Materials & Design 83 (2015) 670–677

Contents lists available at ScienceDirect

Materials & Design

journal homepage: www.elsevier.com/locate/matdes

Mechanical property characterization and simulation of fused deposition modeling Polycarbonate parts

Miquel Domingo-Espin [a], Josep M. Puigoriol-Forcada [a], Andres-Amador Garcia-Granada [a], Jordi Llumà [c], Salvador Borros [b], Guillermo Reyes [a,*]

[a] Grup d'Enginyeria de Productes Industrials, IQS, Universitat Ramon Llull, Spain
[b] Grup d'Enginyeria de Materials, IQS, Universitat Ramon Llull, Spain
[c] Dept. de Ciencia de Materials i Enginyeria Metal.lurgica, EUETIB, Universitat Politècnica de Catalunya, Spain

ARTICLE INFO

Article history:
Received 26 February 2015
Revised 1 April 2015
Accepted 8 June 2015
Available online 19 June 2015

Keywords:
Fused deposition modeling
Mechanical behaviour
Stiffness matrix
Constitutive model
Finite element analysis

ABSTRACT

Building end-use functional parts with additive manufacturing (AM) technologies is a challenging task. Several factors influence their surface finish, dimensional accuracy, mechanical properties and cost. Their orientation inside the building chamber is one of the most significant factors in AM processes. When using Fused Deposition Modeling (FDM) to build such parts, additional factors must be considered.

This paper aims to accomplish two purposes: finding a good model to simulate FDM parts and correlating a finite element analysis (FEA) simulation with physical testing.

The first objective was achieved by experimental tensile test of specimens to determine the nine mechanical constants that defines the stiffness matrix of an orthotropic material. Three Young's modulus, three Poisson's ratio and three shear modulus were experimentally obtained as well as yield tensile and ultimate strength of each specimen.

A simple part was designed and manufactured in different orientations to be physically tested and simulated to achieve the second objective. Polycarbonate (PC) was used as part material. Combined loading including bending and torsion was used. Differences on mechanical response were observed during the physical test of the parts depending on the building direction. Conclusions comment results and the convenience of using a different constitutive model depending on the design and use specifications.

1. Introduction

Nowadays additive manufacturing (AM) technologies are becoming useful techniques to produce parts due to the advantages they present in front of traditional manufacturing techniques. Some of them are: decrease in production cycle, high complexity and personalized parts [1]. On the other hand using these technologies in order to achieve certain product specifications is not a simple task. Some AM technologies have their own software that helps users to set few building parameters, with any or little quantitative information, according to cost and surface finish. Also, manufacturers often avoid information data about mechanical behaviour of AM processed materials. In order to build functional end-use parts using these technologies it is needed to know how different building parameters affect the mechanical behaviour of parts. The common practice among engineers when designing functional parts is to use finite element analysis (FEA) to simulate a part under real loads and fixtures. FEA materials database include isotropic materials, processed by traditional manufacturing processes, but cannot model properly layered manufactured anisotropic materials. AM users need tools to evaluate virtual models of a part with more precise and quantitative data to decide effectively prior to manufacturing the best building parameters. It is important for them to reduce manufacturing cost reaching geometrical and mechanical requirements when setting process parameters.

The manufacturing principle behind all those technologies is to slice a part and to build it layer by layer. Part orientation plays an important role in the surface finish [2–5], dimensional accuracy [6–10], cost [11,12] and mechanical behaviour. It has been reported a dependence of the mechanical behaviour of AM parts on its orientation in the building chamber. It indicates that its mechanical behaviour is not isotropic [13–20]. Results may vary depending on the technology since bonding between layers depends on the material and the process [21].

Fused Deposition Modeling (FDM) presents also a great amount of other building parameters that affects parts features. It has been

---

* Corresponding author.

http://dx.doi.org/10.1016/j.matdes.2015.06.074

observed that the distance between extruded filaments [9,10,19,20], its width [9,10,19,20,22], the pattern which the filaments follow to fill each layer [9,10,19,20] and layer thickness [9,10,20,22], among others, have a great effect on quality and performance of a part. This implies that building strategy election has a significant effect on the properties and the performance of a part. It is really important to characterize AM materials in order to simulate properly end-use parts before manufacturing them. Some attempts to mechanically characterize FDM materials have been reported. The characterization of Acrylonitrile Butadiene Styrene (ABS) [23,24] and Ultem 9085 [25] FDM materials has been performed in order to be able to simulate them with FEA. They all concluded that FDM parts presented different mechanical response depending on how the layers were placed regarding the direction of the load. Hence the building direction of the parts should be chosen according to boundary conditions. Physical models were also manufactured to compare simulation and real test data [24,25]. The correlation presented was good under elastic deformation but not when the yield point was exceeded.

In this paper the mechanical characterization of Polycarbonate (PC) FDM material is performed assuming orthotropic behaviour in order to obtain the stiffness matrix. The mechanical response of a geometrically simple part is physically tested and FEA simulated. Conclusions from this work are useful for defining what is the best approach to simulate such parts.

2. Constitutive orthotropic model

In order to use FEA simulations to predict the behaviour of FDM parts it is necessary to define the constitutive model that govern its mechanical behaviour. The constitutive model presented here is assumed true under linear elastic deformations.

Linear elasticity is described by the Hooke's law, which determines that the relationship between stress and small strains is linearly proportional. For orthotropic materials, defined as a material with three mutually perpendicular planes of symmetry, the compliance matrix has only nine unknown components (Eq. (1)).

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ & S_{22} & S_{23} & 0 & 0 & 0 \\ & & S_{33} & 0 & 0 & 0 \\ & & & S_{44} & 0 & 0 \\ & sym & & & S_{55} & 0 \\ & & & & & S_{66} \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix} \tag{1}$$

where ε_i is for unit elongation, γ_{ij} for unit shearing strain, σ_i for normal stresses and τ_{ij} for shearing stresses.

Considering the conventional engineering constants in the three directions, Eq. (1) can be written in terms of Young's modulus, Poisson's ratio and shear modulus (Eq. (2)).

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} 1/E_x & -\nu_{xy}/E_x & -\nu_{xz}/E_x & 0 & 0 & 0 \\ & 1/E_y & -\nu_{yz}/E_y & 0 & 0 & 0 \\ & & 1/E_z & 0 & 0 & 0 \\ & & & 1/G_{yz} & 0 & 0 \\ & sym & & & 1/G_{xz} & 0 \\ & & & & & 1/G_{xy} \end{pmatrix} \cdot \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix} \tag{2}$$

The equation used commonly in engineering is the product between the general stiffness matrix and the strain tensor (Eqs. (3) and (4)).

$$\bar{\bar{\sigma}} = \bar{\bar{C}} \cdot \bar{\bar{\varepsilon}} \tag{3}$$

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{22} & C_{23} & 0 & 0 & 0 \\ & & C_{33} & 0 & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & sym & & & C_{55} & 0 \\ & & & & & C_{66} \end{pmatrix} \cdot \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} \tag{4}$$

where

$$C_{11} = \frac{(S_{22} \cdot S_{33} - S_{23}^2)}{S};\ C_{22} = \frac{(S_{11} \cdot S_{33} - S_{13}^2)}{S};$$
$$C_{33} = \frac{(S_{11} \cdot S_{22} - S_{12}^2)}{S};\ C_{12} = \frac{(S_{23} \cdot S_{13} - S_{12} \cdot S_{33})}{S};$$
$$C_{13} = \frac{(S_{12} \cdot S_{23} - S_{22} \cdot S_{13})}{S};\ C_{23} = \frac{(S_{12} \cdot S_{13} - S_{11} \cdot S_{23})}{S};$$
$$C_{44} = \frac{1}{S_{44}};\ C_{55} = \frac{1}{S_{55}};\ C_{66} = \frac{1}{S_{66}};$$
$$S = S_{11} \cdot S_{22} \cdot S_{33} + 2 \cdot S_{12} \cdot S_{23} \cdot S_{13} - S_{13}^2 \cdot S_{22} - S_{23}^2 \cdot S_{11} - S_{13}^2 \cdot S_{33} \tag{5}$$

To define the mechanical behaviour of an orthotropic material, nine independent constants: three Young's modulus (E_i), three Poisson's ratios (ν_{ij}) and three shear modulus (G_{ij}), must be found. Five specimens built in six different orientations were tested to know those constants. According to Hooke's law, Young's modulus and Poisson's ratio can be obtained from the tensile strength test as:

$$E_1 = \frac{\Delta\sigma_1}{\Delta\varepsilon_1} \tag{6}$$

$$\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} \tag{7}$$

where 1 is the pulling direction and 2 perpendicular to the load. The in-plane shear modulus can be obtained from the test of a 45°-oriented unidirectional test specimen, according to the following equation:

$$G_{12} = E_1/2 \cdot (1 + \nu_{12}) \tag{8}$$

where 1 is the direction the load is applied and 2 is the perpendicular direction.

3. Experimental procedure

The experimental procedure is divided in three parts. First, the FDM Polycarbonate (PC) parts, printed under specific building parameters, are mechanically characterized in order to obtain the stiffness matrix. Then, a geometrically simple part is fabricated in different orientations and tested. Finally, using the previously obtained stiffness matrix, a FEA simulation is performed to model part behaviour.

3.1. Mechanical characterization

In order to obtain the nine independent constants values of the stiffness matrix, a total of thirty PC samples were built and tested in six different orientations (Fig. 1). It corresponds to 5 samples for each orientation. Since there are no standard tests for AM parts, the samples have been built and tested according to ASTMD638: Standard Test Method for Tensile Properties of Plastics. ASTM standard was preferred instead of ISO because it is the standard used by the manufacturer of the specimen material and also for most of the authors studying the mechanical behaviour of AM part [14,17,21,24,26–34].

After orienting parts as shown in Fig. 1, they were built using a Stratasys Fortus 400mc using the following building parameters: