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Fatigue behaviour of selective laser melting steel components

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ABSTRACT

Selective laser melting (SLM) is a laser based rapid manufacturing technology that builds metal parts layer-by-layer using metal powders and a computer controlled laser. Various important aspects strongly affect the mechanical properties of sintered metal components, such as: porosity, surface roughness, scan speed, layer thickness, and residual stresses. Therefore, properties of SLM manufactured parts must be carefully analysed, particularly under fatigue conditions.

The purpose of this work was to study the effect of scan speed, porosity and microstructure on the mechanical properties and fatigue strength of sintered laser samples. Sintered laser parts were manufactured in maraging steel AISI 18Ni300. Fatigue behaviour is related to process parameters, such as: surface residual stresses, microstructure and porosity.

The results showed that a very high scan speed (400 or 600 mm/s) causes the appearance of high percentages of porosity and a consequent drastic reduction of tensile strength and stiffness. Fatigue behaviour was assessed in terms of the traditional S-N curves and of the da/dN–ΔK crack propagation curves. Fatigue life predictions based on Hartman and Schijve's equation underestimated significantly fatigue lives, particularly for low stress levels. The results of the tests performed at variable amplitude loading were well fitted by Miner's law.

1. Introduction

Selective laser melting (SLM) is a laser based rapid manufacturing technology that builds metal parts layer-by-layer using metal powders and a computer controlled laser [1,2]. A high power laser is used to fuse metallic powder particles, doing a scan of the transversal cross sections of the final component generated from a CAD model. After the consolidation of one powder layer, a fresh layer of powder is deposited and the laser melting process is repeated until a 3D part is completed. This technique is increasingly used in automotive, aerospace, medical and of injection moulds industries, to obtain components with complex shapes. Abundant literature has been previously reported on the scope of SLM using different metal powders, for instance, the fabricating of titanium [3,4], iron-base alloys [5–8], nickel-base alloys [9,10], copper-base alloys [11], titanium-base alloys [12] and metal matrix composites [13].

SML products could show characteristic cast structure, with high superficial roughness, presence of porosity, heterogeneous microstructure and thermal residual stresses, resulting in mechanical properties which can be improved by additional post-processing treatments. Since SLM can be used to manufacture functional components, a good characterization of the sintered parts is essential to control structural integrity, and to guarantee that the components fulfil the final functional requirements. Some scientific and technical aspects of SML sintered microstructure on the mechanical properties have not been well studied and need be yet understood. Sintered materials are usually anisotropic and heterogeneous [14,15], which affects their performance. Earlier studies mainly focused on the influence of sintering parameters and the selection of metal powder on the microstructure of the sintered parts. Scarce information has been published on fatigue properties of laser sintered materials [16,17], particularly thermal fatigue [18]. Thermal fatigue cracking (or heat checking) is one of the most important failure mechanisms in hot working applications. The main reason for heat checking is rapid alternation of surface temperature, which induces stresses high enough to impose an increment of plastic strain [19].

It has been reported that both powder characteristics (e.g., particle shape, size and its distribution, and component ratio) and processing parameters (e.g., laser power, scan speed, scan line spacing, and powder layer thickness) influence the sintered microstructures [20]. Mechanical properties are mainly affected by parameters

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such as: porosity, surface roughness, scan speed, layer thickness, and residual stresses. Internal stresses resulting from steep temperature gradients and the high cooling rates during the processing need also to be taken into account when evaluating the performance of parts manufactured from any metallic powder using selective laser melting process [21]. A major drawback is the occurrence of pores originating from initial powder contaminations, evaporation or local voids after powder-layer deposition [21–24], which act as stress concentrators leading to failure, especially under fatigue loading [25].

The focus of this work is to produce and investigate the fatigue performance of maraging steel specimens obtained by laser sintering. Fatigue tests under constant amplitude and block loadings were carried out. Failure mechanisms and microstructures were analysed in detail. Fatigue life predictions will be performed based on a fracture mechanics approach, and validated by comparison with the experimental results.

2. Materials and testing

The samples were synthesized by Lasercusing®, using the equipment of the brand "Concept Laser" and model "M3 Linear", shown in Fig. 1(a). This apparatus comprises a laser type Nd:YAG with a maximum power of 100 W in continuous wave mode and a wavelength of 1064 nm. The samples were manufactured with layers growing towards the direction corresponding to the application of load for the mechanical tests, as it is shown in Fig. 1(b) using the sintering scan speeds: 200, 400 and 600 mm/s. The test series are identified by the sample code ST followed by the scan speed. Fig. 1(c) shows some round samples after they have been sintered and their surface mechanically polished.

The sintered laser parts were manufactured in maraging steel AISI 18Ni300, with the chemical composition, according to the manufacturers, indicated in Table 1.

Two types of samples were used: round specimens for tensile and fatigue life tests and compact tension specimens (CTS) for fatigue crack propagation tests, with the geometry and dimensions indicated in Fig. 2(a) and (b), respectively.

The tensile and fatigue endurance tests were carried out at room temperature using a 10 kN capacity Instron Electropuls E10000 machine. Tensile tests were performed with the same machine at room temperature using a testing speed of 2 mm/min. Two types of fatigue endurance tests were performed: at constant amplitude sinusoidal load and constant amplitude sinusoidal displacement; both with a frequency within the range of 15–20 Hz and fatigue ratio of R = 0. Variable amplitude loading tests were carried out using the looping loading schematically shown in Fig. 3, composed by three blocks with a stress ratio of R = 0, applied during 1000 cycles each one. Fig. 3 also shows the sequence of the stress range applied during each block, which was repeated until final failure.

Fatigue crack growth tests were conducted, in agreement with ASTM E647 standard, using compact tension specimens (CTS) shown in Fig. 2(b). Experiments were performed in a servo-hydraulic INSTRON, a closed-loop mechanical test machine with a 100 kN capacity, interfaced to a computer for machine control and data acquisition. All tests were conducted in air, at room temperature and with a load frequency of 15–20 Hz. The crack length was measured using a travelling microscope (45×) with an accuracy of 10 μm. The tests were performed in load control mode at R = 0.05. Crack growth rates under constant amplitude loading were determined by the incremental polynomial method using five consecutive points.

3. Results and discussion

3.1. Metallography and porosity

Cross and long sectioning of the samples, were observed in microscope in order to identify the microstructure, as well as the presence of porosity. The samples were prepared according to the standard metallographic practice ASTM E407-99; a chemical attack Picral (picric acid solution 4% in ethyl alcohol) was performed for two minutes. After preparation, the samples were observed using a Leica DM4000 M LED optical microscope.

Fig. 4(a) and (b) shows metallography in longitudinal sections of single sintered samples, for a 200 and 400 mm/s scan speed, respectively, in which it is not noticeable a significant difference in the size and shape of the grains for different scan speeds. However, it is all too evident a significant increase of porosity with the scan rate. A more amplified image of microstructure obtained for a 400 mm/s scan speed is shown in Fig. 4(c) suggesting the existence of a significant number of small porosities and the formation of martensitic needles.

The quantification of the level of porosity was done by analysing the images contrast between the pores and the base material in the photographs by optical microscopy using image processing software Image J. The program creates a border with a blank line and calculates the area of each of these zones. Fig. 4(d) shows an example of an image created by the software. The sum of these areas gives the total porosity of the image. Table 2 shows the values of the porosity in percentage obtained for each batch. A second way to analyse the porosity was performed based on the samples density. The corresponding densities for each scan speed were calculated according to the Archimedes principle (and are also summarised in Table 2). Based on these densities, the porosity can be quantified in comparison with the reference formulations. The reference formulation here considered was the sintered

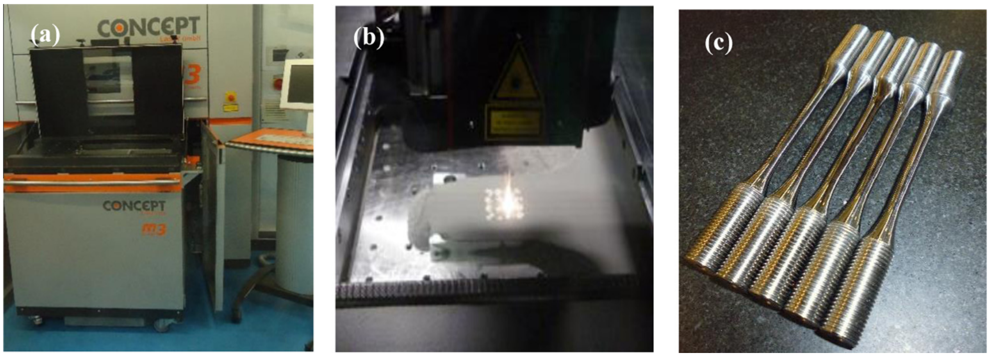

Fig. 1. SLM manufacture process: (a) Machine; (b) Melting process; (c) Sintered and polished samples.

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