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Effects of hot isostatic pressing on the elastic modulus and tensile properties of 316L parts made by powder bed laser fusion

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ABSTRACT

The microstructure and mechanical properties of 316L steel have been examined for parts built by a powder bed laser fusion process, which uses a laser to melt and build parts additively on a layer by layer basis.

Relative density and porosity determined using various experimental techniques were correlated against laser energy density. Based on porosity sizes, morphology and distributions, the porosity was seen to transition between an irregular, highly directional porosity at the low laser energy density and a smaller, more rounded and randomly distributed porosity at higher laser energy density, thought to be caused by keyhole melting. In both cases, the porosity was reduced by hot isostatic pressing (HIP).

High throughput ultrasound based measurements were used to calculate elasticity properties and show that the lower porosities from builds with higher energy densities have higher elasticity moduli in accordance with empirical relationships, and hot isostatic pressing improves the elasticity properties to levels associated with wrought/rolled 316L. However, even with hot isostatic pressing the best properties were obtained from samples with the lowest porosity in the as-built condition.

A finite element stress analysis based on the porosity microstructures was undertaken, to understand the effect of pore size distributions and morphology on the Young's modulus. Over 1–5% porosity range angular porosity was found to reduce the Young's modulus by 5% more than rounded porosity. Experimentally measured Young's moduli for samples treated by HIP were closer to the rounded trends than the as-built samples, which were closer to angular trends.

Tensile tests on specimens produced at optimised machine parameters displayed a high degree of anisotropy in the build direction and test variability for as-built parts, especially between vertical and horizontal build directions. The as-built properties were generally found to have a higher yield stress, but lower upper tensile strength and elongation than published data for wrought/hot-rolled plate 316L. The hot isostatically pressed parts showed a homogenisation of the properties across build directions and properties much more akin to those of wrought/hot-rolled 316L, with an increase in elongation and upper tensile strength, and a reduction in yield over the as-built samples.

1. Introduction

Additive Layer Manufacturing (ALM) based on the melting of pre-alloyed metal powders is a processing route which is rapidly evolving from rapid prototyping with the capability of producing functional net-shape parts with the strength characteristics of wrought parts [1]. It is ideally suited to low-volume production, and can be cost-competitive or cheaper than CNC machining or processes where the capital outlay for items such as dies are high [2]. However, as with all powder-based processes, such as sintering [3], net-shape hot isostatic pressing [4], and powder compaction [5], as well as other net-shape manufacturing methods such as casting [6], there is an inherent porosity associated with the process.

The literature is rich in studies reporting on specific combinations of alloys, ALM techniques and applications. Titanium alloys, such as Ti-6Al-4V are being examined for use as critical aerospace and biomedical applications such as orthopaedic devices, and dental implants, and are understandably receiving a large proportion of the effort.

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Typically the material/process development cycle will start by studying the links between porosity and tensile strength, as exemplified for powder bed fusion processes, of which selective laser melting (SLM) generally referrers to processes specifically using optical based lasers, [7], wire-feed processes [8] and electron beam processes, [1,9–11]. Common conclusions from this type of work are that anisotropic mechanical properties occur to a varying degree, and that there are also various levels of porosity which have a detrimental effect on ductility, accompanied by high levels of hardness and yield strength.

The effects on mechanical properties of surface finishing, heat treatments and hot isostatic pressing are then examined, and for Ti-6Al-4V this is done for powder bed [7,12] and for electron beam [11]. Due to the relatively rough surfaces of additive processes, surface finishing such as polishing or machining can improve mechanical properties, particularly fatigue strength [4,11,13].

For Ti-6Al-4V, heat treatments such as aging and annealing for stress reduction are found to have relatively small effects on mechanical properties, slightly increasing ductility and reducing anisotropy, with some reduction in the yield strength. Generally, more aggressive heat treatments and hot isostatic pressing give a larger reduction in sometimes both yield and upper tensile strength, and are accompanied by an increase in ductility and a reduction in build direction anisotropy, often associated with the adequate closure of small porosity in the case of hot isostatic pressing. This is also the case for nickel alloys such as Inconel 718 [14,15], although in the case of this alloy the ductility can be reduced with heat treatment as a consequence of an acicular δ-phase migrating to grain boundaries. Nickel alloys have also been subject to studies with intended applications in aerospace, concentrating on the microstructural characterisation and effects on mechanical strength of parts build by the powder bed fusion process with Inconel 718, [16] and Nimonic 273, [17], both examining the post-modification by heat treatment of the as-built part.

Heat treatments have significantly more effect on commonly used aluminium alloys such as AlSi10 [18–22] and AlSi12 [23], often intended for automotive and electronic applications, and much of the current focus of powder bed based ALM research using aluminium has been on the Al-Si casting alloys, such as AlSi10, [19], which although possibly easier to process than high strength aerospace Al-alloy grades due to narrower freezing ranges, still pose significant challenges when compared to steels and other higher melting point alloys. High strength aluminium alloys (5XXX and 7XXX-series) are also being considered [24] for aerospace applications for powder bed ALM, and modified compositions such as with higher scandium content,[25] are showing acceptable porosity and promising strength and ductility characteristics. Porosity fractions of aluminium alloys can be reduced to less than 0.5%, certainly comparable to casting routes with fewer inclusions and defects, however, pore sizes tend to be larger than with other ALM alloys, with overall static strength tests showing higher tensile and fatigue strength than cast materials, [22].

Fatigue strength requires longer term tests, which tend to come later in the material/process development cycle, and fatigue studies have been reported for Ti-6Al-4V in [20,26,27], steels [13,28] and aluminium alloys [20,22]. Generally the findings are that while heat treatments and hot isostatic pressing can improve fatigue strength, that mostly these still be below 60–75% of an equivalent wrought, annealed material.

Although much work has already been done on duplex steels such as 304 and 316L on a variety of powder bed systems, [20,29–38], the published data covers a wide range of preparation routes, machine settings and laser powers, different mechanical testing methodologies and various post-process heat treatments. Unlike higher strength H13 and maraging steels such as 18Ni-300, [39] which are used in injection moulding tools and dies, and aeroengine applications, the lower strength 316L is widely used but does not have any one single critical application possibly explaining the wide range of research interests. However, this poses a difficulty in setting a baseline for the required tensile properties of 316L, as demonstrated by the limited validation in the publications comparing ALM with other processes such as hot rolling, wrought or casting.

As pointed out in [20], the proliferation and progress of additive processes means that the mechanical characterisation even for standard alloys struggles to keep pace with the machine developments. This is very evident in the case of 316L steel where even recent publications are reporting tensile properties for samples built with the previous generation of powder bed systems, with low laser powers (85–200 W) and line speeds (down to 200 mm/s), and wider ranges of porosity (1–3%). Laser powers of 500 W and line speeds of 2–3000 mm/s are the norm in the current generation of machines, resulting in lower levels of porosity (0.1–0.5%) expected across all alloys.

The work reported herein aims to add to the body of knowledge on 316L with an in-depth characterisation of the material for a 200 W laser machine, at line speeds in the 600–1000 mm/s range. The claim to be in-depth is based on a thorough description of the measurement methodologies (density, porosity and tensile properties), for both as-built and hot isostatically pressed samples, to be a baseline for future researchers. It also introduces the use of ultrasound testing which has seen a limited amount of use in ALM materials characterisation even though it is a more rapid method of getting elasticity properties than through tensile testing. It is thought that ultrasound techniques can contribute to process improvement, such as by reducing directional variations across the build plate. Another objective of this work is in understanding how porosity distributions and morphologies change with hot isostatic pressing, and, using FE analysis derive empirical relationships for the Young's modulus, [40]. These empirical relationships in conjunction with the non-destructive and fast ultrasound testing, will lead to future improvements of equipment, lasers and powders. Looking ahead, It may also be possible to use similar empirical relationships for tensile and fatigue strength properties versus porosity - reducing the time taken to prepare and optimise a new material on a given powder bed process.

2. Materials and experimental procedure

2.1. Processing parameters and material specification

All components in this study were made using the powder bed laser fusion process of the Renishaw AM250 machine. This uses an Ytterbium fibre laser in Q-switched mode with a maximum power of 200 W and nominal laser spot diameter 70 µm. There are a wide range of parameters that can be varied in order to change the part properties and include but are not limited to, material specific parameters, laser parameters, scan parameters and environmental parameters.

The material used in the current investigation was the austenitic metastable 316L stainless steel powder with a nominal size range 15–45 µm, spherical morphology manufactured via gas atomisation as shown Fig. 1(a). The specification and actual composition (as supplied) of the alloy are shown in Table 1. Actual powder size distributions were D(10)=18.86 µm, D(50)=29.21 µm, D(90)=45.10 µm. Both the powder morphology and particle size distributions have been shown to be important to the densification characteristics, and ultimately to the level of laser power which needs to be delivered at each layer [34], and to this extent the powder used in this study had similar characteristics.

A driving parameter of the densification of ALM parts is the Energy Density (E_d) [J/mm^3] is typically given by, [34]:

$$E_d = \frac{P_{laser}}{\nu_{scan} \cdot s_{Hatch} \bullet t_{Layer}} \tag{1}$$

However, as the laser on the AM250 is RF modulated, so the following relationship has been used: