

Compressive Properties of FDM Rapid Prototypes Treated with a Low Cost Chemical Finishing

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Abstract: In literature several studies have been performed to analyze the surface finish of rapid prototyped parts. These researches have been mainly aimed to the optimal build direction of prototypes to obtain the best possible surface finish on specific surfaces. Very diffuse technologies that suffers considerably of low surface quality are Fused Deposition Modeling (FDM) and extrusion based Rapid Prototyping machines in general. Hand finishing for even the most basic levels of part quality are often required by the customers, forcing the geometrical features of the prototypes to be controlled by the skill level of the operator. This study completes past researches performed by the authors on tensile and flexural properties of chemical dipped specimens after immersion in a dimethyl ketone-water solution. The authors aim to gain a more in-depth knowledge of this process, by analyzing and comparing the compressive properties of finished and non-finished FDM parts through the use of an experimental approach, totalizing about 100 tests.

Keywords: Dimethyl-ketone, finishing, fused deposition modeling, rapid prototyping, roughness

INTRODUCTION

One of the most important Additive Manufacturing (AM) technologies is Fused Deposition Modeling (FDM), a technology used to extrude several types of materials such as conventional and flexible thermoplastics (Cho *et al.*, 2009) and metal (Kim *et al.*, 2009). Among the extrudable materials one of the most widely employed is Acrylonitrile Butadiene Styrene (ABS), which is ideal for conceptual prototyping through design verification and is available in a variety of standard and custom colors. Among the most important advantages of FDM there are good mechanical properties. However one of the most important drawbacks of FDM is related to the high roughness of surfaces, especially if compared to other additive processes such as Stereolithography.

In Galantucci *et al.* (2009) the authors have presented a chemical treatment employed to enhance the surface finish of ABS fused deposition modeled parts that showed to be very promising, yielding significant improvements in the roughness of treated specimens.

The chemical bath was chosen according to the following considerations: ABS is a polymer with a low reticulation degree, including nitrile functionality saving weak interaction with polar solvents such as dimethyl ketone (acetone), ester and chloride solvents. Dimethyl ketone was chosen due to its low cost, very low toxicity and to his very high diffusion. Since the process resulted to be difficultly controlled using pure acetone, the bath was added with water due exploiting its high mixability with

acetone. The process consisted of immersion in a volume of 90% dimethyl ketone and 10% water.

The benchmarks roughness was measured and the effect of the chemical bath on the surface finishing was analyzed in relationship with the machine parameters. The proposed chemical treatment resulted to be economic, fast, easy and highly performing in reducing roughness up to 10% of the initial value. The analysis of the roughness reduction percentages shows that a greater slice height improves the effect of post treatment, while an increasing of tip and part raster width decrease the effects of the treatment (reduction %). The roughness reduction percentage varies between a maximum of 91.3% (group 2, slice height 0.254 mm, Part raster 0.304 mm, tip 10 inches) and a minimum of 70.9% (group 3, Slice height 0.1778 mm, Part raster 0.729 mm, tip 10 inches). In Fig. 1 a qualitative Z map of a treated surface (a) is shown compared to a non treated surface (b). in this map brighter points have a higher Z value than darker points.

As regards dimensional and weight measurements, the specimens shrank by less than 1%, while they increased their average weight by less than 1% showing that the chemical treatment cuts away material but the subtracted ABS is balanced by the absorption of the solution.

Subsequently, in order to assess also mechanical properties of treated parts further researches have been conducted (Galantucci *et al.*, 2010) finding, in conditions of reduced roughness, a minor reduction of the tensile strength but a greater ductility of the specimens. Moreover, bending tests revealed a general improvement of the flexural

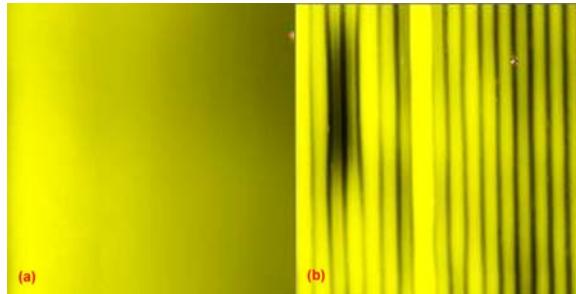


Fig. 1: Z map image of finished and unfinished FDM parts

strength, probably due to a different action of the solution on surfaces built with different patterns and/or a different reaction of treated filaments to traction and compression.

This study offers a more in-depth analysis of the process, addressing the variations of compressive properties of treated ABS parts in order to complete the analysis of mechanical behavior reported in Galantucci *et al.* (2010).

Tensile, flexural and impact strength of parts fabricated using FDM technology are addressed in Sooda *et al.* (2010) where an empirical model is presented, mediating between the processing parameters and the mechanical properties using response surface methodology. The effect of each process parameter on the mechanical property is analyzed, using a factorial plan based on the input variables: layer thickness (slice height), raster angle, raster width and air gap. The variables cannot be selected independently of each other because their interactions are very important. Optimal factor levels are determined for improving the tensile, flexural and impact strength independently and all three strengths simultaneously. The optimal factor setting for tensile and flexural strength is the same, but that the orientation and raster angle for impact strength are different.

The relationship between mechanical properties and process parameters are studied in Ahn *et al.* (2002), where the tensile strength of FDM processed parts is analyzed vs. process parameters such as air gap, raster orientation, raster width, model temperature and color, using an experimental design. The conclusion is that air gap and raster orientation are the factors with the most influence. In Bellini and Guceri (2003), tensile and flexural tests are performed and a very simple Finite Element Model is proposed. It is observed that the road shape and the road-to-road interaction, as well as the “path”, strongly affect the properties and performance of the finished product and that the mechanical properties of the final parts are dependent on two important factors, namely the chosen building direction and the chosen path and therefore on the way each layer is filled by roads.

As regards compressive properties, in Lee *et al.* (2007) the compressive strength is studied on cylindrical specimens fabricated with FDM, 3D printing and Nano Composite Deposition (NCDS), to study the effect of build

direction. Experimental results showed that the compressive strength is 11.6% higher for axial FDM specimens as compared to transverse FDM specimens. In Sooda *et al.* (2012) the focus is on the effect of the parameters layer thickness, part build orientation, raster angle, raster width and air gap on the compressive stress of test specimen. The study develops a statistically validated predictive equation. The equation is used to find optimal parameter setting through quantum-behaved particle swarm optimization, while compressive stress is predicted using Artificial Neural Network (ANN) and is compared with predictive equation.

MATERIALS AND METHODS

The aim of the reported experimental activity is to investigate the influence of the chemical treatment on the compressive strength in order to deepen the knowledge of mechanical behavior of treated FDM prototypes.

The experimental activity has been conducted at the Reverse Engineering and Rapid Prototyping Lab, Dipartimento di Ingegneria Meccanica e Gestionale of the University Politecnico di Bari in Italy, during the year 2011. The design of the specimens have taken into account the standard EN ISO 604 that prescribes for cylindrical specimens a diameter-height ratio (x/L) greater or equal to 0.4. As a consequence a diameter $x = 20$ mm and a height $L = 50$ mm.

The tests were performed with an Instron 4485 universal testing machine, with crosshead speeds equal to 5 mm/min (Fig. 2).

In order to compare properties of treated and non treated specimens, one experimental set using 2-level Central Composite Design (CCD) is used to assess the compressive strength of untreated specimens, while one 3-level CCD was used to evaluate the compressive strength of treated specimens. CCD is chosen due to the expected non linearity of the response variables, because this kind of design can efficiently estimate the quadratic terms in the second-order model. The input variables, levels and response variables are shown in Table 1.

As regards the plan with two input variables, shown in blue letters, the total number of examined specimens is equal to 39, while as regards the plan with three input

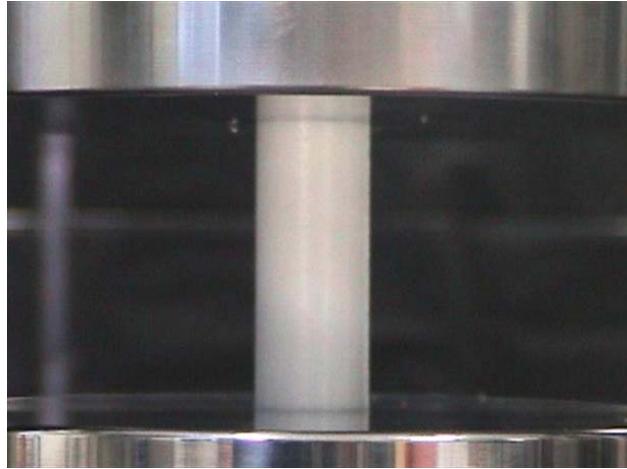


Fig. 2: One specimen before the compression test

Table 1: CCD levels for untreated (blue) and treated (black) specimens

	Levels		
Input variables	-1	0	1
Raster width (mm)	0.404	0.479	0.554
Raster angle (°)	0	30	60
Raster width (mm)	0.404	0.479	0.554
Raster angle (°)	0	30	60
Immersion time (sec)	180	300	420

variables, black letters, the examined specimens have been equal to 60, being the total number of tested specimens equal to $39+60 = 99$.

RESULTS

The first set of experiments (blue rows in Table 1) investigates the influence of the raster width and raster angle on the compressive properties of the FDM specimens. The raster angle is the orientation of the toolpath on the x-y table, the raster width is the width of the extruded material deposited on the slice by the extrusion head, i.e., the toolpath width of the raster pattern used to fill interior regions of the part curves.

The layer thickness or slice height has not been included among the factors due to its minor influence on roughness after treatment (Cho *et al.*, 2009). As a consequence, all the specimens have been fabricated with a slice height equal to 0.254 mm. Moreover, air gap has not been considered because only solid parts have been tested, while only the maximum strength build direction has been used to fabricate the specimens.

In Fig. 3 the response surface shows a very low influence of the raster angle on the compression strength and a tendency to increase as long as the Part Raster width increases. This has been computed as the compressive engineering stress at a 6% deformation, according to EN ISO 604. These results agree with the tensile behavior analyzed by the authors in previous studies.

Untreated Specimens

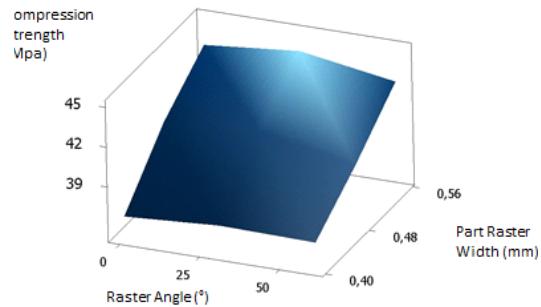


Fig. 3: Response surface for non-finished parts

Treated Specimens

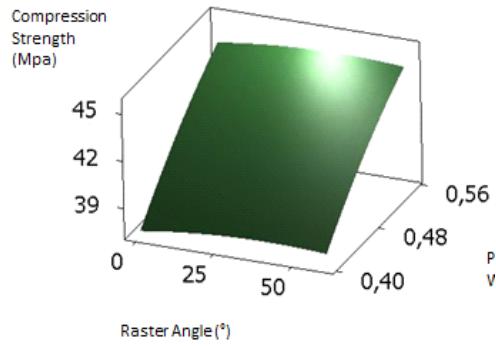


Fig. 4: Response surface for finished parts

The second set of experiments (black rows in Table 1) aims to evaluate the incidence of the immersion time on the compressive properties: the levels of raster width and raster angle are the same as the blue row plus the levels regarding

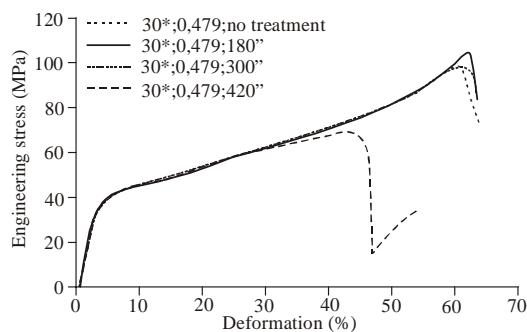


Fig. 5: Examples of tensile stress strain curves for treated and untreated specimens

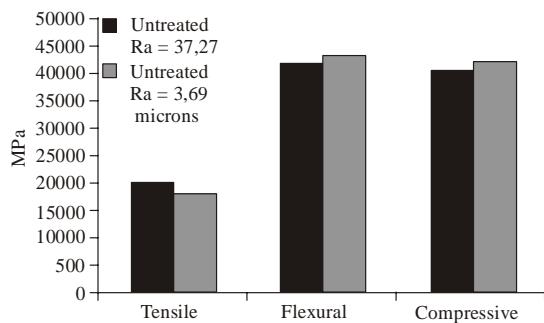


Fig. 6: Average strength of treated (blue) and untreated (red) specimens for several types of load

immersion time, varying in the interval between 180" to 420".

In Fig. 4 the response surfaces is shown for compressive strength, for 180" treated specimens (green). The raster width is a very influent factor for both treated and untreated specimens, but the analysis of these surface points out a small enhancement of the compressive strength, especially for low values of part raster width. This behavior is due to the better collaboration between filaments that are fused together by the chemical solution.

This aspect is highlighted by Table 2 that shows the value of compression strength according to EN ISO 604 of treated and untreated specimens for all the points of the experimental plans. Compressive strength reported for each point of the CCD is averaged on the replications prescribed

by the plan. The compression strength of treated benchmarks lightly increases for all immersion times.

In Fig. 5, the average compressive stress-strain curves are shown for treated and untreated specimens, with a raster angle equal to 30° and a raster width equal to 0.479 mm, with several immersion times (0 to 420"). The curves are very similar with the exception of the curve. With this immersion time it is evident that the penetration of the chemical solution becomes too high and decreases the maximum deformation of the specimen. However the different behavior can be appreciated at very high deformation rates equal to 30%. Normally these deformations are not reached by functional ABS prototypes: the different behavior must be considered as alert for important structural changes in treated parts.

Summarizing the mechanical behavior in terms of average strength, gathering results shown in (Cho *et al.*, 2009; Galantucci *et al.*, 2009) and the present study, Fig. 6 points out the final results. In this figure blue histograms represent the total average measures tensile, flexural and compressive strength for untreated specimens that are characterized by an average roughness equal to 37.27 microns. On the other hand, red bars represent the treated specimens, with a dramatically lower average roughness (3.69 microns): tensile behavior is lightly poorer, in terms of strength, but both flexural and compressive strength increase with the treatment.

CONCLUSION

In this study the compressive properties of FDM prototypes treated with a solution of 90% dimethylketone and 10% water have been analyzed. In preceding studies the treatment resulted in dramatically improve the surface finish of ABS prototypes, showing to increase tensile ductility but also to slightly lower tensile strength. Moreover, bending tests revealed a general improvement of the flexural strength, probably due to a different action of the solution on surfaces built with different patterns and/or a different reaction of treated filaments to traction and

Table 2: Comparison of the compressive strength of untreated and treated specimens

Raster angle (degrees)	Part raster width (mm)	Average compressive strength untreated specimens (Mpa)	Average compressive strength treated specimens (Mpa)		
			180"	300"	420"
0	0.404	36.56	37.75		37.55
0	0.479	40.59		41.10	44.43
0	0.554	43.32	44.20		
30	0.404	37.01		37.91	
30	0.479	40.99	41.49	42.26	42.12
30	0.554	44.01		45.13	
60	0.404	36.88	37.79		38.24
60	0.479	39.65		42.28	
60	0.554	42.88	44.66		44.54

compression. The study has been completed in the present study with compression tests that agreed with preceding studies, resulting in increasing compressive strength.

In conclusion, the results achieved point out the efficacy of the proposed finishing treatments that can be used with immersion times up to 300 sec to reduce roughness up to 90%, keeping mechanical properties in some cases better than those of non-treated parts.

NOMENCLATURE

- AM : Additive Manufacturing
FDM : Fused Deposition Modeling
ABS : Acrylonitrile Butadiene Styrene
SLA : Stereolithography

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