i) directed energy deposition, ii) powder bed fusion and iii) sheet lamination. Directed energy deposition (DED) relies on the selective depositing of melted material, which can be either a laser or electron beam melted powder or a filament/wire material, akin to welding. Powder bed fusion (PBF) is where material within a powder bed is selectively fused together using thermal energy from a laser or electron beam. The third category is sheet lamination, where individual cut out cross-sections can be laminated together using ultrasound. Beyond single-step processing, there is multi-step processing where the first step provides the geometric shape and the second provides the material properties, and this process can also involve adhering dissimilar materials together. The proprietary nature of the manufacturing equipment and metallic powders has resulted in a variety of names for similar processes. ISO/ASTM 52900 [34], and its predecessor ASTM F2792-12a [35], have attempted to standardise the terminology, but this has only recently been adopted in the literature; for example, PBF includes selective laser melting (SLM), selective laser sintering (SLS), direct metal laser sintering (DMLS) and electron beam melting (EBM) among others [1], while DED includes laser engineered net shaping (LENS).

Over the past twenty years there has been significant research into metallic additive manufacturing processes and applications. Tensile coupon tests have been undertaken on PBF 316L stainless steel to investigate anisotropy arising from different building orientations [22,23,25,26,29], the influence of the laser power [3], powder particle size [25] and building layer thickness [25,29] on the material properties, the fatigue performance [26,36] and residual stresses [33,37]. Corrosion resistance has also been assessed and, it has been found that provided full relative density is attained, the resistance is similar to conventionally formed material [38]. Coupon tests have been performed on PH1/15-5PH martensitic stainless steel to study the tensile behaviour in different build orientations [20] and to examine the fatigue behaviour [20,36]. Research has also been carried out into DED 316L [39], the processing parameters for PBF [40] and DED [41] 304 stainless steel, the anisotropy [26,28] and heat treatment [28,30] of PBF aluminium alloys, the anisotropy [17] and heat treatment [31,32] of PBF titanium alloys, the mechanical properties of DED titanium alloys [42,43], the structural integrity of post-processed bronze-nickel alloys [44] and directionality at differing temperatures of a nickel based superalloy [45]. Studies into the structural applications of PBF metallic materials have included examining 316L stainless steel open cellular lattice structures [16,46,46,47] and negative Poisson's ratio structures [48]. The applications of DED MX3D gas metal arc welding (GMAW) in structural engineering have also been explored [49].

1.2. Additive manufacturing in construction

Additive manufacturing offers many potential benefits in construction, such as the ability to produce bespoke individual components, reduced waste, time and material savings, more optimised structural forms and easier integration with building information modelling (BIM) [9,50]. Current constructional additive manufacturing research has focussed mainly upon cementitious materials. Contour crafting, which utilises a cement-based paste against a trowel can be used to produce a 200 m^2 single-storey building within a day [50,51], concrete printing involves extrusion of cement mortar [9] and the D-shape process involves producing a material similar to sandstone by combining adhesives and a sand-like material [6,9,50,52]. In 2014 construction started on the 3D Print Canal House in Amsterdam, Netherlands which is an additive manufactured house made by joining individual plastic blocks [50,53]. Construction has started, again in Amsterdam, on the MX3D bridge, a stainless steel DED GMAW structure that will eventually span an 8 m wide canal [49]. Arup recently redesigned a node detail to be built using PBF and found that while currently it would cost roughly three times that of a conventionally produced node, it is expected to be cheaper through manufacturing developments within five years [54]. It has been estimated that in the future, additive manufacturing technologies may decrease construction costs by 30% through automation and reduced labour requirements [55]. Additive manufacturing techniques have also been proposed to aid in the rapid construction of shelters in disaster hit areas [51].

It is clear from the existing research into metallic additive manufacturing that extensive work has been carried out on the production processes and basic material properties, but there has been very limited research to date into potential structural engineering applications. The aim of this paper is to further investigate the directionality of powder bed fusion stainless steels in both tension and compression and to undertake cross-sectional tests to provide experimental data to appraise the applicability of existing design methods to sections produced through this novel manufacturing route.

2. Experimental investigation

The experimental investigation consisted of tensile and compressive material coupon tests and compressive tests on square hollow section (SHS) stub columns. Two different stainless steel grades were studied - a precipitation hardening martensitic grade PH1 (also known as 15-5 PH, EN 1.4540 and X4CrNiCuNb164), commonly used for aerospace components and parts for corrosive high pressure environments [20,56], and an austenitic grade 316L (also referred to as EN 1.4404 and X2CrNiMo17-12-2), which is widely used for aerospace, automotive, chemical, construction, consumer and nuclear applications [57]. Tensile material properties in a variety of building orientations were determined for both stainless steel grades, with compressive material properties measured for the austenitic 316L grade only. The cross-sections were built vertically, with their longitudinal axis perpendicular to the building layers. The cross-sectional behaviour was examined for the 316L material as this is a common grade of stainless steel used in structural engineering and is included in the European stainless steel