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WATER ABSORPTION AND MECHANICAL PROPERTIES EVALUATION OF SURFACE MODIFIED ABS PRINTING PARTS

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ABSTRACT: The aim of this paper was to investigate the effect of a sealing protective treatment on the water absorption and mechanical properties of acrylonitrile butadiene styrene (ABS) printed parts by fused deposition modelling (FDM). Protective products include aqueous acetone solutions with different concentrations, a polyurethane based varnish and another varnish aqueous acrylic based. The open porosity was estimated by the absorption coefficient and the total amount of water retained obtained from water absorption tests. The mechanical characterization was performed by compressive and tensile tests. Different specimens with different build directions and raster angles were used. Treatment with an acrylic based varnish was found to both preserve the structure fidelity of the samples, to reduce the open porosity, and to maintain the compression and tension properties of the samples in different build directions and raster angles.

KEYWORDS: Acrylonitrile Butadiene Styrene (ABS), Fused Deposition Modelling (FDM), Sealing, Mechanical properties, Open porosity

INTRODUCTION

In the last few years, the rapid prototyping process has experienced great advances, being the use of this technique widespread in new product design for manufacturing. Rapid prototyping combined with computer-aided design allows the manufacture of complex geometries with different materials to obtain the desired properties, in a short time and at low costs (Turner et al., 2014, McCullough et al., 2013, Croccolo et al., 2013, Tymrak et al., 2014).

Several papers deal with the mechanical characterization of parts fabricated with FDM (Bellini et al., 2003, Rodriguez et al., 2001, Croccolo et al., 2013, Tymrak et al., 2014) and some of the works exploit the anisotropic mechanical properties of the specimen (Silva et al., 2010, Lee et al., 2007, Tymrak et al., 2014, Croccolo et al., 2013). In fact, as FDM deposits material directionally the result is a layered specimen that has an anisotropic behaviour. Also due to the methodology of the process
there are air pockets, which affect the mechanical properties (Rodríguez et al., 2003, Li et al., 2002). One of the major drawbacks of this technology is that the strength and stiffness of the FDM components are lower than the ones exhibited by a continuous specimen made of the same polymer obtained by conventional processing, such as injection moulding (Lee et al., 2007). ABS parts become water-impermeable with the application of different sealing products through treatments of brushing, vapour or vacuum infiltration, where the acetone sealing method is an example (Tymrak et al., 2014, McCullough et al., 2013, Mireles et al., 2011).

To our knowledge, there has been limited work in the study of modification of surfaces obtained with FDM and the treatment strategies are not well defined. The present work analyses the effect of the protective treatment on the water absorption and mechanical properties of ABS printed parts by FDM. The chemical surface treatment was performed with aqueous acetone solutions with different concentrations, a polyurethane varnish and an aqueous acrylic based varnish. The porosity before and after treatment was evaluated through water absorption tests while the mechanical properties were determined by compressive and tensile tests. Different build directions and several raster angles were undertaken.

MATERIALS AND METHODS

The experimental procedure involves the ABS sample manufacturing, the application of a protective product followed by the water absorption tests. Three types of products were studied. Compressive and water absorption results of the treated samples enable to choose the product which leads to an effective reduction of porosity, but preserves the mechanical properties and the sample dimensions. The product chosen was also applied in samples with different build directions and raster angles to check whether these variables had any influence on the outcome.

Sample characteristics and protective products

All specimens were printed in a Dimension SST778. The first types of samples were cubes with edge length of 10.08±0.14 mm, which were used in the water absorption tests conducted before and after the application of a protective product. Compressive tests were also undertaken with those cubic shaped specimens. At least three specimens were used under the same testing conditions. The samples were constructed along the Z axis with raster angles of 0/90º or 45/-45º as indicated in Figure 1. Samples will be designated by the build direction and raster angle. According to these parameters cubic samples will be denoted by (Z, 0/90) or (Z, 45/-45).

Standard samples for tensile tests of polymeric materials were produced according to ASTM D638-14 (ASTM_D638-14). Three samples were produced for each manufacturing characteristic with build orientations according to Y and Z axis and for raster angles of 0º, 90º, 45º and -45º. The tensile samples studied were designated by (Y, 45º), (Y, -45º), (Z, 45º), (Y, 0º) and (Y, 90º). Schemes of each manufactured tensile samples are also exhibited in Figure 1 on the right.

Three sealants or protective materials were studied: aqueous acetone solution, a polyurethane varnish Lakeone (www.lakeone.com) and an aqueous acrylic varnish Luxens (www.aki.pt). Both varnishes are appropriate to protect interior wood surfaces. Acetone was diluted in water to give aqueous acetone solutions with concentrations of 45, 50, 70 and 80 vol % of acetone. The varnishes were applied as received, without any further dilution. The acetone solutions were applied by immersion while both polyurethane and acrylic varnishes were applied by brushing. Before any treatment, the ABS cubes were dried in air at room temperature. Cubic samples were soaked into
acetone solutions for immersion durations of 2, 4 and 6h. Following the immersion treatment the samples were removed out of the soaking solution, placed in a Petri dish and allowed to dry at room temperature.

Figure 1 Left: Definition of raster angle $\alpha$ for cubic specimens: a) angle of 0º; b) angle of 90º; c) angle of 45º and d) angle of -45º. Right Tensile specimens with different build directions and raster angles: a) (y,45º); b) (y, -45º); c) (z, 45º), d) (y, 0º); c) (y, 90º).

**Water absorption and mechanical tests**

Capillarity water absorption tests were conducted following ASTM D570 specifications (ASTM_D570-98(2010)e1). The maximum water content, $CI$ and the open porosity $op(\%)$ were evaluated through the water absorption tests. Tensile and compressive tests were conducted. At least three tests were made for each sample manufacturing conditions. In the compression tests, the maximum or yield stress $\sigma_y$ and strain $\varepsilon_y$ were recorded as well as the slope of the linear region, $E$, before the yield point. From the stress-strain curves obtained from the tensile tests, the yield stress $\sigma_y$, and strain $\varepsilon_y$, the plateau stress $\sigma_p$ and strain $\varepsilon_p$ and the ultimate stress $\sigma_u$ and strain $\varepsilon_u$ were obtained. The slope of the initial part of the curve was also taken.

**RESULTS AND DISCUSSION**

A generalized use of FDM final products still requires investigation in order to achieve the mechanical properties needed to meet performance criteria. Research work includes not only the processing parameters but also a subsequent surface treatment. Note that FDM parts have a certain porosity derived from the gaps between the deposited materials. In general, an increase in porosity tends to decrease the mechanical properties.

**Water absorption**

Figure 2 presents the water absorption curves for two untreated cubic samples with raster angles $\alpha$ of 90º and 45º. Although the slope of the initial part of the curve, the absorption coefficient $A$, is almost the same for the two manufacturing conditions, the maximum water content $CI$ and the open porosity $op$ are higher for $\alpha = 90º$. The raster angle affects the porosity of the printed parts with more air pockets in the parts printed at $\alpha = 0º/90º$ in comparison with $\alpha = 45º/ -45º$. 

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Three protective materials were studied: aqueous acetone solutions with different concentrations, polyurethane varnish and an aqueous acrylic varnish. Water-acetone solutions with different concentrations of acetone and for different durations of the treatment were tried. Results show an enormous dispersion and it was not possible to determine a trend with the increase of the duration of the treatment or with the increase of the acetone concentration. Some of the water absorption curves are exemplified in Figure 3, for samples treated with water acetone solutions with concentrations of 50% and 80%, for the polyurethane and the acrylic varnishes, which are compared to the untreated samples, both with raster angles of 90º and 45º. The only acetone solution that reduces both \( C_I \) and \( \text{op} \), is the one with 80% acetone. The same result was obtained either for raster angles of \( \alpha = 90^\circ \) and \( \alpha = 45^\circ \). However, the highest concentration of acetone was found to dissolve partially the surface of the cubes, as may be seen in Figure 4.

The polyurethane treatment was found to reduce the absorption coefficient \( A \), but the maximum water content \( C_I \) and the open porosity \( \text{op} \) remain almost unchanged when compared to the ones obtained for untreated samples. On the opposite, the acrylic varnish provides a decrease of all the water absorption parameters \( A \), \( C_I \) and \( \text{op} \), being the most effective product concerning water absorption. The difference in porosity for the two raster angles considered, 0/90 and 45/-45, is maintained as in the case of the untreated samples.

**Compression tests and tensile tests**

Results allow inferring that the surface modifications induced by the solution with 50% vol. in acetone, polyurethane and acrylic varnishes do not affect the bulk properties of the ABS samples measured by compression tests. All the stress-strain curves for these treatments are consistent with each other and also superimpose with the one obtained for the untreated sample. In this sense, the mentioned sealing products only react in the surface of the samples and do not provide any volume alterations, without changes in their mechanical properties. If the amount of acetone is 80% in vol. there is a clear decrease in the values of yield stress, yield strain and Young’s modulus, and consequently a reduction of strength and stiffness. This means that the mechanisms of dissolution and deposition due to the acetone reaction occurs in a large scale and changes the volumetric properties of the samples. The anisotropy effect due to the different raster angles is not clear as only slight differences in the mechanical compressive parameters are observed.
Figure 3 Water absorption curves of samples submitted to different protective treatments, acetone solutions of concentrations with 50% and 80%, polyurethane and acrylic varnishes, which are compared to the untreated samples, both with raster angles of 90º.

![Water absorption curves](image)

Figure 4 Photographs of ABS cubes of 1 cm size: a) before the application of any treatment; b) after the application of a treatment with acetone 80%.

After having concluded that the acrylic varnish was the protective product that reduces the open porosity, maintains the mechanical properties and provides dimensional stability, several tensile samples obtained with different manufacturing characteristics with build orientations according to Y and Z axis and for raster angles of 0º, 90º, 45º and -45º, were coated with the acrylic product and tested under tension. The yield stress of the (Z, 45º) samples keeps the same values before and after the surface treatment. However samples (Y, 45º), (Y, -45º), and (Y, 0º), (Y, 90º) exhibit higher values of yield stress for the samples treated with the acrylic product. An explanation for this behaviour may be related to the air pockets that were filled with the protective product and consequently increase the strength. The anisotropy is maintained after the treatment. As a consequence, the protective product is not prejudicial to the mechanical properties in the sense that it does not affect the bulk properties of the ABS and may be used in future works.

CONCLUSIONS

The additive processes, such as fused deposition modelling are currently considered to be highly effective fabrication technologies. The present paper presents an analysis of surface treatments with three protective products on the water absorption, compression and tensile properties of ABS parts obtained with FDM. An acrylic based product was found to be effective in reducing the porosity and maintaining the mechanical properties of the samples.

Although the number of the works published in this field is high, more studies are still needed to improve the method and the 3D microstructures, as the final mechanical properties of the parts are influenced by a large number of production parameters. The production parameters and the finishing treatment need to be deeply studied in order to increase the stiffness and the strength of the build parts. The benefit of a treatment that fills the voids and reduces the porosity of ABS printed parts...
enables end-use applications either for pipes in heat exchangers or microfluidic devices in the biomedical field.

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