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Mechanical fatigue of PLA in additive manufacturing

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ABSTRACT

The manufacturing industry increasingly demands mechanical components, which must undergo different loads. Each industry has its own requirements and regulations, where the common demand is that the loads are repetitive according with the components functions. It is then well known that it is necessary to employ the fatigue assessment to evaluate if the component would not fail over its expected working life. In recent years, there has been an increasing interest in additive manufacturing due to it can be an alternative to manufacture designs more organics and enhanced shapes. However, the main weakness with this option is that the obtained components can fail under operational condition with repeated loads. Therefore, these components would not be used as a final product, so up to now this manufacturing process is not suitable for a large-scale production. It is also important to mention that any manufacturing process needs the fatigue prediction to estimate durability considering different sources of dispersion of properties such as the material and manufacturing process. The purpose of this investigation is to proposes an S-N life curve for PLA considering different printers and filament colours to include the scatter in the estimation. This S-N line curve can be used to understand the mechanism of fatigue failure, the structure of the failure was analysed. This curve is based on 5 regions of amplitude depending on the load levels. However, it was not possible to perform it as a percentage of ultimate resistance since it is presented a dispersion in quasi-static loads.

1. Introduction

Previous studies mostly defined the three-dimensional (3D) printing or Additive Manufacturing (AM) as the method of creating 3D components layer-by-layer based on a digital model (CAD file) and sliced (STL). This manufacture process can situate the nozzle to any point by using Cartesian coordinate system. It is therefore the nozzle can be positioned to any point in three-dimensional space by three mutually perpendicular coordinate axes, the X-, Y- and Z-axes. There are also fundamental processing methods to be considered such as binder jetting, bed fusion, sheet lamination, and photo-polymerization. It also known that a 3D printer with different nozzles can handle single or multiple feed materials as ceramic, metals, polymers, thermoplastics, photopolymers, epoxy resin [1]. Hence, the 3D printing process might be employed in distinct engineering applications such as automotive, mechanical, biomedical, construction, aerospace, food industries, and academic research [2,3].

According to [4–6] the additively manufactured components can have fewer mechanical properties of resistance than components fabricated by conventional manufacturing such as injection moulding. It can be happened during the printing process where void

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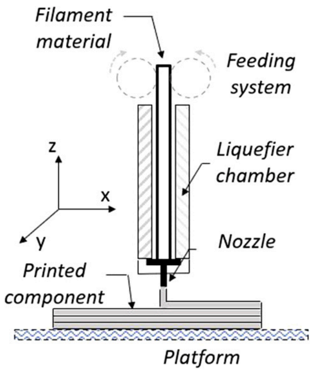


Fig. 1. Schematic representation of the FDM process.

formations and imperfections appeared and could then consequently lead to failure under repetitive loading conditions. As can be seen from Fig. 1, Fused Deposition Modelling (FDM) method is an additive manufacturing process where the melt extrusion technique is employed to continuously deposit filaments of thermal plastics according to a specific 3D design. In other words, the filament material is heated at the nozzle to reach a semi-liquid state and then the heated nozzle is extruded the semi-molten plastic onto a platform, where the printed component is solidified at room temperature.

In order to understand how the 3D printing process affects the mechanical behaviour of printed components is necessary to know the following previous findings [7]. If the colling rates are higher than those in typical fusion process. It can generate complex cohesive forces between layer resulting a remelted material, and therefore anisotropy [8]. This unwanted material property can generate imperfections as porosity, lack of fusion, which can cause stress concentration increasing the crack nucleation risk. It is therefore so important to analyse the durability of polymer materials from Fatigue Performance Tests [9–13].

Different proposals have been made to implement 3D printed components with special alloys such as AISI 316 stainless [14] and titanium [15,16]. One of the common materials used in 3D printing is the Polylactide also known as PLA, which is a thermoplastic polyester. Previous works [17–19] have been reported that these kinds of materials can present significant mechanical features resulting from the thermal process, where its shear viscosity properties are influenced. However, previous work [20] has established that PLA is not ideal for long-them use owing to its biodegradability, it can therefore be employed for prototyping or temporary spare parts [21]. Hence, these eco-friendly materials can generate significant deficiencies in the performance of mechanical systems, where PLA's components were fitted. Safai et al. [22] reported that polymers are considerable vulnerable to fatigue at applied stress below the yield point. This fatigue failure is originated from a microdamage, and then subsequent growth of cracks up to a failure mechanism arise. One of the main problems in additive-manufactured layered components is the durability, this parameter can be obtained using the fatigue endurance involving a component exposed to repetitive loads over an extended period [10,23].

Much of the current literature on the influence fatigue life of 3D printed parts pays particular attention to various printing parameters such as raster orientation, printing orientation, layer thickness, and feed rate [5,13,22]. It also observed that PLA parts with 100% infill density, the additive material can reach highest Young's Modulus and for fatigue assessment can be considered as homogeneous and isotropic materials [24,25].

Algarni et al. [26] also reported that some mechanical loading factor can have a significant impact on polymer fatigue characteristics, the factors stated were stress amplitude, strain, mean stress, stress–strain ratio, cyclic frequency, self-heating effects, and a notch or stress concentration effects. Unlike metals, it is quite difficult to predict the polymer fatigue owing to the thermoplastic polymers have high temperature dependence [27]. Previous research [10] has reported that the printed PLA material can show three different failure mechanisms under fatigue loading conditions: (i) rectilinear filament cracking, (ii)layer debonding and (iii) filament debonding between layers. Strong evidence of these three failure mechanisms was found when it was analysed a sample study case at the present work as shown in Fig. 2.

This work contributes to existing knowledge of 3D printed PLA components under fatigue loading conditions by providing a S-N curve obtained from several fatigue loading tests. The S-N curve typically describes a constant behaviour between the Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) regions. This behaviour apparently results from the number of repetitions at the Very High Cycle Fatigue ($VHCF$) region, which can be defined as the limit of fatigue. However, the fatigue failure also occurred at this region and stated in some materials as correction factors to define a new slope. It is well known that this behaviour is also affected by the type of load parameters and different manufacturing processes. Therefore, it is common for most materials to describe this area by two slopes. Turning now to the experimental evidence on this work, where it is reported the behaviour analysis of printed PLA components. One of the more significant contributions to emerge from this analysis is a novel S-N curve described by five slopes. This curve is related to the effects from the damage accumulation process to the damping and stiffness properties, poor layer adhesion, crack growth and failure propagation. The most important limitation lies in the fact that although fatigue limits have been proposed. It is not achievable to establish a value for the high cycle fatigue area based just only on the scatter inherent to the AM process.

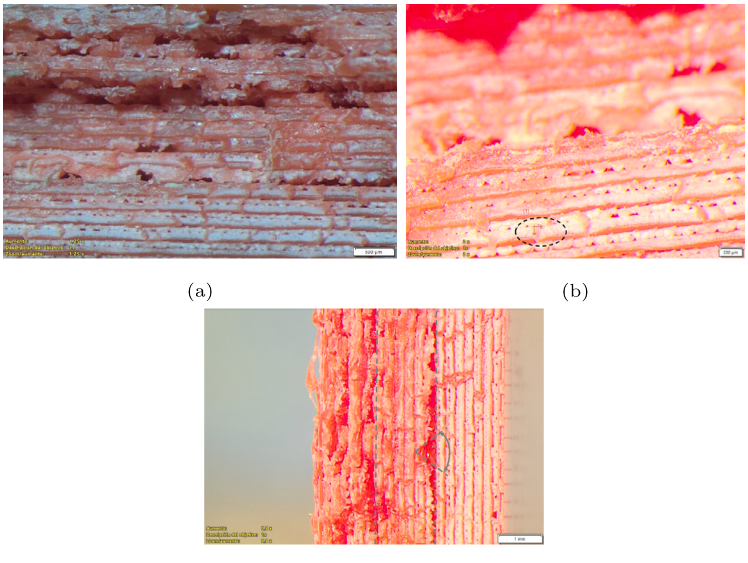


Fig. 2. Failure fatigue mechanisms. (a) debonding, (b) craks (c)delamination.

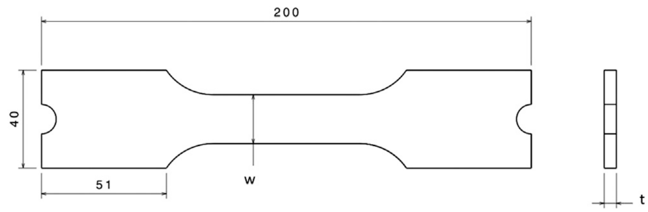


Fig. 3. Specimen dimensions, units in mm.

Table 1
Summary results of the tensile test.

Maximum	49.211 MPa
Minimum	22.581 MPa
Average	33.526 MPa

2. Experimental test

This section describes the experimental test process to evaluate the mechanical behaviour. The first step in this process was to print 43 specimens considering dog-bone geometry and dimensions as presented in Fig. 3. These specimens also have a thickness (t) of 8 mm and a with (w) of 20 mm.

A Ultimaker 3D printed machine and PLA filament with standard diameter of 1.75 mm, from the brand colour plus 3D were employed to manufacture all test specimens. The manufacturing process was done considering the platform and liquefier temperatures at 55 °C and 200 °C, respectively. The infill density was also defined with 100% to avoid internal notches. It is important to mention that the samples were maintained under standard laboratory conditions (room temperature) for 48 h before to test them as considered in the standard ASTM D618-05 [28]. Tension tests were carried out to determine the ultimate tensile strength. Strain gauges were installed at each specimen as shown in Fig. 4 to generate data reported in Fig. 5.

Fig. 5(a) provides the results obtained from an instrumented specimen to generate a strain-time diagram. Tensile testing of these 3d-printed specimens showed that this kind of elements can reach an ultimate tensile strength of 41.65 MPa. This procedure was repeated 11 times and the results are illustrated in Fig. 5(b), these results are labelled with number test, Thickness (T) and PLA Filament Colour (C). The specimens were printed using certain colour filaments such as Grey (G), Blue (B), White (W) and Red(R), respectively. It is important to consider the effect of filament colour on the resistance to repeated loading. Hanon et al. [29] analysed the difference in weight with different filament colours determining a difference of 7.24% between the black and the lightest (white) filament. Marsavina et al. [30] analysed the difference in Young's modulus and the yield strength of different filament colours. The results obtained from 11 tensile test are summarized in Table 1.

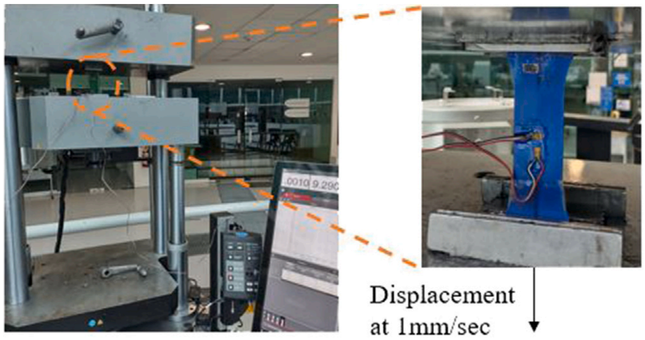
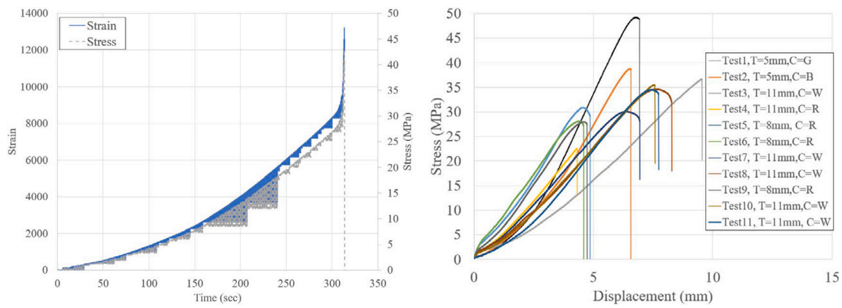


Fig. 4. Tensile test.



(a) (b)

Fig. 5. Tensile measurements (a) strain gauge (b) uniaxial instron test machine.

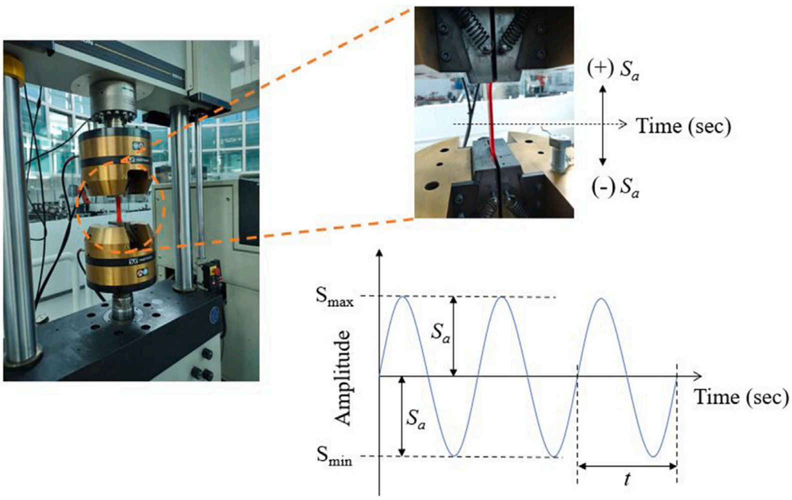


Fig. 6. Fatigue test set up.

The fatigue tests were assessed using an Instron uniaxial, it was noted that there is a temperature-dependent frequency as reported in [7]. Therefore, all fatigue tests were done using frequencies from 1 to 2 Hz and R=−1 following previous works [13,31]. Fig. 6 shows the fatigue test set up, where Sa is the amplitude load.

To analyse the stress flow is important to consider stress direction, which can be a significant factor for fatigue life and printing requirements. In this work, the stress tensor is obtained using finite element simulation and applying a sinus waveform. The pre-processing finite element simulation was performed using hypermesh programme. It was also employed Radios solver and the results were postprocessed using hyperview. The finite element model is generated with 668 quad elements, 20 tria elements of first order. Rigid elements were used to apply the boundary conditions. The load of 2000N was applied associating it to a function to reproduce

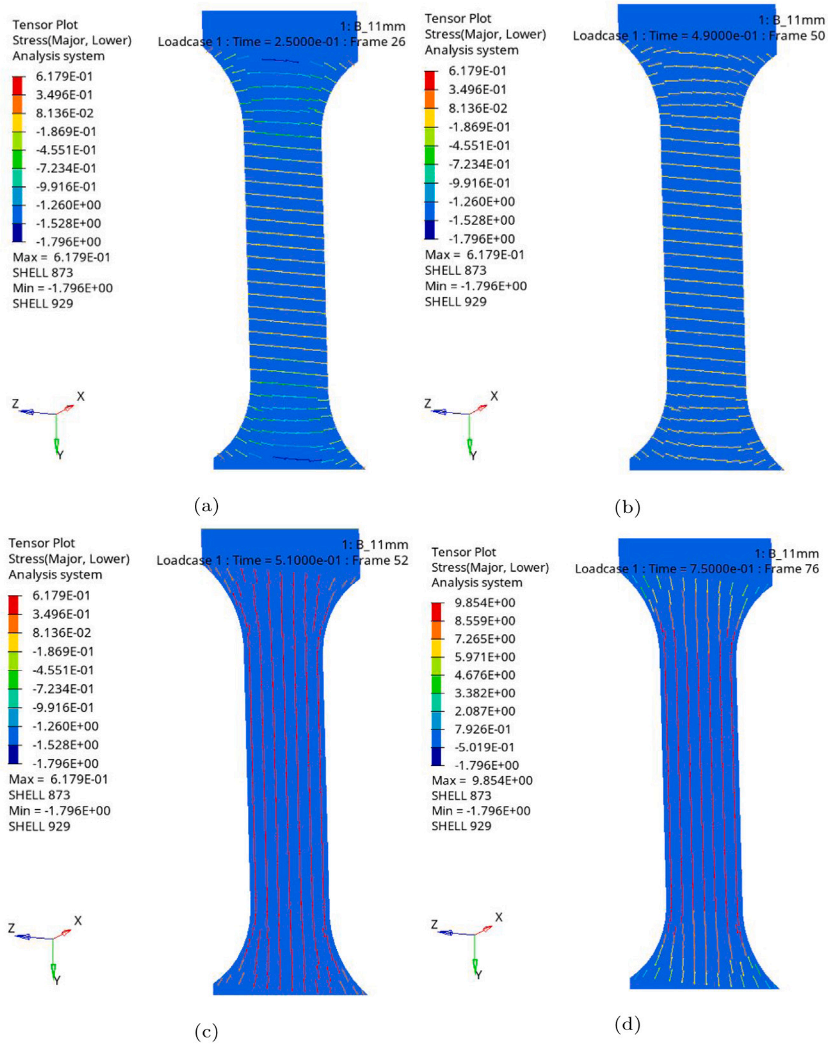


Fig. 7. Tensor results with sinus waveform, thickness of 5 mm (a) 0.25 s, (b) 0.49 s, (c) 0.51 s and (d) 0.75 s.

the sine wave at 1 Hz. The mechanical properties used are: Young's modulus (E) of 3.25 MPa, a Poisson coefficient (v) of 0.328 and a density (ρ) of $1.25e^{-9}$ tonne/mm^3. Results are shown at times where the slope load change, in reversals and prior to cross the mean value, at 0.25 s 7(a), 0.49 s 7(b), 0.51 s 7(c) and 0.75 s 7(d). It can be observed that there are two main directions of the generated stress tensor. The first part of the cycle is concentrated along the width of the specimen, while in the second part, when the specimen is under compression, the forces are aligned along the specimen. These results are similar to those reported in [32] this previous work reported, through correlation of digital images, the effect of the raster angle direction on fracture strength, finding the greatest resistance at raster angle of 45°. Together these results provide important insights into raster direction and its relation to fatigue life.

3. Results and discussion

Fig. 8 reveals that there has been a trend in failure position as it is expected as in other materials as metals.

Fig. 9 presents the experimental results of 43 specimens under test. Some tests below of 800N of load were tested at 2 Hz of frequency,at least one test of these amplitudes were tested at 1 Hz, 0.6 °C on increasing temperature was found at 2 Hz as is shown in Fig. 10.

As in the case of metallic materials there are ductile and brittle failure types according to the fracture mechanics, Fig. 11 provides the different failures at different load levels, Figs. 11(a) and 11(b) with a load of 8.3 MPa, Figs. 11(c) and 11(d) with a load of 6 MPa and Fig. 11(e) with a load of 13 MPa. Fig. 11(a) reports two types of failure, cyclical and brittle. Both types of behaviour are observed based on their ductility characteristics in light areas, while in dark areas they represent rapid propagation due to brittle

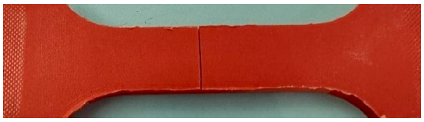


Fig. 8. Failure in component.

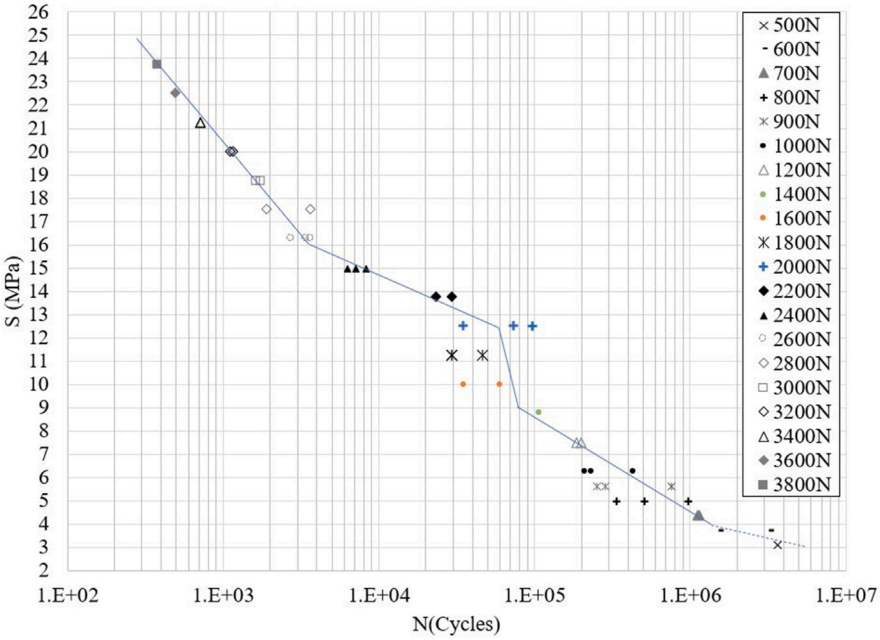
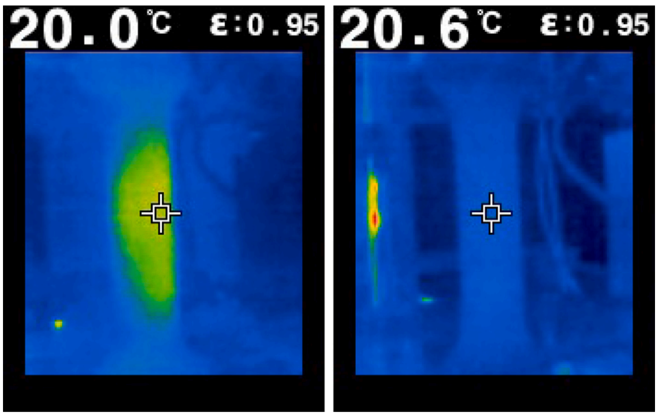


Fig. 9. Fatigue results of specimens of 8 mm of thickness at different load levels.

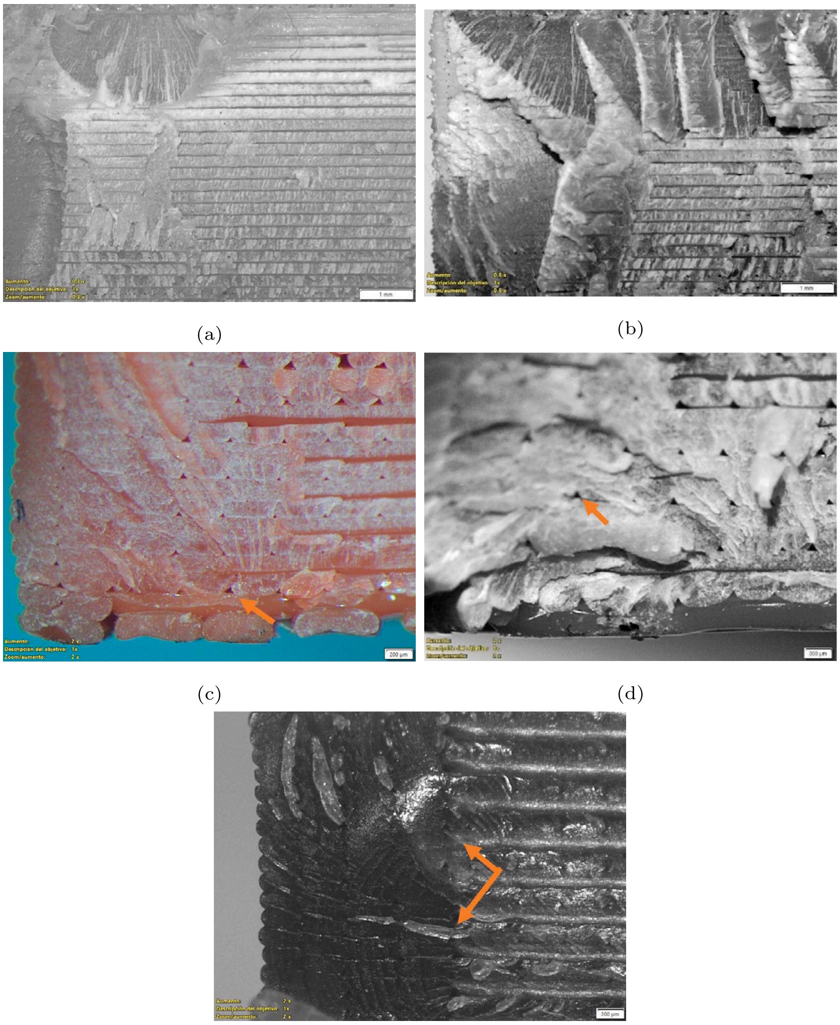


(a) (b)

Fig. 10. Temperature measurements (a)1 Hz and (b)2 Hz.

behaviour. Figs. 11(b) and 11(d) illustrates a typical chevron-type behaviour as in metallic materials at the beginning of the failure. Fig. 11(e) shows cyclical local faults known as beachmark.

Most of the components have the initiation crack on the bed printing side. Mechanical properties of tensile strength can be estimated through hardness tests [29,33], however, comparisons of hardness on the faces of printed parts have not been reported. This opens a possibility to confirm and predict the failure origin. To evaluate this tendency has been performed hardness measurements, with load of 1000 g during 11 seconds [34].



(a) (b) (c) (d) (e)

Fig. 11. Failure analysis, (a) 73,961 (b) 102,752 (c) 105,431 (d) 59,757 and (e) 40,204 cycles.

Table 2
Parameters for the proposed S-N curve.

Point	S	N
S1,N1	16	3,500
S2,N2	12.5	60,000
S3,N3	9	80,000
S4,N4	4	1,400,000

Based on 10 indentations per side, the side of the bed reach a hardness of 18HV, while in the printing side is 13HV. It is therefore not possible to define a general S-N curve, the scatter in mechanical properties is based on the variability of the material and the Manufacturing process. However, in this process is generated a complex structure and is not possible to define a simple S-N curve. To overcome this issue is proposed a Wöhler curve of 5 regions in function on the applied stress as is shown in Fig. 12 and Table 2

Components printed with PLA follows the accumulated damage process described by Miner's rule

$$\sum_i \frac{n_i}{N_i} = 1 \tag{1}$$

where n_i is the number of repetitions during the operation and N_i are the repetitions tolerated and the amplitude S at ith load level. The failure happens when the tolerated repetitions has been reached.

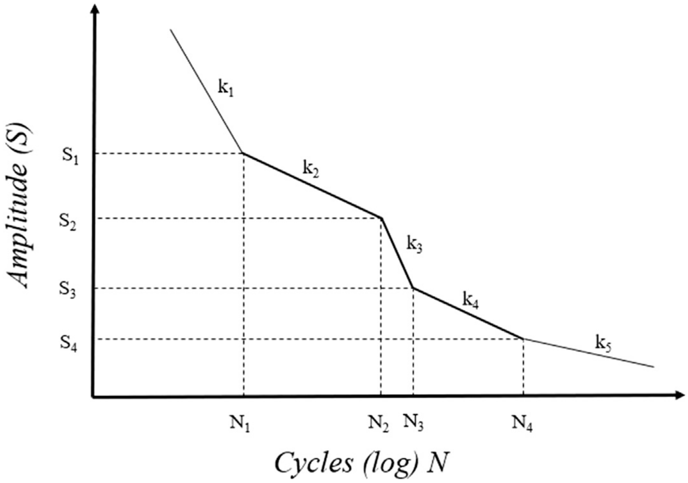


Fig. 12. Proposed S-N curve for PLA.

To predict the component fatigue life can be used the next slopes $k_1 = k_5$=6, k_2=11.511, k_3=0.876, k_4=3.53, Table 2 and Eq. (2).

$$N_2 = N_1 \left(\frac{S_1}{S_2}\right)^k \tag{2}$$

The empirical findings in this study provide a new understanding of 3D printed PLA components under fatigue loading tests. These results also add to the rapidly expanding field of additive manufacturing and optimize this process to use these components not just for prototyping. The single most striking observation to emerge from a discrepancy from a previous reported work [35], where it was stated that the fatigue limit evaluated at $2x10^6$ cycles was 13.5 MPa. However, this study has shown that two specimens under the same fatigue loading level were fatigue limit (3.75 MPa) was reached at different cycles number $1.56x10^6$ and $3.27x10^6$, respectively. Therefore, this work propose a Wöhler curve made of 5 regions to propose a design method of functional components based on a fatigue life assessment approach as stated in Table 2. It is also noted that there is a scatter between different load levels with a maximum value of 0.26, this value is approximately close to 0.3, which was reported as the maximum level of scatter (slog) of this kind of testing. Therefore, it can be seen from the data in Fig. 9 that the results are strongly supported by previous works.

4. Conclusions

This study set out to gain a better understanding of the fatigue testing of 3D-printed polymers. It was also to expand the field of additive manufacturing to use PLA-printed elements not just for prototyping.

This study has also shown that the best raster angle is 45°, this is well defined in Fig. 7. In this figure is shown that the flow forces are subjected to two load directions tensile and compression. Where, it is noted that there is a tensor change at two times 0.25 and 0.75 secs with frequency test of 1 and the ratio of the minimum and maximum loads R=−1. To obtain the best raster angle for other load ratios R is required to analyse their stress tensors at each case. The research has also report that fatigue crack nucleation can be originated from the 3D printed bed. There is evidence in Fig. 11, where specimens with 8 mm of thick have a hardness of 76% compared to the side of the bed. Although 3D printing was done with 100% of infill, there is still observed internal voids as shown in Fig. 11. Further experimental investigations are needed to homogenize this value improving durability against cyclic loads, it is suggested that a thermochemical treatment will be done to reduce fatigue crack nucleation. The empirical findings in this study provide a new understanding of the fatigue life of the PLA printed components. It is proposed that a S-N curve suitable for components with stress below 24 MPa considering that the load frequency at 1 and 2 Hz does not generate overtemperature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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