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On the fatigue strength of 3D-printed polylactide (PLA)

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Abstract

This paper aims to review quantitatively our understanding of the fatigue behavior of additively manufactured (AM) polylactide (PLA). A number of data sets were selected from the technical literature and statistically re-analyzed in terms of S-N curves to define a reference value both for the negative inverse slope and the endurance limit extrapolated at $2{\cdot}10^6$ cycles to failure. The experimental results being post-processed suggest that, as far as AM PLA is concerned, the mean stress effect in fatigue can be modelled by simply using the maximum stress in the cycle. Further, since the printing direction appears to have little effect on the overall fatigue behavior of AM PLA, the stress/strength analysis can be performed effectively by treating this polymer as a homogenous, isotropic and linear-elastic material. According to the statistical re-analysis discussed in the present paper, when appropriate experimental results cannot be generated, the fatigue assessment (for a probability of survival larger than 95%) can be performed by using a reference fatigue curve with negative inverse slope equal to 5.5 and endurance limit (at $2{\cdot}10^6$ cycles to failure) equal to 10% of the material ultimate tensile strength.

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Keywords: Additive manufacturing; polylactide (PLA); fatigue; design curve.

1. Introduction

According to the definition given by ASTM Committee F42, Additive Manufacturing (AM) is *"the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"*.

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Nomenclature

k	negative inverse slope
N_f	number of cycles to failure
N_0	reference number of cycles to failure ($N_0=2\cdot10^6$ cycles to failure)
P_S	probability of survival
R	stress ratio ($R=\sigma_{min}/\sigma_{max}$)
T_σ	scatter ratio of the endurance limit, σ_{MAX}, for 90% and 10% probabilities of survival
θ_f	orientation of the additively manufactured filaments
σ_a	stress amplitude
σ_m	mean stress
σ_{max}	maximum stress in the fatigue cycle
σ_{MAX}	endurance limit at N_0 cycles to failure (in terms of maximum stress in the fatigue cycle)
σ_{min}	minimum stress in the fatigue cycle
σ_{UTS}	ultimate tensile strength

Thanks to its unique features, AM allows objects with complex geometries to be manufactured at a relatively low cost, with this being done by always reaching a high level of accuracy in terms of both dimensions and shape.

Due to the important role AM is expected to play in the near future, systematic R&D activities have been carried out in recent years worldwide so that, nowadays, the technologies to fabricate AM components efficiently are directly available to industry. In this context, examination of the state of the art shows that the most advanced AM techniques allow objects to be fabricated using metals, polymers, composite materials and concrete.

As far as polymers are concerned, a number of different commercial 3D-printers are available in the market that can be used to manufacture objects made of either acrylonitrile butadiene styrene (ABS) or polylactide (PLA). In terms of technological process, polymers are usually additively manufactured (AM) by melting/extruding either powders, wires, or flat sheets.

PLA is a biodegradable, absorbable and biocompatible thermoplastic aliphatic polyester that is widely used for rapid prototyping, to manufacture tools, jigs, and fixtures designed to maximize the production efficiency, and to make biomedical components with complex shape.

Examination of the state of the art shows that since the beginning of the 2000s, the international scientific/industrial community has focused its attention mainly on the development of the manufacturing technology, with this being done by trying to increase the level of productivity by simultaneously reducing the fabrication costs.

Owing to the high level of maturity that characterizes AM of polymers, the next step to fully exploit this powerful technology is reducing the risk of incurring in-service fatigue failures of 3D-printed components made of PLA. To this end, practitioners must be provided with rules suitable for efficiently guiding and informing the design process. In this challenging scenario, the present paper aims to review the-state-of-the-art knowledge of fatigue of AM PLA to give quantitative recommendations helping engineers to perform the fatigue assessment in situations of practical interest.

2. PLA's strength vs. manufacturing variables

Given the parent material, the mechanical behavior of AM PLA under both static (Ahmed, Susmel 2017a, 2017b, and 2018; Ezeh, Susmel 2017) and fatigue loading (Jerez-Mesa et al. 2017) is seen to be influenced mainly by the following parameters: layer thickness, infill percentage, nozzle size, manufacturing orientation, filling pattern, filling rate, feed rate, manufacturing rate, and filling temperature. Another important variable that affects the overall mechanical behavior of objects made of AM polymers is the shell thickness, where the shell plays the role of a perimetric retaining wall. In terms of manufacturing process, when a new layer is being manufactured, the shells are always the first structural elements that are built up by the 3D-printer. According to good practice in AM of PLA objects, the thickness of the shell is recommended to be set equal to a multiple of the nozzle diameter so that the formation of voids and manufacturing defects can be limited and controlled effectively.

If attention is focused on the static behavior of AM components of PLA, the material ultimate tensile strength and the elastic modulus tend to decrease both as the infill angle increases and as thickness of the shell decreases (Lanzotti et al. 2013). In this context, the static strength is seen to depend also on the thickness of the layers (Chacón et al. 2017). In terms of stress-strain response, the mechanical behavior of AM PLA is seen to be predominantly brittle, with the level of ductility varying as the printing direction changes (Ahmed, Susmel 2018; Song et al. 2017).

According to these considerations, strictly speaking, all the key manufacturing variables listed above are seen to affect the overall mechanical response of AM PLA. However, in terms of engineering static assessment, much experimental evidence suggests that the effect of these parameters on the elastic modulus, the yield stress and the ultimate tensile strength can be neglected with little loss of accuracy. This means that, for design purposes, AM PLA can be treated simply as a homogenous, isotropic, and linear-elastic material (Ahmed, Susmel 2018).

Turning to the fatigue behavior, the detailed experimental investigation carried out by Jerez-Mesa et al. (2017) demonstrates that layer height, nozzle diameter, fill density, and printing speed affect the overall fatigue strength in a very complex way, with mutual interactions/effects being difficult to be assessed and quantified without performing time consuming and expensive experimental trials. In this context, it is important to highlight that, according to the Taguchi Experimental Design carried out by Jerez-Mesa et al. (2017) the fatigue strength of the AM polymer being tested reached its maximum value for a fill density of 75% and not of 100% as one would expect.

The considerations reported in the present section clearly suggest that more systematic experimental work needs to be done in order to understand and quantify the effect on the mechanical behavior of AM PLA of the different manufacturing variables. In this context, in the next section attention will be focused solely on fatigue with the aim of deriving some practical rules suitable for designing AM PLA against cyclic loading.

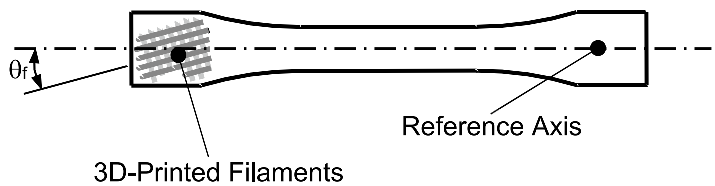

Fig. 1. Definition of manufacturing angle θ_f.

3. Fatigue strength of AM PLA

Letcher and Waytashek (2014) tested, under fully-reversed (i.e., $R=\sigma_{min}/\sigma_{max}=-1$) axial loading, un-notched specimens of PLA manufactured by using commercial 3D-printer MakerBot Replicator 2x. The samples were fabricated flat on the build-plate, with the infill level being set equal to 100%. The bulk material of the specimens was manufactured by using three different raster orientations, i.e., by setting manufacturing angle θ_f equal to 0°, 45° and 90° (see Figure 1 for the definition of angle θ_f). The specimens had rectangular cross-section with width equal to 13mm and thickness to 6mm.

The results generated by Letcher and Waytashek (2014) are summarized in the S-N charts of Figure 2 that plot the maximum stress in the cycle, σ_{max}, against the number of cycles to failure, N_f. The scatter bands reported in these graphs are delimited by two straight lines that correspond to a probability of survival, P_S, equal to 90% and 10%, respectively. They were determined under the hypothesis of a log-normal distribution of the number of cycles to failure for each stress level and assuming a confidence level equal to 95% (Al Zamzami, Susmel 2017). The results from the re-analyses of the data is summarized in Figure 2 and in Table 1 in terms of negative inverse slope, k, endurance limit, $\sigma_{MAX,\ 50\%}$, at $2\cdot10^6$ cycles to failure for a probability of survival, P_S, equal to 50% and scatter ratio of the endurance limit for 90% and 10% probabilities of survival, T_σ.

Table 1. Summary of the results from the statistical re-analyses.

Reference	Fabrication Technology	θ_f [°]	σ_{UTS} [MPa]	R	k	$\sigma_{MAX,\,50\%}$ [(a)] [MPa]	T_σ
Letcher et al. (2014)	AM	0	58.5	-1	5.1	7.4	1.579
Letcher et al. (2014)	AM	45	64.0	-1	6.4	11.0	1.422
Letcher et al. (2014)	AM	90	54.0	-1	4.8	6.2	1.415
Afrose et al. (2016)	AM	0	38.7	0	6.9	4.9	1.159
Afrose et al. (2016)	AM	45	31.1	0	5.9	5.0	1.207
Afrose et al. (2016)	AM	90	33.6	0	5.1	3.4	1.324
Averett et al. (2011)	Standard	-	58.0	0	5.0	9.8	1.397

[(a)]Endurance limit extrapolated at $N_0=2\cdot10^6$ cycles to failure.

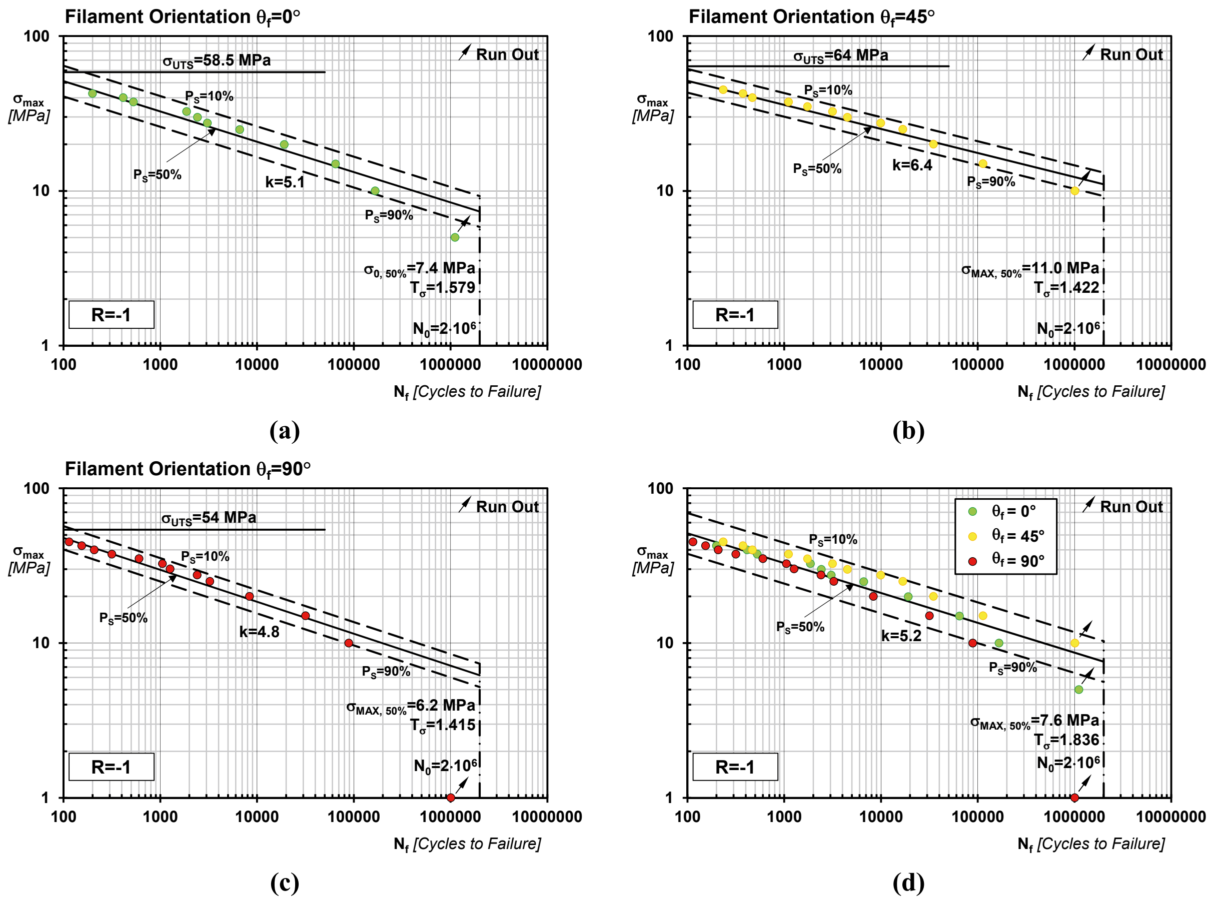

Fig. 2. S-N curves determined by post-processing the experimental results generated by Letcher and Waytashek (2014).

The charts of Figures 2a to 2c together with Table 1 show that both k and $\sigma_{MAX,\,50\%}$ are not influenced markedly by manufacturing angle θ_f, with the fatigue strength being directly related to the static strength.

Owing to the high level of consistency between data sets generated by testing specimens with different values for angle θ_f, the same results were also re-analyzed together as shown in Figure 2d. This chart confirms that, similar to what is observed under static loading (Ahmed, Susmel 2018), also the fatigue results obtained from specimens with different raster orientations can effectively be summarized by using one single scatter band, with such an assumption resulting just in little loss of accuracy. In other words, considering the physiological scattering that always characterizes fatigue data, Figure 2d strongly supports the idea that the fatigue assessment of AM PLA can be performed accurately by simply treating the material as homogeneous and isotropic.

By using 3D-printer Cube-2, Afrose et al. (2016) additively manufactured a series of dog-bone flat specimens having net width equal to 10mm and thickness to 4mm. To investigate the effect of the raster orientation, these samples were fabricated by setting angle θ_f (defined according to Figure 1) equal to 0°, 45° and 90°. The fatigue tests were carried out, in the low-cycle fatigue regime, under zero-tension uniaxial loading (R=0) at a frequency of 1Hz.

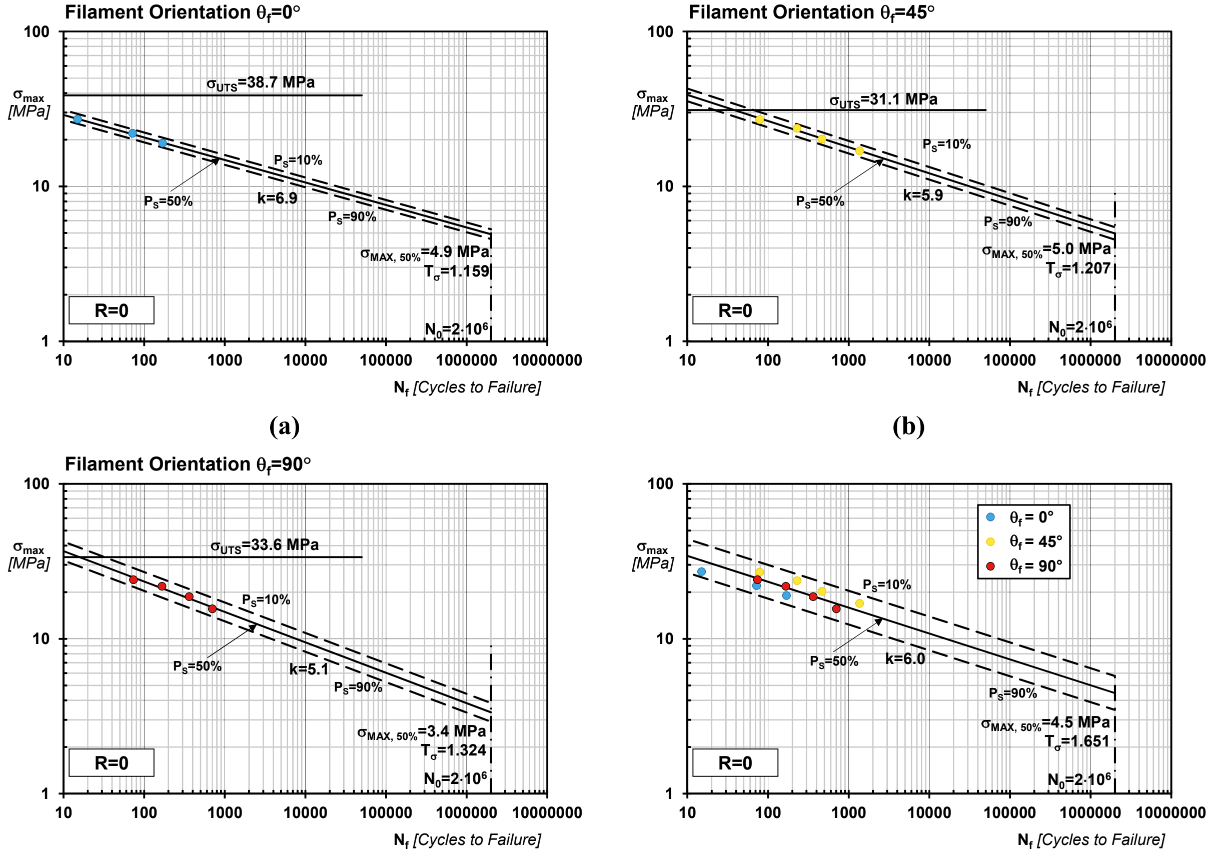

Fig. 3. S-N curves determined by post-processing the experimental results generated by Afrose et al. (2016).

The experimental results generated by Afrose et al. (2016) were re-analyzed by adopting the same strategy as the one that was used to post-process the previous data sets, with the obtained results being summarized in the S-N charts of Figure 3 as well as in Table 1. As to the results obtained from the statistical analysis, it is interesting to observe that the values determined both for k and $\sigma_{MAX,\,50\%}$ are very close to those derived by post-processing the results generated by Letcher and Waytashek (2014) – see Table 1. This result is particularly interesting especially in light of the fact that Afrose et al. (2016) tested their specimens under R=0, whereas Letcher and Waytashek (2014) considered fully-reversed constant amplitude load histories (i.e., R=-1). This suggests that the mean stress effect in fatigue of AM PLA can efficiently be taken into account by addressing the problem simply in terms of σ_{max} – as done recently, for instance, for concrete (Susmel 2014; Jadallah et al. 2016). The validity of this hypothesis can also be justified by observing that, by definition, σ_{max} implicitly contains the mean stress information, since:

$$\sigma_{max} = \sigma_m + \sigma_a \tag{1}$$

According to the above considerations, the experimental data generated both by Letcher and Waytashek (2014) and by Afrose et al. (2016) were then attempted to be re-analyzed together by simply dividing the maximum stress by the material ultimate strength. The result of this normalization process is shown in the graph of Figure 4, where, for design purposes, the scatter band was determined for a probability of survival, P_S, equal to 99% and 1%.

The low value for T_σ obtained from this normalization process (see Figure 4) seems to strongly support the idea that the overall fatigue strength of AM PLA is closely related to its static strength, with the mean stress effect being modelled effectively via σ_{max}.

According to the experimental results as summarized in Figure 4, a reference S-N curve suitable for designing against fatigue AM PLA with infill level equal to 100% can be proposed as follows:

$$k=5.5 \tag{2}$$

$$\sigma_{MAX}=0.1\cdot\sigma_{UTS} \quad \text{at } N_0=2\cdot10^6 \text{ cycles to failure for } P_S\geq95\% \tag{3}$$

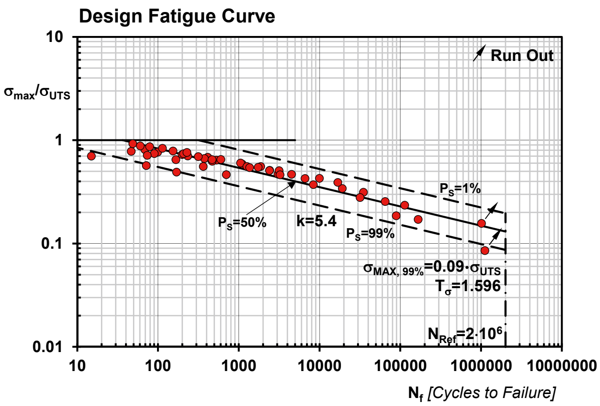

Fig. 4. Normalized Design Fatigue Curve (for an infill level equal to 100%) determined by post-processing the data generated both by Letcher and Waytashek (2014) and by Afrose et al. (2016).

Another important manufacturing parameter that has to be consider in detail is the infill level. Jerez-Mesa et al. (2017) tested, under rotating bending, a number of cylindrical specimens of AM PLA that were manufactured by setting the nozzle diameter equal to 0.5mm, the layer height to 0.3mm, and the fill density equal to 75%. The results generated by Jerez-Mesa et al. (2017) are summarized in the S-N chart of Figure 5, with the statistical re-analysis being performed according to the same procedure followed to post-process the data reported in Figures 2 to 4. The chart of Figure 5 shows that an infill level of 75% resulted in a fatigue curve having negative inverse slope equal to 3.5, i.e., much lower than the average value of 5.5, Eq. (2), characterizing the fatigue behavior of AM PLA with fill density equal to 100%. This difference can be ascribed to the fact that the presence of the manufacturing voids results in localized stress concentration phenomena that have a detrimental effect on the overall fatigue behavior of AM PLA. In other words, it is possible to argue to that additively manufacturing PLA with an infill level lower than 100% results in a material that is intrinsically notched.

To conclude the present re-analysis, in the S-N chart of Figure 6 (see also Table 1) a series of fatigue results generated by testing standard PLA (Averett et al. 2011) is compared to the data obtained by testing AM PLA (Letcher, Waytashek 2014; Afrose et al. 2016). This chart makes it evident that the fatigue strength of standard PLA is just slightly higher than the one of AM PLA, with the experimental results generated by testing conventional PLA still falling within the reference scatter band as determined in Figure 4. This confirms that, as far as PLA is concerned, AM is capable of fabricating components showing a fatigue performance similar to the one characterizing components manufactured using conventional and well-established technologies.

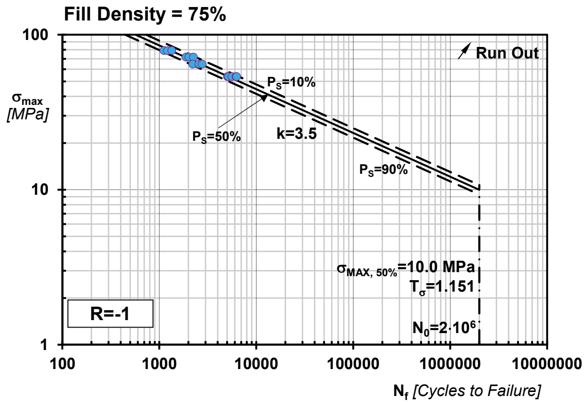

Fig. 5. S-N curve determined by post-processing the experimental results generated by Jerez-Mesa et al. (2017) by testing under rotating bending cylindrical specimens of AM PLA manufactured by setting the infill level equal to 75%.

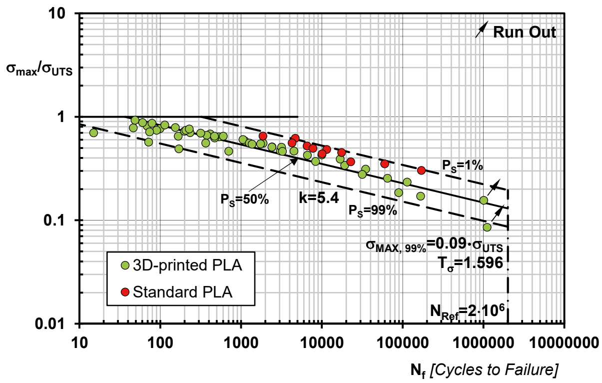

Fig. 6. Fatigue strength of standard PLA (Averett et al. 2011) vs. fatigue strength of AM PLA.

4. Conclusions

By post-processing a number of experimental results taken from the technical literature and generated by testing un-notched specimens, the fatigue behavior of AM PLA was investigated by focusing attention on the effect of (i) raster orientations, (ii) non-zero mean stress, and (iii) infill level. According to the outcomes from this investigation, the following conclusions can be drawn (for a fill density of 100%):

- as per the static case, the fatigue strength of AM PLA is seen to be affected marginally by the raster orientation;
- since the effect of the filaments' orientation on the fatigue behavior of AM PLA can be neglected with little loss of accuracy, for fatigue design purposes, AM PLA can be modelled as a homogenous and isotropic material;
- the mean stress effect in fatigue of AM PLA can be assessed in terms of maximum stress in the cycle;
- when appropriate experiments cannot be run, components of AM PLA can be designed against fatigue (for $P_S \geq 95\%$) by using a reference design curve having negative inverse slope, k, equal to 5.5 and endurance limit (determined in terms of maximum stress and extrapolated at $2\cdot10^6$ cycles to failure) equal to $0.1\cdot\sigma_{UTS}$;
- AM PLA is characterized by a fatigue performance similar to the one of PLA manufactured using conventional and well-established technologies;

- AM PLA manufactured with an infill level lower than 100% behaves like an intrinsically notched material, with this lowering the material's overall fatigue strength.

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