A territorial round-robin experiment for the evaluation of mechanical properties of FDM PLA produced by distributed facilities

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Abstract. Mechanical characteristics of the produced materials through additive manufacturing (AM) are influenced by a multitude of parameters. In particular, Free Filament Fabrication (FFF) is one of the most adopted technologies due to low machine cost and its simplicity. In recent years, a lot of printer manufacturers emerged as well as many printer control software. This proliferation led to the development of non-standardized ways of printing, such as different machines architecture or software algorithms to control the printing process: in this way, the object produced with a combination of a printer and software is rarely directly comparable (in terms of mechanical characteristics) with the same object produced using a different combination. This work aims to investigate possible variations in material mechanical properties due to different combinations of printers and filament manufacturers: to do so, different makers in Parma area have been involved to produce specimens with their equipment maintaining the same geometry and identical printing settings.

1. Introduction
During the recent sanitary emergency related to Covid-19 infections, intensive care units got exceptionally stressed putting the sanitary system into an exceptional need of consumables, like circuital adapters, respiratory C-PAP masks and personal safety devices. In such a widespread crisis there are three levels of intervention that onset gradually. At the first level is the top-down intervention of governments, the second stage is then the mobilization of industries and professionals. If these responses are not enough, as recorded in these months worldwide, the third level is represented by population. In those recent days, the third level of intervention consisted in self-organized groups of Makers who put their know-how and their additive manufacturing facilities available to design and produce alternatives to commercial consumables [1–3].

As in many other regions and countries, this happened in Parma, too. Makers4Parma is the name of a self-organized community of Makers, made of small companies, craftsmen, professionals and hobbyists that grew in less than 24 hours in reply to help request from intensive care unit of city Hospital. A number of about 40 3D printing facilities were put in availability for the production of respiratory mask adapters, protective shield mounting arcs and other consumables (figure 1). A large number of pieces were produced satisfying the initial request for the Hospital and the following requests of associations and organizations in first line against the pandemic.
The idea of this work arises in the described scenario, from the observation of produced parts. Almost all the collected components were able to fulfill their function, but both the aesthetical/geometrical and mechanical quality of parts were widely different from piece to piece, although manufactured starting from same geometry (STL file) and following basic setup guidelines.

Figure 1. Adapters and protective shields mounting arcs printed by Makers4Parma network.

2. A quick review of the parameters influencing mechanical properties of FFF materials.

Analysis of mechanical properties of FFF parts represents an important subject of interest, with some of the first studies on this topic dating back to 1996 [4]. Since then, process parameters influence on mechanical properties (tensile, compressive, flexural, impact and fatigue strength) have been widely scrutinized for different categories of materials and sets of process parameters/manufacturing conditions. Most influencing FFF process parameters are categorized in the work of Popescu et al. [5]:

- Slicing parameters: layer thickness, nozzle diameter, road width, flow rate, deposition speed, infill, raster orientation, raster pattern, air gaps (raster to raster, perimeter to raster), number of contour/perimeters, top thickness, bottom thickness;
- Building orientation: usually testing specimens are oriented horizontally, vertically or laterally, but other orientations can be also used;
- Temperature conditions: environment (or envelope) temperature, extrusion temperature, bed or platform temperature.

All these affect the mechanical behavior of the printed parts, at different levels: not all FFF parameters have the same effect on the final material, the most important being raster to raster air gap, building orientation, raster angle, layer thickness and infill percentage. Raster angle determines the anisotropy level of the FFF objects and, therefore, their mechanical strength in a specific direction.

An attempt was made to classify the influence of the different parameters in order of importance, as in the work of Durgun et al. [6]. Onwubolu et al. [7] determined that to maximize tensile strength of ABS specimens, layer thickness and raster width should be minimal: the finding is corroborated in various other works. Li et al. [8] showed that in the case of PLA specimens, as well, mechanical performances are improved when layer thickness possesses the least values. On the other hand, Ahn et al. [9] reached to the conclusion that layer thickness does not significantly affect ABS samples mechanical properties. In the same work [9], Ahn et al. investigated ABS compressive behavior, suggesting optimal building orientation rules to obtain best strength.
Ziemian et al. [10] determined that, in the case of ABS specimens, highest tensile strength is reached having raster aligned to specimen axis. The same author studied flexural strength [10], showing through experimental testing that the ultimate strength value is the best for 0° raster orientation in respect to specimen axis. Chacón et al. [11] characterized the effect of build orientation, layer thickness and feed rate on PLA samples through tensile as well as three points bending tests: upright orientation shows the lowest mechanical properties.

Impact strength was studied, as well, indicating as in the work of Alvarez [12] that 100% infill maximize its value.

Even material colors could affect mechanical results: Ahn et al. [9] concluded that color has no significative influence over the mechanical properties of ABS specimens, whilst Wittbrodt et al. [13] showed that color influences the polymers percentage of crystallinity, impacting on mechanical strength, of PLA samples.

Given the increasing transformation of rapid prototyping methods towards direct fabrication of consumer objects, a substantial lack of studies on the effects of aging was found: the only reference on the matter has been the work of Bass et al. [14] which, using a method different from FFF (in particular Material Jetting [58]) showed how the ultimate tensile stress of some parts increased and the elongation decreased over time. Material properties were not significantly altered by lighting conditions.

Another important aspect that must be addressed is the difference between the mechanical properties of bulk polymers (as indicated by producers in the material specification sheet), the mechanical properties of testing specimens and the mechanical performance of manufactured end-parts. Bellini and Güçeri [15], in determining mechanical behavior of ABS specimens, compared bulk filament tensile testing properties and printed material ones, showing great difference between the two.

In conclusion, printing parameters affecting FFF produced material, can be subdivided in five broad categories, as reported in table 1.

| Process parameters | Infill and supports | Material | Printer | Miscellaneous |
|--------------------|---------------------|----------|---------|---------------|
| - Print speed       | - infill type       | - family | - manufacturer | - final density / final porosity |
| - Orientation       | - infill density    | - type   | - extruder | - Dimensional accuracy |
| - Extrusion temperature | - supports type | - manufacturer | - nozzle | - Slicing software |
| - Build plate temperature | - support density | - filament diameter | - architecture | - Manufacturing conditions |
| - Build volume temperature | - support material | - filament color | - structure | |
| - Layer thickness   | - Wall thickness    | - additives | |
| - Orientation       | - Extrusion flow    | - adhesion | |
| - Cooling           |                     | - viscosity | |

3. **Aim of the activity.**

Aim of the research here presented is a preliminary investigation of the influence of non-conventionally investigated parameters onto mechanical properties of FFF manufactured materials. While process parameters are the most commonly discussed in literature [6–12], the effects depending on filament manufacturer, its colour, printing system and slicing software are addressed by few works [9,13] and cannot be evaluated by cross-comparison of different works because of inconsistency.

The **Round Robin for Additive Manufacturing** (RR4AM) is then a territorial experiment aimed to evaluate the variability on mechanical properties of FFF manufactured PLA material, supplied by different production facilities.
**Table 2.** Common printing parameters used for specimens production.

| Parameter                  | Value                        |
|----------------------------|------------------------------|
| Material                   | PLA                          |
| Layer height               | 0.2 mm                       |
| Specimens on build plate   | 3                            |
| N.° of walls               | 2                            |
| Top/Bottom layers          | 0                            |
| Infill overlap             | 15%                          |
| Infill pattern             | lines/rectangular            |
| Printing temp.             | 220 °C                       |
| Initial/Final printing temp.| 220 °C                      |
| Bed temperature            | 0/40 °C                      |
| Print speed                | 40 mm/s                      |
| Build plate adhesion type  | skirt or none                |
| Orientation                | on X-Y plane, along Y        |

**Figure 2.** Specimen position and orientation on the build plate.

**Figure 3.** Shipment letter example.

4. Experiment workflow.
The experiment is arranged in 5 steps: (i) Recruiting, (ii) Production, (iii) Delivery, (iv) Test and (v) Dissemination.

The Recruiting phase consisted in a Call for Makers addressed to the Makers4Parma network, presenting the research and asking to apply spontaneously to the experiment, producing a batch of 3 specimens from specific geometry and taking care to strictly follow printing guidelines. Applications were collected with an online form. In two weeks, starting from 60 e-mail addresses, 25 Makers got registered.

The Production phase started sharing production guidelines to registered makers. Together with the STL file of the specimens to be produced, detailed instructions about printer setup have been shared to participants. A printing job consisted in the production of a Batch of 3 Specimen. Each Maker could participate with a maximum of 5 batches. Printing setup is summarized in table 2, while the Batch layout into building volume is represented in figure 2.

The unique requirement for the filament was to adopt PLA as base material, with no further specifications, recording filament manufacturer, colour and eventually special characteristics.

The production of each specimens batch ended with the Delivery which consists in the registration of the specimen batch on a specific online form, connected with a spreadsheet which automatically collects the entries and generates a unique batch-code and a shipment letter to be attached with specimens. A sample of the shipment letter and the information collected is in figure 3.

A number of 14 makers effectively produced at least one batch for a total number of 23 batches (69 specimens) which have been tested during the Test stage. Results here presented are the outcome of the final Dissemination phase of the experiment.

5. Experimental setup.

Tensile tests were performed on submitted batches, according to ASTM D638 standard [16]. A MaCh5 machine, a commercial desktop universal testing machine produced by MaCh3D srl (www.mach3d.it) has been used for tests. The specific machine has a load capacity of 5 kN and a global run of 110 mm. A proprietary conformal gripping system is used which adopts the specific specimen shape as in figure 4 with its dimensions. MaCh5 and the specific specimen gripping ends are discussed in [17].

The final test setup is depicted in figure 5. Load is measured by means of the onboard 5kN load cell (with an accuracy of 0.005 N). A commercial 3rd party extensometer directly connected to MaCh5 apparatus is used for accurate strain measure; the extensometer gage length is 50 mm. Tests were performed at a crosshead speed of 5 mm/min with 5 Hz sampling rate.

6. Experimental sample.

As previously stated, the collected experimental sample consists of 23 batches of 3 specimens each. 19 samples were produced using FFF technique with generic PLA filament. The remaining 4 batches, manufactured with an HP Multi Jet Fusion machine, are not relevant for this work1.

The experimental sample here analysed is composed by 13 makers, 11 filament manufacturer, 9 filament colours, 3 specialized filaments (other than standard), 7 FFF printers manufacturers, 4 build plate temperatures and 3 slicing software. All the characteristics are commercially available (no custom or self-made elements), an outlook of the them is given in table 3.

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1 Results are available for share upon request.
Figure 4. MaCh3D specimen [17].

Figure 5. MaCh5 experimental setup.

Table 3. Experimental sample composition and details.

| Filament      | Printer             | Process | Software |
|---------------|---------------------|---------|----------|
| Manufacturer  | Manufacturer/Model  | Plate temp | Slicer   |
| 3DJAKE        | Anycubic           | 0       | Cura     |
| Amazon        | Bq/WITBOX 1        | 40      | Prusa    |
| EOLAS         | Creality/CR-10S    | 50      | Simplify3D |
| FILOALFA      | Geeetech/Ender 3   | 60      |          |
| Makerbot      | Prusa/Ender 3 Pro  |         |          |
| Prusa Research| Wasp/Geetech/13 Pro B |         |          |
| Raise3D       | 3DPR               |         |          |
| RS components | Prusa/I3-MK3        |         |          |
| Smart Material| Wasp/4070          |         |          |
| SUNLU         | 3DPR/Cubo          |         |          |
| Formfutura    |                     |         |          |
7. Results.
Each specimen is measured in width (w) and thickness (t) at 3 points along its constant section length. Average width (w) and thickness (t) were calculated and used for determination of the cross-sectional area (A) of the specimen. The weight (Q) of each specimen is measured with a Mettler PE 600 weighing scale with an accuracy of 0.01 g. From each tensile test the following mechanical parameters were recorded: Young modulus, E; Proof stress at 0.2% deviation, \( \sigma_{p0.2} \); Maximum stress, \( \sigma_{\text{max}} \); Failure stress, \( \sigma_f \); Failure strain, \( \varepsilon_f \). For each tested batch, average values and standard deviation have been determined.

The overall results of the round-robin experiment are summarized in table 4. PLA material manufactured with FFF technique, from different printing systems, starting from different PLA filaments shows widely dispersed mechanical properties, that are generically poorer than injection moulded PLA material. Young modulus and proof stress have a variability of about 35%, while the maximum and the failure stresses are less dispersed with a 25% variability. Large deviation is present in elongations data, with a dispersion higher than 60%.

Table 5 and 6 shows the results for each tested batch. Stress-strain plots for the entire experiment are shown in figure 6. In some cases, failure strain was not recorded because of out-of-scale measures. Within each single batch, repeatability of mechanical properties is definitely better than those of the overall experiment. For example, Young modulus and stress parameters have a dispersion lower than 5% except some isolated cases.

Referring to stress-strain curves, a region of the \( \sigma, \varepsilon \) space in which wider portion of tested specimen are located can be identified as shown in figure 6 (b). Two exceptions occur: Batch ID N20-218, shows a curve that is slightly under the region defined by other batches; the batch refers to a material with “shiny” colour characteristic. This is the only batch with this specification, although no strong conclusions can be taken, it seems that the “shiny” characteristic leads to a material with lower stiffness and lower maximum stress but slightly higher elongation and tenacity. Another region is then described by batches ID J9-81, K8-80 and L7-80, showing poor mechanical performance and large elongations. All of these batches come from a single printing system, using different filaments. According specimens weights, it seems that the printing system suffered of under-extrusion issue, leading to low-weight specimens and entailing poor mechanical behaviour.

### Table 4. Summary of mechanical properties for the entire experiment.

|       | \( E \) (MPa) | \( \sigma_{p0.2} \) (MPa) | \( \sigma_{\text{max}} \) (MPa) | \( \varepsilon_{\text{Rmax}} \) (mm/mm) | \( \sigma_{\text{ult}} \) (MPa) | \( \varepsilon_{\text{ult}} \) (mm/mm) |
|-------|---------------|----------------------|------------------------|--------------------------------------|---------------------|---------------------|
| mean  | 2428.9        | 35.8                 | 40.8                   | 0.0284                               | 38.6                | 0.0412              |
| std.dev. | 874.8        | 13.3                 | 11.0                   | 0.0187                               | 9.7                 | 0.0238              |
| MAX   | 3521.8        | 53.1                 | 54.2                   | 0.0904                               | 50.6                | 0.0903              |
| MIN   | 997.8         | 10.5                 | 13.2                   | 0.0158                               | 12.7                | 0.0161              |
| CV    | 36.0%         | 37.2%                | 27.0%                  | 65.8%                                | 25.0%               | 57.9%               |
| Ref. values [18] | 3500 | 70 | 60 | -- | 60 | 0.07 |


Table 5. Summary of geometrical parameters and weights of each batch.

| Batch Id | w, width | t, thickness | A, cross-section | Q, weight |
|----------|----------|--------------|------------------|-----------|
| J10-94  | mean mm  | std.dev. mm | CV %             | mean g    | std.dev. g | CV %     |
| J10-94  | 12.93    | 0.17        | 1.3%             | 3.02      | 0.01       | 4%       |
| J9-81   | 12.95    | 0.03        | 2%               | 2.70      | 0.03       | 1%       |
| L7-80   | 12.94    | 0.03        | 2%               | 2.69      | 0.05       | 2%       |
| K8-80   | 12.96    | 0.02        | 2%               | 2.89      | 0.04       | 1.2%     |
| M6-68   | 12.96    | 0.03        | 2%               | 2.93      | 0.03       | 0.9%     |
| M5-68   | 13.01    | 0.02        | 1%               | 2.95      | 0.03       | 1%       |
| L1-4    | 12.97    | 0.02        | 2%               | 2.86      | 0.02       | 0.6%     |
| L1-7-82 | 12.96    | 0.03        | 2%               | 2.84      | 0.02       | 0.7%     |
| I2-197  | 13.01    | 0.01        | 0.1%             | 2.88      | 0.03       | 1.1%     |
| I3-217  | 12.98    | 0.02        | 2%               | 2.86      | 0.03       | 0.9%     |
| N20-218 | 12.94    | 0.02        | 2%               | 2.85      | 0.02       | 0.7%     |
| J11-198 | 12.89    | 0.01        | 0.2%             | 2.88      | 0.02       | 0.8%     |
| J12-189 | 12.99    | 0.03        | 2%               | 2.86      | 0.02       | 0.5%     |
| M13-189 | 13.07    | 0.02        | 2%               | 2.99      | 0.02       | 0.8%     |
| J18-217 | 12.85    | 0.02        | 2%               | 2.83      | 0.02       | 0.6%     |
| O27-133 | 12.83    | 0.02        | 2%               | 2.84      | 0.02       | 0.8%     |
| J28-104 | 12.81    | 0.01        | 0.1%             | 2.88      | 0.03       | 1%       |
| K16-176 | 13.62    | 0.14        | 1.1%             | 2.77      | 0.10       | 3.6%     |
| O29-171 | 13.01    | 0.08        | 0.6%             | 3.09      | 0.08       | 2.5%     |

Table 6. Summary of mechanical properties of each batch.

| Batch Id | E, Young modulus | σ<sub>0.02</sub>, proof stress | σ<sub>max</sub>, max stress | σ<sub>Failure</sub> | γ<sub>Failure</sub> |
|----------|------------------|---------------------------------|-----------------------------|-------------------|-------------------|
|          | mean MPa         | mean MPa                        | mean MPa                    | mean MPa          | mean %            |
| J10-94  | 2589.9           | 14.7                            | 45.4                         | 41.6              | 0.0373            |
| J9-81   | 1319.4           | 11.8                            | 12.3                         | 1.5               | 0.0884            |
| L7-80   | 1207.9           | 3.6                             | 3.6                          | 1.0               | 0.3135            |
| K8-80   | 1017.5           | 3.6                             | 3.6                          | 1.0               | 0.3135            |
| M6-68   | 2668.8           | 42.4                            | 1.2                          | 1.2               | 0.3135            |
| M5-68   | 3449.6           | 48.7                            | 1.2                          | 1.2               | 0.3135            |
| L4-2    | 3288.8           | 52.0                            | 1.2                          | 1.2               | 0.3135            |
| L17-82  | 3169.9           | 45.5                            | 1.2                          | 1.2               | 0.3135            |
| I2-197  | 2988.9           | 43.9                            | 1.2                          | 1.2               | 0.3135            |
| I3-217  | 2617.4           | 36.8                            | 1.2                          | 1.2               | 0.3135            |
| N20-218 | 1776.6           | 33.8                            | 1.2                          | 1.2               | 0.3135            |
| I19-218 | 3172.3           | 50.1                            | 1.2                          | 1.2               | 0.3135            |
| J12-189 | 3029.5           | 45.4                            | 1.2                          | 1.2               | 0.3135            |
| M13-189 | 3212.2           | 44.8                            | 1.2                          | 1.2               | 0.3135            |
| J18-217 | 3316.0           | 48.0                            | 8.0                          | 1.2               | 0.3135            |
| O27-133 | 3260.2           | 47.6                            | 8.0                          | 1.2               | 0.3135            |
| J28-104 | 3275.8           | 47.7                            | 8.0                          | 1.2               | 0.3135            |
| K16-176 | 2618.3           | 35.9                            | 8.0                          | 1.2               | 0.3135            |
| O29-171 | 2686.7           | 43.3                            | 8.0                          | 1.2               | 0.3135            |
Figure 6. stress vs strain plots for the entire round-robin experiment.
8. Discussion.
Some elaborations of tensile test results were performed to verify trends and correlations between results.

8.1. Specimen dimensions and final weight.
In figure 7 (a), (b), (c) and (d), specimen width (w), thickness (t), cross-section area (A) and weight (Q) are presented, respectively, in terms of mean values and standard deviation. Comparing results, dimensional accuracy along width and thickness are not correlated together. In other terms, dimensional printing accuracy is not correlated with z-direction precision. Higher precision is shown along x-y, while in z-direction final dimensions are generally lower than nominal.

As for the cross section (A), there is a global trend towards sections with an area below the nominal value. Considering then the values of recorded weights (Q) a slight under-extrusion trend is shown. Comparing A and Q behaviours there is no apparent correlation between the two parameters.

To be noted the behaviour of batches ID J9-81, K8-80 and L7-80, which shows a large under-extrusion with no apparent relation to cross section.

8.2. Mechanical properties.
Correlating mechanical properties 2-by-2 (figure 8), some trends can be extrapolated.

Specific fractions may be calculated as follows:

\[ \frac{E \ [GPa]}{\sigma_{\text{max}} [MPa]} = 65.2 \]
\[ \frac{\sigma_{p0.2}}{\sigma_{\text{max}}} = 0.96 \]
\[ \frac{\sigma_f}{\sigma_{\text{max}}} = 0.90 \]

Considering elongation, an exponential correlation is shown between Young modulus (E) and failure strain (\( \varepsilon_f \)).

8.3. Mechanical properties versus specimen weight.
Correlating the mechanical properties versus effective weight (Q), as shown in figure 9 for Young modulus and maximum stress, an exponential law apparently fit experimental data with good approximation.

Defining a coefficient U, called “extrusion coefficient”, defined as the fraction between final effective weight (\( Q_{\text{eff}} \)) and nominal weight (\( Q_n \)) of the FFF manufactured components:

\[ U = \frac{Q_{\text{eff}}}{Q_n} \]

in addition to be an efficient and easy check for manufacturing quality, it may allow to a preliminary evaluation of the mechanical properties of the material itself.

8.4. Mechanical properties versus build plate temperature.
Considering the build plate temperature, plotting, for example, maximum stress versus this parameter reveals that it has no influence in mechanical properties. A flat regression line is shown if excluding the points that are affected from other parameters.

8.5. Miscellaneous.
The influence of material manufacturer and printer system on mechanical properties can be found into results, isolating available and comparable data. The same is for material colour and material specification. The numerosity of the experimental sample and the data dispersion do not allow to define trends and any further consideration, if not those of the necessity of a significatively wider statistical population or a more confined one, for example addressing a specific hardware (printer manufacturer), material manufacturer, material characteristic and maybe colour.
Figure 7. Comparison of geometrical properties and weights.
Figure 8. Correlation between mechanical properties.

Figure 9. Correlation between mechanical properties and effective weight.
9. Conclusions.
Arose from the observation of different aesthetical and mechanical properties of parts produced through FFF using same material type but produced by different printing systems and Makers, the research studied the influence of non-commonly studied parameters on the mechanical properties of FFF manufactured PLA material. Distributed production was possible thanks to participation of Makers4Parma network.

Mechanical properties were measured on 19 batches of specimens produced with PLA filament according to a completely defined printing setup. Large dispersion in mechanical properties is shown on both stiffness, strength and elongation. Nonetheless, a correlation between Yield strength, proof stress, and final stress versus maximum stress is shown.

The mechanical properties most influencing parameter is the final mass of the manufacture. The defined extrusion coefficient is a governing parameter for the evaluation of the final mechanical properties of the FFF manufactured material.

Geometrical precision of the printing machine does not clearly show a significative effect on mechanical properties nor a correlation with the final mass of the samples.

The collected test samples were not enough to extrapolate influences of material manufacturer and printer system on material mechanical properties, although an influence is enlightened.

Being this preliminary stage of the round-robin for Additive Manufacturing experiment successfully concluded, the next stage of the project consists in an open call for makers to submit batches of specimens for a longer period of time, reaching a wider range of users. The possibility of restricting research variables (for example addressing a single material manufacturer) has been considered.

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