IMPROVEMENT OF THE TRANSVERSE MECHANICAL PROPERTIES OF CF REINFORCED ABS 3D-PRINTED PARTS TREATED WITH ACETONE VAPOUR

N. Blanco, I. Saad and J. Torrent

AMADE, Escola Politècnica Superior, Universitat de Girona, c/. de la Universitat de Girona 4
E-17003 Girona, Spain
Email: norbert.blanco@udg.edu, ilyasssaad@gmail.com, jordi.torrent@udg.edu.
Web Page: http://amade.udg.edu

Keywords: CF reinforced ABS, composite 3D printing, mechanical properties, acetone

Abstract

3D printing of polymeric materials using the Fused Filament Fabrication (FFF) (also known as Fused Deposition Modelling (FDM)) technique has made possible the fabrication of polymer parts with complex geometries impossible just a few years ago. However, in spite of the many advantages of this manufacturing process one of the main drawbacks is related to the intrinsic low mechanical properties of the polymer materials used. In order to improve these mechanical properties there are different commercially available composite polymer filaments reinforced with short carbon fibres or commercial printing systems able to reinforce the parts with long and oriented carbon, glass or aramid fibres. Anyway, because of the working principle, these fibres reinforce the material in the direction of the filament improving the mechanical properties in this direction but not in the transverse directions. In the present work the effect of using acetone vapour to partially melt the thermoplastic filaments and improve the adhesion between filaments and increase the transverse mechanical properties of 3D printed composite specimens is analysed. The results show that maximum stress and strain at failure of 3D printed composites can be improved when the material is treated with acetone vapour after the fabrication.

1. Introduction

Nowadays the use of the new Additive Manufacturing (AM) techniques make facilitate the fabrication of new products with complex geometries that only a few years ago was impossible or very complicated and expensive. Among these new AM techniques, 3D printing of polymer is becoming an interesting manufacturing process in many different industrial sectors, such as the aerospace industry, for the fabrication of geometrically complex and light parts [1]. However, the fabrication of fully functional and load-bearing parts with these techniques is difficult due to the low strength of the 3D printing polymer materials [2]. The reinforcement of the polymer matrices with different reinforcements in the form of particles, fibres or nanomaterials, improves the structural behaviour of 3D printed parts [3]. Focusing on the fabrication of polymer composite parts with AM, the Fused Filament Fabrication (FFF) (also known as Fused Deposition Modelling (FDM)) is the most widely used technique because it is easy to use and inexpensive, it allows for multiple polymeric materials to be used and combined, accurate and relatively high strong parts can be obtained and it allows for using fibres as the reinforcement of the polymeric matrix [2].

Although there is a commercially available solution and different research attempts to use long fibre as the reinforcement of polymeric matrices for FFF 3D printing, in most of the cases this reinforcement comes in the form of short fibres, typically carbon or glass fibres. Tekinalp et al. [4] and Ning et al. [5] investigated the effect of the reinforcement proportion on the mechanical properties of the resulting composite and it was found that increasing the quantity of short fibres up to a certain limit, 40% wt, improved both Young's modulus and tensile strength. However, the formation of voids during the printing process and the low adhesion between the deposited filaments results in poor improvement of the mechanical properties in the transversal directions to the filament. Consequently, the resulting material presents an orthotropic material behaviour [6].

Even if using short fibres as reinforcement for 3D printed composites improves their mechanical properties, these are still low when compared to the mechanical properties of traditional composite materials with polymeric matrices. This is even more obvious when considering the transverse directions to the reinforcement. To overcome this negative effect and improve the mechanical properties of printed composite parts different supplementary post-treatments can be applied, such as infiltration or consolidation [2]. In this work, acetone vapour is used as a post-treatment to partially melt the polymer filaments and improve the adhesion between them in order to improve the transverse mechanical properties of the material. The results show that maximum stress and strain at failure of 3D printed composites can be improved when the material is treated with acetone vapour after the fabrication.

2. Materials and methods

In order to determine the improvement on the mechanical properties of 3-D printed parts made of ABS thermoplastic reinforced with short carbon fibres once treated with acetone vapour, several specimens were printed and tested. All the specimens were manufactured using a commercial PRUSA i3 3D printer according to the geometry of the ASTM D638 Type I specimen for tensile testing [2.1]. The specimens were manufactured using the CarbonX filament produced by 3DXTECH, an ABS thermoplastic filament reinforced with 15% high-modulus short carbon fibres. The nominal properties of the material are summarised in Table 1.

Table 1. Nominal material properties of the fibre-reinforced ABS filament CarbonX.

Material property	CarbonX 3DXTECH
Density (g/cm^3)	1.11
Tensile modulus (MPa)	4018
Tensile strength (MPa)	44
Flexural modulus (MPa)	5260
Flexural strength (MPa)	76
Heat distortion temperature (ºC)	102.5

The specimens were printed considering three different printing directions in order to capture the effect of the printing direction on the mechanical properties of the material as well as the effect of the acetone vapour on the mechanical properties depending on the printing direction. Actually, as already mentioned, it was assumed that the melting effect of the acetone vapour should improve the adhesion between the deposited filaments and, thus, improve the mechanical properties of the part in both transverse directions. In Fig. 1 it can be observed a schematic representation of the specimens according to the three different printing directions. During the manufacturing process, the printing parameters (mainly printing velocities and temperatures) were adjusted to obtain the best printing quality results for each specimen configuration. It is worth mentioning that for the correct print quality of the specimens-z, the whole 3D printer was enclosed in a plastic box to obtain a more uniform temperature field along the length of the specimen and avoid air currents. Also, specimens-z were printed in groups of eight with removable connections between them to ensure their vertical stability.

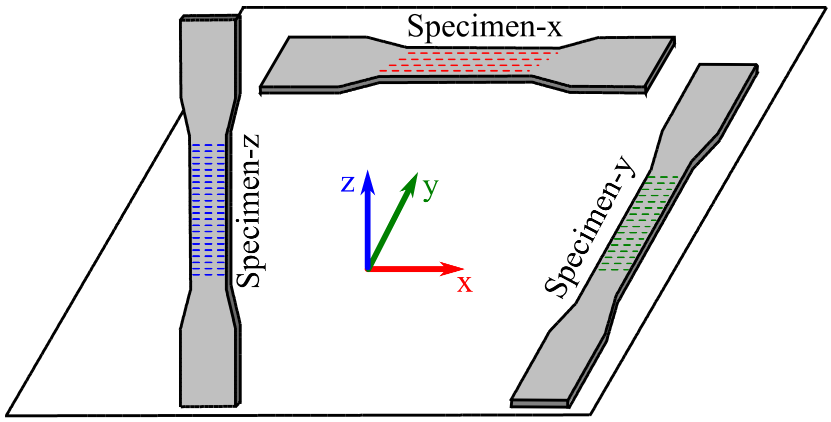

Figure 1. Schematic representation of the three characteristic directions considered for printing the specimens (the dashed colour lines in the specimens represent the orientation of the filament).

To treat the specimens with acetone vapour an in-house chamber was build using two metallic cans equipped with an electrical fan to ensure a homogenous vapour flow inside the chamber. For the treatment, the specimens were placed inside the chamber using a metallic support and paper tissue previously soaked in a certain quantity of acetone was placed around the walls of the chamber, closing it and connecting the fan. The best conditions and duration of the acetone vapour treatment were determined in a series of preliminary test and it was concluded that two time periods would be considered: 15 and 30 minutes. As a consequence of the vapour treatment, there was a slight increment of weight in the specimens confirming that the material absorbed the acetone vapour. The mean values of the percentage in weight increment due to the acetone treatment are summarised in Table 2. As it can be seen in this table, this absorption of acetone was not uniform but depending on the specimen configuration. These differences suggest that the acetone vapour can penetrate deeper into the material depending on how the filament has been deposited during the manufacturing process, i.e. the specimen type.

Table 2. Mean percentage of weight increment after treating the specimens with acetone vapour.

Specimen type	Mean % of weight increment	
	Acetone 15 min.	Acetone 30 min.
Specimen-x	1.85	2.55
Specimen-y	2.03	3.34
Specimen-z	2.89	4.91

In fact, the acetone vapour absorption melted the external part of the specimens and slightly modified the configuration of the material, as it can be seen in Fig. 2. While before the acetone treatment the different layers can be clearly distinguished in the cross-section of the specimen, after treating it with acetone the layers or filaments of material towards the external surfaces of the specimen have melted and they cannot be separated anymore.

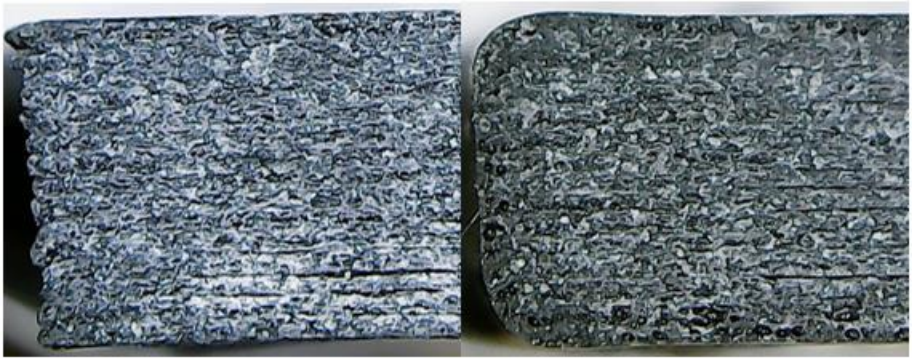

Figure 2. Comparison of the partial cross-sections of two specimens-x before (left) and after (right) being treated with acetone vapour during 30 minutes.

After finishing the manufacturing and treatment of the specimens, these were tested under uniaxial tensile stress following the ASTM D638 standard. A total of 45 specimens were tested, 5 per specimen type and treatment conditions. The tests were performed using a MTS Insight machine equipped with a 10 kN load-cell under controlled displacement at a test speed of 2 mm/min. During the test, in addition to the load and displacement signals of the testing machine, the axial and the in-plane transverse strains in the gauge length of the specimens were also recorded by means of an axial extensometer and a strain gauge, respectively. As indicated in the standard, the Young's modulus and Poisson ratio of the material were determined in the range between 500 and 1200 με.

3. Results and discussion

The typical material response under the tensile test varied depending on the specimen type but was independent on the treatment. Only in the case of specimen-y there is a difference in the stress-strain curve between the specimens treated with acetone vapour and those that not. Fig. 3 includes the representative stress-strain curves for the three types of specimens without acetone vapour treatment plus a typical stress-strain curve for specimens-y treated with acetone vapour (both for 15 and 30 minutes).

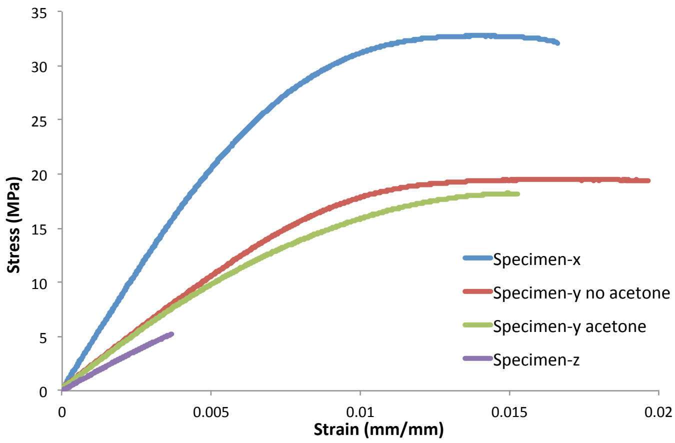

Figure 3. Representative stress-strain curves for the three specimen types (for specimens-x and –z the curves are similar with and without acetone vapour while for specimens-y the response varies if they are treated with acetone vapour or not).

As expected, the experimental results summarised in Fig. 3 show that the Young's modulus (initial slope in the curves) and the maximum stress for specimens-x are higher than for specimens-y and –z. Also as expected, specimens-z show a much poorer mechanical behaviour (Young's modulus, maximum stress and strain at failure) than specimens-y, even if the load is applied transversally to the filament in both types of specimens. This confirms that parts manufactured using 3D printing present orthotropic material properties depending on the considered direction with respect to the filament. On the other hand, the acetone vapour treatment in specimens-y results in a reduction of the strain at failure without plastic behaviour while the stiffness and limit stress remain similar. The average values for the maximum stress, Young's modulus, Poisson ratio and strain at failure for the 3 types of specimens and 3 different treatment conditions are summarised in Fig. 4.

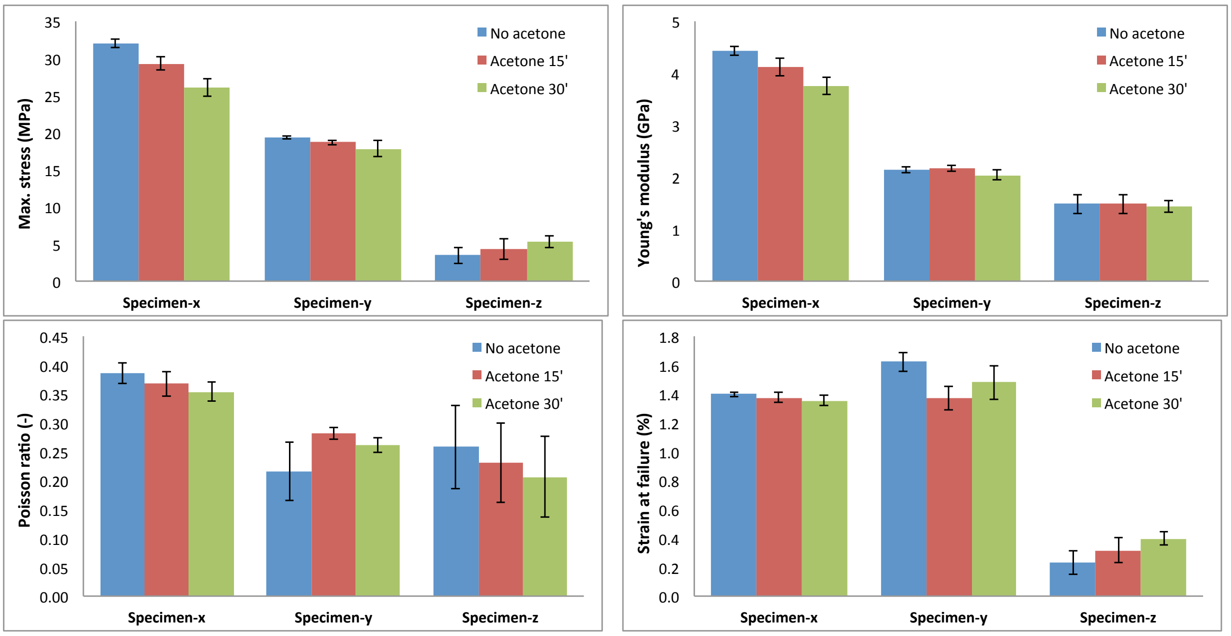

Figure 4. Average values of the maximum stress, Young's modulus, Poisson ratio and strain at failure for the 45 coupons tested under tensile loading.

As it can be seen in Fig. 4, when the filament is in the direction of the applied load, specimens-x, the acetone vapour treatment reduces the four mechanical properties analysed, especially for maximum stress, Young's modulus and Poisson ratio. In all the cases, longer treatment times imply higher reductions. For the case of the specimens-y, there is no clear tendency on the effect of the treatment with acetone vapour. Although there is an increase of the Poisson ratio when the specimens are treated with acetone vapour, there is a reduction of the strain at failure and almost no variation, or a very slight reduction, in terms of Young's modulus and maximum stress. Finally, the maximum stress level and the strain level at failure of specimens-z linearly increase when treated with acetone vapour. However, the Young's modulus remains virtually the same and there is a reduction in the value of the Poisson ratio. The variations of the different mechanical properties in function of the treatment time with acetone vapour for the three types of specimens are better represented in Fig. 5. In this figure, the values of the four mechanical properties of the specimens treated with acetone vapour have been normalised with respect to the values corresponding to the specimens without conditioning.

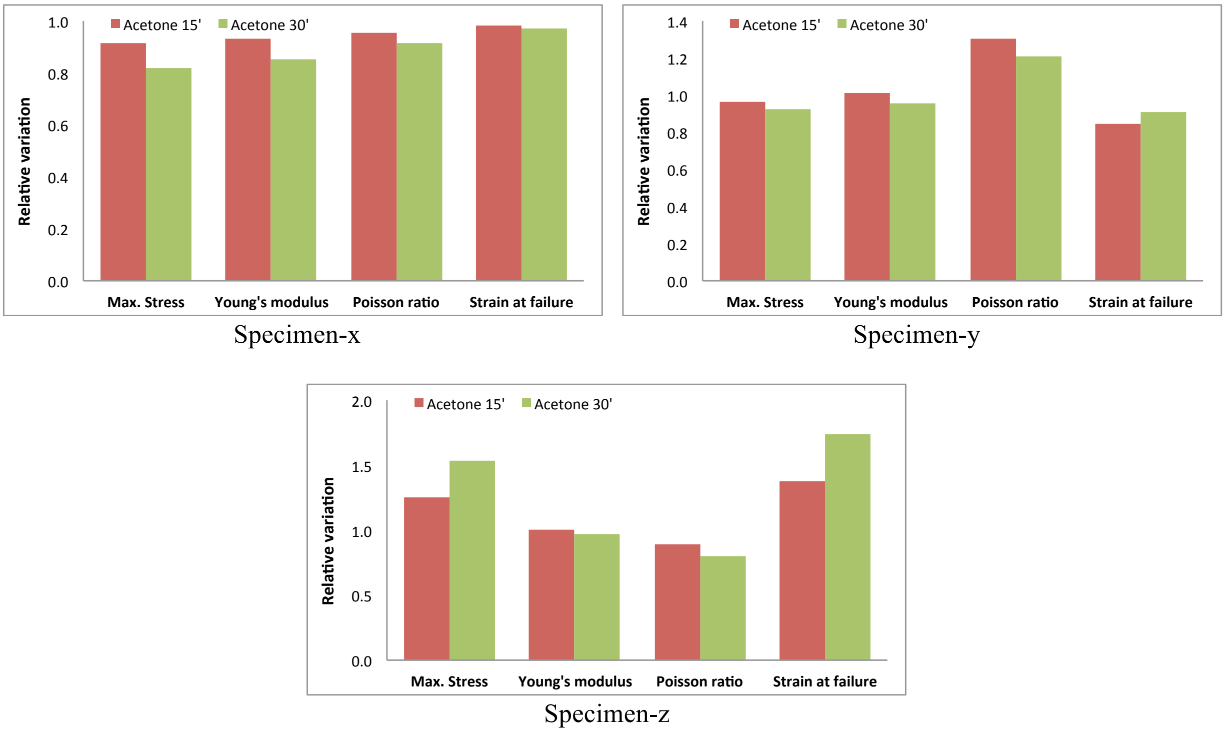

Figure 5. Relative variation of the maximum stress, Young's modulus, Poisson ratio and strain at failure with respect to the values of the non-treated specimens for the three specimen configurations.

After analysing the experimental results of the tensile tests, it can be concluded that the effect of conditioning specimens-x with acetone vapour is very low but negative, as the four mechanical properties analysed are slightly reduced. In the case of specimens-y, there is no clear tendency on the effect of the acetone vapour on the material. For specimens-z, the maximum stress is increased by 25 and 54% and the strain at failure is increased by 38 and 74% when treated with acetone vapour during 15 and 30 minutes, respectively.

4. Conclusions

The improvement of the transverse mechanical properties of CF reinforced ABS 3D-printed parts treated with acetone vapour has been investigated in this work. The objective was to determine if the melting effect of the acetone vapour on the deposited filaments of 3D-printed parts improved the adhesion between these filaments. A total of 45 tensile specimens were manufactured according to the ASTM D638 using an ABS thermoplastic filament reinforced with high-modulus short carbon fibres considering three different directions for the deposition the filament (specimens-x, –y and –z). One-third of the specimens of each type were tested as manufactured, one-third after been treated with acetone vapour during 15 minutes and the rest after being treated during 30 minutes. The absorption of the acetone vapour was confirmed by the weight increment in the specimens, which was more important for specimens-z and less for specimens-x. Also, the analysis of the cross-sections of the specimens confirmed the melting effect of the acetone vapour smoothing the external surfaces and partially erasing the separation between layers. After the analysis of the tensile tests of the different specimens it can be concluded that the effect of the acetone vapour on the specimens with the filament oriented to the load direction is very low and negative as the Young's modulus, the maximum stress and the strain at failure are slightly reduced. However, for the specimens printed in the vertical direction and, therefore, with the lowest mechanical properties, treating the material with acetone vapour improves the maximum stress and the strain at failure up to 54 and 74%, respectively. In conclusion, treating CF reinforced ABS 3D-printed parts with acetone vapour improves the adhesion of the deposited filaments between layers and, thus, improves the resistance of the material in this transverse direction.

References

[1] E. Kroll, D. Artzi. Enhancing aerospace engineering students' learning with 3D printing wind-tunnel models. *Rapid Prototyping Journal*, 17(5):393-402, 2011.
[2] X. Wang, M. Jiang, Z. Zhou, J. Gou, D. Hui. 3D printing of polymer matrix composites: A review and prospective. *Composites Part B*, 110:442-458, 2017.
[3] S.K. Malhotra, K. Goda, M.S. Sreekala. Part One Introduction to Polymer Composites. In: Polymer Composites. 1st ed. Wiley-VCH, 2012.
[4] H.L. Tekinalp, V. Kunc, G.M. Velez-Garcia, C.E. Duty, L.J. Love, A.K. Naskar, C.A. Blue, S. Ozcan. Highly oriented carbon fiber polymer composites via additive manufacturing. *Composites Science and Technology*, 105:144-150, 2014.
[5] F. Ning, W. Cong, J. Qiu, J. Wei, S. Wang. Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. *Composites Part B*. 80:369-378, 2015.
[6] S.-H. Ahn, M. Montero, D. Odell, S. Roundy, P.K. Wright. Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*. 8(4):248-257, 2002.
[7] ASTM D638-14, Standard Test Method for Tensile Properties of Plastics, ASTM International, West Conshohocken, PA, 2014, www.astm.org.