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Micro-FDM Process Capability and post-processing effects on mechanical properties

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Abstract. The mechanical behaviour of specimens fabricated using FDM machine has been thoroughly studied and several works have been presented. However, they are focused on few materials, in particular ABS, while very few papers analysed the mechanical properties of FDM samples made by PLA filament. Even though ABS is well known for its superior mechanical properties, some applications might require materials with other properties, such as PLA. Therefore, a deeper investigation of the effect of the process on its properties is needed. In this study, at first, the influence of the main FDM process parameters, such as raster angle, extrusion width, air gap and extrusion temperature, on mechanical performance of PLA samples has been evaluated. The mechanical tests have been carried out on miniaturized tensile specimens focusing on the tensile test main properties: ultimate tensile stress, Young modulus and elongation at break. Moreover, an experimental campaign has been carried out on the effect of a thermal post-processing, in order to evaluate the effects of the treatment and its relation with the process parameters on the mechanical properties of the specimens.

Keywords: Fused deposition modelling, additive manufacturing, tensile test, annealing.

1. INTRODUCTION

Among the Additive Manufacturing (AM) technologies, Fused Deposition Modelling (FDM) is becoming more and more popular, mainly due to the lost cost of investment required and its easiness to use. It allows the manufacturing of 3D products with a great variety of geometry and in short time. For these very reasons, it began as a process for creating prototypes, but it is now becoming largely used for the production of end-use parts. However, it present a few limitations, such as the material range and the anisotropy of the products. Indeed, the product are built up layer by layer, extruding a molten thermoplastic filament, which creates each layer following a specified toolpath. The thermal fusion of the polymer allows the bond between the layers and across the adjacent beads, but some voids are present and the anisotropic structure affects the properties of the part. Therefore, in order to manufacture end-use parts with suitable mechanical properties, not only is important the choice of the material, but also a correct process control, which is often more influent than the material [1]. Several works have been presented in the literature in order to study and improve the mechanical properties of FDM products, including the control of the process parameters during fabrication and the development of materials with superior properties and compatible with the technology [2, 3]. However, these works studied the properties of Acrylonitrile Butadiene Styrene (ABS), one of the most common polymer used to obtain tough parts with acceptable strength in FDM and very few considered other materials [4, 5, 6]. Therefore, considering the peculiar properties of Polylactic acid (PLA), namely stiffness and environmental impact, this paper is focused on the effects of the process parameters on the tensile tests of miniaturized samples made of PLA. Miniaturization can have a high impact on several industrial fields - such as biomedical, electronics, optics and high-precision micro mechanical industry - and the advantages of AM technologies could help the spreading of microproducts. Moreover, in order to study the effect of temperature history on FDM specimens a thermal post-treatment (annealing) has been investigated in relation with the process parameters. The effects of heat treatments on mechanical properties of PLA has been widely investigated in last years [7]. Tensile modulus and heat deflection temperature (HDT) are increased by annealing at 100°C. The effects of thermal post-process was investigated also with respect to the chemical composition of the PLA. Additives change the native crystallinity of the material and its sensitivity to annealing, however, no matter the chemical composition of PLA (reinforcement additives) the tensile modulus increases while the elongation at break decreases with thermal post-processing (4h@100°C). Tensile strength does not exhibit a specific trend, it can be increased or decrease depending on material composition. The cause of this improved mechanical properties is referred to an increase of crystallinity and secondary bonds [8, 9, 10]. However, they are mostly applied on the injection moulding

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process, and there is a lack of research works on the combination of the PLA material with FDM and the effects of annealing on mechanical properties at different process conditions. More insight are requested into this specific technological niche, in order to investigate whether this could be a solution to some of the limitations of the fabrication technology.

After the description of material and methods in section two, in the third section, the focus has been given on FDM micro-part production capability and process parameter optimization; while in the fourth section, an investigation on heat treatment and process parameter effects on mechanical properties is presented.

2. MATERIAL AND METHODS

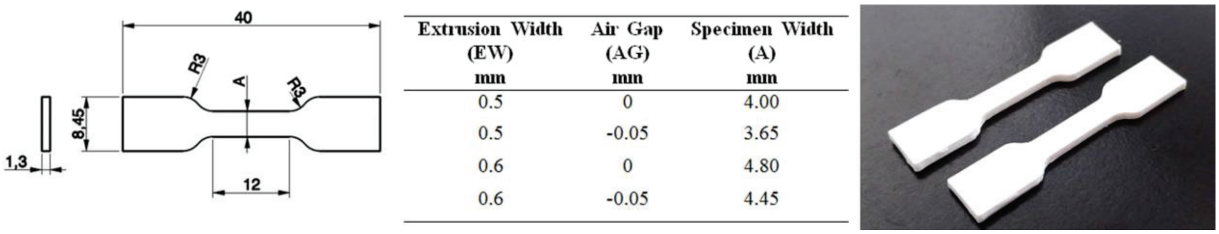
A first design of experiment *(DoE)* has been developed focusing on the influence on ultimate tensile stress (*UTS*), elongation at break (*EB%*) and Young modulus (*E*) of four of the most influent parameters according to the literature and preliminary studies, i.e. raster angle (*RA*), air gap (*AG*), extrusion width (*EW*) and extrusion temperature (*ET*). The first two parameters define the filling of the layer in terms of orientation and distance between two depositions in the raster. The other parameters (layer thickness, extruder speed, the temperature of the build platform and the filament cooling) have been fixed for all the tests. Preliminary tests have been performed in order to guarantee the achievement of the values of A*G* and *EW* by calibration of the parameter extrusion multiplier*,* which controls the ratio of extrusion and feed speeds. The DoE has been conceived in which several process parameters, summarized in table 1, have been combined to obtain a variety of process conditions. Each of the 24 conditions has been replied 3 times and 3 miniaturized dog-bone specimens have been fabricated at each replication.

TABLE 1. Process parameter values.

Factor	Unit	Low level	Central level	High level
Air Gap (*AG*)	mm	-0,05	-	0
Extrusion Width (*EW*)	mm	0,5	-	0,6
Extrusion Temperature (*ET*)	°C	200	-	230
Raster angle (*RA*)	degrees	0°/0°	+45°/-45°	0°/90°
Layer thickness	mm		0,1	
Extrusion speed	mm/min		2400	
Bed Temperature	°C		50	
Cooling	-		OFF	

In order to define a miniaturized geometry for mechanical test specimens, several geometries have been proposed in recent years, downscaling the models of the standards ISO 527 [11] and ASTM D638 [12] or creating original geometries [13, 14]. The dimensions of the proposed geometry is reduced enough to comply with the definition of micro-component [15], and, at the same time, adequate to perform tensile mechanical tests.

The specimen geometry has been defined based on ISO527-5B. However, in order to avoid incomplete filling of the samples, the specimen width (*A*) is modified taking into account the variation of Air Gap and Extrusion Width with the aim of deposit 8 beads for all the layers with a raster angle of 0°. Figure 1 shows the nominal width of the specimen when *AG* and *EW* are varied and where a negative value of *AG* means that an overlap of adjacent depositions occur.



Extrusion Width (EW) mm	Air Gap (AG) mm	Specimen Width (A) mm
0.5	0	4.00
0.5	-0.05	3.65
0.6	0	4.80
0.6	-0.05	4.45

FIGURE 1. Mini dog-bone geometry.

The specimens are fabricated in PLA (PlastInk) with filament diameter of 1.75 mm, density of 1.24 gr/cm^3, colour white and a nominal decomposition temperature of 250 °C. The FDM samples have been manufactured using a

GIMAX3D S2 machine equipped with a double extrusion head, heated build platform, nozzle diameter of 0.4 mm, with a resolution of 40 μm for X and Y axes and a resolution of 10 μm for Z axis. The part program has been generated using Simplify3D CAM software. The specimen width (*A*) has been measured for each sample by optical microscope (Zeiss Discovery V.20) while the thickness has been measured with a Mitutoyo digital caliper with a nominal resolution of 0.01 mm. The tensile tests on FDM specimens have been carried out using a Shimadzu EZ-S equipped with a 500 N load cell and crosshead speed 1 mm/min, according with ISO527 standards.

A second DoE has been executed in order to identify the effects of annealing on mechanical properties. For this purpose, the extrusion temperature and raster angle have been varied while air gap and extrusion width have been fixed to 0 and 0.5 mm respectively. The levels chosen for the two factors are reported in table 2. The other process parameters are equal to the values set in the previous experimental setup (table 1). Each FDM fabrication run consists of 3 samples replied for three times (replications).

TABLE 2. Process parameter values.

Factor	Unit	Low level	Central level	High level
Extrusion Temperature (ET)	°C	200	-	230
Raster angle (RA)	degrees	0°/0°	+45°/-45°	0°/90°
Air Gap (AG)	mm		0	
Extrusion width (EW)	mm		0.5	

For each DoE an analysis of variance (ANOVA) has been carried out based on the following variables: UTS, EB% and E, checking that the ANOVA hypotheses of normality distribution, equal variances, and independence of residuals were fully satisfied.

3. PLA MECHANICAL PROPERTIES AND FDM CAPABILITY

The statistical analysis shows that the raster angle is highly significant ($P < 0.001$) for UTS and EB%, while EW is highly significant for E. The extrusion temperature is statistically significant ($P < 0.05$) for EB% and E. Moreover, the interaction between raster angle and extrusion width (RA*EW) is statistically significant for UTS with a P value of 0.025, RA*ET has a P value of 0.007 for EB and EW*AG is statistically significant ($P = 0.049$) for E.

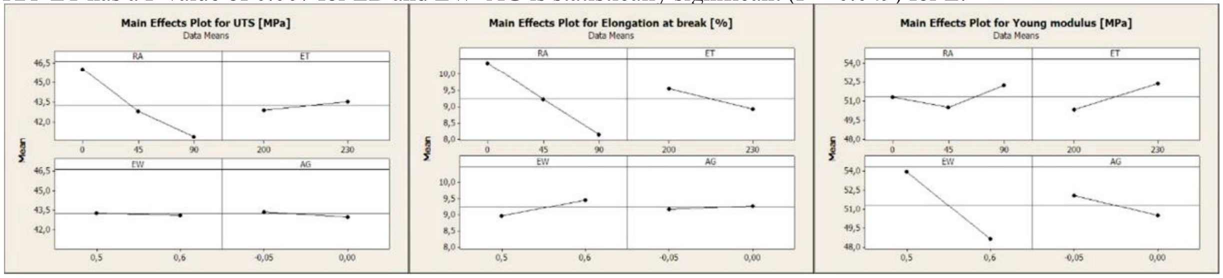


FIGURE 2. Main effects plots of UTS, Elongation at break (*EB%*) and Young modulus (*E*).

FIGURE 2 reports the main effects plots for UTS, EB% and E. Raster angle has a similar trend on UTS and EB%. The minimum value is obtained with the lowest level of RA (0°/90°), for which the samples are weakened by the one other layer where the infill orientation is perpendicular to the force during the test. The highest result is for samples where the beads are deposited along the direction of the tensile test (RA = 0°/0°) as expected. Lower extrusion width leads to a higher Young modulus, as well as higher extrusion temperature for which a better coalescence between the beads can be achieved.

4. EFFECTS OF ANNEALING ON PLA MECHANICAL PROPERTIES.

In this section the effect of a thermal treatment on the PLA samples is investigated. The samples are fabricated following a reduced DoE of the section 3 where extrusion temperature and raster angle have been varied while air gap and extrusion width have been fixed to 0 and 0.5 mm respectively.

The thermal treatments adopted is characterized by a trapezoidal profile showed in figure 3, where an annealing temperature (T_a) of 80 ± 1 °C is kept constant for a time interval (t_a) of 10 minutes. The rising time (t_r) and falling time (t_f) are set to 40 minutes in order to have slow heating and cooling phases (± 2 °C/min). The annealing temperature is higher (+35%) than the glass transition temperature (T_g) of PLA, which is around 60 °C. The crystallization and bonding processes is promoted along the period when the temperature is higher than the T_g and consequently an extended annealing time ($t_{a\text{-}ext}$) of 30 minutes should be considered.

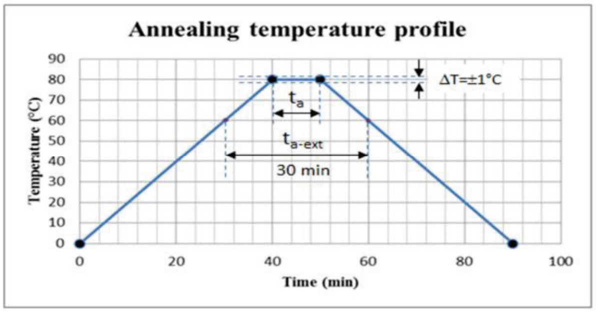


FIGURE 3. Annealing temperature profile (right).

The ANOVA shows that for *UTS* and *EB%* raster angle and its interaction with the temperature are statistically significant ($P < 0.001$), while the extrusion temperature is statistically significant ($P = 0.001$) for the Young modulus. As expected, the main effect plots in figure 4 show a trend similar to the case of the specimens that were not annealed (figure 2), but a comparison, as reported in the figure 5, can highlight the effect of the annealing.

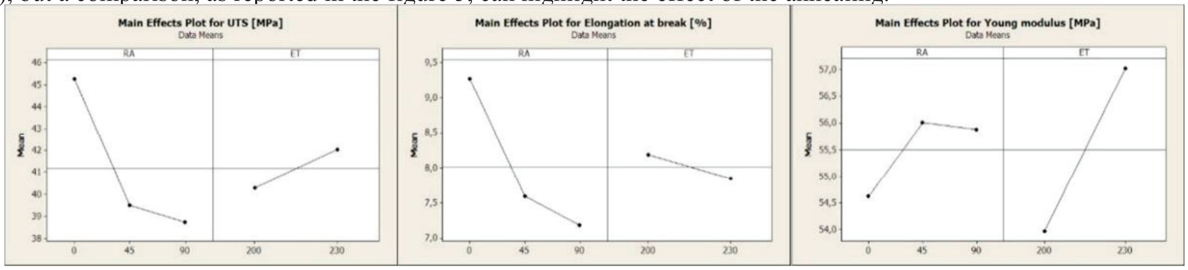


FIGURE 4. Main effects plots of *UTS* and Elongation at break and Young modulus for the annealed samples.

While the annealing adopted does not statistically influence the UTS, it is resulted statistically influent on Elongation at break ($P = 0.001$) and on Young modulus ($P = 0.005$). In particular, it causes a decrease of EB% and an increase of E in agreement with the literature [7]. Concerning the Young modulus a smaller dispersion of the data has been also observed. It must be underline that the annealing increases the side bonds between adjacent beads within a layer and between layers. Consequently, this effect produces an enhancement of the Young Modulus for non-zero raster angle. On contrary, side bonding has lower influence for zero value of raster angle since the beads are oriented along the load application direction and their bonds are less important. This effect can be clearly seen in figure 5, where the values of the Young modulus of the samples annealed is much higher for specimens with raster angle ±45° than for samples with beads at 0°/0°.

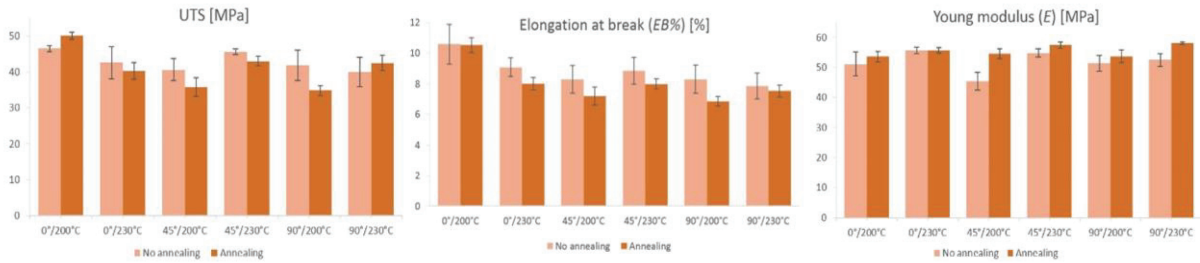


FIGURE 5. Histograms of *UTS*, *EB%* and *E* for different process parameters and annealing.

In addition, results show that the lower the extrusion temperature, the higher the gain of stiffness achieved with annealing. This latter fact can be easily explained since low extrusion temperatures result in lower bonding (by surface melting) between beads during the fabrication.

5. CONCLUSIONS.

In this paper, fused deposition modelling (FDM) technology has been analysed in terms of process capability for micro-component manufacturing and mechanical properties. In addition, post-process heat treatment (annealing) has been applied to PLA specimens in order to investigate its effects on mechanical properties at different process conditions. The experimentations have been carried out on micro dog-bones samples designed on the base of ISO527-5B.

The orientation of infill (raster angle) affects toughness and ductility of PLA samples since the more oriented along the stress direction the infill is, the higher the UTS and elongation at break are. On contrary no effect has been found on Young modulus (stiffness). This latter property is significantly improved by the extrusion temperature. Higher values of extrusion width result in lower values of Young modulus but no effect is found on UTS and EB%. No statistical significance has been found for the air gap parameters.

These results entail that it is possible to improve mechanical properties of the PLA products through an adequate choice of raster angle, temperature and extrusion width but an accurate study of the operating load conditions should be performed in order to carefully evaluate the stress states.

Finally, the effect of the annealing on tensile mechanical properties has been investigated in conjunction with process parameters. The results confirmed that the annealing improves the Young modulus, worsens the EB% and has no effect on UTS. Moreover, the improvement on Young modulus is more significant for samples with non-zero raster angle. This result should be more investigated, but preliminary it can be explained with a bonding process between beads which promote cross-linking and improved stiffness. In addition, results show that the lower the extrusion temperature, the higher the gain of stiffness achieved with annealing. This latter fact can be easily explained since low extrusion temperatures result in lower bonding (by surface melting) between beads during the fabrication.

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REFERENCES

1. O. Ivanova, et al., Rapid Prototyping Journal, 19 (5), 353-364 (2013)
2. O.A. Mohamed et al., Adv. Manuf. 3, 42-53 (2015).
3. M. Dawoud et al., Journal of manufacturing Processes 21, 39-45 (2016).
4. M. S. Hossain et al., Int. Solid Freeform Fabrication Symposium: An Additive Manuf. Conf. Austin, 2013, 380-392 (2013).
5. A. Bagsik, Proceedings of ANTEC 2011, Boston (2011).
6. O. Lužanin et al., Journal for Technology of Plasticity, 39 (1), 49-58 (2014).
7. J. Wootthikanokkah et Al., Journal of applied polymer science, DOI: 10.1002/APP.38715 (2013).
8. Y. Srithep, P. Nealey, L.S. Turng, Polymer engineering and science, 580-588, DOI: 10.1002/pen.23304 (2013).
9. A.M. Harris, E. C. Lee, Journal of applied polymer science, Vol. 107, 2246-2255 DOI: 10.1002/APP.27261 (2008).
10. L.S. Turng, Y. Srihep, Society of Polymer Engineers Plastic Research online, DOI: 10.2417/spepro.005392 (2014).
11. E. Haberstroh et al., Macromolecular Materials and Engineering, 287 (12), 881-888 (2002).
12. C. H. Wu et al, Polymer Engineering and Science, 45 (7), 1021-1030 (2005).
13. T. Koch et al., Macromolecular Symposia WILEY-VCH Verlag GmbH, 181 (1), 499-506 (2002).
14. L. Xie et al., Microsystem Technologies, 15 (6), 913-917 (2009).
15. J. Giboz et al., Journal of Micromechanics and Microengineering 17, 96 (2007).