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Compliant flexural behaviour in laser sintered nylon structures: Experimental test and Finite Element Analysis – correlation

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ABSTRACT

The aim of this paper is to present a simple and easily tuneable method of creating compact structures with gradient flexural properties using Selective Laser Sintering (SLS). The method makes use of a sine-wave ridged pattern commonly found in nature which produces a compliant bending pattern along various directions defined by the reference axes. These patterns have been adopted due to the ease with which it is possible to parametrically control the height, width, pitch and thickness of the designed structure. A series of 3-point bending tests and finite element analyses of flat and ridged specimens have been performed in order to obtain more appropriate material definition for the inclusion of such patterns into more complex structures.

Results show that a parametrically defined ridged pattern has the ability to induce passive bending behaviour on structures. Differences in bending stiffness between 20% and 50% were observed for the directions parallel and perpendicular to the ridged pattern lines and a capacity to redistribute stresses across the bending specimen was highly dependent on the ridged pattern direction.

1. Introduction

Since the onset of Additive Manufacturing (AM) a number of key properties have been investigated in order to define the mechanical behaviour of the resulting parts. One of the most comprehensively studied AM processes is Selective Laser Sintering (SLS), particularly of nylon 12 powders. The current body of knowledge of SLS-processed nylon defines it as a hygroscopic polymer with a considerable moisture absorbance capacity [1], that possesses a characteristic porosity as a result of thermal distribution inside the SLS chamber [2], exhibiting a transversely isotropic behaviour in Young's modulus and strain to failure, but generally orthotropic in terms of ultimate tensile strength [3] and with mechanical properties that decline as the powder refreshing ratio is reduced in the SLS process [4].

The ability of AM methods to increase part density and to selectively remove material from areas of low stress concentration within structures has led to a number of systems for optimizing the mechanical behaviour of AM parts. Such optimization has been generally sought by controlling the density of the internal structure by means of 3-dimensional scaffold structures with variable lattice pattern topologies/distributions [5–7], by engineering internal spring structures varying the elastic constrains and controlling the element's thickness [8,9], or by morphing the properties of tailored materials by using process specific parameters, such as energy density, build temperature, scan patterns and thickness [10–13].

Pilipović et al. [14] also investigated the effect of laser sintering parameters on flexural behaviour of SLS nylon powder, by varying parameters such as power, intensity and layer thickness concluding that bigger power intensity reflects into a higher flexural stress, however correlations with existing information were not performed and detailed testing data was not provided. There are, however other authors that performed similar flexural experiments with SLS nylon. Kamil and Dalgarno [15] analysed the effect of different axis orientations for both: three and four point bending test of Duraform PA specimens. Ajoku [2] also performed flexural tests on Duraform PA showing that specimens built in the *Y* orientation produced the highest flexural strength and modulus values, while the flexural test parts built along *Z* orientation showed the lowest values.

Although these methods have the potential to produce functionally graded structures, using such strategies requires labour-intensive powder removal from intricate internal structures, and detailed process planning and experimentation with the right parameter combination that produces the desired outcome, hence becoming time consuming and inefficient for simple parts. In the case of shell-based parts or thin-walled components the use of lattice structures for optimization becomes impractical due to the restrictions in the design space and the unsuitability of the design for some structural applications especially when large deflections are expected.

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One alternative to the problem of creating a tuneable mechanical response in additive manufacturing parts is by creating a continuous 3D pattern that responds to loading in specific ways when activated, such as the case of passive bending. The method presented in this work enables additive manufacturing parts to have graded flexural behaviour along a single thin-walled structure by means of including a tailored sine wave pattern. Such patterns promote bending along pre-defined directions by controlling the main parameters: pitch, wave width, height and guiding axis/line.

Compliant corrugated shell structures are mechanisms capable of undergoing large, reversible displacements [16]. Such structures are known for their anisotropic properties particularly when applied to planar faces, exhibiting higher stiffness in the longitudinal direction and compliant in the transverse direction, or perpendicular to the corrugation [17]. Corrugated/ridged patterns with various profile shapes can be found in nature, with various types of insects having corrugated wings for deployable mechanisms [17] and some other examples found in tree leaves (Fig. 1) whose ridged structure allows them to withstand loads perpendicular to their surfaces simply by flexing or reorienting in winds [18]. For such planar surfaces, different types of folds have the ability to provide an adequate-tuned flexural stiffness.

Similar structures have been applied for the design of lightweight-resistant packaging structures [19] where the flexural stiffness of the core structure and liners is one of the main factors for determining the stacking strength of corrugated fibreboard boxes. As fibreboard behaves orthotopically, flexural stiffness is expected to be higher in the direction parallel to the ridged curve. Lee and Park [19] reported differences between 29–48% between both directions of bending by varying the ridge pattern design for fibre board.

Yokozeki et al. [20] explored the design of composite structures with corrugated patterns and the inclusion of a stiff rod as reinforcement. Results confirmed the '*ultra-anisotropic*' behaviour of composite-ridged structures and their suitability as structural components of flexible wing structures. Besides single-pattern corrugation, the use of multiple corrugation lines was suggested by Seffen [16] as a means to relieve bending along the compliant directions without out-of plane distortions. However such patterns would be applicable in parts where high flexibility is needed without significant motion restrictions. Corrugated patterns of various shapes are also found in rubber shoe-soles to provide comfort and facilitate flexing along the ridged lines.

The work presented in this paper proposes a sine-wave ridged pattern that can be projected onto surfaces with the aim of tailoring the flexural behaviour by promoting movement towards predefined orientations. Three-point bending tests were performed in order to quantify the flexural behaviour of the structures, followed by Finite Element Analysis (FEA) to validate the use of an orthotropic FEA material definition that can be applied to more complex-customised structures.

2. Methodology

2.1. Test selection and specimen design

For rigid plastics the measurement of modulus and strength in flexure is as common as tensile tests due to the simplicity of the test setup and specimen geometry [21]. From the variety of flexural test (three, four point, cantilever) three-point loading is the most common, despite the difficulties in replicating the friction behaviour for modelling purposes [22]. Three-point flexural tests were performed with a set up as shown in Fig. 2. Experiments were conducted using an Instron 4505 electromechanical system. The load cell used was the Instron 100 kN 2518 Series Sandwich at a cross head speed of 5 mm/min.

For a rectangular beam the modulus in flexure is calculated by using Eq. (1) where, L is the test-span distance, b is the specimen width, h is the specimen thickness and $(\Delta F/\Delta s)$ the slope between the applied force (F) and displacement (s).

$$E = (L^3/4bh^3)(\Delta F/\Delta s) \tag{1}$$

Two types of specimens were designed in Autodesk inventor V13.0: Flat standard specimens and ridged specimens with a selected

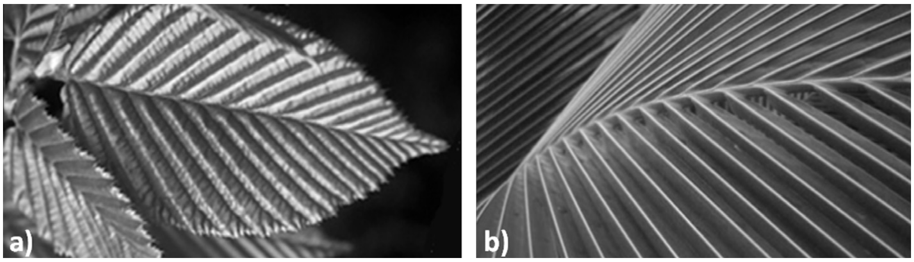

Fig. 1. (a) Ridged pattern providing support to withstand perpendicular loads and (b) typical V-pattern of palm leaves.

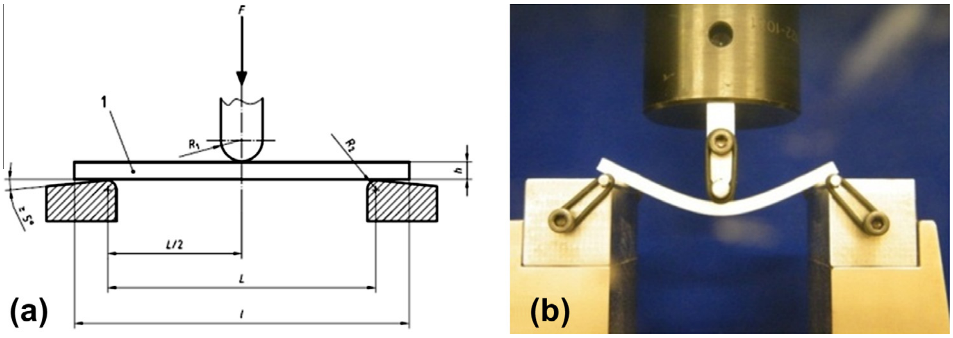

Fig. 2. (a) Test specimen at start of test as defined by EN ISO 178:2003 and (b) specimen positioned during bending test.